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The relative efficacy of herbicides for the control of *Deschampsia flexuosa* (L.) Trin. in woodland establishment in the UK

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Summary

Deschampsia flexuosa is a commonly occurring calcifuge grass which can be detrimental to tree regeneration. In the work reported here, two experiments using pot-grown plants and one field experiment were set up to investigate the relative efficacy of various herbicides in controlling *D. flexuosa*. Cycloxydim, glyphosate and imazapyr applied in the summer killed virtually all pot-grown plants of *D. flexuosa* within 1 year of treatment. Hexazinone and propyzamide were also effective at the recommended doses. Mixture B enhanced the efficacy of several herbicide treatments but pre-spraying plant moisture stress had no effect on subsequent herbicide activity. Cycloxydim and imazapyr applied in spring or summer gave excellent long-term control in the field. It is concluded that if non-chemical approaches such as canopy manipulation or cultivation fail to give adequate control of *D. flexuosa* and herbicide use becomes necessary to allow tree regeneration, then cycloxydim applied at 0.45 kg a.i. ha^{-1} appears to be an effective alternative to the use of more broad-spectrum products, and gives very good tree tolerance. If herbicide use is required prior to tree establishment, glyphosate may be a cheaper option and will control a broader spectrum of weeds, although it is slightly less effective than cycloxydim on *D. flexuosa*.

Introduction

Deschampsia flexuosa (L.) Trin. (wavy hair-grass) is an evergreen, perennial, rhizomatous, patch-forming, calcifuge grass growing to heights of 100 cm and usually found in soils of pH 5.0 or less (Grime *et al.*, 1988; Hubbard, 1992). It has a wide natural distribution with examples being recorded as far afield as the Arctic and South America (Scurfield, 1954). It is native throughout the UK, and is found particularly on well-drained, drier sites in upland pastures, moorland, acidic heaths and woodlands, although it is not usually present in calcareous or arable habitats. *Deschampsia flexuosa* propagates both vegetatively through rhizomes and by seed (Scurfield, 1954; Grime *et al.*, 1988). Although seed is not long lived in the soil (Hill and Stevens, 1981),

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small plants can often persist in dense shade beneath tree canopies (Grime *et al.*, 1988). After natural or artificial gap creation in the canopy, suppressed plants respond to the increased light levels by rapidly increasing in size (Scurfield, 1954; Kooijman *et al.*, 2000). Grime *et al.* (1988) assign this type of response to the category of a stress-tolerant competitor, which implies *D. flexuosa* may be less well adapted to conditions of repeated disturbance.

Although a desirable natural component of many native woodland types (Rodwell and Patterson, 1994), in common with other grass species (Davies, 1987), *D. flexuosa* can severely restrict the growth and establishment of young trees (Heinsdorf, 1978). Natural regeneration of trees can be particularly uncertain where a dense cover of *D. flexuosa* is present (Scurfield, 1954; Baker, 1985; Bergmann, 1994; Sera *et al.*, 2000; Arkle *et al.*, 2002; Hanssen, 2002). *Deschampsia flexuosa* may compete primarily for moisture (Heinsdorf, 1978), influencing tree growth through its high evapotranspiration in periods of summer drought (Muller *et al.*, 1998). Harmer (1996) found that height increment, number of branches and root weight of young trees were all reduced by competition from *D. flexuosa*. Harmer (1996) also concluded that it may be a more competitive grass species than *Poa trivialis* L. or *Calamagrostis epigejos* (L.) Roth.

Deschampsia flexuosa can be suppressed by cultivation, but in the UK, unless total site preparation is practised, plough or scarification lines will often be re-colonized from adjacent undisturbed areas within 18 months (D. West, pers. comm.). Hence even with pre-planting cultivation, further control may be required to allow trees to establish. *Deschampsia flexuosa* is tolerant of grazing (Scurfield, 1954), which suggests that as for other grass species, repeated cutting is not an effective control option (Davies, 1987). Persistent shade from heavy-canopied tree species, particularly conifers, can eliminate *D. flexuosa* (Hill and Stevens, 1981). However, it is unlikely that the selective manipulation of lighter-canopied broadleaved trees to encourage growth of tree seedlings, but not surviving grass seedlings, will be successful. Although raising soil pH might theoretically help to control *D. flexuosa*, in one study 6000 kg ha^{-1} of limestone was applied to a site over 12 years with no appreciable effect (Olsson and Kellner, 2002). Given the potential negative environmental impacts of attempts to raise soil pH (Godbold, 2003), it is doubtful whether such an approach to weed control is practical or desirable.

