**CSIRO** PUBLISHING
www.publish.csiro.au/journals/trj *The Rangeland Journal*, 2011, **33**, 277–286

# Impact of control strategies on bellyache bush (*Jatropha gossypiifolia* L.) mortality, seedling recruitment, population dynamics, pasture yield and cost analysis

*Faiz F. Bebawi*[A,D], *Joseph S. Vitelli*[B], *Shane D. Campbell*[A] *and Robert J. Mayer*[C]

[A]Biosecurity Queensland, Department of Employment, Economic Development and Innovation, Tropical Weeds Research Centre, PO Box 187, Charters Towers, Qld 4820, Australia.
[B]Biosecurity Queensland, Department of Employment, Economic Development and Innovation, Ecosciences Precinct, PO Box 267, Brisbane, Qld 4011, Australia.
[C]Department of Employment, Economic Development and Innovation, PO Box 1085, Townsville, Qld 4810, Australia.
[D]Corresponding author. Email: Faiz.Bebawi@deedi.qld.gov.au

**Abstract.** Bellyache bush (*Jatropha gossypiifolia* L.) is an invasive weed that has the potential to greatly reduce biodiversity and pasture productivity in northern Australia's rangelands. This paper reports an approach to develop best practice options for controlling medium to dense infestations of bellyache bush using combinations of control methods. The efficacy of five single treatments including foliar spraying, slashing, stick raking, burning and do nothing (control) were compared against 15 combinations of these treatments over 4 successive years. Treatments were evaluated using several attributes, including plant mortality, changes in population demographics, seedling recruitment, pasture yield and cost of treatment.

Foliar spraying once each year for 4 years proved the most cost-effective control strategy, with no bellyache bush plants recorded at the end of the study. Single applications of slashing, stick raking and to a lesser extent burning, when followed up with foliar spraying also led to significantly reduced densities of bellyache bush and changed the population from a growing one to a declining one. Total experimental cost estimates over 4 successive years for treatments where burning, stick raking, foliar spraying, and slashing were followed with foliar spraying were AU\$408, AU\$584, AU\$802 and AU\$789 ha$^{-1}$, respectively. Maximum pasture yield of 5.4 t ha$^{-1}$ occurred with repeated foliar spraying. This study recommends that treatment combinations using either foliar spraying alone or as a follow up with slashing, stick raking or burning are best practice options following consideration of the level of control, changes in pasture yield and cost effectiveness.

**Additional keywords:** burning, foliar spraying, slashing, stick raking, treatment combinations.

## Introduction

Bellyache bush (*Jatropha gossypiifolia* L.), native to the drier islands of the Caribbean and the Venezuelan coastline (Heard *et al*. 2002), is one of the major invasive weeds of the rangelands of northern Australia (Martin *et al*. 2006; Bebawi *et al*. 2007). Bellyache bush has the potential to spread over 75% of the Australian continent (Lazarides and Hince 1993).

Morphologically, bellyache bush has a shallow root and indeterminate shoot system (Parsons and Cuthbertson 2001; Bebawi *et al*. 2007, 2009). A shallow root system means that plants can be easily uprooted during high floods and dispersed downstream within water catchments. An indeterminate shoot system means that a plant's growth is not delimited by one growing point on its axis but several points. This attribute gives bellyache bush the advantage of surviving harsh slashing, grazing or foraging activities of most of its shoot parts without losing vitality to regenerate from other parts of the shoot. Consequently bellyache bush is very resilient to physical destruction unless the shoot system is cut close to ground level (Bebawi and Campbell 2002*a*). In its native environment, bellyache bush reaches a height of 0.5–2.0 m and 1–3 cm in basal diameter (Francis 2004). In Queensland, plants are capable of growing to 4 m with a canopy spread of 2 m and a basal diameter up to 15 cm (Bebawi and Campbell 2002*a*; Vitelli and Madigan 2004).

Ecologically, bellyache bush is a prolific seeder, with mature plants able to produce up to 12 000 seeds annually (Bebawi and Campbell 2002*b*). The bellyache bush seed bank is not only long-lived under certain conditions (>10 years – F. F. Bebawi, S. D. Campbell, unpubl. data) but can also be as high as 3.8 million seeds ha$^{-1}$ at 1–5-cm soil depth in north Queensland (Bebawi and Campbell 2002*d*; Bebawi *et al*. 2007). Bellyache bush can also reach reproductive maturity quickly under optimum


10.1071/RJ10038 1036-9872/11/030277

growth conditions. In a pot trial, plants flowered and produced capsules 55 and 65 days after germination, respectively (Bebawi *et al*. 2005).

The combination of morphological and ecological attributes exhibited by bellyache bush presents great challenges for its management in the rangelands of northern Australia (Bebawi *et al*. 2007). Attributes that include a long-lived and large seed bank, early maturity, a potential to flower and set seed all year, multiple dispersal mechanisms, resilience to decapitation (Bebawi and Campbell 2002*a*), myrmecochory and toxicity to humans and livestock are important factors that landholders, local governments, and state and national authorities need to consider when developing management plans for bellyache bush (Bebawi *et al*. 2007).

Other challenges of logistics and safety also daunt the grazing industry where bellyache bush infestations prevail. For example, dense infestations of bellyache bush form impenetrable thickets that hinder mustering, obscure fence lines and firebreaks and reduce general mobility of both humans and livestock within grazing properties. They also create favourable shelter sites for feral animals that need to be controlled thus increasing management costs. Ultimately, business viability of grazing enterprises which totally rely on pasture production is significantly threatened when pastures are displaced by dense infestations of bellyache bush (Miller and Pitt 1992; Csurhes 1999; Bebawi *et al*. 2007).

