Refining low-volume, high-concentration herbicide applications to control *Chromolaena odorata* (L.) King & Robinson (Siam weed) in remote areas

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Abstract

Chromolaena odorata (L.) King & Robinson (Siam weed) is a highly invasive plant and a high priority for control in north Queensland. It can be effectively treated using high-volume, ground-based herbicide spray equipment, but operational information shows that this control method becomes increasingly difficult in areas where vehicle access is prevented by rougher terrain. Low-volume, high-concentration herbicide applications have proven capable of causing high mortality in these remote situations. Two trials were undertaken between May 2010 and May 2012 to refine effective rates of aminopyralid/fluroxypyr, fluroxypyr and metsulfuron-methyl, only using low-volume, high-concentration applications on Siam weed.

Fluroxypyr on its own was as effective as aminopyralid/fluroxypyr as both herbicides caused 95-100% mortality at overlapping rates containing 5 to 18.85 g a.i. L^{-1} of fluroxypyr. Metsulfuron-methyl caused 100% mortality when applied at 3 and 6 g a.i. L^{-1}. Effective control was achieved with approximately 16 to 22 mL of the solutions per plant, so a 5 L mixture in a backpack could treat 170 to 310 adult plants.

There are several options for treating Siam weed on the ground and the choice of methods reflects the area, plant density and accessibility of the infestation. Control information from Siam weed field crews shows that low volume, high concentration herbicide applications applied using a splatter gun are a more efficient method for controlling larger, denser remote infestations than physical removal. By identifying effective herbicides that are applied through low-volume equipment, these trials provide an additional and more efficient tool for controlling Siam weed in remote areas.

Keywords: aminopyralid, fluroxypyr, metsulfuron-methyl, splatter gun

Introduction

Chromolaena odorata (L.) King & Robinson (Siam weed) is a large multi-stemmed perennial Asteraceae shrub. Native to tropical parts of the Americas it is considered one of the world's most invasive tropical and sub-tropical weeds (Zachariades *et al.* 2009). Siam weed was first discovered on mainland Australia in 1994 near the towns of Mission Beach and Tully in the Tully River catchment on the tropical coast of north east Queensland. It was then identified in other tropical coastal areas of Queensland, including the Johnstone River and Maria Creek catchments (1994), Murray River catchment (1997) and Russell River catchment (2005). Outlying infestations have also been discovered near the town of Mossman (since 2003), in the drier inland areas of the Upper Herbert River catchment south of Mount Garnet (since 1997), and in the Black, Ross, Haughton and Burdekin River catchments west of Townsville (since 2003). In recognition of this serious problem, a national weed eradication program targeting Siam weed commenced in 1994. The eradication program concluded in 2012 after the continued discovery of new and disparate infestations created delimitation, infestation management and resource issues that severely reduced the feasibility of eradication.

The eradication program sought to impose effective control treatments on the entire population. Summaries of the main ground treatment methods for controlling Siam weed in each infested catchment during the last seven years of the program are outlined (Table 1); the source of this data is described in the methods section. These field records show that the physical control of plants (removal by hand) accounted for 63% of ground control activities across all catchments (Table 1). Ground-based high-volume foliar applications of fluroxypyr- or triclopyr-based herbicides were used to treat 35% of infestations across all catchments. Foliar spraying was a more common treatment method in the Tully, Murray, Mulgrave and Johnstone River catchments where it accounted for at least 48% of treatments due to more infestations being accessible to vehicles.

Foliar herbicide applications effectively treated Siam weed for the duration of the eradication program; however they rely on field crews being able to transport equipment and sufficient volumes of water and herbicide to the infestations to treat the plants. Many Siam weed infestations, particularly in the catchments near Townsville, occur on steep, rocky ground and are hundreds of metres away from tracks, where they can not be accessed by high-volume ground-based spray equipment. High-volume spraying was only recorded on 4-12% of treatment days in the greater Townsville area (Ross, Black, Burdekin and Haughton Rivers, Table 1) where access was the most difficult. Most plants were physically controlled by field crews walking to remote infestations and digging out plants, including the root crown (the basal ball from which plants re-shoot), from rocky soils on steep hills in humid tropical conditions.