The use of herbicides is an alternative method for the control of *D. flexuosa* and, since the 1960s, atrazine, glyphosate and propyzamide have all been used successfully in the UK (Willoughby and Dewar, 1995). However, there are pressures to reduce applications of highly mobile triazines, due to their potential, if misused, to contaminate water bodies (Heather and Carter, 1996). The soil-acting herbicide propyzamide will control *D. flexuosa*, but is not appropriate in all situations as it cannot be used on soils with high levels of organic matter. This herbicide also requires an adequate period of cold, wet winter weather after tree planting to be effective (Willoughby and Dewar, 1995). Glyphosate is a broad spectrum, foliar-applied herbicide used as a directed spray around young trees during establishment and as an overall spray on some conifer species in autumn and winter (Willoughby and Dewar, 1995). Although it can be effective at controlling *D. flexuosa* when used at higher rates (Willoughby, 1997), misapplication of glyphosate often causes long-term damage to trees. Even where trees are not killed, sub-lethal injury may be such that overall growth rates are not improved by removing the grass weed competition. Imazapyr is a non-selective broad spectrum herbicide that may have potential for controlling *D. flexuosa* (Winfield and Bannister, 1988; Lund-Hoie and Rognstad, 1990). It has a residual weed-killing effect for up to 2 years, but crop tolerance of some conifer species is achieved through applications being made 5 months prior to planting (Willoughby and Dewar, 1995). Other broad-spectrum herbicides that may give some control of *D. flexuosa* are glufosinate-ammonium (Willoughby and Dewar, 1995) and hexazinone (Himme *et al.*, 1983).

Foliar-acting graminicides which have little or no effect on broad-leaved plants have been in use in agricultural crops for more than 20 years. Cycloxydim, fluazifop-*p*-butyl and propaquizafop have approval from the UK Department for Environment, Food and Rural Affairs (DEFRA) for use in forest and farm woodland situations (Willoughby and Clay, 1996). However, manufacturers' labels generally indicate that only a few agricultural grass weed species are susceptible and then only at early growth stages. In regenerating woodlands a wider variety of grass species, including *D. flexuosa*, can be a problem, and these often occur at more advanced growth stages than in agricultural situations due to a lack of suppression by a crop. If graminicides could be used to control mature *D. flexuosa* plants, they may have advantages over other less selective herbicides, as there would be little risk of applications damaging young trees. In the work reported here, the efficacy of a range of herbicides in controlling *D. flexuosa* was investigated in experiments on pot-grown plants and in the field.

Efficacy of foliar-acting herbicides can sometimes be considerably enhanced with the use of additives to the spray solution (Southcombe and Seaman, 1990). Their use can result in increased efficacy and rainfastness or enable dose reduction. Earlier work with grass weeds of forestry indicated that increased efficacy was sometimes achieved with additives to glyphosate and imazapyr (Clay and Lawrie, 1988, 1990; Willoughby, 1997), and manufacturers' recommendations exist for the use of specific additives with cycloxydim, fluazifop-*p*-butyl and glyphosate (Whitehead, 2003). The effect of various additives was also tested in one of the experiments reported below.

The efficacy of foliar-acting herbicides that are translocated throughout target weeds can be affected by growth stage and the condition of the weed foliage (Caseley and Walker, 1990). Poorly growing plants in drought conditions are often less susceptible compared with those making vigorous growth. As *D. flexuosa* is often found growing on drier sites subject to moisture deficits, the effect of different watering regimes on herbicide efficacy was also investigated in one experiment.

Materials and methods

Experiment 1

Deschampsia flexuosa plants were collected from Thetford Forest in Norfolk at the beginning of May 1992. The plants were grown outside at Long Ashton Research Station, Bristol, UK (51° 25′ N, 2° 40′ W) in 15-cm-diameter pots containing a 50 : 50 mixture of acid heathland soil and peat.