Bellyache bush plants are relatively easy to kill with single (applied once) control techniques such as herbicides, machinery and fire (Bebawi and Campbell 2002*b*, 2002*c*, 2002*d*; Bebawi *et al*. 2004). However, large-scale seedling recruitment from the seed bank will generally occur afterwards (Bebawi *et al*. 2004). Therefore, control strategies need to not only deal with the original infestations but also the cohorts of seedlings that emerge while a viable seed bank remains. Whether this can be achieved using repeat applications of the same treatment (e.g. foliar spraying, slashing, stick raking or burning) or require a combination of treatments has not been determined.

The objective of this study was not only to determine the impact of single applications of foliar spraying, slashing, stick raking and burning on bellyache bush mortality, seedling recruitment, population dynamics, pasture yield and associated costs over several successive years but also to determine the impact of combinations of these treatments over several years.

## Materials and methods

### Site description and conditions

The study site comprised four large blocks (~1000 by 100 m) located on a cattle property (20°01′38′S, 146°01′55′E) 12 km north-west of Charters Towers, north Queensland. All blocks were fenced to exclude cattle for the duration of the study. Percent vegetation cover at the experimental site was estimated using the BOTANAL package developed by Tothill *et al*. (1992). Vegetation at the field site was open woodland with a canopy dominated by *Eucalyptus* spp. (10.0 ± 0.3% cover), a mid-storey dominated by bellyache bush (70.0 ± 1.5% cover) and an under-storey dominated by pasture grasses such as buffel grass (*Cenchrus ciliaris*) and native couch (*Brachyachne convergens*) (15.9 ± 0.1% cover). Long-term annual mean rainfall for this region is 658 mm year$^{-1}$ (BOM 2011). The maximum daily temperature range in summer (December–February) is between 32.6 and 34.8°C and in winter (June–August) is between 24.8 and 26.6°C (BOM 2011). Rainfall at the field site was measured via an automatic weather station (Campbell Scientific, Townsville, Qld, Australia). For the duration of the trial, annual rainfall recorded at the site was consistently less than the long-term mean (658 mm year$^{-1}$) for the area. In 2002, 2003, 2004 and 2005 the site received 485, 342, 597 and 544 mm, respectively.

### Experimental design

A 5 × 4 factorial experiment was implemented using a randomised complete block design and four replications. This resulted in a total of 80 plots (Table 1), each ~8 × 65 m in size and surrounded by a 5-m buffer. Factor A comprised five initial control techniques (primary treatments) applied in 2002: nil treatment (control), foliar spraying, slashing, stick raking and burning. Plots were sprayed, slashed and stick-raked in April, but burning was delayed until later in the dry season (August) to provide time for the fuel load to cure sufficiently. Factor B comprised four follow-up control methods (secondary treatments) applied in 2003, 2004 and 2005: nil treatment, foliar spraying, slashing, or burning applied successively on nominated plots for the three successive seasons (Table 1).

### Treatment application

Stick raking was undertaken using a Caterpillar D7 Bulldozer with a 7-m blade. The stick rake was operated at a depth of ~5 cm below ground to maximise removal of bellyache bush plants. A tractor-mounted slasher was used for the slashing treatments, and was set at a cutting height of ~10 cm above ground. For all herbicide applications, metsulfuron methyl at 6 g a.i. 100 L$^{-1}$

**Table 1. Treatment number and treatment combinations**

Treatments 1–5 represent singular treatments (applied once treatments) and treatments 6–20 represent treatment combinations with follow-up treatments applied over 3 successive years

| Treatment No. | Year 1 | Year 2 | Year 3 | Year 4 |
|---|---|---|---|---|
| 1 | Control | Control | Control | Control |
| 2 | Burn | Control | Control | Control |
| 3 | Slash | Control | Control | Control |
| 4 | Stick rake | Control | Control | Control |
| 5 | Spray | Control | Control | Control |
| 6 | Control | Burn | Burn | Burn |
| 7 | Control | Slash | Slash | Slash |
| 8 | Control | Spray | Spray | Spray |
| 9 | Burn | Burn | Burn | Burn |
| 10 | Burn | Slash | Slash | Slash |
| 11 | Burn | Spray | Spray | Spray |
| 12 | Slash | Burn | Burn | Burn |
| 13 | Slash | Slash | Slash | Slash |
| 14 | Slash | Spray | Spray | Spray |
| 15 | Stick rake | Burn | Burn | Burn |
| 16 | Stick rake | Slash | Slash | Slash |
| 17 | Stick rake | Spray | Spray | Spray |
| 18 | Spray | Burn | Burn | Burn |
| 19 | Spray | Slash | Slash | Slash |
| 20 | Spray | Spray | Spray | Spray |

(DuPont Brush Off Brush Controller, Macquarie Park, NSW, Australia) plus an alcohol alkoxylate wetting agent at 0.01% (v/v) (BS1000 bio-degradable surfactant, Murrarie, Qld, Australia) was used. Metsulfuron methyl is one of the registered foliar herbicides for controlling bellyache bush in Queensland (Csurhes 1999; Bebawi *et al*. 2007; Infopest 2010) and generally does not damage pasture grasses. A twin-diaphragm pump, powered by a 3.7-kW motor was used to spray the plants to the point where the spray mixture dripped from the foliage (spray volume 3500 L $ha^{-1}$). The handgun was fitted with a D6 nozzle and the operating pressure adjusted to 500-kPa pressure.

