Evaluation of the selectivity of herbicides as potential replacements for atrazine in forestry

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Summary

With the imminent withdrawal from the market of the herbicide atrazine, alternative treatments need to be identified for pre and post-emergence control of weeds in newly-planted forestry and farm woodland in the UK. To assist in the identification of replacement herbicides, one container based and two field experiments investigated the tolerance of young trees to a range of different products.

In the container experiment, pyridate was well tolerated by all species (*Acer pseudoplatanus* L., *Fagus sylvatica* L., *Fraxinus excelsior* L., *Larix kaempferi* (Lindl.) Carriere, *Pinus nigra* ssp. *laricio* Maire, *Prunus avium* (L.) L., *Populus x canadensis* Moench and *Quercus robur* L.) when applied in May or August; localised leaf injury on some broadleaved species was soon outgrown. Cyanazine caused short term leaf damage to broadleaved tree species but generally no long term adverse effects at the recommended dose. The mixture of cyanazine plus terbuthylazine caused unacceptable injury to the broadleaved species but was safe on the conifers when applied in August. Amidosulfuron generally had no long-term adverse effects but tribenuron-methyl was more damaging on some broadleaved species.

In a field experiment the tolerance of nine tree species (*A. pseudoplatanus, F. excelsior, P. avium, P. canadensis, Q. robur, P. nigra* ssp. *laricio, Pseudotsuga menziesii* (Mirb.) Franco, *Picea abies* (L.) H. Karst and *Picea sitchensis* (Bong.) Carriere to a range of foliar-acting herbicides applied alone and in mixture with pendimethalin was tested. Amidosulfuron, diflufenican plus terbuthylazine, pyridate and tribenuron-methyl applied alone and in mixture with pendimethalin, as directed, sprays to the base of dormant trees in February appeared to be well tolerated by all species. Mixtures with the foliar-acting herbicide glyphosate caused shoot damage in the sprayed area but no greater than that caused by glyphosate alone. Paraquat alone or in mixture with pendimethalin, applied to tree bases in February did not appear to damage broadleaved species, but did damage sprayed shoots of all conifer species. Dichlobenil applied in February as a granular product appeared to be safe on most species but caused marked leaf-margin chlorosis on cherry. A mixture of clopyralid, cycloxydim and metazachlor applied over foliage on tree bases in May did not appear to cause long-term damage.

In a further field experiment, florasulam and amidosulfuron applied over the same nine species of trees in March when dormant had no adverse effect; treatment with these herbicides at flushing in May did not appear to cause damage to coniferous species, but did cause severe damage to *P. avium* and short-term leaf chlorosis, necrosis and stunting of *A. pseudoplatanus, F. excelsior, P. canadensis* and *Q. robur*.

Of the herbicides tested, only dichlobenil is likely to be immediately available as a direct alternative for atrazine in certain limited situations, but even then any treatment using this active ingredient will almost certainly be considerably more expensive than the use of triazines. The results reported here identify other herbicides that have the potential for use in combination in mixtures as possible substitutes for atrazine, but additional work on crop tolerance and efficacy is required.

Introduction

Atrazine has been widely and successfully used in forestry for many years (Willoughby and Dewar 1995). This is largely because it is relatively cheap, selective to trees, generally extremely effective for pre and post-emergence weed control, and hence provides cost effective long-term control of most annual and perennial weed species (Willoughby and Dewar 1995). Other triazines can also be very effective. Cyanazine mixed with lower doses of atrazine has also been used for pre and post-emergence weed control in newly-planted farm woodland (Willoughby and Clay 1996). Although no longer approved for use in the UK, terbuthylazine has been used in the past in forestry to give broad-spectrum weed control whilst being safe as an overall treatment on conifers and dormant broadleaved trees (McCavish and Turner 1984; Williamson and Tabbush 1988).

However, the use of atrazine and other triazine herbicides is being restricted in many countries because of concerns about the contamination of ground water. Following review under EU Directive 91/414, in most European countries atrazine and cyanazine have already been withdrawn from use, but 'essential use' provisions allow these actives to continue to be used until 2007 in the UK (Whitehead 2006). There is therefore a pressing need to develop alternative weed control treatments. Although some alternatives to the use of herbicides exist and should be utilised as a first resort where possible (Willoughby *et al.* 2004), the immediate adoption of a wholly chemical free approach is unlikely to be practical in many situations given the cost implications, particularly in afforestation and restocking on more fertile soils. If herbicides still need to be used, to minimise inputs, atrazine alternatives would ideally comprise selective, non-residual, contact herbicides applied as spot treatments only to potentially competitive weed species.

However, in practice in forestry and farm woodland plantings, a variety of annual and perennial weeds emerge over a long period of time, the crop has little suppressing effect in early years, and there is little information on which species are non competitive to guide decisions on the need for treatment or product choice. Therefore, the use of a post-planting broad-spectrum residual herbicide may be attractive to some managers as it might significantly reduce the number of subsequent treatments that are necessary. As no single herbicide may be able to directly replace triazines, a range of treatments need to be available, including herbicides with pre and post- emergence activity. There is also a need to establish the crop safety of product mixtures and sequences.

