Supplementary Materials 1

Eradication and Control Cost Model for *Andropogon gayanus*

We collected eradication and control cost estimates for 95 hypothetical gamba grass infestations from Centrogen Weed Specialist Company in September 2008. At the time of data collection Centrogen was the main weed management contractor in the Darwin region. Several weed managers at Centrogen worked together to collectively provide estimates of total weed management costs from each infestation, including labour, equipment, chemical, travel, monitoring and planning costs. For each infestation we provided the managers with attributes known to influence management costs, including the parcel location on a map, the land use of the parcel, parcel proximity to a road, the size of the infestation, the density of the infestation (classified as scattered, medium or dense) and private benefit from weed management (classified as low or high). The 95 infestations were designed to provide an even distribution of all attribute combinations (size of infestation ranged from 0.5-500ha and density classes ranged from scattered to dense). In addition to cost estimates for all management inputs, the Centrogen team provided comments on the management approach used for control and eradication of different infestation types (classified by size and density). Control of gamba grass was defined as the management of gamba grass to prevent spread and prevent further increases in density. Control efforts include actions such as chemical treatment of the boundaries of infestations and the burning of gamba grass to increase accessibility for treatment of plants along edges of infestations. Control efforts must occur in perpetuity in order to effectively stop increases in size of gamba grass infestations. Eradication of gamba grass was defined as the local eradication of a gamba grass infestation through intense chemical treatment of the infestation over a timeframe of 6-8 years depending on infestation size and density.

Eradication model

Based on the comments accompanying the data from Centrogen, we determined that the management approaches used for the three density classes were methodologically different and we separated the data by density class to determine predictive cost models for each class. In addition, based on discussions with Centrogen the major drivers in management approach, and therefore weed management costs, are density class and size of infestation. Therefore our modelling approach focuses on these two parameters. The data provided by Centrogen gave bi-annual treatment costs for 10 years (20 treatments). We aggregated the data to annual treatment costs (20 treatments). Centrogen provided both total cost of treatment for each infestation and the breakdown of cost components.

Total cost (TC) for year t is given by:

$$TC_t = L_t * \left(58 + E + \frac{C}{L} * 0.20\right) + M_t + P$$

Where L_t is the labour hours for year t, labour costs per hour are $58, E is the equipment cost per hour and is a function of size and access, C is total chemical litres, L is total labour hrs, M_t is the per year monitoring cost and P is planning costs if t=1 and 0 otherwise (planning costs are only incurred in year one). When applying the model to estimate the cost of eradication of infestations we do not extrapolate beyond the largest sized infestation in the data set to avoid overestimation of expected economies of scale in labour costs (largest infestation 250 ha for scattered, 500 ha for medium and 200 ha for dense infestations).

*Labour costs per year (L_t*58)*

The management approach for eradication did not differ based on land use type or private benefit from gamba eradication. Therefore, we only considered density, size and year of treatment when modelling labour hours per year. We stratified the data by density class and used total labour hours per year per ha of infestation as our dependent variable. We performed a time series regression of labour hours per ha (L_{ha}) and tested 3 functional forms for the relationship between the dependent variable and t (years): linear, log-log, quadratic. The best fitting relationship was quadratic. Economies of scale are commonly found in per ha management costs (Adams et al. 2012; Armsworth et al. 2011; Ban et al. 2011; Frazee et al. 2003). We therefore included size of infestation as a predictor to capture likely economies of scale. However, the cost estimates provided by Centrogen demonstrate diminishing economies of scale through time (Figure 1).