Fires associated with burning treatments were undertaken towards the end of the dry season and lit close to midday in order to maximise uniformity in fire behaviour over the plots. Using drip torches to promote a continuous fire line, plots were burnt as head fires following an initial back burn phase to protect neighbouring plots. For all burns, fuel load, fuel moisture and soil moisture content of the plots about to be burned were estimated on the day of burning (Table 2). Soil moisture content was determined gravimetrically from 36 randomly selected soil samples (0–5 cm below the litter layer) collected from the total plots to be burned and fuel load was estimated by removing all above-ground plant material from 48 randomly placed quadrats (50 × 50 cm) from the total plots to be burned. Samples for soil moisture were collected in waterproof glass jars and samples for fuel load were placed in brown paper bags and transferred to the laboratory where their fresh weights were measured. The glass jars, with caps removed, and the brown paper bags containing the pasture samples were then oven-dried at 100°C for 48 h. Afterwards, the dry weight of the soil and pasture was recorded and soil moisture, fuel moisture and fuel load were calculated (Table 2).

Climatic conditions were recorded during burning and included ambient temperature, relative humidity and wind speed (Table 2). Maximum temperatures of fires were measured by placing 20 type K steel-encased thermocouples randomly within the first 20 cm of the vertical profile of the fuel body where bellyache bush plants were located (Table 2). The data collected from the thermocouples were stored in data loggers (Data Electronics Pty Ltd, East Brisbane, Qld, Australia) buried underground before the fire.

### Mortality of original plants

Prior to the application of the initial treatments in 2002, 20 live juvenile (up to 20 cm high), 20 adult (20–100 cm high) and 20 old (>100 cm high) bellyache bush plants were randomly selected in each plot of the five treatments (initial control methods) which had nil treatment in subsequent seasons (treatments 1–5 in Table 1). This classification (juvenile, adult, and old) is used in an arbitrary sense across the trial in relation to assessing bellyache bush density. These selected plants were individually identified by pushing a metal peg (with an identifying tag attached) into the ground beside the base of each plant. Plants were monitored for mortality before the onset of the wet season in December each year. In cases where there was doubt as to whether a defoliated plant was still alive, a sharp knife was used to cut a small nick in the base of the stem. If the plant was alive, it exuded a colourless latex and the characteristic colour of the internal parts of the cut bark was green. No adverse effect was observed on these plants due to the cut.

### Population dynamics

To quantify population changes of bellyache bush associated with respective treatment regimes, plants were counted both before the first treatments were implemented and thereafter just before the onset of the wet season in December each year. The number of juvenile, adult and old plants was recorded within 80 systematically placed 50 × 50-cm quadrats/plot arranged in four parallel transects. To avoid errors arising from edge effects, measurements were not taken within 1 m of plot boundaries.

### Pasture yield

Within the same quadrats used to record population changes, the yield and composition of pasture grasses was visually estimated before the onset of the wet season and monitored annually for the duration of the experiment using the comparative yield method (CYM) developed by Haydock and Shaw (1975) and the BOTANAL package by Tothill *et al*. (1992). The CYM is a non-destructive sampling technique which involves two overlapping methods. One is an accurate determination of dry matter (DM) yield in a few samples (standards) and the other is a visual estimate of herbage in many samples, including the standards. Regression equations between the estimated non-yield parameter and the DM yield of the standards provide the calibration technique which is then used to estimate the DM yields of the plot samples. Detailed descriptions of the CYM method are provided in Haydock and Shaw (1975) and Tothill *et al*. (1992). Pasture composition is not reported in the present study.

### Cost estimates

Estimates of control costs were calculated for all treatment combinations. For slashing and stick raking, average hourly rates (AU$60 and AU$100, respectively), based on commercial prices (including labour and plant hire) obtained from several local contractors were multiplied by the time taken to treat individual

**Table 2. Conditions and maximum fire temperature during the primary, first, second, and third follow-up burn treatments**
Values listed are means and standard errors

| Treatments | Site conditions | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fuel load (t $ha^{-1}$) | Fuel moisture (%) | Maximum fire temp. (°C) | Ambient temp. (°C) | Wind speed (km $h^{-1}$) | Relative humidity (%) | Soil moisture (%) |
| Primary | 2.1 ± 0.2 | 22.3 ± 0.9 | 675.3 | 30.5 ± 0.4 | 4.4 ± 0.8 | 27.4 ± 2.0 | 1.4 ± 0.4 |
| First follow-up | 2.7 ± 0.6 | 21.3 ± 1.9 | 694.9 | 31.5 ± 0.3 | 7.6 ± 0.7 | 10.7 ± 0.2 | 0.6 ± 0.1 |
| Second follow-up | 3.1 ± 0.8 | 22.0 ± 1.3 | 670.9 | 25.9 ± 0.6 | 5.3 ± 0.7 | 22.9 ± 2.7 | 1.1 ± 0.1 |
| Third follow-up | 5.5 ± 0.7 | 23.7 ± 1.4 | 801.3 | 34.3 ± 0.9 | 14.6 ± 0.9 | 33.3 ± 2.7 | 1.0 ± 0.1 |

plots. Foliar spraying costs were based on fuel, herbicide, surfactant and labour per plot. For all plots treated by slashing, stick raking or foliar spraying, a conversion factor was also applied to present costs on a standardised per-ha basis.

Because of the relatively small size of plots it was not considered appropriate to determine the cost of burning based on the experimental fires implemented in this study. Instead, an average cost of AU$22 $ha^{-1}$ was used based on the average of a total of nine rangeland fires (within Australia and the United States) reported in the literature (Engle 1988; Hodgkinson and Beeston 1995; Teague *et al.* 1997; Mitchell *et al.* 2000; Paynter and Flanagan 2004). Before calculating an average cost per ha, burning cost estimates were standardised by converting them to current Australian dollar values to account for inflation and currency variations.

