Natural products as herbicides for tree establishment

D.V. CLAY[1], F.L. DIXON[1] AND I. WILLOUGHBY[2]*

[1] Avon Vegetation Research Limited, PO Box 1033, Nailsea, Bristol BS48 4FH, England
[2] Forest Research, Alice Holt Lodge, Wrecclesham, Farnham, Surrey GU10 4LH, England
* Corresponding author. E-mail: ian.willoughby@forestry.gsi.gov.uk

Summary

The selectivity and efficacy of the foliar-acting natural-product herbicides bilanaphos and citronella oil were tested in comparison with glufosinate-ammonium. When applied to tree-base foliage of 10 species of broadleaved and coniferous trees in May or June they caused contact damage to the sprayed area only. Overall application of bilanaphos and glufosinate-ammonium and directed application of citronella oil to dormant trees in winter had no adverse effect on broadleaved trees but severely damaged conifer species. When sprayed on five species of actively growing herbaceous perennial weeds in May, bilanaphos gave good short-term control of *Senecio jacobaea* and perennial grasses and glufosinate-ammonium of *Rumex obtusifolius*. Citronella oil at a high dose largely killed foliage of all species within 1 day of application but most species re-grew strongly. *Senecio jacobaea* was the most susceptible species, with good control 2 months after application of the higher dose. Both these natural-product herbicides are of potential use for tree establishment but costs of development and registration may be prohibitive. Public perceptions have not yet been assessed.

Introduction

Effective weed control is essential for tree establishment in the UK and synthetic herbicides, sprayed pre- or post-planting, are currently the commonest means of achieving this. However, for environmental reasons, there is pressure to reduce the use of synthetic pesticides in crops including forestry. One solution proposed is the use of herbicidal chemicals derived from plants or other biological processes. These 'natural' products could be used to supplement or replace conventional products. Allelochemicals from many species of plants have been shown to inhibit plant growth (Putnam, 1988). However, despite extensive research, few natural products have been found with worthwhile herbicidal activity (Copping, 1996, 1998). Some allelochemicals from plants have been used as leads for the discovery of synthetic herbicides with benign environmental properties, e.g. mesotrione (Duke *et al.*, 2000; Mitchell *et al.*, 2001). In the work reported here two 'natural' products, bilanaphos and citronella oil, have been tested for selectivity on forestry crops and efficacy on weeds. Bilanaphos (bialaphos) is produced through fermentation by the micro-organism *Streptomyces hygroscopicus*; it was introduced in Japan as the herbicide Meiji Herbiace for the control of many species of annual and perennial weeds (Tachibana, 1986). It has

Forestry, Vol. 78, No. 1, 2005. doi:10.1093/forestry/cpi001

similar properties to the synthetic herbicide glufosinate-ammonium, a contact herbicide approved for use in British forestry pre-planting and as a directed spray around trees (Tomlin, 1997; Willoughby and Dewar, 1995). Some testing of selectivity of bilanaphos on forest trees has been done in Canada (Jobidon, 1991; Sy *et al.*, 1994). Barrier H, a product containing citronella oil obtained from the grass *Cymbopogon winteranius* Jowett, has been developed as a spot spray for the control of *Senecio jacobaea* L. in grassland in the UK (Barrier Biotech, 2000). It is applied as a 'Ready to Use' formulation to individual plants at the rosette stage at any time of year.

Selectivity of bilanaphos as a directed spray in spring or an overall spray in winter was tested on 10 broad-leaved and coniferous tree species in comparison with glufosinate-ammonium (Experiment 1). Citronella oil was applied as a directed spray to the bases of the same species in winter and spring in comparison with paraquat and glyphosate (Experiment 2) as part of a larger trial comparing tolerance to foliar-acting herbicides. Efficacy of bilanaphos and citronella oil applied in May on five herbaceous perennial weed species was tested in comparison with glufosinate-ammonium (Experiment 3). The doses of citronella oil used were comparable to those resulting from the recommended spot application on *S. jacobaea*, there being no recommendation for overall spraying.