Low-volume, high-concentration applications of herbicide using a small backpack and handgun equipment capable of splattering fixed volumes of the herbicide mixture onto plants have been recognised as an effective and efficient way of treating some woody shrubs for many years (e.g. Toth and Smith 1984). Recent research has led to more widespread use on weeds such as *Lantana camara* L (lantana) (e.g. State of Queensland 2006, Somerville *et al.* 2011). The advantages of this method over high-volume spraying include: more specific targeting of vegetation to be treated; reduced off-target damage; application of small volumes of a high-concentration herbicide mixture to plants to reduce chemical usage; there being no requirement to cover all foliage; and greater suitability for use in remote areas (State of Queensland 2006, Somerville *et al.* 2011).

Siam weed has been found to be susceptible to low-volume high-concentration applications of herbicides (Brooks *et al.* 2012). Out of four herbicides tested in a screening trial, at rates registered for other woody weeds, aminopyralid/fluroxypyr and triclopyr/picloram/aminopyralid proved highly effective. Glyphosate at the rate recommended for control of lantana and metsulfuron-methyl at rates registered for a number of weeds provided poor control, killing only 57 and 43% of plants, respectively (Brooks *et al.* 2012).

Two further trials were undertaken to refine rates of aminopyralid/fluroxypyr and to test whether herbicides containing only fluroxypyr could provide similar efficacy. Higher rates of metsulfuron-methyl than those included in the initial screening trial reported in Brooks *et al.*

Figure 1. Siam weed is a large branching shrub with multiple leaders (stems) arising near ground level. The largest Siam weed plant in the trials had 35 leaders and was controlled with a splatter-gun application of 1:34 Starane™ Advanced at the first trial site. This plant was photographed a) before treatment on the 26th March 2010; b) 20th June 2010, 37 DAT; and c) 6th May 2011, 357 DAT.

(2012) were also tested. Data collected by eradication program field crews were analysed to characterise infested catchments. This data was also used to assess the frequency, treated areas and effort resulting from applying three ground-based Siam weed control methods, including the splatter gun.

Methods

Site details

Two trials were established to the north of the 'Pinnacles' (hills to the south west of Townsville) and near the Alice River (Table 2): assessment dates are also included in this table. The vegetation at both sites was predominantly a sparse *Eucalyptus* or *Corymbia* woodland with open mid-storey trees and shrubs and a grassy ground layer dominated by *Heteropogon* species (Queensland Herbarium 2011). The sites all had a locally common duplex soil, specifically soil type Dy3.43 (map unit Va78), a hard setting soil with mottled yellow clayey subsoils and a moderately deep A horizon (Isbell *et al.* 1968). Trial sites were occasionally grazed but were otherwise unmanaged.

Trial design and assessment

Each trial was established using a randomised complete block design, with six or seven herbicide treatments (including an untreated control), replicated three times. Plots (experimental units) ranged in size from 5 m^2 to 90 m^2 (average approximately 20 m^2) and included ten large tagged Siam weed plants.

The number of leaders (Figure 1a–c), maximum live leader length, average plant height and diameter of the basal ball (root crown) were measured for all tagged plants prior to the application of treatments. These measurements were used to calculate the mean number of leaders, basal area and longest leader values for each plot, as summarised (Table 3). The mean plant height was used to check the amount of herbicide solution needed prior to treatment. Pre-treatment data were analysed (using analysis of variance) to ensure that the average size of plants was similar across all treatments for the respective trials. The plants in the second trial had smaller basal diameters and appeared younger than the plants in the first trial (Table 3).

The herbicide treatments chosen for the two trials are shown (Table 4). Both trials included the treatment aminopyralid/fluroxypyr at a rate of 1 g a.i. aminopyralid and 14 g a.i. fluroxypyr L^{-1} of solution as a standard for comparative purposes, following the release of the minor use permit (APVMA 2011). In the first trial, two rates of aminopyralid/fluroxypyr that were

Table 1. Percentages of days that different Siam weed ground control methods were recorded in infested catchments, and the mean accessibility scores for each catchment, where four was the hardest to access. Values followed by the same letter are not significantly different (P>0.05), l.s.d. statistic = 0.1875, n=6935). Data was summarised from eradication program field crew records.