### *Data analysis*

GENSTAT was used for all statistical analyses (GENSTAT 8.1 Committee 2005) and Fisher's least significant difference test was used to determine significant differences between treatments whenever analysis showed treatment effects to be statistically significant.

For mortality data, a repeated-measures ANOVA over time was used, following the tagged plants in treatments 1–5. An arcsine transformation was applied to percentage data before statistical analysis and means then back-transformed to percentages.

For population density data, separate analyses were undertaken to test the effects of 'initial' and 'follow-up' treatment combinations on populations of juvenile, adult, old and combined ages for each year. For year 1 there were just the five initial control methods applied, with four replicates of each initial treatment in each block to be used subsequently for the four follow-up treatments (see Table 1). ANOVA were carried out on plant densities over years 2, 3 and 4 using a 5 × 4 factorial. A repeated-measures form of analysis was also carried out on density data to compare changes between years.

The age pyramid method of Dajoz (1977) was also applied to assess and illustrate the impact of control techniques on population structure (demographics). The method relates changes in populations to levels of seedling recruitment and levels of mortality for different age groups within a population and hence to relative proportions of the different age classes present. Dajoz (1977) illustrates three kinds of age pyramids. The first has a wide base, indicating a high proportion of young individuals and is characteristic of rapidly increasing populations. The second is an intermediate type with a fairly large percentage of young, and the third has a narrow base with a larger proportion of older individuals than young ones. This last one is characteristic of a declining population.

Pasture yield and control costs were both subjected to the same range of statistical analyses as described above for plant density.

## Results

### *Mortality of original plants*

A significant ($P = 0.03$) initial control technique × growth stage × year of assessment interaction occurred for mortality of original bellyache bush plants (Table 3). In plots where no treatments were initially applied (controls), natural attrition was high for juvenile plants, with 71% mortality recorded within the first 12 months and mortality of adult and old bellyache bush plants averaged 44% after 4 years. Implementation of foliar spraying, slashing or stick raking caused high mortality (≥99%) after one initial application, irrespective of growth stage. Burning killed a large portion (≥90%) of juvenile and adult plants but 21% of old plants survived to the second year. All of these plants subsequently died by 2005.

**Table 3. Mortality (%) of tagged juvenile, adult and old bellyache bush plants in treatments 1–5**

Plant assessment occurred before the onset of the wet season each year. Means followed by the same letter are not significantly different ($P > 0.05$)

| Initial control techniques | Year of assessment | Growth stage: Juvenile | Adult | Old |
|---|---|---|---|---|
| Control (do nothing) | 2002 | 71d | 35e | 35e |
| | 2003 | 71d | 35e | 35e |
| | 2004 | 71d | 43e | 46e |
| | 2005 | 84bcd | 43e | 46e |
| Foliar spraying | 2002 | 100a | 100a | 100a |
| | 2003 | 100a | 100a | 100a |
| | 2004 | 100a | 100a | 100a |
| | 2005 | 100a | 100a | 100a |
| Slashing | 2002 | 100a | 100a | 100a |
| | 2003 | 100a | 100a | 100a |
| | 2004 | 100a | 100a | 100a |
| | 2005 | 100a | 100a | 100a |
| Stick raking | 2002 | 99a | 99a | 99a |
| | 2003 | 99a | 99a | 99a |
| | 2004 | 99a | 100a | 99a |
| | 2005 | 99a | 100a | 99a |
| Burning | 2002 | 96ab | 90abc | 79cd |
| | 2003 | 99ab | 94abc | 89abc |
| | 2004 | 99ab | 97ab | 92abc |
| | 2005 | 100a | 100a | 100a |

### *Population dynamics*

There were significant interactions ($P < 0.01$) between initial and follow-up treatments for juvenile, adult, old and 'combined' densities of bellyache bush, both within years and across years.

Before the implementation of treatments, bellyache bush density averaged 96 700 plants $ha^{-1}$, of which 67, 23 and 10% were classified as juvenile, adult and old plants, respectively. Based on the age pyramid method of Dajoz (1977), the presence of large numbers of juvenile plants indicated a growing population. The pre-treatment average densities from this study are presented as the bottom three lines of a pyramid in Fig. 1. Even after the initial primary treatments, a similar trend occurred across all treatments because of large-scale seedling recruitment. Disturbance from mechanical techniques (slashing and stick raking) resulted in significantly higher seedling recruitment than selective foliar spraying (year 1 in Table 4). Twelve months after implementation of initial primary treatments, there were 20 800 juvenile plants $ha^{-1}$ in foliar-sprayed plots compared with 108 500 and 66 800 juvenile plants $ha^{-1}$ in slashed and stick-raked plots, respectively.

Follow-up control activities resulted in a decline in the population of bellyache bush for all treatment combinations when

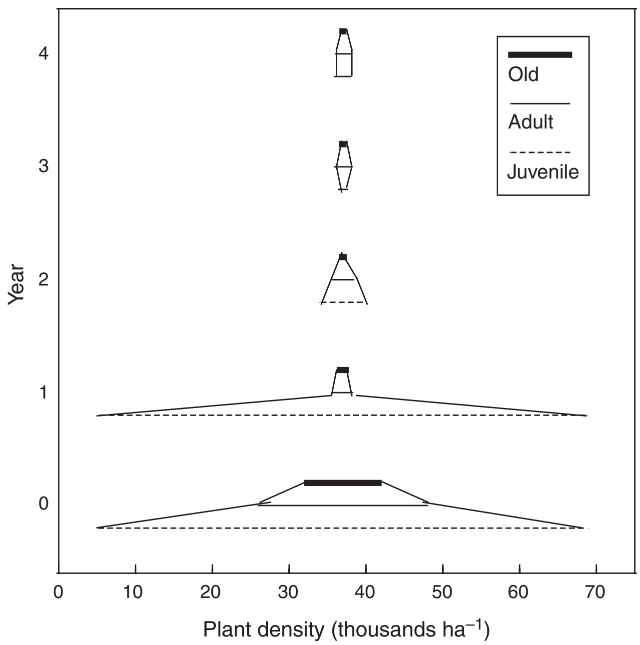


**Fig. 1.** Annual age pyramid showing changes in population demographic structure which changes from a growing population with a broad base of juvenile plants of bellyache bush to declining population with fewer juveniles associated with follow-up treatments over all control techniques.

compared with the total control (nil treatment) (Table 4). The shape of the age pyramid also changed markedly at the second and third follow-up treatments (Fig. 1), with a lower density of juveniles at the base followed by a greater density of adult and old plants at the top. This indicated a declining population (Fig. 1).