Materials and methods

Experiments 1 and 2 were carried out on trees planted in March 1998 in a sandy silt loam soil at Failand, near Bristol, England (National Grid ref. ST518730). Tree species planted were: ash (*Fraxinus excelsior* L.), cherry (*Prunus avium* L.), oak (*Quercus robur* L.), poplar (*Populus deltoides* × *nigra* cv. Ghoy) and sycamore (*Acer pseudoplatanus* L.), and the conifers Corsican pine (*Pinus nigra* var. *Maritima* Arnold), Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), Japanese larch (*Larix kaempferi* (Lamb.) Carr.), Norway spruce (*Picea abies* (L.) Karsten) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Poplar was planted as 25-cm-long cuttings to a depth of ~20 cm. Remaining species were 1 year old at planting; each plot contained a single row of five plants of each species spaced 40 cm apart. Rows were 0.5 m apart; plots were 2.5 m wide × 5 m long. Coniferous species were kept together in a block as were the broad-leaved species, but species order was randomized within the block.

Experiment 1: effect of bilanaphos on trees

The herbicide treatments applied were bilanaphos as Herbi (180 g l^{-1}, SL, Meiji Seika) at 1.0 and 2.0 kg a.i. ha^{-1} and glufosinate-ammonium as Challenge (150 g l^{-1}, SL, Aventis) at 0.75 kg a.i. ha^{-1}. Herbicide treatments were applied using an Oxford Precision Sprayer. Spring applications on 20 May 1999 were made either to the soil between the rows of trees, or to a 10 cm width at the tree bases using a lance fitted with a single 8004 E flat fan nozzle, at a spray volume of 500 l ha^{-1}, and a pressure of 52.5 kPa. For the plots treated in winter all species were cut back 1 month before spraying to leave shoots no more than 60 cm in height; poplars on these plots were reduced to one shoot. One set of untreated plots was cut back in the same way. An overall application was made on 17 January 2000 to dormant trees with a boom fitted with five 11 004 low-pressure nozzles delivering 500 l ha^{-1}, at a pressure of 210 kPa giving a 2.5 m wide swath. The stage of growth of individual species at the spring application was: deciduous trees, new shoots 10–20 cm long except oak, which were 5–15 cm; conifers, new shoots mainly 5–15 cm long except larch, which were 2–5 cm long. There were three replicates of each treatment arranged in randomized blocks and two untreated control plots per block.

Tree stem diameters at 5 cm and heights were recorded in April 1999 and again in February 2000 and incremental growth calculated. With the May application, necrosis of foliage on the sprayed area was recorded during the growing season using a score of 0–3, where 0 = no damage, 1 = 1–15 per cent necrosis, 2 = 16–60 per cent necrosis and 3 = 61–100 per cent necrosis. Tree health was also recorded in October using a score of 0–7, where 0 = dead; 1 = stem alive, no foliage; 2 = shoot die-back and/or severe stunting, no new growth; 3 = die-back and/or stunting, slight new growth; 4 = 50 per cent inhibition in growth compared with best untreated trees, damage symptoms on sprayed area (leaf distortion, dead shoot tips, etc.), 5 = some damage on sprayed areas (leaf distortion and/or necrosis, occasional shoot tip death), 6 = slight damage to a few shoots on sprayed areas (leaf distortion, chlorosis or necrosis) and 7 = as best untreated.

Data from this and subsequent experiments were subjected to analysis of variance (ANOVA) using Genstat (Genstat 5 Committee, 1993) and statistically significant differences are expressed at the $P \leq 0.05$ level. Although necrosis and tree health data are not continuous but ordered categorical data, they were analysed using ANOVA rather than more sophisticated non-parametric methods. The plot is the basic unit for the ANOVA with the mean score over five plants analysed.

Experiment 2: effect of citronella oil on trees

The tree species used and plot layout were the same as for Experiment 1, with two replicates. Citronella oil, as Barrier H (229 g l^{-1}, EC, Barrier Biotech Ltd) was applied as a directed spray to a 30-cm band at the base of dormant trees on 30 March 2001 and to actively growing trees on 18 June. The spray was applied from a single 8006 flat fan nozzle at 126 kPa at a volume rate of 1000 l ha^{-1} product. Reference treatments of paraquat (as Gramoxone 100, 20 per cent a.i. SL) and glyphosate (as Roundup Biactive, 36 per cent a.e. SL) were applied to the basal 15 cm of trees on 20 February 2001 using an 8004E nozzle at 105 kPa giving a volume rate of 300 l ha^{-1}. These treatments were part of a larger experiment including 20 other treatments.