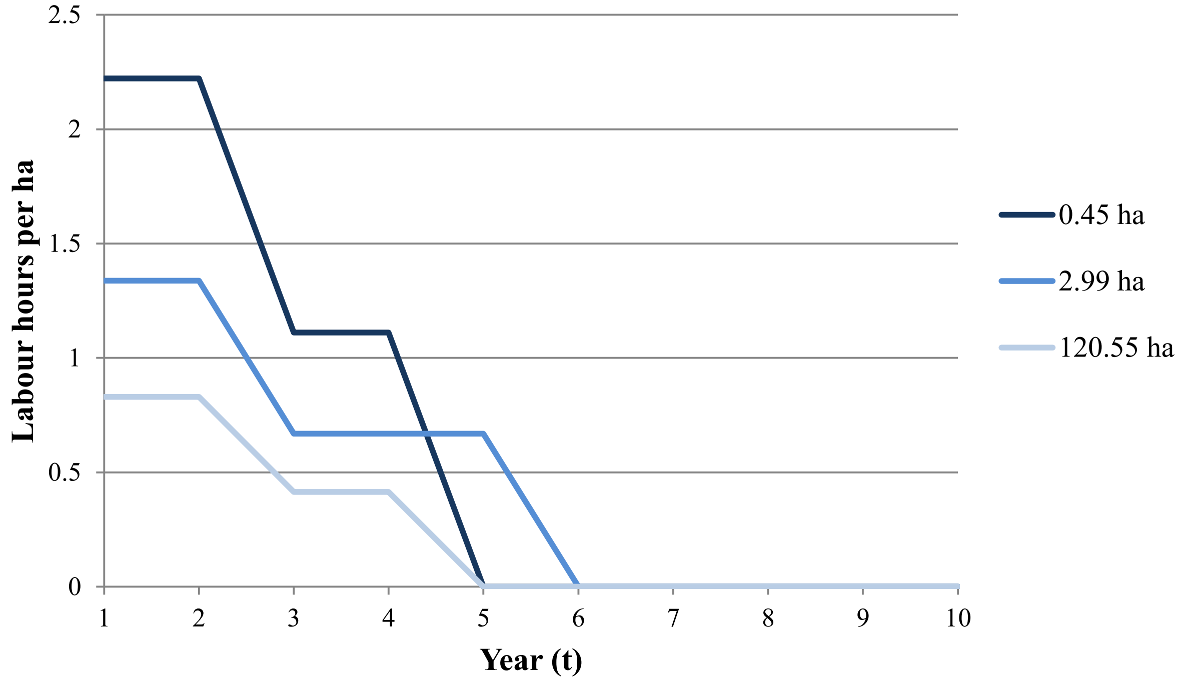

Figure 1. Sample time series for three scattered infestations of variable size. The diminishing economies scale can be observed (the time series converge through time).

This may be attributed to the fact that larger infestations diminish in size as treatment proceeds. To capture this we included size of infestation (given by area in ha) as a time specific variable; for example areaXt_1 would be equal to area of infestation for t=1 and 0 for all other values of t and similarly areaXt_2 would be equal to area of infestation for t=2 and 0 for all other values of t. We included only significant area variables. The final models for labour hours per ha as a function of time (in years) for each density class are given in Table 1. The per hour labour cost given by Centrogen was $58 per hour. Therefore, total labour hours is given by $L_t = L_{ha}$*area and total costs for a given year would be equal to 58* L_t.

Table 1. Time series models for labour hours per ha (L_{ha}) by density class. *p<0.05, all others p<0.0001

	L_{ha} - Scattered			L_{ha} -Medium			L_{ha} -Dense	
	Coefficient		SE	Coefficient		SE	Coefficient	SE
constant	2.17497		0.08354	3.61743		0.1388	5.80778	0.24197
t	-0.5580		0.03341	-0.9275		0.05664	-1.3383	0.10106
t^2	0.0346		0.00290	0.0577		0.00496	0.07702	0.00895
$areaXt_1$	-0.0042		0.00065	-0.0028		0.00078		
$areaXt_2$	-0.0022		0.00062	-0.0016	*	0.00076		
$areaXt_3$	-0.0011	*	0.00061					
n	17			15			13	
R^2 (adjusted)	0.7972			0.8150			0.8078	

*Equipment costs per year (L_t*E)*
The type of equipment used in the weed management treatment is dependent on size, density and whether there are access issues to the infestation. Access issues relate to whether an infestation is remotely located on a property or whether geographic features such as hillsides or rocky escarpments are present. When there are access issues, quad bikes are required to access the infestation as opposed to the use of 4x4 vehicles. The rules used by Centrogen to assign equipment types and the associated costs per hr (E) are provided in Table 2. Total equipment costs per year are calculated as L_t*E.