There are few other broad-spectrum herbicides, selective to crop species, that are recommended for use in forestry situations in the UK (Whitehead 2006). Grass species can be controlled in winter by propyzamide and in the growing season with selective graminicides such as cycloxydim, fluazifop-p-butyl and propaquizafop (Willoughby and Clay 1996). Isoxaben, metamitron and metazachlor can be used as pre-emergence treatments in forestry plantings generally, and lenacil and pendimethalin in farm woodland, but these are not effective on emerged weeds. Clopyralid is also approved for post-emergence weed control in forestry and farm woodland and can be used as an overall spray in many species (Dixon *et al.*, 2005). Dichlobenil as a granule treatment is recommended for long-term control of weeds in established amenity trees in the UK (Whitehead 2006). It has been used in the past in forestry situations (Mayhead 1975), however it is a relatively expensive treatment (Willoughby and Clay 1999), and can cause damage to conifers where granules build up next to stem bases through wind or water movement (Anon. 1975). Apart from these selective treatments, directed spraying of broad-spectrum herbicides such as glyphosate or glufosinate-ammonium may give satisfactory control but there is risk of significant crop damage from misapplication (Willoughby and Dewar 1995; Willoughby 1996; McCavish and Insley 1998). A number of herbicides used in agricultural crops in the UK may be suitable for use in forestry, farm woodland and nurseries if satisfactory crop tolerance is found. Under the current UK long term off-label arrangements, some of these could be used automatically, subject to observing dose limits and conditions of use requirements, while others would need specific off-label approval before use (Whitehead 2006).

Foliar-acting sulfonyl urea herbicides have become widely and successfully used for broadleaved weed control in arable crops in the UK where they are often perceived to be environmentally benign because of the very low quantities of active ingredients used, limited soil persistence and their low mammalian toxicity (Tomlin 1997). There is limited information on the tolerance of commonly grown forestry species to these herbicides and on their potential for control of emerged weeds in such situations. In tests of tree tolerance, thifensulfuron-methyl and tribenuron-methyl caused damage to small broadleaved tree seedlings but not conifer seedlings (Clay *et al.* 1992). Overall spraying of tribenuron-methyl damaged shoots from newly-planted cuttings of *Populus* and *Salix* species (Clay and Dixon 1993). On larger transplants of broadleaved and coniferous tree species thifensulfuron and tribenuron methyl were generally safe at most application dates (Lawrie and Clay 1994a, b; Jimenez and Saavedra (1997). Fraser *et al.* (2001) reported tolerance of dormant broadleaved tree species to amidosulfuron and florasulam but damage on actively growing trees from amidosulfuron but not florasulam. Britt *et al.* (2000) found mixtures of amidosulfuron with pendimethalin very phytotoxic to actively growing *Salix viminalis* L. (willow). These results suggest that sulfonyl urea herbicides may be selective as overall sprays on dormant trees and directed sprays in the growing season but further investigation of tolerance is needed.

Other candidate herbicides are diflufenican (DFF) and pyridate. DFF has contact and residual activity on a wide range of weeds up to the small seedling stage (Tomlin 1997). In tests of pre emergence selectivity, conifer species were undamaged by post-sowing treatments (Clay *et al.* 1988) and newly planted trees by post-planting applications (Britt and Smith 1996). Cuttings of *Populus* and *Salix* species were not damaged by overall sprays of DFF plus isoproturon in spring (Clay and Dixon 1996). Britt *et al.* (2000) concluded that DFF was of low phytotoxicity to actively growing *Salix viminalis*. Pyridate is a foliar-acting herbicide effective on a wide range of broadleaved weed species when applied to small actively growing seedlings (Dixon and Clay 2004). Overall spraying of *Populus* and *Salix* species in active growth has given only slight short-term damage (Dixon and Clay 1996) suggesting it may be selective on tree species.

In order to achieve broad-spectrum weed control in late winter, mixtures of herbicides with contact and residual activity are likely to be required, but there is little information on crop tolerance. Similarly, mixtures of foliar-acting herbicides may be needed for use post flushing in spring. Dixon *et al.* (2005) found no increase in phytotoxicity from mixtures of clopyralid and graminicides compared with individual herbicides, but information on the effects on trees of other combinations is needed.

Given the imminent withdrawal of triazines from the market, it seems opportune to review the data from previously unpublished tree tolerance experiments carried out in recent years, to see if any potential replacements can be identified. Hence in this paper three previously unreported experiments are detailed. The tolerance of eight tree species grown outside in containers, to cyanazine, cyanazine plus terbuthylazine, pyridate, amidosulfuron and tribenuron methyl was investigated in Experiment 1, whilst Eexperiments 2 and 3 investigated the tolerance of established trees of nine species to various combinations of amidosulfuron, glyphosate, paraquat, pyridate, tribenuron methyl, diflufenican, pendimethalin, metazachlor, cycloxydim, clopyralid and florasulam.

Materials and methods

Experiment 1 – within growing season treatments

In March 1994 two-year-old bare-rooted *Acer pseudoplatanus* L. (sycamore), *Fagus sylvatica* L. (beech), *Fraxinus excelsior* L. (ash), *Prunus avium* L. (cherry), *Larix kaempferi* (Lindl.) Carriere (Japanese larch), *Quercus robur* L. (oak), one-year-old rooted *Populus x canadensis* L. Moench c.v Ghoy (poplar), and two-year-old *Pinus nigra* ssp. *laricio* Maire (Corsican pine) supplied in containers were planted singly into 18cm diameter containers. The containers contained a mixture of six parts John Innes compost, four parts peat and two parts grit, to which was added 5g litre^{-1} Osmocote 8-9 month duration slow release fertiliser (18:11:10 N:P_2O_5:K_2O)

and 3.3g/ litre magnesium limestone. Trees were grown outdoors with trickle irrigation at Long Ashton Research Station, near Bristol, UK (51° 25' N, 2° 40' W). In March 1995 Osmocote fertiliser tablets (5g litre^{-1} 6 month duration) were placed in each pot and the containers were topped up with compost. Each of the eight species were was subject to five herbicide treatments at two rates, with two untreated controls, at two application dates. There were five replicates of each treatment giving 60 containers of each species at each date. Containers were set out in a randomised block design with species and application dates kept separate.