A range of herbicides was applied at three doses (one-quarter, one-half and full manufacturers' recommended rate) using a laboratory track sprayer fitted with a Lurmark 80015E Flat Fan nozzle at a pressure of 210 kPa and a spray volume of 227 l ha^{-1}. Treatments were sprayed on 14 July 1992 when the plants were 10–15 cm tall and actively growing, with 75–100 per cent cover of the pot surface. The herbicides used were: cycloxydim (Laser; 200 g l^{-1} e.c.; BASF plc.), fluazifop-*p*-butyl (Fusilade 5; 125 g l^{-1} e.c.; Syngenta Crop Protection UK Ltd), glufosinate-ammonium (Challenge; 150 g l^{-1} s.l.; Bayer CropScience Ltd), glyphosate (Roundup; 360 g l^{-1} s.l.; Monsanto (UK) Ltd), hexazinone (Velpar; 240 g l^{-1} s.l.; DuPont (UK) Ltd), imazapyr (Arsenal; 250 g l^{-1} s.l.; Nomix-Chipman Ltd) and propyzamide (Kerb 50W; 500 g kg^{-1} w.p.; Dow AgroSciences.). The doses used are shown in Table 1. One of three surfactants were also added separately to each of the herbicide treatments: Agral (948 g l^{-1} alky phenol ethylene oxide; Syngenta Crop Protection UK Ltd) at 0.1 per cent, Mixture B (500 g l^{-1} nonyl phenol ethylene oxide condensate and 500 g l^{-1} primary alcohol ethylene oxide condensate; Amega Sciences) at 2.0 per cent, or Galion (600 g l^{-1} polyoxyalkylene glycol; Intracrop) at 0.5 per cent of the spray solution. With cycloxydim, Actipron (970 g l^{-1} highly refined mineral oil; Joseph Batsons Ltd) was added at 0.8 per cent of the spray solution instead of Agral, as this was the adjuvant recommended on the product label for use with all applications of cycloxydim (BASF, 2002). After spraying, plants were grown outside on a hard standing area and watered using trickle irrigation. There were seven herbicide treatments at three doses with three surfactants, plus four controls, arranged in three randomized blocks (replicates), giving 201 pots in total. Plants were over-wintered in plunge beds and protected from frost with fleece. Visual assessments of plant health were made at intervals throughout the experiment using a scale of 0–7, where 0 = dead, 1 = shoot base green but foliage dead, 2 = severe necrosis of green shoots, 3 = ~80 per cent reduction in growth and no healthy regrowth, 4 = ~50 per cent reduction in growth with some normal shoot growth, 5 = ~20 per cent reduction in growth with much normal shoot growth, 6 = some chlorosis and necrosis of occasional leaves and

Table 1: Effect of additives on the efficacy of herbicides for the control of *D. flexuosa* in Experiment 1

		Plant health (score 0–7)						Shoot fresh weight (g pot^{-1})		
		29 July 1992			4 Nov. 1992			24 July 1993		
Herbicide	Dose (kg a.i. ha^{-1})	Agral	Mix B	Galion	Agral	Mix B	Galion	Agral	Mix B	Galion
Cycloxydim*	0.11	3.0	2.7	4.0	1.0	1.0	1.7	0.0	0.0	1.3
	0.23	3.0	2.3	3.3	1.0	1.0	0.7	0.0	0.0	0.0
	0.45	2.3	2.0	1.7	0.7	0.7	0.7	0.0	0.0	0.0
Fluazifop-*p*-butyl	0.07	6.3	5.7	6.7	4.0	5.0	5.0	25.1	44.1	45.3
	0.14	5.3	4.7	5.7	4.3	3.0	4.0	39.6	8.2	38.5
	0.28	4.0	4.3	3.7	3.0	2.7	2.3	20.7	7.1	3.9
Glufosinate ammonium	0.19	6.3	5.0	6.7	5.7	5.7	5.3	62.1	59.0	68.3
	0.38	4.3	3.3	3.7	4.0	4.7	5.3	29.0	45.1	50.0
	0.75	1.7	1.7	3.3	3.0	2.7	4.3	4.7	4.3	49.3
Glyphosate	0.36	3.3	3.0	4.0	3.3	1.3	3.3	17.8	0.9	13.0
	0.72	2.3	1.7	1.7	1.7	1.3	0.7	0.0	0.0	0.0
	1.44	2.3	1.0	1.3	0.3	0.3	0.3	0.0	0.0	0.0
Hexazinone	0.42	6.7	3.3	5.3	5.3	4.0	4.3	48.9	45.2	50.4
	0.84	3.7	2.3	2.7	4.3	3.3	3.3	32.9	31.4	18.1
	1.68	2.0	1.3	1.7	2.3	1.3	1.0	3.1	4.7	0.0
Imazapyr	0.05	4.3	5.0	5.0	1.7	1.3	1.0	1.4	0.0	0.0
	0.10	5.0	5.0	5.3	1.0	1.0	0.7	0.0	0.0	0.0
	0.20	4.7	5.0	3.7	1.0	1.0	1.0	0.0	0.0	0.0
Propyzamide	0.38	6.7	7.0	7.0	5.0	4.3	5.3	44.6	28.9	57.2
	0.75	6.7	6.0	5.3	3.7	4.3	3.0	11.7	24.9	10.5
	1.50	6.0	5.7	5.3	1.3	1.3	1.7	0.0	0.0	1.6
Untreated control		7.0	7.0	7.0	5.4	5.4	5.4	47.5	47.5	47.5
SED (res. d.f. = 132) treated *vs* treated		0.67	0.67	0.67	0.80	0.80	0.80	13.27	13.27	13.27
t (at $P \leq 0.05$)		1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.48	1.98
LSD		1.35	1.35	1.35	1.61	1.61	1.61	26.67	26.67	26.67
SED (res. d.f. = 132) control *vs* treated		0.53	0.53	0.53	0.63	0.63	0.63	10.49	10.49	10.49
t (at $P \leq 0.05$)		1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
LSD		1.07	1.07	1.07	1.27	1.27	1.27	21.08	21.08	21.08