Tree health was assessed visually in April, May, July and September using a score of 0–7 as for Experiment 1.

Experiment 3: efficacy on weeds

This experiment was also sited at Failand, near Bristol on an area of established herbaceous perennial weed species. Plots were marked out at the end of March 2001 to give plots between 1 × 2 m and 1 × 4 m depending on the number and density of species in each area, to allow a minimum sprayed area for each species for each treatment of 1 m^2. Species present were mixed perennial grasses, *Ranunculus repens* L. (creeping buttercup), *Rubus obtusifolius* L. (broad-leaved dock), *Senecio jacobaea* L. (common ragwort) and *Urtica dioica* L. (common nettle). The experiment was a randomized block design with three blocks, each containing five treatments including an untreated plot (the untreated plot allows the response of weeds to the herbicide applications to be calculated relative to untreated weeds but data from the untreated plot were not included in the ANOVA). *Urtica dioica* was not treated with the low-dose citronella oil treatment due to insufficient plots.

Herbicide treatments were applied on 27 April 2001 using an Oxford Precision Sprayer fitted with a 1 m boom. Bilanaphos was sprayed at 1.0 and 2.0 kg a.i. ha^{-1}, and glufosinate-ammonium at 0.75 kg a.i. ha^{-1}, with 11 003 flat fan nozzles fitted in the boom and operating at a spray pressure of 126 kPa, and in a spray volume of 340 l ha^{-1}. Citronella oil, as a ready-to-use formulation was applied at 440 and 2200 l ha^{-1} product. Both doses were applied using the same sprayer. The 440 l ha^{-1} dose was applied by making two passes over each plot using 11 003 nozzles and sprayed at a pressure of 140 kPa. The 2200 l ha^{-1} dose was applied using 8006 nozzles fitted to the boom operating at a pressure of 210 kPa. Three passes were made over each plot.

All species were vegetative at the time of application: *R. obtusifolius* was between 20 and 40 cm tall; *U. dioica* between 20 and 50 cm tall, *R. repens* was more prostrate and spreading; with a maximum of 10 cm height; *S. jacobaea* was present as small rosettes 7–20 cm in diameter with a maximum height of 15 cm; grasses were 15–25 cm in height.

Percentage green cover of each species was assessed 1, 4 and 8 weeks after application and percentage control calculated in relation to untreated plots as follows: 100 – (percentage cover treated/percentage cover untreated × 100).

Results

Experiment 1: effect of bilanaphos on trees

There was no visible damage to any trees from applications of bilanaphos or glufosinate-ammonium to the soil in May (data not shown) or any effect on longer-term growth. The effects of applications to stem bases were therefore analysed separately

Table 1: Effect of herbicides applied to stem bases on 20 May 1999 on tree foliage on 1 June 1999

Herbicide	Dose (kg a.i. ha^{-1})	Ash	Cherry*	Oak	Poplar	Sycamore	Corsican pine	Douglas-fir	Japanese larch	Norway spruce	Sitka spruce
Bilanaphos	1.0	0.4	0.2	1.3	0.9	0.7	1.1	2.2	1.9	1.9	1.3
Bilanaphos	2.0	0.6	0.3	1.9	1.2	0.9	1.1	2.1	1.7	2.3	1.9
Glufosinate	0.75	0.7	0.5	1.3	1.1	1.3	0.9	2.0	1.7	1.8	1.3
Untreated		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SED* (d.f. = 9)		0.16	0.11	0.17	0.19	0.11	0.15	0.22	0.10	0.23	0.16

Score of treated area: 0 = no damage, 3 = 100 per cent necrosis.
* SED = standard error of difference between two treatment means.
* Data not recorded.

(Table 1). With applications to the base of young plants in May the amount of leaf damage depended on the amount of foliage present; however, there was no evidence of any effect of treatments on longer-term growth, as shown by the diameter increments for the year (Table 2) or by height increments (data not shown). Species such as oak, poplar and the conifers, with more foliage near ground level, showed more leaf necrosis on the sprayed zone but there was no evidence of any damage above the sprayed part. There was generally a small increase in the amount of damage with the higher compared with the lower bilanaphos dose when assessed in June. The amount of damage from glufosinate-ammonium compared with bilanaphos varied somewhat between species, but neither herbicide was consistently more damaging.