Details of herbicide products used in all experiments are given in Table 1.

Table 1. Herbicide product details (Experiments 1 - 3)

Active ingredient	Product name	Formulation	Concentration (g litre^{-1})	Manufacturer	Experiment Number
amidosulfuron	Eagle	WG	750	Aventis CropScience UK Ltd	1, 2, 3
cyanazine	Fortrol	SC	500	Feinchemie (UK) Ltd	1
cyanazine+terbuthylazine	Angle 567	SC	306:262	Ciba Agriculture	1
pyridate	Lentagran WP	WP	450	Syngenta Crop Protection UK Ltd	1, 2
tribenuron-methyl	Quantum	TB	500	DuPont (UK) Ltd	1, 2
glyphosate	Roundup Biactive	SL	360*	Monsanto (UK) Ltd	2
paraquat	Gramoxone 100	SL	200	Syngenta Crop Protection UK Ltd	2
diflufenican+terbuthylazine	Bolero	SC	200:400	Syngenta Crop Protection UK Ltd	2
pendimethalin	Stomp 400	SC	400	Cyanamid Agriculture UK	2
dichlobenil	Casoron	GR	67.5	n2n enviro Ltd	2
metazachlor	Butisan S	SC	500	BASF plc	2
cycloxydim	Laser	EC	200	BASF plc	2
clopyralid	Dow Shield	SL	200	Dow AgroSciences	2
florasulam	Boxer	SC	50	Dow AgroSciences	3

* acid equivalent

Herbicide treatments of amidosulfuron, cyanazine, cyanazine plus terbuthylazine, pyridate and tribenuron methyl were applied at the doses shown in Table 3 at two growth stages to separate sets of trees using a laboratory track sprayer fitted with a Spraying Systems 80015E nozzle at a pressure of 280 kPa and in a spray volume of 345 litres ha^{-1}. Rates were generally based upon standard rate for weed control and three times standard rate. The first application was made when the majority of trees were at first flush on the 12 and 13 May 1994 (*P. nigra* flushing was variable and hence spraying was delayed until July), and the second to growing trees on 11 August 1994.

Experiment 2 – dormant season treatments, plus cycloxydim, metazachlor and pendimethalin within growing season

The experiment was sited at Failand, near Bristol, UK (51° 27' N, 2° 41' W), in a mixed plantation of nine forestry species; five broadleaved species (*A. pseudoplatanus, F. excelsior, P. canadensis, P. avium* and *Q. robur)* and four conifers (*P. nigra* ssp. *laricio,* and *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir), *Picea abies* (L.) H. Karst (Norway spruce), *Picea sitchensis* (Bong.) Carriere (Sitka spruce)) established in 1998. Five trees of each species were planted 0.4 m apart along the plots with rows 0.5 m apart down the plot, giving plots 2 m wide by 5 m long. There were 26 herbicide treatments plus two untreated controls set out in two randomised replicate blocks. 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%.

Herbicide treatments of amidosulfuron, glyphosate, paraquat, pyridate, tribenuron methyl and diflufenican plus terbuthylazine were applied alone and in mixture with pendimethalin on 22 February 2001 at the doses shown in Tables 5 and 6 using an Oxford Precision back pack sprayer fitted with a single 8004 nozzle at 105 kPa and in a spray volume of 300 litres ha^{-1}. Dichlobenil granules and diflufenican (DFF) plus terbuthylazine in mixture with glyphosate +/- pendimethalin were also applied at the doses shown in Tables 5 and 6. Metazachlor was applied alone and in mixture with cycloxydim with Actipron a non ionic surfactant added at 0.8% of the spray volume and clopyralid on 18 June at the doses shown in Table 6. Herbicides were sprayed between the rows covering the basal 15 cm of the broadleaved species and to the top of the canopy between the conifer rows. Dichlobenil granules were applied to the soil between the trees using a hand held pepper pot applicator (15.6 g product per inter row).

Experiment 3 – dormant and within growing season treatments with amidosulfuron and florasulam

The experiment used the same plantation of trees as for Experiment 2. To make treatment easier, the broadleaved trees species were cut back to 50cm height in January 2002, except *P. canadensis* which were cut to 5 cm above ground level at the same time.

Table 2. Experiment 3: Stage of growth at application date

Species	2 March 2002	15 May 2002
A. pseudoplatanus	Mainly dormant, few green buds	Leaves expanded, shoots 20cm
F. excelsior	Dormant	Leaves expanded, shoots 15cm
P. canadensis	Cut back, no buds	Leaves expanded, shoots 20cm
P. avium	Bud burst	Leaves expanded, shoots 20cm
Q. robur	Dormant	Leaves expanded, shoots 7 cm
P. abies	Dormant	New shoots 0 – 8 cm #
P. sitchensis	Dormant	New shoots 0 – 5 cm #
P. nigra	Dormant	New shoots 0 – 8 cm
P. menziesii	Dormant	New shoots 0 – 8 cm

Damage on older needles caused by aphids

Herbicide treatments of amidosulfuron at 30 g and florasulam at 7.5 g a.i. ha^{-1} and were applied as an overall spray to deciduous trees and to the foliage between the rows of conifers on 2 March 2002 and 15 May 2002 at the stages of growth described in Table 2. Herbicides were applied using an Oxford Precision back pack sprayer at a pressure of 147 kPa and in a spray volume of 200 litres ha^{-1}. There were five treatments including one untreated control and three replicates of each treatment.