River Catchment (number of days with treatment recorded)	% ground treatment days			Mean accessibility score
	Foliar spray	Hand removal	Splatter gun[1]	
Haughton River and Alligator Creek (66)	12	86	2	3.54a
Black River and Bluewater Creek (419)	10	84	6	3.27b
Ross and Bohle Rivers, Central and Stuart Creeks (513)	11	85	4	3.14bc
Burdekin River (44)	4	96	0	2.98c
Upper Herbert River (372)	38	62	0	2.27d
Mossman River (175)	32	68	0	1.95e
Johnstone Rivers, Maria and Liverpool Creeks (852)	52	48	<1	1.91e
Tully and Murray Rivers (807)	48	52	0	1.64f
Mulgrave River (51)	57	43	0	1.62f
Overall (3301)[2]	35	63	2	2.59

[1]The splatter gun was only used from 2009 onwards.
[2]Two cases of physically controlled single plants in the Mitchell River catchment are not shown as they were the only control records for that catchment.

Table 2. Trial locations, treatment dates and assessment time frames for the treatment of Siam weed.

Trial	Latitude	Longitude	Treated	Pre-treatment assessment	Final assessment (DAT)
First	19°22′22″S	146°36′15″E	14/5/10	26/3/10	357
Second	19°21′53″S	146°35′25″E	20/5/11	11/5/11	371

lower than the standard were included. The standard (highest rate) and middle rates of aminopyralid/fluroxypyr are comparable to the middle and lower rates of the product that contains fluroxypyr only. A higher rate of the fluroxypyr alone (18.85 g a.i L^{-1} of solution) was included as this rate is registered for the control of other weeds and is closer to the minor use permit rate of 19.59 g a.i. fluroxypyr L^{-1}. In trial two, both aminopyralid/fluroxypyr and fluroxypyr were applied at very low rates, approximately 5 g a.i. fluroxypyr L^{-1} of solution. Metsulfuron-methyl was also applied at two higher rates (3 and 6 g a.i L^{-1} of solution) than that used in the initial screening trial (1.2 g a.i L^{-1} of solution, Brooks *et al.* 2012). The non-ionic wetter/spreader/penetrant Pulse® (Nufarm) (1020 g L^{-1} polyether modified polysiloxane) and red Spraymate™ Spray Marker Dye (150 g L^{-1} Rhodamine B) was added to each herbicide mixture at a rate of 2 mL and 1 mL L^{-1} of solution, respectively. When purchased in small quantities, 'over the counter', these additives cost $0.18 L^{-1} of splatter gun solution.

Treatments were applied using a manually operated 'Forestmaster' applicator fitted with a 'lantana' nozzle manufactured by N.J. Philips (Somersby, New South Wales, Australia), before noon on the treatment dates (Table 2). Herbicide mixture was applied across the plots from a distance of 6 to 10 metres in 20 mL 'shots' which delivered approximately 4 mL of solution per 0.5 m of bush height. The equipment was rinsed with clean water between applications.

Post treatment mortality assessments of tagged plants were undertaken 357 and 371 days after treatment (DAT) for trial 1 and 2, respectively (Table 2). Additional assessments of both trials were undertaken 74 days and 207 DAT (data not shown). No treated plants were mature at these interim assessment times indicating that the herbicide applications on the dates outlined in Table 2 prevented plants from flowering and seeding.

To avoid the trials contributing to the spread of Siam weed all flower buds were removed from control plot plants within the trial site and a buffer was maintained through splatter gun applications of aminopyralid/fluroxypyr in accordance with the minor use permit (APVMA 2011). All live Siam weed plants in or around the trial sites were similarly treated at the time of the final assessment.

Siam weed program treatment data

During the eradication program, field crews and collaborators recorded site visits, control methods, effort and Siam weed populations, and these data were entered into an Access® database (Jeffery 2012). Summaries of areas treated, treatment method, number of staff, plant density and plant numbers were extracted from the database of field visit records for the last seven years of the eradication program (2005–2012). Data was extracted for each cell code in each river catchment. The cell code represents a fixed 100 m x 100 m square (1 ha) management area in which at least one Siam weed plant was recorded during the program. The field crews recorded the treated area as an estimate of the area occupied by Siam weed. We removed data that was: duplicated; infrequent; incomplete; belonging to a trial; belonging to fire and aerial treatment records; and records where no area was recorded. Absence records, where cells were searched but no plants

Table 3. The number of leaders, basal area and height of Siam weed plants in each trial before treatment. Mean data is presented ± the standard error of the mean.