There was no obvious damage to the broad-leaved deciduous tree species from overall applications of bilanaphos and glufosinate-ammonium while the trees were dormant (Tables 3–5). The health of the larch was initially reduced by the higher dose of bilanaphos but there was no effect on subsequent growth. All the evergreen coniferous species suffered severe longer-term damage from the higher dose of bilanaphos. Whilst the lower dose of bilanaphos and the glufosinate-ammonium treatment caused necrosis of sprayed foliage and initial growth inhibition on all species, subsequent growth was normal and only the growth of the Douglas-fir, as measured by basal stem diameter, was reduced in the longer term by both treatments, and Sitka spruce by the glufosinate-ammonium. Ash, poplar and sycamore trees on some treated plots grew appreciably better than on the untreated plots (Table 5).

Experiment 2: effect of citronella oil on trees

The application of citronella oil to the basal 30 cm of trees in March immediately damaged

Table 2: Effect of herbicides applied to soil between trees and to stem bases on 20 May 1999 on tree diameter

Herbicide	Dose (kg a.i. ha^{-1})	Ash	Cherry	Oak	Poplar	Sycamore	Corsican pine	Douglas-fir	Japanese larch	Norway spruce	Sitka spruce
Bilanaphos	1.0	7.7	1.9	5.6	17.2	5.7	7.9	9.0	6.7	7.3	7.7
Bilanaphos	2.0	6.3	1.5	6.5	18.9	5.9	7.7	12.6	8.1	9.5	9.6
Glufosinate	0.75	8.0	0.7	5.6	18.4	6.3	6.3	12.8	5.9	8.5	8.5
Bilanaphos	1.0	6.9	2.5	4.8	18.7	5.1	7.9	7.8	7.2	7.6	7.7
Bilanaphos	2.0	7.4	2.5	6.9	18.2	6.3	7.4	12.0	8.8	6.7	9.2
Glufosinate	0.75	7.1	2.5	7.1	20.4	5.7	8.6	12.8	7.3	6.4	8.5
Untreated		6.8	1.3	5.6	19.9	5.8	8.7	11.6	7.4	7.2	8.8
SED (d.f. = 15)		1.06	–*	0.78	1.81	1.01	1.55	2.23	1.35	1.15	0.78

Values are increase (in mm) at 5 cm height, April 1999 to February 2000.
* Data not analysed due to variability.

Table 3: Effect of herbicides applied overall on 17 January 2000 on tree health on 5 May 2000

Herbicide	Dose (kg a.i. ha^{-1})	Ash	Cherry	Oak	Poplar	Sycamore	Corsican pine	Douglas-fir	Japanese larch	Norway spruce	Sitka spruce
Bilanaphos	1.0	7.0	6.4	7.0	7.0	7.0	3.3	2.9	6.9	5.5	4.2
Bilanaphos	2.0	7.0	6.2	7.0	7.0	7.0	2.5	2.7	4.9	3.2	3.3
Glufosinate	0.75	7.0	6.2	7.0	7.0	7.0	3.5	2.9	6.5	5.4	5.1
Untreated		7.0	6.3	7.0	6.7	7.0	7.0	7.0	7.0	6.7	7.0
SED (d.f. = 6)		–*	0.72	–*	0.24	–*	0.37	0.33	0.20	0.24	0.60

Health score (0–7): 0 = tree dead, 4 = 50 per cent growth inhibition, 7 = healthiest untreated.
* Data not analysed as there were no differences between treatments.

Table 4: Effect of herbicides applied on 17 January 2000 on tree health on 15 August 2000

Herbicide	Dose (kg a.i. ha^{-1})	Ash	Cherry	Oak	Poplar	Sycamore	Corsican pine	Douglas-fir	Japanese larch	Norway spruce	Sitka spruce
Bilanaphos	1.0	7.0	4.3	7.0	7.0	7.0	4.4	3.6	6.3	5.7	4.9
Bilanaphos	2.0	7.0	3.7	7.0	7.0	7.0	3.6	2.9	5.8	3.9	3.4
Glufosinate	0.75	7.0	3.7	7.0	7.0	7.0	4.5	3.5	6.4	5.1	5.3
Untreated		7.0	5.0	7.0	7.0	7.0	7.0	6.9	6.2	7.0	7.0
SED (d.f. = 9)		–†	0.73*	–†	–†	–†	0.36	0.08	0.33	0.43	0.57