Assessments and analysis

Height was assessed in Experiment 1, along with above-ground fresh weight, determined by cutting plants at root collar level and immediately weighing. Plant health and vigour were visually monitored in all experiments at regular intervals using a score of 0 – 7; where 0 = dead, 4 = 50% reduction in growth compared with best untreated and 7 = as best untreated; data collected from the experiments were subjected to Analysis of Variance using Genstat (Genstat 1993). All S.E.D.s presented are for control versus treatment means.

Results

Experiment 1 – within growing season treatments

Cyanazine, and cyanazine plus terbuthylazine applied to broadleaved species in May, caused leaf damage (chlorosis and necrosis) to most species initially (Table 3) as well as longer term growth suppression from the higher dose (Table 4). Application in August caused initial damage to all species but only growth of *F. excelsior, F. sylvatica* and *P. canadensis* was reduced by these treatments. Applications of these herbicides had few adverse effects on the growth of *L. kaempferi* or *P. nigra* ssp. *laricio*.

Pyridate applied at both dates caused short-term damage (leaf chlorosis) to all broadleaved species except *P. avium* sprayed in May but there were no consistent adverse effects on subsequent growth. Pyridate applied to the conifers had no adverse effect from applications during flushing but the August application caused needle chlorosis on both species; subsequent growth was unaffected.

Amidosulfuron, applied in May, caused short-term damage (chlorosis and stunting) to *F. excelsior, P. avium* and *P. canadensis*; height of these species was reduced (data not shown) but there was no effect on final shoot weight. Amidosulfuron applied in August caused leaf damage on most species, with growth of *P. avium* again affected.

Tribenuron methyl at both doses and application rates caused leaf damage (chlorosis and shoot tip die back) to all the broadleaved species except May treatments on *F. sylvatica* and *Q. robur*. By the following year, shoot weight was also reduced in *F. excelsior, P. avium* and *P. canadensis*. The coniferous species were unaffected by any treatments with amidosulfuron or tribenuron methyl.

Experiment 2 – dormant season treatments, plus cycloxydim, metazachlor and pendimethalin within growing season

Although there were some differences in species susceptibility to the different herbicide treatments, generally treatments appeared to be well tolerated by most species with very few symptoms of damage.

The treatments of amidosulfuron, pyridate, tribenuron methyl and diflufenican (DFF) applied alone and in mixture with pendimethalin generally had few visible effects on any species. The higher dose of amidosulfuron caused short-term chlorosis of *P. avium* and *P. menziesii* and longer-term health reduction of *A. pseudoplatanus*. Where diflufenican was mixed with glyphosate or glyphosate and pendimethalin significant reductions in health resulted, this was particularly evident with all the broadleaved species sprayed with the three way mixture and *P. avium* and *Q. robur* with the mixture with glyphosate. Dichlobenil appeared to be safe on most species and only caused significant reductions in the health of *P. avium* in July.

Glyphosate was particularly damaging on many species causing chlorosis and multiple and distorted shoot regrowth on the sprayed areas. In the longer term only *Q. robur* was significantly affected by the low dose (1.8 kg a.e. ha^{-1}), but the higher dose of 3.6 kg a.e. ha^{-1} significantly reduced the health of *F. excelsior, P. abies, P. sitchensis, P. nigra* ssp. *laricio, P. avium, P. menziesii* and *Q. robur* and the low dose mixed with pendimethalin resulted in significant damage to *A. pseudoplatanus, F. excelsior, P. abies, P. sitchensis, P. avium* and *Q. robur*.

Table 3. Experiment 1: Effect of foliar acting herbicides on tree health (0–7) one month after first application date (upper half of table) and one month after second application (lower half of table)