	Number of leaders	Mean of summed plant basal area per plot (cm^2)	Mean length of longest leader (m)
		Trial 1 (n=21 plots)	
Mean±sem	43.1±3.1	106.6±11.1	2.0±0.1
Range	23–751	52–2511	1.1–2.7
		Trial 2 (n=18 plots)	
Mean±sem	23.6±1.4	41.93±6.3	1.76±5.6
Range	17–38	15–107	1.3–2.1

[1]One plot included a 17.25 cm basal diameter plant that had more than double the basal area of the next biggest plant: this plant was controlled by the 1:34 Starane™ Advanced treatment and is shown in Figure 1.

were found were also excluded. After this processing over 19 000 records of cell visits remained. The cell visit records were summarised into 3 301 days where an area was recorded and Siam weed was treated by foliar spray, hand removal of plants or splatter gun (Table 1). The maximum number of workers and the mean plant density score was also extracted for each day in each catchment. A mean density score was calculated from multiple plant density records of 'low', 'scattered', 'medium' or 'high' plant numbers in each cell which were allocated a score of 1 to 4 respectively and averaged per day. In some cases more than one of the three main treatments was recorded in a cell on a day (for example, some staff sprayed while others physically removed isolated plants): in these cases the same treated areas were used for both methods. Database records of most infested points also included a site access category of 'easy', 'moderate', 'difficult' or 'inaccessible' when discovered. These categories were allocated a score of 1 to 4 respectively, and average accessibility for each cell and then catchment area was calculated.

To put the treated areas in context, a sample of GPS track files from eradication field crews were also summarised (M. Jeffery and S. Brooks, unpublished data). On an average day (around five hours of search and control depending on travel, breaks and wash-down time) crews covered 2.6 to 5.5 ha per worker, depending on the catchment, with an average of 3.7 ha $worker^{-1}$ day^{-1} across all catchments.

Data analysis

One way analysis of variance with blocking was used to analyse plant measurements and mortality data from the herbicide trials. Significant differences between treatments and area means were determined using Fisher's protected least significant difference (l.s.d) test. Genstat 14th Edition (VSN International) was used for all statistical tests.

The daily treated areas per catchment and per worker were categorised by size and treatment method. One way analysis of variance was used to analyse the mean accessibility scores, treated area per person and mean density data from the eradication program database of field records. The treated area per person values calculated were square root transformed prior to analysis and back transformed means are shown. The mean accessibility scores are out of a maximum of 4, which is hardest to access, for all cell codes with access records between 1994 and 2012 (n=6935). A linear regression model adequately explained the relationship between % days with foliar spray and mean accessibility score.

Results

Trial one

Only the untreated control (with 10% mortality) differed from the six herbicide treatments, all of which exhibited high mortality (>95%), irrespective of the rates applied (Table 1). As such, at comparable rates of fluroxypyr there was no significant difference between the herbicide that contained fluroxypyr, and the one that contained aminopyralid and fluroxypyr. Accidental spraying of two plants in one of the control plots contributed to the mortality recorded in the control treatment. The cost of herbicide solution including wetter and dye ranged between \$0.98 and \$2.41 L^{-1} for the treatments applied and between 1.6 and 4.8 cents per plant depending on the herbicide and rate applied (Table 4). On average plants were treated with a dose between 16.7 and 20.7 mL (Table 4), Observations and photographs of each plot indicated that the existing grass cover in the sprayed plots was retained at the same level as the control plots during the trial.

Trial two

No significant difference (P>0.05) was recorded between the herbicide treatments for the mortality of Siam weed 371 DAT (Table 4). Both metsulfuron-methyl treatments caused 100% mortality. All the treatments containing fluroxypyr also gave high mortality even when applied at very low rates (c. 5 g fluroxypyr L^{-1} of spray solution). This was the lowest rate of fluroxypyr applied across the two trials. As for trial one, neither the rates nor herbicide ingredients were important in determining the fate of the plants.

The cost of herbicide solution including wetter and dye ranged between \$0.77 and \$2.41 L^{-1} for the treatments applied and between 1.3 and 4.8 cents per plant depending on the herbicide and rate applied (Table 4). On average plants were treated with a dose between 16.7 and 22.0 mL (Table 4). As for trial one, observations and photographs of each plot indicated that the existing grass cover was at least retained at the same level as the control plots in the herbicide treated plots during the course of the trial.

Treated areas and ground control methods.