Health score (0–7): 0 = tree dead, 4 = 50 per cent growth inhibition, 7 = healthiest untreated.
* d.f. = 6.
†Data not analysed as there were no differences between treatments.

foliage of Corsican pine, Douglas-fir and Norway and Sitka spruce, causing severe necrosis to sprayed shoots (data not shown). This damage persisted throughout the growing season; however, unsprayed shoots were unaffected and trees grew normally so the damage was inconspicuous by September (Tables 6 and 7). The deciduous species, which were dormant at the time of application, were unaffected. The later application of citronella oil severely damaged all sprayed foliage, with necrotic foliage of all species except poplar persisting throughout the summer. There was no indication of any damage on unsprayed parts of trees. Paraquat caused severe damage to sprayed foliage of conifers but there was no indication of damage on unsprayed parts; application to dormant broad-leaved tree species generally had no adverse effect. Glyphosate caused some distortion on new growth on sprayed shoots of ash and oak, and chlorosis and stunting of new growth on Norway and Sitka spruce, but there were no longer-term adverse effects from the lower dose (Tables 6 and 7).

Experiment 3: efficacy on weeds

Data for the five species are presented in Table 8. Degree of control is described as good where it is >80 per cent after 1 month and moderate where control is between 60 and 80 per cent at the same date. With *R. repens*, citronella treatments reduced percentage green cover rapidly; with the higher dose, necrosis developed within 1 h and all green leaves were killed within 1 week. However, by 1 month after application plants were regrowing strongly and only the higher dose gave moderate control. Bilanaphos and glufosinate stunted plants within 1 week of treatment but did not reduce green cover and all treatments were regrowing after 2 months.

Green cover of *R. obtusifolius* was significantly reduced within 1 week by all treatments, with the higher rate of citronella oil being particularly effective. However, by 1 month after application, although plant health was severely reduced, there was some regrowth from all treatments except glufosinate which gave

Table 5: Effect of herbicides applied on 17 January 2000 on tree diameter

Herbicide	Dose (kg a.i. ha^{-1})	Ash	Cherry*	Oak	Poplar	Sycamore	Corsican pine	Douglas-fir	Japanese larch	Norway spruce	Sitka spruce
Bilanaphos	1.0	9.13		6.27	4.07	8.27	6.60	5.80	11.95	5.67	6.87
Bilanaphos	2.0	8.47		6.20	4.33	8.20	−0.80	2.13	10.67	3.80	2.67
Glufosinate	0.75	7.60		5.67	3.27	8.17	5.07	5.28	10.73	7.07	4.47
Untreated		5.63		6.60	2.27	5.50	8.90	9.07	11.44	5.40	6.63
SED (d.f. = 9)		1.40		1.14	0.97	1.28	2.19	1.13	1.81	0.92	0.88

Values are increase (in mm) at 5 cm height, January–December 2000.
* Data not recorded

Table 6: Effect of citronella oil, paraquat and glyphosate on tree health on 25 May 2001

Herbicide	Dose (kg a.i. ha^{-1})	Application date	Ash	Cherry	Oak	Poplar	Sycamore	Corsican pine	Douglas-fir	Norway spruce	Sitka spruce
Citronella	229	30 Mar.	7.0	7.0	7.0	7.0	7.0	5.0	7.0	5.2	7.0
Paraquat	0.6	20 Feb.	7.0	7.0	7.0	5.7	7.0	4.1	4.1	4.9	6.0
Paraquat	1.0	20 Feb.	7.0	7.0	7.0	6.0	7.0	3.4	4.3	4.4	4.9
Glyphosate	1.8	20 Feb.	5.4	6.5	6.1	5.6	6.7	7.0	6.2	6.3	6.9
Glyphosate	3.6	20 Feb.	5.4	7.0	5.7	6.2	6.6	6.1	6.2	5.0	6.0
Untreated			7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
SED (d.f. = 24)			0.26	0.25	0.27	1.16	0.13	0.27	0.75	0.40	0.08

Score (0–7): 0 = dead, 7 = healthiest untreated.

good control. Bilanaphos and the higher citronella dose gave moderate control.