Herbicide	Dose (kg a.i. ha^{-1})	*A. pseudoplatanus*	*F. excelsior*	*F. sylvatica*	*L. kaempferi*	*P. avium*	*P. canadensis*	*P. nigra*	*Q. robur*
Date of application		12 May	12 May	12 May	12 May	12 May	12 May	1 Jul	12 May
Length of new growth (cm)		1-7	15	3	-	15-20	1-7	5-15	3
cyanazine	2.0	6.2	5.2#	5.4	6.8	5.6#	4.6#	6.8	6.0
cyanazine	6.0	5.2#	4.0#	4.6#	6.2	4.0#	2.0#	6.6	6.2
cyanazine+terbuthylazine	6.8	5.0#	4.2#	5.4	7.0	3.2#	1.8#	6.4	6.0
cyanazine + terbuthylazine	20.4	3.4#	3.0#	3.2#	6.6	2.0#	1.0#	6.6	4.4#
pyridate	0.9	6.0	4.0#	5.6	6.8	6.8	3.8#	6.4	4.8#
pyridate	2.7	5.4#	4.0#	5.0#	6.8	6.8	3.4#	6.2	4.8#
amidosulfuron	0.03	6.2	5.2#	6.6	6.6	4.0#	3.2#	5.6	6.4
amidosulfuron	0.09	6.0	5.2#	6.4	6.4	4.0#	3.2#	5.8	6.4
tribenuron methyl	0.015	5.0#	4.6#	6.2	6.8	3.6#	2.8#	5.8	6.0
tribenuron methyl	0.045	4.6#	4.6#	6.6	6.6	3.4#	2.4#	5.2	6.2
untreated control		**6.7**	**6.6**	**6.3**	**6.7**	**7.0**	**6.6**	**5.6**	**6.7**
S.E.D. (df = 45)		0.50	0.46	0.57	0.31	0.37	0.37	0.39	0.48
L.S.D. ($t = 2.02$, $p \le 0.05$)		1.01	0.93	1.15	0.63	0.75	0.75	0.79	0.97
Date of application		11 Aug	11 Aug	11 Aug	11 Aug	11 Aug	11 Aug	11 Aug	11 Aug
Stage of growth at application		S	GS	C	GS*	S	AG, S	GS	GS
cyanazine	2.0	5.0#	2.4#	3.8#	4.6#	3.2#	3.2#	5.2	5.6
cyanazine	6.0	4.0#	2.2#	3.0#		2.4#	3.0#	5.2	4.6#
cyanazine+ terbuthylazine	6.8	4.2#	2.2#	3.2#	4.0#	2.6#	3.0#	5.2	5.0
cyanazine+ terbuthylazine	20.4	4.6#	2.4#	3.0#		2.4#	3.0#	5.2	4.2#
pyridate	0.9	4.6#	3.6#	4.2#	4.8#	4.2#	4.4#	5.0	4.4#
pyridate	2.7	3.8#	4.0#	3.6#		4.6#	4.2#	5.2	3.4#
amidosulfuron	0.03	5.4#	4.8#	4.6#	5.6	5.0#	4.4#	6.0	5.2
amidosulfuron	0.09	5.0#	4.2#	4.0#		5.0#	4.0#	5.4	5.6
tribenuron methyl	0.015	5.0#	4.6#	4.4#	5.4	5.6	4.6	5.0	5.2
tribenuron methyl	0.045	5.0#	4.4#	4.4#		4.8#	4.0#	6.0	5.0
untreated control		**5.9**	**6.3**	**5.6**	**5.8**	**6.0**	**5.1**	**6.1**	**5.8**
S.E.D. (df = 45)		0.41	0.32	0.36	0.27	0.30	0.30	0.57	0.36
L.S.D. ($t = 2.02$, $p \le 0.05$)		0.83	0.65	0.73	0.55	0.61	0.61	1.15	0.72

C = chlorotic; S = senescent; AG = active growth; GS = no active growth but no signs of senescence; * = shortage of plants only allowed low dose to be applied; # = more than one L.S.D less than the control at $p \le 0.05$.

Paraquat was less damaging than glyphosate and, applied alone or in mixture with pendimethalin, did not lead to consistent damage on the broadleaved species except on *Q. robur*, where health in July was significantly reduced by the higher dose. Significant damage was recorded in May on all the conifers from both doses and the mixture with pendimethalin. By July, 5 months after application, the health of *P. abies* and *Pinus nigra* was still significantly reduced by all paraquat treatments, as was the health of *P. menziesii* from the high dose and *P. sitchensis* from the high dose and the mixture with pendimethalin.

For the applications to actively-growing trees, pendimethalin and metazachlor were safe on all species, however the mixture of metazachlor with cycloxidim and clopyralid did result in significant damage to *A. pseudoplatanus*, *F. excelsior*, *P. avium* and *Q. robur*.

Experiment 3 – dormant and within growing season treatments with amidosulfuron and florasulam

There was no visible damage to the conifers throughout the growing season from either application, consequently the data are not presented. Growth on some broadleaved species was poor due to grazing by deer, leading to increased plot variability.

Both herbicides applied to dormant broadleaved trees appeared to have no adverse effects on tree health (Table 7). However when the herbicides were applied to the rapidly-growing shoots in May, both herbicides caused damage initially in the form of stunting and chlorosis particularly to *F. excelsior*, *P. canadensis* and *Q. robur*. *P. canadensis* recovered completely with no symptoms apparent in August whereas other species continued to show some leaf damage.

Table 4. Experiment 1: Effect of foliar acting herbicides on tree fresh weight (g), assessed at July 1995, i.e. 14 months after first application date (top half of table) and 11 months after second application date (lower half of table)