Of all treatment combinations implemented, repeated foliar spraying on an annual basis was the only one to reduce the density of bellyache bush of all sizes to zero in year 4 (Table 4). This was achieved after three follow-up sprayings subsequent to the initial primary application. Foliar spraying as a follow-up to slashing, stick raking and to a lesser extent burning also proved effective (average 99% reduction) but did not remove all bellyache bush plants within the study period. Slashing three times reduced the average population by 97%, irrespective of the initial primary treatment. Similarly, three annual burns following foliar spraying resulted in a 97% decline in the bellyache bush population.

### *Cost estimates*

Significant interactions ($P < 0.01$) were detected between initial and follow-up control techniques for annual treatment application costs (Table 5).

Burning was estimated to be the least expensive technique to implement as both an initial treatment and for follow-up control (AU\$22 $ha^{-1}$). For year 1 applications of the other initial treatments, stick raking was the next cheapest (AU\$230 $ha^{-1}$), with spraying and slashing significantly more costly (>AU\$360 $ha^{-1}$). For subsequent yearly applications, costs ranged from AU\$153 to AU\$929 for slashing and AU\$74 to AU\$277 for spraying (Table 5).

Over the 4-year study period, total application costs (both initial and follow-up) were lowest in treatment combination applications that utilised burning as a follow-up treatment. Foliar spraying was the next cheapest option. While the cost of burning was estimated to remain relatively constant (AU\$22 $ha^{-1}$) over time, foliar spraying costs tended to decline. Slashing was the most expensive follow-up option, although it was cheaper if used after initial stick raking which removed much of the debris from the ground, making slashing easier and faster to undertake. Total cost estimates over 4 successive years for treatments where burning, stick raking, foliar spraying, and slashing were followed with foliar spraying were AU\$408, AU\$584, AU\$802, and AU\$789, respectively (Table 5).

### *Pasture yield*

Significant differences were detected between initial control techniques and between follow-up treatments ($P < 0.01$) for pasture yields (Table 6). In control plots that received no treatment, pasture yield did not change significantly during the study, averaging 1080, 1210, 1160 and 1250 kg $ha^{-1}$ in years 1, 2, 3, and 4, respectively. In contrast, pasture yield increased over time for all other treatment combinations, including those that received only initial primary treatments and no follow-up control (Table 6).

The two highest pasture yields recorded were 4990 and 5400 kg $ha^{-1}$. These were in plots that received three follow-up treatments of foliar spraying after the initial primary treatments of nil control and foliar spraying, respectively.

## Discussion

### *Control strategies*

This study has identified control strategies that can achieve population level reductions in medium to dense infestations of bellyache bush. It has also highlighted the futility of once-off management activities and the importance of a follow-up program to treat seedling regrowth. Single applications of foliar spraying, slashing and stick raking all caused high mortality ($\geq$99%) of the original population, yet 12 months afterwards bellyache bush density was again high (>20 000 plants $ha^{-1}$) due to the presence of new plants. To achieve control of both original plants and seedling regrowth, foliar spraying once each year for 4 years proved the most efficient of the 20 treatment combinations tested, with no bellyache bush plants recorded at the end of the study. Initial applications of slashing, stick raking and to a lesser extent burning, followed by annual foliar spraying, also led to markedly reduced densities of bellyache bush.

While foliar spraying with metsulfuron methyl proved highly efficient for treating initial infestations and for follow-up control (irrespective of the primary treatment), there have been concerns of resistance potentially developing from the repeated use of this herbicide on some weed species (Vitelli and Pitt 2006; Osten *et al*. 2007). To minimise the risk of herbicide tolerance, it is recommended that land managers rotate the use of metsulfuron methyl with other chemicals, particularly ones with a different mode of action (Vitelli and Pitt 2006). In the case of bellyache bush, the only other currently registered herbicide, fluroxypyr, would be appropriate to use in rotation with metsulfuron methyl (Bebawi *et al*. 2007, 2009). It is generally equally as effective but more expensive (Bebawi *et al*. 2007, 2009; Randall *et al*. 2009; Infopest 2010).