The main ground treatment methods and associated areas recorded by program staff in all catchments between 2005 and 2012 are shown (Table 5). After categorising the treated area data there was a tendency for control by hand removal on smaller areas and herbicide applications on larger areas. On a per worker basis, the average and median areas treated with high- (foliar) or low- (splatter gun) volume herbicide equipment were up to 2 to 3 times higher than the areas treated manually, so where infestations are accessible and

Table 4. Herbicide treatments used on Siam weed plants in splatter gun trials 1 and 2, and the mortality obtained at the final assessment. Plant mortality values followed by the same letter within respective trials are not significantly different (P>0.05).

Trial and herbicide trade name	Herbicide mix rate	Amount of active ingredients in 1 L of spray solution	Cost[1] ($A) and (amount (mL or g)) of herbicide in 1 L solution at trial rate	Volume of spray solution deployed[2] (mL)	Plant mortality (%)
Trial 1					
Hotshot™	1:9	14.00 g fluroxypyr + 1.00 g aminopyralid	2.41 (100)	600	100.0a
	1:14	9.33 g fluroxypyr + 0.67 g aminopyralid	1.67 (67)	620	100.0a
	1:27	5.00 g fluroxypyr + 0.36 g aminopyralid	0.98 (36)	500	96.7a
Starane™ Advanced	1:16.7	18.85 g fluroxypyr	2.41 (94)	540	100.0a
	1:23	13.88 g fluroxypyr	1.82 (69)	540	96.7a
	1:34	9.51 g fluroxypyr	1.32 (48)	500	100.0a
Control					10.0b
Trial 2					
Brush-Off®	5 g L^{-1}	3 g metsulfuron-methyl	1.17 (5)	660	100.0a
	10 g L^{-1}	6 g metsulfuron-methyl	2.16 (10)	520	100.0a
Hotshot™	1:9	14.00 g fluroxypyr + 1.00 g aminopyralid	2.41 (100)	600	92.5a
	1:27	5.00 g fluroxypyr + 0.36 g aminopyralid	0.98 (36)	560	96.7a
Starane™ Advanced	1:65	5.05 g fluroxypyr	0.77 (25)	500	96.7a
Control					0b

[1]Based on commercial prices of 20 L of liquid herbicide or 200 g container of Brush-Off® at the time of the first trial. Wetter and dye at $0.18 L^{-1} of solution were included in these costs.
[2]Total amount deployed over 30 plants in 3 plots in 20 mL "shots".

large enough to warrant spraying these methods are preferred.

On 15% of days, crews controlled less than 11 m^2 of plants per day and 45% of days controlled less than 101 m^2 of Siam weed plants (Table 5). So, the treated areas can be small compared with the overall search area (3.7 ha $worker^{-1}$ day^{-1}), however searching large areas for small numbers of plants obviously contributes to the frequency of hand removal treatments outlined (Tables 1 and 5). Physical control is favoured in infestations with a low or scattered density of plants and after several years of continuous control only small isolated plants remain. This is reflected in the percentage of physical control days in areas such as Mossman, Upper Herbert and Tully Rivers which are slightly higher than Johnstone and Mulgrave River areas where newer, denser infestations were treated in the last seven years of the eradication program (Table 1). Site access also influences control measures illustrated by the significant negative relationship ($P<0.001$, $r^2=0.83$) between the proportion of days of foliar spraying and mean site access scores (% foliar days = -25.18 x mean access score + 91.79).

Splatter guns were used on 47 occasions with the permit rate of 1:9 Hotshot™ in the catchments west and south of Townsville between 2009 and 2012 (Tables 1 and 5). To compare the efficiency of splatter gun and hand removal treatments, a subset of the areas treated by both methods in the same region was extracted from the database and presented (Table 5). Splatter guns were used to treat 10% of the areas greater than 101 m^2 after 2009 and this resulted in a considerably greater mean and median treated area per person when compared to hand removal in the same catchments by the same crew. Mean areas treated by splatter gun in the Townsville area are up to 2 to 3 times greater than hand removal when all areas, as well as areas above 10 m^2 are considered (Table 5). The mean area of Siam weed treated per staff member per day by splatter gun applications on Siam weed is also 1.8 times higher than for higher-volume foliar sprays across all catchments (Table 5), despite the greater need to traverse to infestations.