* With the cycloxydim treatments Actipron at 0.8 per cent spray solution was substituted for Agral as recommended on the product label.

7 = as healthiest untreated plants. Plant fresh weights were recorded on 24 June 1993.

Experiment 2

In February 1993, pot-grown plants were divided and re-potted as in Experiment 1 and grown outside using trickle irrigation. On the 24 June the pots were divided into three separate groups and thereafter until spraying were subjected to three different watering regimes. One group was watered daily from overhead to simulate excessively wet conditions, whilst a second group were watered using trickle irrigation to simulate intermediate soil moisture. The third group were subjected to dry conditions, being protected from rain and only watered by hand when the plants were nearly wilting, which in practice was every 4 or 5 days. Plants were actively growing and 10–15 cm in diameter at the time of spraying. Herbicide treatments were applied at two rates on 28 July 1993; cycloxydim, fluazifop-*p*-butyl, glyphosate, imazapyr and propyzamide were sprayed at the doses shown in Table 2, using the same spray conditions as in Experiment 1. There were four replicates of the six herbicide treatments (including an untreated control) at two rates and with three watering regimes. The replicates were set out as four randomized blocks, with the watering regimes as split plots, giving 144 plots in total. After spraying the plants were kept under cover for 24 h before being placed outside and watered by trickle irrigation. Plants were over-wintered in plunge beds and protected from frost with fleece. Visual assessments on plant health were made at intervals throughout the experiment using a scale of 0–7 as described in Experiment 1 and shoot fresh weights were recorded on 1 June 1994.

Experiment 3

An experiment was sited on a dense sward of *D. flexuosa* within Thetford Forest, UK (52° 26′ N, 0° 41′ E). The site was predominately flat, sheltered to the north and west by adjoining plantations, and had an Argillic Brown Sand soil (Worlington Association). The area had been mown annually for the previous 7 years and had not had trees growing on it since 1985. Herbicide treatments of cycloxydim, fluazifop-*p*-butyl, glyphosate, imazapyr and propaquizafop (Falcon; 100 g l^{-1} e.c.; Makhteshim-Agan (UK) Ltd) were sprayed on 19 April and 26 July 1994 at the doses shown in Table 3. Surfactants were added to the treatments of cycloxydim and fluazifop-*p*-butyl as recommended on the label. Sprayprover (950 g l^{-1} highly refined mineral oil; Fine Agrochemicals Ltd), used as a substitute for Actipron, was added to cycloxydim at 0.8 per cent of the spray volume and Enhance (900 g l^{-1} phenol ethylene oxide condensate; Greenhill), used as a substitute for Agral, at 0.1 per cent of the spray volume of fluazifop-*p*-butyl. The treatments were applied at a spray volume of 200 l ha^{-1} using a Cooper Pegler CP3 knapsack sprayer fitted with a blue nozzle giving an output of 1200 ml min^{-1} at a pressure of

