Research reports

Predicting the cost of eradication for 41 Class 1 declared weeds in Queensland

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Summary
The feasibility of state-wide eradication of 41 invasive plant taxa currently listed as 'Class 1 declared pests' under the *Queensland Land Protection (Pest and Stock Route Management) Act 2002* was assessed using the predictive model 'WeedSearch'. Results indicated that all but one species (*Alternanthera philoxeroides*) could be eradicated, provided sufficient funding and labour were available.

Slightly less than one quarter (24.4%) (*n* = 10) of Class 1 weed taxa could be eradicated for less than $100 000 per taxon. An additional 43.9% (*n* = 18) could be eradicated for between $100 000 and $1M per taxon. Hence, 68.3% of Class 1 weed taxa (*n* = 28) could be eradicated for less than $1M per taxon. Eradication of 29.3% (*n* = 12) is predicted to cost more than $1M per taxon. Comparison of these WeedSearch outputs with either empirical analysis or results from a previous application of the model suggests that these costs may, in fact, be underestimates. Considering the likelihood that each weed will cost the state many millions of dollars in long-term losses (e.g. losses to primary production, environmental impacts and control costs), eradication seems a wise investment. Even where predicted costs are over $1M, eradication can still offer highly favourable benefit:cost ratios.

The total (cumulative) cost of eradication of all 41 weed taxa is substantial; for all taxa, the estimated cost of eradication in the first year alone is $8 618 000. This study provides important information for policy makers, who must decide where to invest public funding.

Introduction
Eradication is a very appealing management strategy, since the ongoing costs of alternative management options are avoided when it is achieved. However, weed eradication programs can be very expensive. The numerous preconditions for sensibly embarking upon an eradication program include: costs (and benefits) of eradication should be estimated, benefits should outweigh costs, and funding should be sufficient to carry the program through to completion (Panetta and Timmins 2004, Panetta 2009, Parkes and Panetta 2009, Gardener *et al.* 2010).

Earlier work has employed regression techniques to model costs on the basis of either hypothetical (Cunningham *et al.* 2004) or actual (Woldendorp and Bomford 2005) weed eradication programs. These attempts had varying success, but the approach has been criticized on two counts (Panetta 2009, Parkes and Panetta 2009). First, little can be gleaned from either failed or incomplete programs, in the former case because failure can arise from a number of factors, in the latter because costs continue to rise with time. Second, and perhaps more fundamentally limiting, there are very few instances of completed programs against large (>1000 ha) incursions. The largest successful program (2480 ha) that has been documented was one targeting *Bassia scoparia* (L.) A.J.Scott in Western Australia. However, this incursion (of an intentionally introduced species for which there was no need for delimitation) was highly atypical (Panetta 2009).

Other authors have adopted a theoretical approach to the estimation of eradication effort or cost. The simplest of these models provided a measure of eradication effort based upon the product of the total infested area and summed scorings for various impedance factors (see Table 1) (Panetta and Timmins 2004). Cacho *et al.* (2006) built on this framework through an approach that emphasized species detectability. By incorporating detectability into a population model, these authors showed that for a given level of detectability and search effort, the greatest influence on eradication program length was exerted by search speed, control effectiveness, germination rate and seed longevity. Cacho and Pheloung (2007) subsequently developed the 'WeedSearch' model that could be utilized to determine the probability of eradication within a given timeframe, as well as program duration and program costs for different weed eradication scenarios.

WeedSearch has been workshopped on several occasions since its release, but apart from the report by Robison and Darin (2009), nothing has been published concerning either the model or its application. During 2009, Biosecurity Queensland staff used WeedSearch to assess the 41 Class 1 declared plant species. (Class 1 pests, listed under the *Land Protection (Pest and Stock Route Management) Act 2002*, qualify for listing if they pose a significant threat to Queensland but are either not yet naturalized or are potentially vulnerable to eradication.) The purpose of this paper is to present the results of the WeedSearch assessment and to promote a wider use of the model, while highlighting some of the current limitations to its application.

Materials and methods
Model description

WeedSearch combines population dynamics and search theory to calculate the probability that a weed invasion will be eradicated based on the amount of time invested in searching for it. This approach has a sound rational basis, as Harris and Timmins (2009) and Hester *et al.* (2010) have concluded that the strongest determinant of the total cost of control is the extent of the area that must be searched; even though fewer weeds may require treatment as a program advances, the searchable area does not decrease over time unless individual infestations are eradicated. WeedSearch is run in Microsoft Excel and the software and manual are available at http://www-personal.une.edu.au/~ocacho/weedsearch.htm.

The model is built around the concept of impedance (i.e. factors that may impede eradication—Panetta and Timmins 2004) and requires input for a number of parameters relating to logistic considerations, detectability, biological characteristics, management effectiveness and economics (Table 1). In all, input data for 23 questions are required. More detailed information can be found in the WeedSearch Software Manual (Cacho and Pheloung 2007).

WeedSearch generates a range of outputs, including an estimate of eradication cost and timeframe. It can be run in either a deterministic or stochastic mode. If the latter is utilized, the model outputs include mean values and SD for both time to eradication and program cost. In the present case the model was run in a stochastic mode with 100 iterations.