**Table 4. Population densities of bellyache bush plants of three different ages based on size (juvenile, adult, old) for the 20 treatment combinations, over the 4 years**

Plant assessment occurred before the onset of the wet season each year

| Year | Follow-up treatment | Initial treatment: Nil | Burn | Slash | Spray | Stick rake | l.s.d. ($P=0.05$) |
|---|---|---|---|---|---|---|---|
| *(i) Juvenile plant density (plants ha$^{-1}$): pre-treatment average 64 000* | | | | | | | |
| 1 | – | 43 500 | 58 200 | 108 500 | 20 800 | 66 800 | 44 600 |
| 2 | Nil | 10 200 | 5000 | 21 700 | 3700 | 17 500 | – |
| | Burn | 6500 | 6400 | 6500 | 4700 | 5100 | 12 700 |
| | Slash | 12 400 | 4000 | 11 200 | 6100 | 14 100 | – |
| | Spray | 5100 | 2900 | 900 | 4400 | 500 | – |
| 3 | Nil | 3100 | 3500 | 1500 | 1200 | 2400 | – |
| | Burn | 3400 | 1100 | 1200 | 900 | 2400 | 2500 |
| | Slash | 1100 | 600 | 1400 | 1000 | 1000 | – |
| | Spray | 100 | 100 | 900 | 1000 | 200 | – |
| 4 | Nil | 8400 | 9000 | 7000 | 4500 | 5900 | – |
| | Burn | 3600 | 5000 | 7100 | 700 | 5200 | 5600 |
| | Slash | 1000 | 1000 | 600 | 1900 | 1500 | – |
| | Spray | 900 | 2200 | 100 | 0 | 0 | – |
| l.s.d. ($P=0.05$) for comparing the same treatment across years 2–4 = 9400 | | | | | | | |
| l.s.d. ($P=0.05$) for comparing year 1 treatment means with follow-up treatment combinations in years 2–4 = 43 700 | | | | | | | |
| *(ii) Adult plant density (plants ha$^{-1}$): pre-treatment average 22 300* | | | | | | | |
| 1 | – | 8000 | 4200 | 4000 | 100 | 3200 | 3900 |
| 2 | Nil | 13 600 | 7500 | 27 200 | 4400 | 17 000 | – |
| | Burn | 1100 | 10 400 | 3100 | 1100 | 9500 | 13 800 |
| | Slash | 2400 | 4500 | 4200 | 500 | 7100 | – |
| | Spray | 900 | 200 | 400 | 600 | 100 | – |
| 3 | Nil | 18 200 | 12 700 | 23 700 | 7000 | 24 100 | – |
| | Burn | 3000 | 7400 | 3500 | 700 | 9100 | 13 400 |
| | Slash | 600 | 1200 | 3600 | 1100 | 1700 | – |
| | Spray | 0 | 200 | 0 | 0 | 100 | – |
| 4 | Nil | 16 900 | 14 200 | 21 200 | 7600 | 24 000 | – |
| | Burn | 3100 | 6400 | 5000 | 1600 | 7600 | 13 100 |
| | Slash | 500 | 900 | 1100 | 900 | 700 | – |
| | Spray | 700 | 100 | 200 | 0 | 100 | – |
| l.s.d. ($P=0.05$) for comparing the same treatment across years 2–4 = 3900 | | | | | | | |
| l.s.d. ($P=0.05$) for comparing year 1 treatment means with follow-up treatment combinations in years 2–4 = 5400 | | | | | | | |
| *(iii) Old plant density (plants ha$^{-1}$): pre-treatment average 9300* | | | | | | | |
| 1 | – | 5800 | 2700 | 0 | 0 | 200 | 2500 |
| 2 | Nil | 9700 | 3000 | 9200 | 100 | 1100 | – |
| | Burn | 500 | 2600 | 0 | 0 | 100 | 7500 |
| | Slash | 0 | 0 | 0 | 0 | 0 | – |
| | Spray | 0 | 0 | 0 | 0 | 0 | – |
| 3 | Nil | 11 100 | 3600 | 15 700 | 500 | 1900 | – |
| | Burn | 200 | 1700 | 0 | 0 | 500 | 11 300 |
| | Slash | 0 | 0 | 0 | 0 | 0 | – |
| | Spray | 0 | 0 | 0 | 0 | 0 | – |
| 4 | Nil | 9600 | 6600 | 15 600 | 900 | 5600 | – |
| | Burn | 0 | 1100 | 100 | 0 | 900 | 9100 |
| | Slash | 0 | 0 | 0 | 0 | 0 | – |
| | Spray | 0 | 0 | 0 | 0 | 0 | – |
| l.s.d. ($P=0.05$) for comparing the same treatment across years 2–4 = 2800 | | | | | | | |
| l.s.d. ($P=0.05$) for comparing year 1 treatment means with follow-up treatment combinations in years 2–4 = 4600 | | | | | | | |
| *(iv) Total plant density (plants ha$^{-1}$) of all three age classes: pre-treatment average 96 700* | | | | | | | |
| 1 | – | 57 300 | 65 200 | 112 500 | 20 900 | 70 200 | 47 100 |
| 2 | Nil | 33 600 | 15 500 | 58 200 | 8200 | 35 600 | – |
| | Burn | 8100 | 19 400 | 9600 | 5900 | 14 700 | 28 700 |
| | Slash | 14 700 | 8500 | 15 500 | 6600 | 21 200 | – |
| | Spray | 6000 | 3100 | 1200 | 5000 | 600 | – |
| 3 | Nil | 32 500 | 19 900 | 41 000 | 8700 | 28 400 | – |

**Table 4.** (*continued*)

| Year | Follow-up treatment | Initial treatment Nil | Burn | Slash | Spray | Stick rake | l.s.d. ($P = 0.05$) |
|---|---|---|---|---|---|---|---|
| | Burn | 6600 | 10 200 | 4700 | 1600 | 12 000 | 22 100 |
| | Slash | 1700 | 1900 | 5000 | 2100 | 2700 | – |
| | Spray | 100 | 400 | 900 | 1000 | 400 | – |
| 4 | Nil | 34 900 | 29 900 | 43 900 | 13 000 | 35 500 | – |
| | Burn | 6700 | 12 500 | 12 200 | 2400 | 13 700 | 21 800 |
| | Slash | 1500 | 1900 | 1700 | 2700 | 2200 | – |
| | Spray | 1600 | 2400 | 400 | 0 | 100 | – |

l.s.d. ($P = 0.05$) for comparing the same treatment across years 2–4 = 10 000
l.s.d. ($P = 0.05$) for comparing year 1 treatment means with follow-up treatment combinations in years 2–4 = 41 400