Table 2. Equipment type and associated per hr costs (E) assigned to treatment of infestation based on size, density class and presence of access issues.

Size and density class	Access	Equipment	Cost per hr (E)
<100 ha (all density classes)	No access issues	1 4x4	$71.50 per hr
<100 ha (scattered/medium)	Access issues	2 quad bikes	$44.00 per hr
<100 ha (dense)	Access issues	1 4x4 and 2 quad bikes	$115.50 per hr
100-500 ha (all density classes)	Regardless of access	1 4x4 and 2 quad bikes	$115.50 per hr
>500 ha (all density classes)	Regardless of access	2 4x4	$143.00 per hr

*Chemical costs per year (L_t *C/L*0.20)*
Centrogen applies variable rates of chemical (in litre per hour application) depending on time of year and size of infestation. However over the course of a full eradication treatment the total chemical applied to an infestation is less variable. Therefore, we summed total chemical litres across all years of treatment provided by Centrogen and used total chemical litres as the dependent variable (C). Per our methods for estimating labour hours, we stratified the data by density class and used total chemical litres summed across all years as our dependent variable and tested functional forms of C and area of infestation (area) including: linear, log-

log and quadratic. The log-log relationship was the best fit for all density classes. The final models for each density class are given in Table 3.

Table 3. Linear regression model for total chemical litres (C) as a function of area. The log-log relationship was used for all models (dependent variable log(C). All values p<0.0001.

	Scattered		Medium		Dense	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
constant	2.61058	0.05075	3.05643	0.02923	3.46786	0.03815
log(area)	0.87856	0.04135	0.85471	0.02659	0.90382	0.04124
n	17		15		13	
R^2 (adjusted)	0.9657		0.9866		0.9736	

We assume average chemical litres per year and therefore chemical costs per year are given by:

$C_t = L_t * C / L * 0.20$

Where C is estimated total chemical litres, L is total labour hours calculated as $\sum_1^{10} L_t$ and 0.20 is the cost of a litre per hour of glyphosate.

Monitoring costs (M_t)
Centrogen monitors groups of infestations (approximately 20 infestations per monitoring set in neighbouring properties) at an average per infestation cost of $280 per year per infestation or for rural properties $637 per infestation per year.

Planning Costs (P)
Centrogen undertakes an initial planning session for each infestation in the first year of treatment. The expected number of hours needed for planning is based on size of infestation and the hourly cost of planning is $70.40. The total planning cost (P), accrued in year 1, is given in Table 4.

Table 4. The number of expected hours and total planning cost (P) for an infestation based on size.

Size (area in ha)	Hours	Total planning cost (P)
<20 ha	1.5	105.6
20 - 99 ha	3	211.2
> 100 ha	4	281.6

Control model
Based on the comments accompanying the data from Centrogen, we determined that Centrogen has a standard control approach which is based on the size (categorized by broad size classes) and density of the infestation. The control approach generally included chemical treatment of the perimeter of the infestation including a buffer zone depending on the size and density of the infestation. Chemical application was therefore applied at a standard application rate (litres per hour) depending on infestation size and density. We have

summarized the control approach, given by bi-annual treatments aggregated to annual costs, by size and density class.
Total cost (TC) for year t is given by:

$$TC_t = L_t * (58 + E + C_t * 0.20) + M_t + P$$

Where L_t is the labour hours for year t, E is the equipment cost per hour and is a function of size and access, C_t is chemical litres per hr, M_t is the per year monitoring cost and P is planning costs if t=1 and 0 otherwise (planning costs are only incurred in year one). M_t and P are calculated in the same manner as for eradication costs, for details see *Monitoring Costs* and *Planning Costs* sections above.