Green cover of *S. jacobaea* was significantly reduced by the higher dose of bilanaphos and both doses of citronella within 1 week of application, with the high dose of citronella giving almost total removal of all green leaves. By 1 month after application all treatments had significantly reduced green cover with the higher doses of bilanaphos and citronella being the most effective. Plant health with bilanaphos and glufosinate was poorest at this time, whereas lower-dose citronella-treated plants were recovering. By 2 months after application the plants treated with glufosinate and the lower dose of citronella were regrowing; with citronella oil, although plant numbers were significantly lower (data not shown), growing plants were large therefore green cover was greater. The higher dose of citronella maintained its effectiveness with virtually no regrowth and 75 per cent kill of treated plants.

Initially only the higher dose of citronella reduced percentage green cover of *U. dioica*, killing most of the green vegetation. By 1 month after application the higher doses of bilanaphos gave moderate and the higher dose of citronella oil gave good control, respectively, but control was reduced after 2 months.

The higher dose of citronella killed grass foliage within 1 week of treatment; the lower dose had less effect but gave better control than the bilanaphos and glufosinate treatments. Subsequently the grass regrew strongly on these treatments. After 1 month the higher dose of bilanaphos gave good control, and the lower dose and glufosinate moderate control. Regrowth on all plots was vigorous 2 months after treatment, but was least on the higher dose of bilanaphos.

Discussion

There was no evidence of adverse effects on trees from applications of bilanaphos to the soil or of translocation to other parts of trees when applied to stem bases. This suggests that the herbicide may be safe to use in the same situations in which

Table 7: Effect of citronella oil, paraquat and glyphosate on tree health on 17 September 2001

Herbicide	Dose (kg a.i. ha^{-1})	Application date	Ash	Cherry	Oak	Poplar	Sycamore	Corsican pine	Douglas-fir	Norway spruce	Sitka spruce
Citronella	229	30 Mar.	6.0	6.9	6.0	7.0	7.0	6.1	5.7	6.1	7.1
Citronella	229	18 June	4.5	4.8	4.7	7.0	5.0	4.5	4.5	4.8	5.0
Paraquat	0.6	20 Feb.	7.0	6.3	6.0	5.6	7.0	5.0	4.8	5.0	6.0
Paraquat	1.0	20 Feb.	6.3	7.0	5.5	7.0	5.9	4.3	4.5	4.5	4.8
Glyphosate	1.8	20 Feb.	5.3	6.5	5.1	6.5	5.8	7.0	5.5	7.0	7.0
Glyphosate	3.6	20 Feb.	5.1	6.0	5.3	5.0	6.1	5.8	3.5	5.8	6.0
Untreated			6.1	6.5	5.9	7.0	6.5	7.0	6.3	7.0	6.8
SED (d.f. = 27)			0.52	0.36	0.16	–*	0.50	0.50	0.81	0.42	0.35

Score (0–7): 0 = dead, 7 = healthiest untreated.
* Data not analysed due to large variability in data.

Table 8: Effect of natural product herbicides on the percentage control of five weed species

Herbicide	Dose (kg a.i. ha^{-1})	*R. repens*	*R. obtusifolius*	*S. jacobaea*	*U. dioica*	Graminae
Percentage control (3 May 2001)						
Bilanaphos	1.0	4.0	52.7	5.0	15.7	54.0
Bilanaphos	2.0	2.0	64.0	47.0	24.3	29.0
Glufosinate	0.75	2.0	68.3	13.3	30.0	27.3
Citronella oil	101.0	41.7	51.0	72.3	–	56.0
Citronella oil	504.0	100.0	82.3	97.7	85.7	95.3
SED (d.f. = 8)		14.13	10.99	9.46	14.51*	10.84
Percentage control (22 May 2001)						
Bilanaphos	1.0	28.7	66.3	72.0	43.3	71.7
Bilanaphos	2.0	19.0	61.7	93.3	75.7	92.7
Glufosinate	0.75	14.0	86.3	58.0	44.7	70.3
Citronella oil	101.0	18.3	18.3	38.0	-	0.0
Citronella oil	504.0	65.0	53.3	95.0	88.0	40.3
SED (d.f. = 8)		18.15	14.49	10.83	16.23*	12.38
Percentage control (22 June 2001)						
Bilanaphos	1.0	26.3	54.7	57.7	34.3	0.0
Bilanaphos	2.0	17.7	36.3	71.7	58.3	36.7
Glufosinate	0.75	0.0	68.3	32.3	26.7	6.7
Citronella oil	101.0	45.7	28.3	24.3	-	0.0
Citronella oil	504.0	50.7	55.7	94.0	66.0	0.0
SED (d.f. = 8)		15.16	18.13	15.75	22.82*	11.83