Herbicide	Dose (kg a.i. ha^{-1})	*A. pseudoplatanus*	*F. excelsior*	*F. sylvatica*	*L. kaempferi*	*P. avium*	*P. canadensis*	*P. nigra*	*Q. robur*
Date of application:		12 May	12 May	12 May	12 May	12 May	12 May	1 July	12 May
Length of new growth (cm)		1-7	15	3	-	15-20	1-7	5-15	3
cyanazine	2.0	254.7	244.7	82.0	295.0	154.0	519.0	113.2	88.8
cyanazine	6.0	213.4	47.6#	48.4	299.0	73.0#	280.0#	102.4	129.8
cyanazine + terbuthylazine	6.8	177.7	117.5#	68.1	298.0	64.0#	182.0#	98.2	102.2
cyanazine + terbuthylazine	20.4	90.2#	74.5#	13.9#	284.0	0.0#	0.0#	103.4	40.0#
pyridate	0.9	227.1	155.3#	54.9	292.0	116.0	534.0	89.1	71.9
pyridate	2.7	145.0#	164.6	50.5	418.0	181.0	552.0	122.9	82.1
amidosulfuron	0.03	158.4	209.3	85.1	228.0	135.0	429.0	80.5	117.7
amidosulfuron	0.09	192.1	189.1	73.9	275.0	121.0	565.0	75.4	86.7
tribenuron methyl	0.015	216.4	128.3#	60.6	331.0	97.0#	504.0	84.9	60.6
tribenuron methyl	0.045	219.6	112.4#	84.4	404.0	89.0#	417.0#	70.1	81.1
untreated control		**217.3**	**217.0**	**64.3**	**254.0**	**199.0**	**569.0**	**58.3**	**105.8**
S.E.D. (df = 45)		35.5	29.9	21.4	63.7	46.9	73.0	18.9	24.8
L.S.D. (t = 2.02, p ≤ 0.05)		71.71	60.40	43.23	128.67	94.74	147.46	38.18	50.10
Stage of growth at application 11Aug		S	GS	C	GS *	S	AG, S	GS	GS
cyanazine	2.0	211.8	177.3#	63.2	454.0	253.0	438.0#	48.8	143.5
cyanazine	6.0	184.3	142.0#	50.5#		171.0	103.0#	59.1	141.1
cyanazine + terbuthylazine	6.8	237.3	203.5#	38.5#	373.0	195.0	290.0#	45.5	121.0
cyanazine + terbuthylazine	20.4	224.4	191.5#	39.1#		221.0	107.0#	57.4	133.4
pyridate	0.9	212.0	186.9#	61.6	428.0	240.0	468.0	54.2	139.6
pyridate	2.7	204.5	239.9	86.7		268.0	549.0	58.9	121.7
amidosulfuron	0.03	248.0	234.9	75.3	483.0	198.0	504.0	78.2	135.6
amidosulfuron	0.09	213.4	236.6	73.7		143.0	509.0	57.5	124.9
tribenuron methyl	0.015	245.0	116.5#	64.2	475.0	210.0	522.0	70.4	122.8
tribenuron methyl	0.045	244.2	72.2#	39.8#		110.0	472.0	75.1	141.3
untreated control		**246.9**	**249.7**	**84.0**	**473.0**	**204.0**	**559.0**	**58.4**	**136.5**
S.E.D. (df = 45)		36.01	21.52	12.38	50.2	59.1	57.3	16.64	25.13
L.S.D. (t = 2.02, p ≤ 0.05)		72.74	43.47	25.01	101.40	119.38	115.75	33.61	50.76

C = chlorotic; S = senescent; AG = active growth; GS = no active growth but no signs of senescence; * = shortage of plants only allowed low dose to be applied; # = more than one L.S.D less than the control at p ≤ 0.05.

Discussion

As highlighted earlier, the value of applying atrazine before bud burst in late winter comes from its capacity to control existing weed growth and prevent significant ingress of weeds for the rest of the growing season, making for straightforward weed management. While cyanazine and terbuthylazine also have this capacity, and the results of these experiments and earlier work indicate that they can be used selectively over dormant trees or as directed sprays in the growing crop, terbuthylazine has been withdrawn from use in the UK, and cyanazine is only available for use in farm woodland situations in the UK until 2007 (Whitehead 2006). The only treatment tested that provides equivalent activity to atrazine is dichlobenil which generally appeared to be safe in this experiment. Although approved for use in the UK, compared with other herbicides this treatment is very expensive (Willoughby and Clay 1999), and there have been reports in the past of damage to some conifer species, particularly on poorly drained soils (Anon. 1975; S. Hendry and B. Rayner, pers. comm.); on trees of the *Rosaceae* family, it often gives conspicuous leaf margin chlorosis as seen on the *P. avium* in this work. However this symptom, caused by uptake of a breakdown product in the soil, may not always be associated with a growth reduction (Clay and McKone 1979).

An alternative to a single herbicide possessing both pre and post emergence activity is the use of a mixture of a residual and a foliar acting herbicides. For residual herbicides the field experiment confirmed the selectivity of pendimethalin applied to dormant trees (Willoughby and Clay 1996). Diflufenican (DFF) in mixture with terbuthylazine appeared to be safe alone and mixed with pendimethalin. This cereal crop herbicide can give long-term pre and early post emergence control of a wide range of broadleaved and some grass weeds (Cramp *et al.*, 1985) and has shown selectivity in forestry situations (Clay *et al.* 1988; Britt and Smith 1996; Clay and Dixon 1996). However in the UK it is only currently available in mixtures in which the other components may be damaging to tree crops (Clay and Dixon 1996; Britt *et al.* 2000).

Where glyphosate and paraquat were tested as possible tank mix partners for pendimethalin, glyphosate gave some damage on broadleaved trees and paraquat significant damage on conifers. Damage was not increased with the mixture of either herbicide with pendimethalin or where DFF was added to glyphosate. Since glyphosate has sometimes given damage to dormant broadleaved tree species (Willoughby 1996) and paraquat is known to sometimes damage dormant *F. sylvatica* (Harmer *et al.* 2000) and trees with immature bark (Fryer and Makepeace 1978) further work is needed to define conditions where these treatments will be safe. Glufosinate-ammonium may be a safer broad-spectrum contact herbicide for use in broadleaved tree species in late winter (Willoughby 1996), but currently usage is restricted to applications made between March and the end of September.

The alternative foliar-acting herbicides tested in these experiments, amidosulfuron, florasulam, pyridate and tribenuron-methyl, appeared to be safe for use as directed sprays on dormant crops both alone or mixed with pendimethalin. While some are recommended for use in early spring their efficacy on the size and diversity of weed species encountered in forestry and farm woodland requires testing; they will not give control of grass weeds. Where there is a need for post-emergence weed control after tree flushing, these experiments have shown that overall spraying of amidosulfuron, florasulam, pyridate or tribenuron-methyl appeared to be safe on conifers but damaging on some broadleaved tree species. If control of grass weeds is also required mixture with a graminicide may be needed but selectivity of such treatments requires testing. Mixture with graminicides has not increased phytotoxicity of clopyralid to trees (Dixon *et al,*. 2005) and the clopyralid/cycloxydim/metazachlor treatment applied in June in this work only had minor effects on tree health.