**Table 5. Cost estimates (AU\$ ha$^{-1}$) for applying control techniques annually to the different treatment plots**

| Year | Follow-up treatment | Initial treatment Nil | Burn | Slash | Spray | Stick rake | l.s.d. 1[A], 2[B] ($P = 0.05$) |
|---|---|---|---|---|---|---|---|
| 1[C] | Nil | 0 | 22 | 418 | 362 | 230 | 110, 65 |
| 2[D] | Nil | 0 | 0 | 0 | 0 | 0 | 328, 193 |
| | Burn | 22 | 22 | 22 | 22 | 22 | |
| | Slash | 732 | 420 | 361 | 929 | 293 | |
| | Spray | 277 | 199 | 224 | 224 | 204 | |
| 3[D] | Nil | 0 | 0 | 0 | 0 | 0 | 196, 115 |
| | Burn | 22 | 22 | 22 | 22 | 22 | |
| | Slash | 390 | 229 | 258 | 390 | 166 | |
| | Spray | 84 | 95 | 92 | 126 | 74 | |
| 4[D] | Nil | 0 | 0 | 0 | 0 | 0 | 217, 128 |
| | Burn | 22 | 22 | 22 | 22 | 22 | |
| | Slash | 402 | 265 | 264 | 455 | 153 | |
| | Spray | 96 | 92 | 97 | 99 | 84 | |
| Total[E] | Nil | 0 | 22 | 549 | 309 | 187 | 554, 327 |
| | Burn | 66 | 88 | 507 | 485 | 306 | |
| | Slash | 1524 | 937 | 1189 | 2139 | 882 | |
| | Spray | 457 | 408 | 789 | 802 | 584 | |

[A]For comparing with means which are not 0, 22, 66 or 88.
[B]For comparing means against 0, 22, 66 and 88.
[C]Based on all 20 treatments (including the five with 'nil treatment' as follow-ups).
[D]Only the 15 treatments with actual (i.e. not 'nil') treatment follow-ups.
[E]Total costs for years 1–4, for all 20 treatment combinations.

**Table 6. Pasture yields (kg ha$^{-1}$) following initial and follow-up treatments**
Yield assessment was determined before the onset of the wet season each year

| Year | Follow-up treatment | Initial treatment Nil | Burn | Slash | Spray | Stick rake | l.s.d.[A] ($P = 0.05$) |
|---|---|---|---|---|---|---|---|
| 1 | – | 1080 | 750 | 690 | 780 | 730 | n.s.[B] |
| 2 | Nil | 1210 | 990 | 670 | 1600 | 880 | 810 |
| | Burn | 1270 | 1390 | 870 | 1120 | 910 | 810 |
| | Slash | 780 | 1050 | 730 | 970 | 1510 | 810 |
| | Spray | 1950 | 1440 | 1560 | 2180 | 1490 | 810 |
| 3 | Nil | 1160 | 1560 | 1200 | 1900 | 1290 | 830 |
| | Burn | 1970 | 2090 | 1660 | 2170 | 1390 | 830 |
| | Slash | 1400 | 1900 | 1100 | 1470 | 1650 | 830 |
| | Spray | 2630 | 1700 | 2260 | 3110 | 2480 | 830 |
| 4 | Nil | 1250 | 3570 | 2720 | 4370 | 3460 | 1190 |
| | Burn | 4130 | 4940 | 3980 | 4390 | 3200 | 1190 |
| | Slash | 3310 | 3980 | 3250 | 3440 | 4910 | 1190 |
| | Spray | 4990 | 4090 | 4260 | 5400 | 4800 | 1190 |

[A]l.s.d. ($P = 0.05$) for comparing the same treatment across years 2–4 = 680.
[B]n.s., Not significant.

With respect to mechanical control, bellyache bush plants proved susceptible to slashing and stick raking, but seedling recruitment was high following initial treatment and persisted for several years. Present results are consistent with the findings of a cutting experiment, which identified that bushes could be killed if cut off close to ground level, particularly when actively growing (Bebawi and Campbell 2002*a*). Slashing reduced bellyache bush populations as a follow-up technique across all initial treatments implemented in the present study, but its use will be restricted to areas with suitable terrain and a minimum of debris on the ground. There was also between 1500 and 2700 plants $ha^{-1}$ remaining after 4 years, depending on the initial treatment applied, which would require further control to prevent the population from increasing again in future years.

Burning was generally the least efficient of the treatments tested, due to a combination of plants avoiding being burnt and large-scale seedling recruitment. Previous research has demonstrated that bellyache bush is highly sensitive to fire but, if the fuel load is patchy, several burns may be required before the majority of plants within an infestation are killed (Bebawi and Campbell 2002*c*). Vitelli and Pitt (2006) suggested that fuel loads of greater than 2500 kg $ha^{-1}$ are required to cause high mortality of most susceptible woody species. In the present study the fuel load during the initial burn was relatively low (average of $2100 \pm 200$ kg $ha^{-1}$) and patchy; some plants were not burnt or had minimal fire damage.

### Ecological and environmental considerations

Under the rainfall conditions experienced during this study, annual follow-up treatments were satisfactory for treating seedling regrowth. However, rainfall during the study period was below average in all years. In average or above-average rainfall years, seedlings could reach reproductive maturity within 12 months. For example, in a pot trial, plants flowered within 55 days when being regularly watered. In an earlier field study in north Queensland, the time to first flowering averaged 74 days in cleared areas, 294 days in rocky sites and 454 days in grazed pastures (Bebawi *et al*. 2005). Consequently, under favourable growth conditions (such as high rainfall and limited or no pasture competition), more frequent follow-up control programs would be needed to avoid replenishment of the seed bank.