* d.f. = 6.

glufosinate-ammonium is currently recommended. Bilanaphos is recommended for use in tree crops in Japan (Tomlin, 1997).

There was no obvious damage to the broadleaved deciduous tree species from overall applications of bilanaphos and glufosinate-ammonium while the trees were dormant, which would indicate that these treatments may be safe to the trees. The growth of the larch was reduced by the highest dose of bilanaphos; some buds were swelling at the time of treatment and this may have increased susceptibility compared with deeply dormant plants. All the evergreen coniferous species suffered severe longer-term damage from the higher dose of bilanaphos. Whilst the low dose of bilanaphos and the glufosinate-ammonium treatment caused necrosis of sprayed foliage on all these species, only the growth of the Douglas-fir was reduced in the longer term by both treatments, and Sitka spruce by the glufosinate-ammonium. Willoughby (1996) also found overall spraying of glufosinate-ammonium damaged the same conifer species, particularly Douglas-fir. Experiments in Canada, applying bilanaphos over conifers in summer, showed there was appreciable damage to actively growing trees but less effect where growth had ceased (Jobidon, 1991; Sy *et al.*, 1994). On the basis of our results, bilanaphos is likely to be too damaging to be considered for use over dormant conifer species.

It would appear that bilanaphos may be safe to use in similar situations where glufosinate-ammonium is recommended, including carefully directed spraying between trees in leaf. Glufosinate-ammonium is currently only approved for use between 1 March and 30 September in the UK. At present bilanaphos is not available for use in the UK.

Citronella oil appeared to give similar results on tree selectivity to glufosinate-ammonium, broadleaved tree species being tolerant to directed sprays in winter, but sprayed foliage was killed by the summer application. The absence of damage to the unsprayed parts suggests careful use as a foliar-acting herbicide in the growing season would be possible.

With the efficacy experiment, clear differences in weed susceptibility and speed of action were found. The standard treatment of glufosinate-ammonium gave good medium-term control (2 months plus) of *R. obtusifolius* but only short-term control of *U. dioica*, *S. jacobaea* and perennial grasses; it was ineffective on *R. repens*. Manufacturer's literature indicates repeated treatments are needed for control of perennial weeds. Bilanaphos gave good medium-term control of *S. jacobaea* and the grasses especially at the higher dose and short-term control of *R. obtusifolius*, and *U. dioica* at the higher dose; it also was ineffective on *R. repens*. The results suggest that a dose of between 5.6 and 11.1 l ha^{-1} product will be needed to achieve similar results to glufosinate-ammonium on perennial weeds but a lower dose may be effective on annual weeds. Relative susceptibilities of the different weed species were similar for bilanaphos and glufosinate-ammonium, which is expected in view of the product working through the same active ingredient in plants. Citronella oil gave moderate control of *R. repens*, *U. dioica,* and good control of *S. jacobaea* at the highest dose and short-term control of *R. repens* and *S. jacobaea* at the lower dose. It also gave good short-term control of grasses, especially at the highest dose, and was extremely effective at the highest dose on *R. repens* in the short-term, but regrowth began within 1 month. Doses used as a spot treatment on ragwort probably range from 1000 to 2000 l ha^{-1} so the results on regrowth from this trial are consistent with that. The manufacturer's literature suggests re-treatment of larger *S. jacobaea* plants may be necessary after 28 days (Barrier Biotech, 2000).

The citronella oil product may also have pre-emergence herbicide activity, which could increase its value as a herbicide treatment, although this was not tested in this experiment. Dudai *et al.* (1999) found that soil application of an essential oil from the related species *Cymbopogon citratus* (lemon grass) inhibited germination of both mono- and dicotyledonous plant species.