Discussion

Herbicide efficacy

In this study, herbicides containing fluroxypyr provided high mortality of adult Siam weed plants at rates of fluroxypyr as low as 5 g a.i L^{-1} of mixture. Metsulfuron-methyl when applied at the high rates of 3 and 6 g a.i L^{-1} of mixture were also very effective with all treated plants controlled. These findings add to an initial screening trial that identified aminopyralid/fluroxypyr and triclopyr/picloram as two promising herbicides for control of Siam weed using low-volume, high-concentration applications (Brooks *et al.* 2012).

The efficacy of herbicides containing only fluroxypyr had not been tested when minor use permit 11833 (APVMA 2011) was released but they have proven

Table 5. The frequency of Siam weed area treated per day and areas treated per staff member by ground control methods. Mean areas per staff member and mean site densities treated followed by the same letter are not significantly different (P>0.05). Comparisons were made between foliar and hand removal treatments in all catchments, and between hand removal and splatter gun treatments in the Townsville catchments from 2009–2012.

Treatment method (n)	% of daily treated areas m^2				Daily treated area		
	1 to 10	11 to 100	101 to 1000	1000+	Mean (m^2 $staff^{-1}$)	Median (m^2 $staff^{-1}$)	Mean density at site
All catchments							
Foliar spray (1168)	4[1]	29	44	23	192.2a	101.9	
Hand removal (2085)	21	31	34	14	78.4b	33.3	
Townsville 2009–2012							
Hand removal (687)	17[2]	25	36	22	110.9a[2]	50.3	1.9a
Splatter gun (47)	0	13	47	40	344.1b	262.5	3.1b

[1]These 47 cases could be foliar sprays from 4 wheel drive bikes or backpacks.

[2]If the 117 cases in the 1 to 10 m^2 treated area by hand removal in Townsville area were excluded the mean area per staff is 155.5 m^2 and significance levels are unchanged.

highly effective and slightly cheaper as low-volume applications. The current study confirms that aminopyralid is not necessary to cause high mortality of Siam weed and that fluroxypyr alone at rates lower than were included in the permit is sufficient. However, we did not investigate the effect of aminopyralid on seedling emergence, which may confer some advantage of aminopyralid/fluroxypyr over fluroxypyr herbicides. Having said this, it is unlikely sufficient herbicide mixture would contact the soil for pre-emergent effects following splatter gun applications.

Given that many Siam weed infestations are located in environmentally sensitive areas where the minimisation of non-target impacts is a priority, land managers may prefer to use methods which apply less concentrated herbicide solutions. Fluroxypyr, at 0.7 g a.i L^{-1}, was the favoured chemical of control teams and field records show it is used in 70% of the high-volume foliar applications. This active ingredient not only provides high mortality of plants but also kills a large proportion of seeds located on plants at the time of spraying (Patane *et al*. 2009). This is important as Siam weed is most detectible amongst other vegetation when it is flowering between May and June, and can be treated when seeding between late July and November. Low-volume, high-concentration applications of fluroxypyr could have a similar effect on Siam seed, but this was not tested in these trials, where treatments were completed by early May and trial area maintenance sprays were completed by early July.

Siam weed infestations can contain lantana as well. Aminopyralid/fluroxypyr is one of the most effective chemicals for control of lantana using high-volume foliar spray applications (Love and Corr 2008), but research would be needed to quantify mortality rates from splatter gun applications. If confirmed to be effective, and then registered, both Siam weed and lantana could be controlled at the same time. The control of lantana from within Siam weed infestations is highly advantageous as it allows easier access to sites for follow up survey and control activities. The most commonly used herbicide on lantana in splatter guns, (40 g a.i L^{-1} of glyphosate, e.g. State of Queensland 2006, Somerville *et al*. 2011) was not suitably effective in an earlier Siam weed trial (Brooks *et al*. 2012).

The efficacy of metsulfuron-methyl when applied at ≥3 g a.i L^{-1} mixture was much higher than the 43% mortality recorded in a screening trial when applied at 1.2 g a.i L^{-1} of mixture (Brooks *et al*. 2012). There may be an effective rate between 1.2 and 3 g a.i L^{-1}. However, even if an intermediate rate was identified, the use of metsulfuron-methyl would still only be recommended on a rotational basis with Group I, fluroxypyr-based herbicides. The repeated use of Group B herbicides (ALS inhibitors) such as metsulfuron-methyl could lead to development of herbicide resistance (Vitelli and Pitt 2006). Siam weed in Malaysia was mentioned by Chuah and Ismail (2010) as one of several weeds resistant to herbicides including Group B chemicals.