In conclusion, these experiments provide some useful initial information on the relative tolerance of a range of commonly-grown forestry tree species to a variety of herbicide treatments applied at specific rates, but for all of the herbicides tested, additional work on crop tolerance and efficacy is required. Of the herbicides investigated, it appears as if only dichlobenil might prove to be a direct substitute for triazines, and even then there remain issues over crop tolerance and expense. Glyphosate (for conifers) and paraquat or glufosinate ammonium (for broadleaves) may offer opportunities for broad-spectrum control of some established weeds with dormant trees, with residual control offered by tank-mix partners such as pendimethalin. Once trees have flushed, mixtures of clopyralid, cycloxydim and metazachlor might be used to control some grasses or seedling weeds, although some broadleaves may suffer from foliage scorch with clopyralid. Alternatively, directed sprays of broad-spectrum herbicides such as glyphosate, glufosinate ammonium or paraquat could be used. Initial indications are that specific rates of amidosulfuron, florasulam, pyridate and tribenuron methyl may have future potential for use over dormant or actively growing conifers, over dormant broadleaves, and, in the case of pyridate, actively growing broadleaves, to control emerged herbaceous species, but further work is needed to confirm tree tolerance and efficacy in field conditions before these herbicides could be safely recommended. There is also a need to define more carefully when it is necessary to use broad-spectrum herbicide mixtures on dormant crops in early spring to give complete season long weed control or whether later targeted use of non-residual

Table 5. Experiment 2: Effect of herbicides applied on 22nd February on tree health (scored 0 - 7) 3 months after application

Herbicide	Dose (kg a.i. ha^{-1})	*A. pseudoplatanus*	*F. excelsior*	*P. abies*	*P. sitchensis*	*Pinus nigra*	*P. canadensis*	*P. avium*	*P. menziesii*	*Q. robur*
amidosulfuron	0.03	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
amidosulfuron	0.06	7.0	6.5	7.0	7.0	7.0	7.0	6.1#	4.5#	7.0
amidosulfuron + pendimethalin	0.03 + 2.0	7.0	6.8	7.0	7.0	7.0	7.0	7.0	7.0	6.6
glyphosate	1.8	6.7#	5.4#	6.3	6.9	7.0	5.6#	6.5	6.2	6.1#
glyphosate	3.6	6.6#	5.4#	5.0#	6.0#	6.1#	6.2	7.0	6.2	5.7#
glyphosate + pendimethalin	1.8 + 2.0	7.0	4.8#	5.1#	7.0	7.0	2.6#	6.5	7.0	5.7#
paraquat	0.6	7.0	7.0	4.9#	6.0#	4.1#	5.7#	7.0	4.1#	7.0
paraquat	1.0	7.0	7.0	4.4#	4.9#	3.4#	6.0	7.0	4.3#	7.0
paraquat + pendimethalin	0.6 + 2.0	7.0	7.0	4.7#	4.1#	3.4#	7.0	7.0	3.7#	7.0
pyridate	0.9	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
pyridate	1.8	7.0	7.0	7.0	7.0	7.0	6.3#	7.0	7.0	7.0
pyridate + pendimethalin	0.9 + 2.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
tribenuron methyl	0.01	7.0	7.0	7.0	7.0	7.0	6.9	7.0	7.0	7.0
tribenuron methyl	0.02	7.0	6.5	7.0	7.0	7.0	5.6#	7.0	7.0	7.0
tribenuron + pendimethalin	0.01 + 2.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
DFF	0.3	7.0	7.0	6.8	7.0	7.0	7.0	7.0	7.0	7.0
DFF	0.6	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
DFF + pendimethalin	0.3 + 2.0	7.0	7.0	7.0	7.0	7.0	6.7	7.0	6.0	7.0
DFF + glyphosate	0.3 + 1.8	6.9	5.3#	6.5	7.0	7.0	6.8	6.8	6.6	4.7#
DFF+pendimethalin+glyphosate	0.3 + 2.0 + 1.8	7.0	4.9#	5.8#	7.0	7.0	4.0#	4.7#	6.1	5.6#
dichlobenil	8.4	7.0	7.0	7.0	7.0	7.0	6.7	7.0	7.0	7.0
pendimethalin	2.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
untreated control		**7.0**	**7.0**	**7.0**	**7.0**	**7.0**	**7.0**	**7.0**	**7.0**	**7.0**
S.E.D. (df = 24)		0.13	0.26	0.40	0.08	0.27	0.99	0.25	0.75	0.27
L.S.D. (t = 2.06, $p \leq 0.05$)		0.27	0.54	0.82	0.16	0.56	2.04	0.52	1.55	0.56

= more than one L.S.D less than the control at $p \leq 0.05$.

Table 6. Experiment 2: Effect of herbicides applied on 22nd February on tree health, (scored 0 - 7) 5 months after application