The results with citronella oil and bilanaphos show that 'natural' product herbicides are capable of giving effective control of weeds in the establishment of forest trees. However, there remain serious questions over the likelihood of their widespread adoption in the future. While 'organic' growing systems may be able to sustain more expensive weed control treatments, use of these products is likely to be expensive and, with citronella oil applied at very high rates, cost of transport and application would be considerable. 'Natural' product herbicides are not necessarily any less toxic than synthetically produced compounds. Citronella oil as Barrier H has an oral LD50 (to rats) of 7200 mg kg−1 (Barrier Biotech, 2000), but the LD50 of bilanaphos is 268 mg kg−1, suggesting it is considerably more toxic than the commonly used synthetic herbicide glyphosate (LD50 of 5600 mg kg−1) (Tomlin, 1997). As 'natural' compounds already present in the environment and presumably readily degradable, they may be inherently more acceptable to some advocates of 'organic' forestry. However, as with synthetic herbicides, any introduction of 'natural' product herbicides into the UK would require a potentially time consuming and costly product registration process to be undertaken. Critically, the attitude of the public, non-governmental organizations and forest managers to the use of 'natural' product herbicides for vegetation management is yet to be determined.

Acknowledgements

This work was funded by the Forestry Commission and this support is gratefully acknowledged. Thanks are due to the manufacturers for the supply of the experimental herbicides.

References

Barrier Biotech 2000 *Technical Information*, Barrier Biotech Ltd, Attleborough, Norfolk, UK.

Copping, L.G. 1996 *Crop Protection Agents from Nature: Natural Products and Analogues*. Royal Society of Chemistry.

Copping, L.G. 1998 *The BioPesticides Manual*, 1st edn. British Crop Protection Council, Farnham, Surrey.

Dudai, N., Poljakoff-Mayber, A., Mayer, A.M., Putievsky, E. and Lerner, H.R. 1999 Essential oils as allelochemicals and their potential use as bioherbicides. *J. Chem. Ecol.* **25**, 1079–1089.

Duke, S.O., Dayan, F.E. and Rimando, A.M. 2000 Natural products and herbicide discovery. In *Herbicides and their Mechanisms of Action*. H.S. Cobb and R.C. Kirkwood (eds). Sheffield Academic Press, Sheffield, pp. 105–133.

Genstat 5 Committee 1993 *Genstat 5 release 3 Reference Manual*. Clarendon Press, Oxford.

Jobidon, R. 1991 Potential use of bialaphos, a microbially produced phytotoxin, to control red raspberry in forest plantations and its effect on black spruce. *Can. J. For. Res.*, **21**, 489–497.

Mitchell, G., Bartlett, D.W., Fraser, T.E.M., Hawkes, T.R., Holt, D.C, Townson, J.K. and Wichert, R.A. 2001 Mesotrione: a new selective herbicide for use in maize. *Pest Manage. Sci.* **57**, 20–28.

Putnam, A.R. 1988 Allelopathy: problems and opportunities in weed management. In *Weed Management in Agroecosystems: Ecological Approaches*. M.A. Altieri and M. Liebman (eds). CRC Press, Boca Raton, FL, pp. 77–88.

Sy, M., Jobidon, R. and Margolis, H. 1994 Different tolerance of coniferous species to the microbially produced herbicide bialaphos. 1. Morphology and growth effects. *Can. J. For. Res.* **24**, 2191–2198.

Tachibana, K. 1986 Herbicidal characteristics of bialaphos. In *Pesticide Science and Biotechnology*. R. Greenhalgh and T.R. Roberts (eds). International Union of Pure and Applied Chemistry/Blackwell, Oxford, pp. 145–148.

Tomlin, C.D.S. 1997 *The Pesticide Manual*, 11th edn. BCPC Farnham, Surrey.

Willoughby, I. 1996 Dormant season application of broad spectrum herbicides in forestry. In *Aspects of Applied Biology*. 44. *Vegetation Management in Forestry, Amenity and Conservation Areas*, Association of Applied Biologists, Wellesbourne, Warwickshire, CV35 9EF, U.K., pp. 55–62.

Willoughby, I. and Dewar, J. 1995 *The Use of Herbicides in the Forest*. Field Book 8, Forestry Commission, HMSO, London.

Received 17 July 2003