Table 2: The effect of herbicide activity on *D. flexuosa* in Experiment 2

Herbicide	Dose (kg a.i. ha^{-1})	Plant health (score 0–7) 10 Aug. 1993 (2 WAT*)	Plant health (score 0–7) 18 Oct. 1993 (12 WAT*)	Shoot fresh weight (g pot^{-1}) 1 June 1994 (11 MAT*)
Cycloxydim	0.23	4.4	0.4	0.02
	0.45	3.8	0.3	0.00
Fluazifop-*p*-butyl	0.14	5.9	4.7	12.18
	0.28	5.2	3.4	6.65
Glyphosate	0.72	4.9	2.4	3.19
	1.44	2.7	0.0	0.06
Imazapyr	0.10	5.3	2.5	3.61
	0.20	4.7	0.9	0.00
Propyzamide	0.75	6.3	4.1	12.01
	1.0	5.8	2.2	3.92
Untreated control		6.8	4.8	9.82
Residual d.f.		108	108	108
SED treated *vs* control		0.22	0.38	1.88
t		1.98	1.98	1.98
LSD		0.44	0.75	3.72
SED treated *vs* treated		0.25	0.44	2.17
t		1.98	1.98	1.98
LSD		0.50	0.87	4.30

* WAT = weeks after treatment; MAT = months after treatment.

100 kPa. Plots were 3 m × 1 m with a 1-m buffer between plots, laid out as a randomized block design, with three replicates of five herbicides at two rates at two dates, plus one untreated control in each replicate, giving 63 plots in total. Plant health was assessed at 2, 8 and 16 weeks after treatment using a subjective scale ranging from 1 to 5; where 1 = healthiest untreated and 5 = dead.

Data from all three experiments were subject to analysis of variance using Genstat (Genstat, 1993) and SEDs generated. Fisher's least significant difference test (Snedecor and Cochran, 1967) was then performed at the $P \leq 0.05$ level, giving a 95 per cent probability that significant results did not occur by chance. For Experiment 3, in addition to analysis of variance and least significant difference tests within individual assessment dates, REML analysis was used to generate Wald statistics (Genstat, 1993), which were used to examine overall significance levels across all assessment dates.

Results

Experiment 1

There were few long-term differences among additives in their effect on herbicide activity. However, Mixture B did appear to increase the initial efficacy of some herbicides, especially when they were used at lower doses (Table 1). Cycloxydim, glyphosate and imazapyr were the most effective treatments, resulting in the death of virtually all plants within 1 year of treatment. Within this group, the lowest dose of glyphosate

Table 3: Effect of herbicide activity on field-grown *D. flexuosa* in Experiment 3

Herbicide	Dose (kg a.i. ha^{-1})	Application date	Health score (1–5; 1 = healthy, 5 = dead) 3 May 1994	14 June 1994	16 Aug. 1994	15 Nov. 1994	24 Aug. 1995
Cycloxydim	0.23	19 April	2.3	3.7	3.7	2.0	2.7
	0.45	19 April	2.0	3.7	4.0	3.3	3.7
Imazapyr	0.38	19 April	1.0	3.0	4.0	4.7	4.3
	0.75	19 April	1.0	3.7	4.3	5.0	5.0
Glyphosate	0.90	19 April	2.0	3.3	2.7	2.0	2.0
	1.80	19 April	3.7	4.0	4.0	2.7	3.0
Fluazifop	0.38	19 April	1.0	2.7	3.7	2.0	2.3
	0.75	19 April	1.0	1.3	1.7	1.7	2.3
Propaquizafop	0.08	19 April	1.0	1.7	1.7	1.3	2.0
	0.15	19 April	1.0	1.7	2.0	1.3	2.0
Cycloxydim	0.23	26 July			2.3	5.0	5.0
	0.45	26 July			3.0	5.0	4.7
Imazapyr	0.38	26 July			3.0	5.0	5.0
	0.75	26 July			2.7	5.0	5.0
Glyphosate	0.90	26 July			1.3	2.0	1.7
	1.80	26 July			2.7	4.3	3.7
Fluazifop	0.38	26 July			1.0	1.3	2.0
	0.75	26 July			2.3	2.0	2.7
Propaquizafop	0.08	26 July			1.0	1.7	2.3
	0.15	26 July			1.7	1.0	1.3
Untreated control			1.0	1.0	1.7	1.3	2.0
SED (d.f. = 40)			0.17	0.27	0.42	0.44	0.65
t			2.02	2.02	2.02	2.02	2.02
LSD			0.34	0.55	0.85	0.89	1.31