Herbicide	Dose (kg a.i. ha^{-1})	*A. pseudoplatanus*	*F. excelsior*	*P. abies*	*P. sitchensis*	*Pinus nigra*	*P. canadensis*	*P. avium*	*P. menziesii*	*Q. robur*
amidosulfuron	0.03	7.0	6.0	7.0	7.0	7.0	7.0	6.5	7.0	7.0
amidosulfuron	0.06	6.0#	6.0	7.0	7.0	7.0	7.0	7.0	5.0	7.0
amidosulfuron + pendimethalin	0.03 + 2.0	7.0	6.5	7.0	7.0	7.0	7.0	7.0	6.0	7.0
glyphosate	1.8	6.5	5.5	7.0	6.5	7.0	6.5	7.0	5.5	5.0#
glyphosate	3.6	7.0	4.5#	5.5#	5.5#	6.0#	5.5#	6.0#	4.0#	5.0#
glyphosate + pendimethalin	1.8 + 2.0	6.0#	5.0#	5.5#	6.0#	7.0	5.5#	6.0#	5.5	5.0#
paraquat	0.6	7.0	6.5	6.0#	6.5	5.0#	5.5#	6.5	5.5	7.0
paraquat	1.0	6.5	6.0	4.5#	5.0#	4.0#	7.0	7.0	4.5#	5.5#
paraquat + pendimethalin	0.6 + 2.0	6.5	6.5	5.0#	5.0#	4.0#	6.0	6.5	5.0	7.0
pyridate	0.9	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
pyridate	1.8	7.0	7.0	6.5	7.0	7.0	6.5	7.0	6.5	7.0
pyridate + pendimethalin	0.9 + 2.0	7.0	6.5	7.0	7.0	7.0	7.0	7.0	5.5	7.0
tribenuron methyl	0.01	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
tribenuron methyl	0.02	7.0	5.5	7.0	7.0	7.0	7.0	7.0	7.0	7.0
tribenuron + pendimethalin	0.01 + 2.0	7.0	5.5	7.0	7.0	7.0	7.0	7.0	7.0	7.0
DFF	0.3	7.0	6.5	7.0	7.0	7.0	7.0	7.0	7.0	7.0
DFF	0.6	6.5	6.5	7.0	7.0	7.0	7.0	7.0	6.5	7.0
DFF + pendimethalin	0.3 + 2.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	4.5#	7.0
DFF + glyphosate	0.3 + 1.8	6.5	5.5	7.0	6.5	7.0	7.0	6.0#	6.5	5.0#
DFF+pendimethalin+glyphosate	0.3 + 2.0 + 1.8	6.0	5.0#	5.5#	7.0	7.0	6.0#	6.0#	5.5	6.0#
dichlobenil	8.4	7.0	7.0	7.0	7.0	7.0	7.0	5.5#	6.5	6.5
pendimethalin	2.0	6.5	6.5	7.0	7.0	7.0	7.0	7.0	6.7	7.0
metazachlor *	1.25	7.0	6.5	7.0	7.0	7.0	6.9	6.5	7.0	7.0
metazachlor+cycloxydim+clopyralid *	1.25+0.45+0.2	5.5#	5.0#	7.0	7.0	6.5	7.0	5.5#	6.0	6.0#
untreated control		**7.0**	**6.8**	**7.0**	**7.0**	**7.0**	**7.0**	**7.0**	**6.5**	**7.0**
S.E.D		0.38	0.62	0.46	0.33	0.35	0.39	0.46	0.79	0.27
df		27	27	27	27	27	23	25	25	27
T		2.05	2.05	2.05	2.05	2.05	2.07	2.06	2.06	2.05
L.S.D. ($p \leq 0.05$)		0.78	1.27	0.94	0.68	0.72	0.81	0.95	1.63	0.55

* = Applied on 18 June, and results shown are for health scored 1 month after treatment;
# = more than one L.S.D less than the control at $p \leq 0.05$.

Table 7. Experiment 3: Health (0–7) of broadleaved species treated with amidosulfuron or florasulam on 2nd March or 15th May

Herbicide	Dose (kg a.i. ha^{-1})	Application Date	*A. pseudo platanus*	*F. excelsior*	*P. canadensis*	*P. avium*	*Q. robur*
Assessed 29 May 2002							
amidosulfuron	0.03	March	7.0	7.0	7.0	6.9	7.0
amidosulfuron	0.03	May	5.3	4.3#	4.0#	4.3	5.0#
florasulam	0.0075	March	7.0	6.3	7.0	6.3	7.0
florasulam	0.0075	May	5.0#	3.7#	4.3#	4.7	4.3#
untreated control			**6.3**	**6.3**	**6.0**	**5.9**	**6.3**
S.E.D.			0.52	0.69	0.41	0.75	0.45
df			8	8	7	6	8
T			2.3	2.3	2.4	2.4	2.3
L.S.D. ($p \leq 0.05$)			1.20	1.59	0.98	1.8	1.04
Assessed 13 August 02							
amidosulfuron	0.03	March	5.7	5.1	7.0	4.0	5.3
amidosulfuron	0.03	May	4.7	4.4	7.0	3.3#	5.5
florasulam	0.0075	March	6.3	6.3	7.0	5.0	5.9
florasulam	0.0075	May	6.1	5.1	7.0	4.3	4.7
untreated control			**5.6**	**5.4**	**7.0**	**5.2**	**5.9**
S.E.D.			0.56	0.67	-	0.74	0.59
df			8	8	-	6	6
T			2.3	2.3	-	2.4	2.4
L.S.D. ($p \leq 0.05$)			1.29	1.54	-	1.78	1.42

 # = significantly different from untreated control at $p \leq 0.05$, using L.S.D. test.

contact herbicides on competitive weeds is more appropriate. Where economic cost is less of an issue, non-chemical approaches will be the best long term solution to the loss of triazine products such as atrazine.

Disclaimer

This scientific paper is a summary of the results of experimental work, and is not intended as a recommendation, endorsement or approval of any product to the exclusion of others that might be available. Research experiments are by their nature small in scale, and as all applications are made at users own risk, they are always advised to test small areas to gain familiarity with new products and techniques before engaging in any large scale treatments. Regardless of any information contained in this paper, the herbicide product label remains the authoritative source of information for the safe use of a herbicide, and must be referred to determine approval status and conditions of use before any applications are made.

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