The complete removal of bellyache bush through repeated foliar spraying within a 4-year timeframe is consistent with preliminary results from a seed longevity experiment that we undertook in conjunction with this integrated trial. No buried seeds remained viable after 4 years of being exposed to natural rainfall conditions. In contrast, if rainfall was excluded using rain shelters to simulate prolonged dry conditions, some viable seed was still present after 10 years (F. F. Bebawi, S. D. Campbell, unpubl. data). Consequently, under dry conditions the duration of control programs may need to be longer than 4 years.

### Cost estimates

Except for burning, the estimated treatment costs in this study were based on times taken to treat small experimental plots and as such are most likely an overestimate when compared with actual control programs where much larger areas are generally treated. Nevertheless, they proved adequate for undertaking comparative assessments of the various treatment combinations implemented. Overall, control costs for single treatments ranged between AU$22 (burning) and AU$418 $ha^{-1}$ (slashing). Treatment combination costs using slashing tended to remain high as most of the area continued to be treated. Treatment combination costs using foliar spraying, however, tended to drop with each follow up due to the selective nature of this operation. The spray operators' plot surveillance efforts remained fairly constant each year, with foliar cost reductions attributed to the reduced spray volume needed to treat the declining population which comprised persisting and new bellyache bush plants.

The cost of controlling bellyache bush in the present study was consistent with control costs for other rangeland weeds such as parkinsonia (*Parkinsonia aculeata*) (McKenzie *et al*. 2004) and calotrope (*Calotropis procera*) (Vitelli *et al*. 2008). McKenzie *et al*. (2004) tested a range of chemical and mechanical techniques to treat a dense infestation of parkinsonia, with the cost of a single application ranging between AU$20 $ha^{-1}$ (double pulling) and AU$412 $ha^{-1}$ (basal bark spraying).

Given the relatively high costs of control for weeds such as bellyache bush, it is critical that control programs are well planned before implementation of treatments and that the frequency of treatments is sufficient to reduce the replenishment of the seed bank. However, in many instances the area infested with bellyache bush is often only a small proportion of the total area of a property (see case studies presented in Randall *et al*. 2009). As such, the cost of control also needs to be considered in the broader context of the area that is being protected through removal of bellyache bush from the landscape.

### Pasture yield changes

Under the experimental conditions of this study, there is evidence that control of bellyache bush can significantly improve pasture yield. Over the 4 years of the study, best results were generally obtained when foliar spraying was used as the follow-up treatment. Three applications of metsulfuron methyl on an annual basis after initial treatments of foliar spraying, stick raking, slashing, or burning, resulted in 5.9-, 5.6-, 5.2-, and 4.5-fold increases in pasture yield, respectively. Treatment combinations that utilise selective foliar spraying have the distinct advantage of counteracting the adverse effects on pasture dynamics that arise from pasture destructive methods such as slashing, stick raking, and burning. For example, Harrington *et al*. (1984) found that undisturbed grass can reduce the survival of shrub seedlings in semiarid woodlands of Australia.

Annual pasture yield on two cattle properties not infested with bellyache bush in the vicinity of Charters Towers, averaged 2535 and 2860 kg $ha^{-1}$ for unfertilised native and sown pastures, respectively, whereas 2695 and 3455 kg $ha^{-1}$ were recorded for fertilised native and sown pastures within the same properties (McIvor and Gardener 1995). In years of high rainfall, pasture yields could be even greater. One property located south of Charters Towers recorded an average of 5000 kg $ha^{-1}$ in above-average wet years (O'Reagain *et al*. 2009).

Our results for maximum pasture yield of 5400 kg $ha^{-1}$ were above that reported by McIvor and Gardener (1995) and O'Reagain *et al*. (2009) but were within the range (4000–7000 kg $ha^{-1}$) reported under lower rainfall and good growing conditions in north-east Queensland by McIvor *et al*. (1995). The variability between our results and those of McIvor and Gardener (1995) and O'Reagain *et al*. (2009) may be due primarily to exclusion of grazing from our site in addition to inherent site physical conditions.

With pasture yields of only 1250 kg $ha^{-1}$ recorded in untreated plots after 4 years of no grazing, carrying capacity in medium to dense infestations of bellyache bush would generally be less than 0.1 steers $ha^{-1}$. In contrast, McIvor and Gardener (1995) estimated that sustainable stocking rates for native pastures in the Charters Towers region should range between 0.2 and 0.25 steers $ha^{-1}$, based on average pasture yields of 2540 and 3630 kg $ha^{-1}$ for native and sown pastures, respectively. Any increases in pasture production as a result of control of bellyache bush, will help offset the cost of treatments and lost production associated with spelling of pastures, if needed to allow a build up of fuel for burning and/or to expedite pasture recovery after treatment.

## Conclusion

Based on efficacy and economic considerations, this study has found foliar spraying of a selective herbicide to be the best option for both initial and follow-up control of medium to dense infestations of bellyache bush. Several other combinations of treatments also led to marked reductions in the density of bellyache bush but would require more prolonged follow-up to achieve overall control.

## Acknowledgements

We gratefully acknowledge the families of Ralph Woodard, Bob Taylor and Gregg Elliot for allowing us to undertake research on their properties. We also thank the former CRC for Australian Weed Management for providing financial support to the project. We are grateful to D. Panetta for reviewing the manuscript, S. Hester for assistance with calculating the cost of burning, and the staff of the Tropical Weeds Research Centre for their assistance with implementation of treatments.

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Manuscript received 20 July 2010; accepted 9 August 2011