was less effective, except when Mixture B was added. Fluazifop-*p*-butyl at the two higher doses reduced growth initially, but by the following year only the highest dose and the middle dose plus Mixture B showed any effect. Glufosinate-ammonium reduced growth initially but the effects were short-lived and after 1 year most treatments were regrowing strongly, except those treated with the highest dose plus Agral or Mixture B. Hexazinone reduced growth initially but by the following July only the highest dose and the middle dose plus Galion resulted in a significant reduction in growth. Propyzamide was the slowest acting herbicide and caused very little damage initially; however, by 1 year after application the middle dose with Agral or Galion had reduced regrowth, and the highest dose had killed most plants, with no differences between additives.

Experiment 2

Pre-spraying moisture stress had no effect on the growth of the plants or subsequent herbicide activity (data not presented). Results shown in Table 2 are the mean of the three moisture stress treatments. With the exception of the lowest dose of propyzamide, all herbicide treatments resulted in significant damage within 2 weeks of application, and the highest dose of the each herbicide caused significantly more damage than the lowest dose. By 3 months after treatment, there were appreciable differences in herbicide activity which persisted through to the following year and, 11 months after treatment, cycloxydim, glyphosate and imazapyr were the most effective treatments. Cycloxydim killed virtually all plants at both doses. Whereas, with glyphosate and imazapyr, the lower doses reduced growth considerably and higher doses killed almost all plants, propyzamide was ineffective at the low dose but showed moderate levels of activity at the high dose. Fluazifop-*p*-butyl had little effect even at the higher dose.

Experiment 3

There were significant differences between treatments ($P \leq 0.001$) and significant interactions between rate and herbicide ($P \leq 0.001$), with the higher rates tending to be more effective. There were also interactions between date and herbicide ($P \leq 0.01$), with the later dates tending to be more effective.

With the April application date, most of the herbicides were slow to show any effects, but both doses of cycloxydim and glyphosate were showing significant reductions in growth within 2 weeks of application (Table 3). In the longer term, all of the treatments reduced growth, with the applications of imazapyr showing the greatest reductions. Seven months after application, the *D. flexuosa* on the plots treated with the recommended dose of imazapyr (0.75 kg a.i. ha^{-1}) were dead and those on the lower dose were almost killed; cycloxydim at the recommended dose (0.45 kg a.i. ha^{-1}) was the next most effective treatment showing significant reductions in growth. These effects were still evident the following summer.

With the July application date, only the treatments of imazapyr and the recommended doses of cycloxydim and glyphosate showed reductions in growth initially. However, within 8 weeks of application, the cycloxydim and imazapyr treatments had killed all foliage and this was maintained throughout the growing season with only a slight amount of regrowth from the recommended dose of cycloxydim the following year. The recommended dose of glyphosate (1.80 kg a.e. ha^{-1}) also caused considerable reductions in growth within 8 weeks, which was maintained for the rest of the first year, but there was some regrowth the following year.

Discussion

Generally the three experiments investigating relative herbicide efficacy on *D. flexuosa* gave consistent results. However, overall herbicide activity was greater in the pot experiments than in field conditions, which corresponds to general experience (Copping *et al.*, 1990). The greater activity can be due to the softer growth that often occurs with both indoor and outdoor grown pot-plants as a result of frequent watering and the use of protected sites. In addition, unlike field-grown plants, root growth is restricted to the confines of the pot. When herbicides are washed down into the soil they may become concentrated around the roots and root uptake may occur from herbicides that are normally only considered to have contact foliar action. However, results from the experiments reported here confirm that whilst absolute efficacy may be less in the field, experiments using pot-grown plants provide a cost-effective method of establishing relative herbicide efficacy.