*Labour costs per year (L_t*58)*
The control approach requires larger labour effort for an initial period, until the infestation is reduced, followed by basic recurrent effort annually in perpetuity. The initial treatments require a larger effort until the infestation is reduced, at which point an annual recurrent effort of 4 hours per year is sufficient to control the infestation. Scattered infestations, regardless of size, require 2 years of more intense treatment followed by recurrent control treatments. Medium infestations, regardless of size, require 3 years of increased treatment followed by recurrent control treatments. Dense infestations, regardless of size, require 5 years of increased treatment followed by recurrent control treatments. The initial labour time per year required by Centrogen is dependent on the size (categorized by broad size classes) and density of the infestation and is given in Table 1.

Table 1. Initial labour effort per year by density class and size. This labour effort applies for a variable length dependent on density class (2,3 or 5 years for scattered, medium and dense respectively) then reducing to a recurrent 4 hours per year in perpetuity.

Size (ha)	**Scattered**	**Medium**	**Dense**
<5 ha	4	5	5
5-19ha	6	6	6
20-40ha	6	8	8
>40ha	8	10	10

A sample labour time series for infestations of 30 ha over 10 years is given in Figure 2.

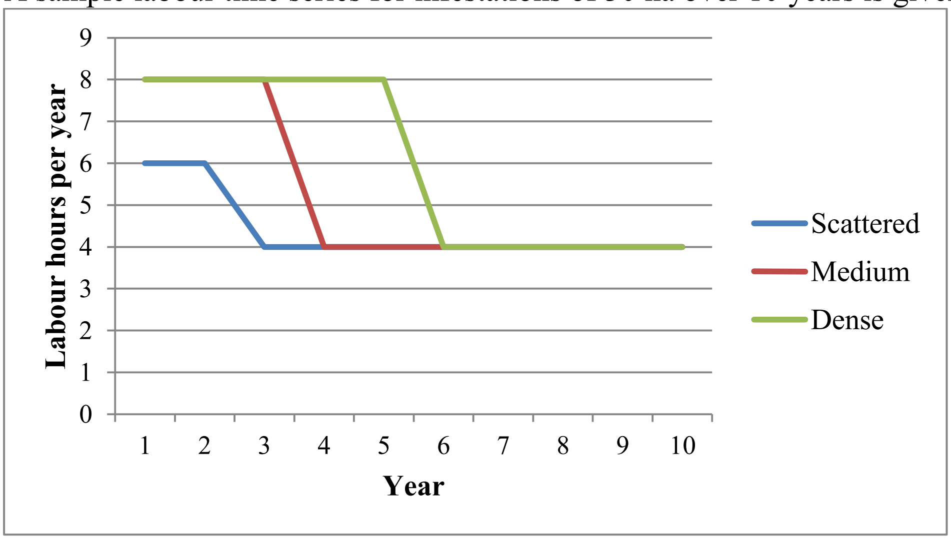

Figure 2. Sample labour time series for control of a 30ha infestation for all three density classes.

*Equipment costs per year (L_t*E)*
The type of equipment used in the weed control model is the same as the eradication model. See eradication model equipment costs section for details.

*Chemical costs per year (L_t *C*0.20)*
Centrogen applies 100 L per hr to control scattered infestations (independent of size of infestation). For medium infestations Centrogen applies a larger chemical load initially (on average 170 L per hr) for the first three years and then reduces the load to 100 L per hr (independent of size of infestation). For dense infestations Centrogen applies a larger chemical load initially (on average 170 L per hr) for the first five years and then reduces the load to 100 L per hr (independent of size of infestation).

Therefore, chemical costs per year are given by:

$C_t = L_t * C * 0.20$

$$\text{Where } C = \begin{cases} 170l\ per h\ if\ density\ class = medium\ and\ t \leq 3 \\ 170l\ per h\ if\ density\ class = dense\ and\ t \leq 5 \\ 100l\ per\ hr\ otherwise \end{cases}$$

Where C is the chemical load per hour, L_t is labour hours per year and 0.20 is the cost of a litre per hour of glyphosate.

References

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