Equipment and application

The back pack equipment and hand gun used in the current study was easier to carry and required less water than high-volume foliar spray applications. With only relatively small amounts (approximately 16–22 mL) of the high-concentration solutions needed for low-volume applications to achieve effective control of an individual plant, a single operator could treat about 170–310 adult plants with one load of mixture from a 5 L backpack.

Since the inclusion of low-volume 'splatter gun' applications in the minor use permit (APVMA 2011), Siam weed control teams based in Townsville have used gas-powered splatter guns to treat some larger, remote infestations (Tables 1 and 5). Data from the Siam weed eradication teams, and the study of Thompson (2013) on lantana, demonstrate that splatter guns provide for a greater area treated per unit of time than high-volume foliar sprays or physical control. Thompson (2013) reported that splatter guns used 11% more herbicide (on lantana) compared with foliar sprays but covered a greater area (2.24 times) in the same time. Siam weed field crews frequently used multiple 5 L herbicide mixtures each day so there was a need to carry sufficient water, gas and herbicide for a crew of three or four to treat an infested area (A. Clarke personal communication). At wetter times of the year, water can be filtered from nearby creeks to reduce the effort required to carry water to some infestations. Setting up water points and gradually treating and moving into less accessible areas were key parts of the splatter gun treatment strategy described by Somerville *et al*. (2011). The use of metsulfuron-methyl granules would avoid the need to carry liquid herbicides to treat infestations, though crews would need to replace the volume of the liquid herbicide with the same volume of water.

Alternative methods

The density, past management and accessibility of Siam weed all influence the choice of control measures. Where large or dense infestations with good access are encountered, then the first choice treatment is a high-volume foliar spray. Where infestations are not accessible to high-volume sprays, control of isolated plants has usually involved physical control. Manual control is an effective control measure, but it is slow, strenuous, disturbs the soil and workers may need to excavate the Siam weed root crown from beside rocks. So, there is a clear need for alternative control methods for larger Siam weed patches in less accessible areas.

Tools such as high-volume spraying from an aerial platform and cutting leaders at the base and treating each cut leader with a picloram-based gel are also listed under the minor use permit 11833 (APVMA 2011) providing some alternatives to the physical control of Siam weed in remote areas. The ability of the program to complete aerial applications and surveys varied annually, with: the availability of a suitable helicopter; permission to fly over some land tenures; weather; and program and stakeholder budgets, all variables. Operational staff indicated that spot spraying dense infestations under scattered trees with a hose and nozzle from an aerial platform is painfully slow, while aerial boom spraying potentially covers considerably greater areas (R. Winton personal communication). The off- and on-target damage by both aerial application methods has not yet been comprehensively assessed. Due to the cost of helicopter hire, aerial spot spraying may be limited to the initial management of the very dense and the least accessible infestations.

The application of a picloram gel to the freshly cut base of all leaders is also a suitable and effective treatment (J. Vitelli unpublished data, APVMA 2011), particularly for isolated plants where it is difficult to excavate the plant. It was suspected that the occasional treatment of large plants by this method was under represented from the field crew database when utilised on days when the vast majority of plants were hand removed. It is important to remember that some of the trial plants had more than 20 leaders and some trial areas had more than one plant per m^2 over hundreds of square metres. While this study did not compare cut-stump and splatter methods, Thompson (2013) found they could treat an area of lantana nine times larger with a splatter gun than with a cut-stump method in the same amount of time.

Remote infestations could also be burnt, however single burns will not control larger plants (Williams *et al*. 2004, S. Brooks unpublished data) and fires (as well as aerial applications) may not penetrate creek-line vegetation where Siam weed readily occurs (personal observations). Yeates and Schooler (2011) identified a further reduction in lantana density with a splatter gun treatment applied after a fire, so the effective treatments identified in these trials may be useful in treating shorter post-fire regrowth of Siam weed.

In a conclusion similar to that of Thompson (2013), this study shows that over the same crew, region and time frame, the area treated by splatter gun was much greater than that of physical control. Splatter gun applications effectively treat large plants up to 10 m away whereas, to apply treatments such as physical removal and cut-stump, field staff have to access the base of each plant, irrespective of the surrounding vegetation or terrain. Low-volume high-concentration applications of herbicide provide an additional treatment option for areas not accessible to high-volume ground-based spray equipment.

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