With the exception of glyphosate, the herbicides tested were generally slow-acting. In all three experiments, cycloxydim, glyphosate and imazapyr were the most effective treatments. Whilst doses as low as one-quarter of the recommended rate of cycloxydim (0.11 kg a.i. ha^{-1}) and imazapyr (0.05 kg a.i. ha^{-1}) killed plants in Experiment 1, higher doses were required in Experiment 2 where the plants were more established at the time of application. In the field, only imazapyr at 0.75 kg a.i. ha^{-1} resulted in complete death of all the plants in the treated plots, but recommended doses of cycloxydim (0.45 kg a.i. ha^{-1}) and glyphosate (1.80 kg a.e. ha^{-1}) resulted in substantial reductions in plant growth. Since the experiments took place, commercial decisions by the manufacturers mean that imazapyr and hexazinone are no longer available for use in the UK.

Propyzamide appeared to be effective in the pot experiments and offers excellent tree tolerance (Willoughby and Dewar, 1995). However, efficacy in field conditions is likely to be less, and to be effective, applications are limited to the winter, before the end of December or February, depending on formulation and location. In some instances, particularly where planting takes place late in the season to avoid frosty conditions, it may not be possible to apply propyzamide within the recommended time scale. In addition, it is relatively expensive, costing around £130 ha^{-1} for a complete overall mechanized spray (all herbicide costs quoted here would be around 50 per cent less for a 1-m band application on 2 m × 2 m spaced trees).

Glyphosate is a cheap (around £60 ha^{-1} for an overall mechanized application), safe, effective option for controlling *D. flexuosa*, either before planting, or when the grass starts to re-invade after cultivation, if trees are not sufficiently established. In addition, glyphosate will control a wide range of other weeds, not just *D. flexuosa*. However, once planting has taken place, applications need to be very carefully targeted to avoid damaging trees. This may be costly (up to £90 ha^{-1} for a complete, directed spray applied by knapsack sprayer) and not always practical around very small trees overtopped by grass.

Cycloxydim (at 0.45 kg a.i. ha^{-1}) appears to be an effective alternative herbicide for the control of pure areas of *D. flexuosa*. It is very well tolerated by trees (Willoughby and Clay, 1999) including very young seedlings (I. Willoughby, unpublished), so directed sprays need not be used. The cost for an overall mechanized application is likely to be in the region of £100 ha^{-1}.

The experiment with additives failed to show many clear-cut effects and it may be that the dose rates of cycloxydim, glyphosate and imazapyr used were generally too high for use with pot-grown plants to show any differences. However, Mixture B appeared to give improved control with the lowest glyphosate dose. In addition, compared with Agral, which is the non-ionic surfactant usually used, Mixture B gave some improvement in control with fluazifop-*p*-butyl and Galion with hexazinone. Earlier work with these additives on other perennial grass weeds of forestry also showed inconsistent results, with Galion and Mixture B sometimes, but not always, enhancing efficacy and improving rainfastness (Clay and Lawrie, 1988, 1990). Willoughby (1997) found that in field conditions, Mixture B improved the rainfastness of glyphosate when it was applied at a rate of 0.66 kg a.i. ha^{-1} to *Poa annua*, but not when it was applied at the same rate on *D. flexuosa*. Where glyphosate is being used when rainfall is likely within 24 h of spraying, it remains advisable to consider using Mixture B as an additive. The additives Agral (for fluazifop-*p*-butyl) and Actipron (for cycloxydim) should also continue to be used, as recommended by manufacturers.

Recommendations for cycloxydim and glyphosate both warn against spraying in drought conditions, as efficacy is reduced (BASF, 2002; Whitehead, 2003). The absence of differences in speed of action or final efficacy of herbicides on *D. flexuosa* grown in different moisture regimes, despite the fact that what were thought to be sublethal doses were included as treatments, may be due to the aforementioned increased efficacy sometimes found with pot-grown plants. Alternatively, it may suggest that moisture deficit has less of an effect on the leaf condition of stress-tolerant plants such as *D. flexuosa,* compared with other species that are less well adapted to growing in dry conditions.

The results of these experiments suggest that if herbicide use is required to reduce competition from *D. flexuosa* and allow trees to establish, glyphosate is a cheap, broad spectrum, effective pre-regeneration or pre-planting treatment. If further herbicide applications are required to control re-colonization after cultivation, or after a tree canopy is opened up to allow more light onto tree seedlings, cycloxydim appears to be an effective alternative treatment to propyzamide, and is a safer option for use over trees than glyphosate.

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