Data acquisition and assumptions

All Class 1 weed taxa formally recorded as either cultivated or naturalized in Queensland were included (the Queensland Herbarium's HERBRECS database was consulted to help produce a definitive list of Class 1 weed taxa detected in Queensland). Class 1 taxa believed restricted to garden specimens were also covered, since these taxa have been 'biologically released' into the environment and are therefore valid targets for eradication. A review of literature was undertaken to help answer the 23 questions for each taxon. In cases where published data could not be found, experts were consulted to make reasoned estimates (so-called 'expert elicitation'). As part of this process, a workshop was held to review draft data on a range of weed taxa.

Table 1. Data input requirements for WeedSearch.

INITIAL CONDITIONS
Area
Total search area (ha)
Density of mature plants (no. ha^{-1})
IMPEDANCE
Logistics
Search speed (m h^{-1})
Biological attributes
Pre-reproductive period (years)
Maximum seed longevity (years)
Fecundity (seeds m^{-2})
Mortality of first year juveniles (%)
Perennial or annual
Size of mature plant (average in m^{2})
Plant longevity (average in years)
Population growth rate
Detectability
Effective sweep width for adult (m)
Effective sweep width for juvenile (relative to adult)
Management
Control effectiveness (% kill)
ECONOMICS
Discount factor (%)
Administration ($ y^{-1})
Transport ($ visit^{-1})
Labour ($ h^{-1})
Chemical ($ L^{-1})
Machinery ($ h^{-1})
DECISIONS
Search mode (parallel or random)
Searches per year
Search time (h ha^{-1})

We experienced considerable difficulty estimating 'total search area' for many species, with the exceptions of *Chromolaena odorata* (L.) R.M.King and H.Robinson, *Limnocharis flava* (L.) Buchenau, *Mikania micrantha* Kunth ex H.B.K., *Clidemia hirta* (L.) D.Don, *Miconia* spp., *Chrysanthemoides monilifera* subsp. *rotundata* (DC.) T.Norl., *Gmelina elliptica* Sm. and *Mimosa pigra* L., all of which have been reasonably well delimited. Such data are not routinely collected for Class 1 taxa. We decided not to use coarse presence/absence data collected within 17 × 17 km grid squares as part of the Department's Annual Pest Distribution Survey, since this was considered to yield gross overestimates of search area. For most species, we relied upon a combination of specific collection sites for specimens lodged with the Queensland Herbarium, and specific locations (generally GPS points) stored in the Department's 'PestInfo' database.

While we found data on the number of point locations where a particular species had been collected, we had to make reasoned estimates of the total search area ('gross' infestation area; Rejmánek and Pitcairn 2002). An estimate of total search area is a fundamental input for WeedSearch, since the model applies search theory to calculate search effort, labour costs, etc. For most species, we assumed a standard (default value) search radius of 200 m around each point location (= 12.5 ha per point). Where data existed to justify a departure from this default value, we used them. For example, *M. nervosa*, a bird-dispersed species, has been detected 496 m from an initial infestation site (Brooks *et al.* 2009).

In cases where species appeared to exist as reasonably discrete infestations (i.e. infestations are considerable distances apart) we treated each site as a separate population and a separate search area, and ran the model for each site – calculating a cumulative cost at the end. This made practical sense, particularly for species with infestations that were hundreds of kilometres apart, since separate travel costs and search effort are required for each site. However, this approach was difficult to apply for species that exist as specimens scattered across very large areas, with no clear demarcation between subpopulations (e.g. *Gleditsia triacanthos* L., *Nassella neesiana* Trin. et Rupr. and *C. odorata*). For these weeds, we assumed a 200 m search buffer around each data point, calculated a sum of all points (thereby accepting a single, cumulative search area) and ran the model once.

To answer questions relating to 'effective sweep width' we either made reasoned estimates, based on field experience, or made a standard response consistent with detectability data published by Harris *et al.* (2001). Other components of search effort (number of searches per year, search time and search speed) were determined through expert elicitation.

In the absence of data, a population growth rate (λ) of 1.2 was used as a default value. Clearly, this variable will be highly context dependent. The default value was considered to be within the bounds of what is realistic, considering the data that exist for a few species, and the fact that some weed populations in novel ranges may actually fail to replace themselves over the short term (i.e. $\lambda < 1$) (Hyatt and Araki 2006). In cases where data were found, appropriate values were used.

Other routine assumptions were administration costs of $5000 per site and travel costs of $200 per site.

Two species of *Cecropia* and two species of *Neptunia* were treated as single taxa (genera), since all species will be subject to the same operational considerations and actions in the first instance. *Thunbergia fragrans* Roxb. was omitted from the analysis since its status as a Class 1 pest is being reviewed. Records of *Opuntia dillenii* (Ker Gawl.) Haw. and *Prosopis juliflora* (Sw.) DC. were omitted due to taxonomic uncertainty (i.e. these species may be no different to Class 2 *O. stricta* and other *Prosopis* species).

Results

The WeedSearch model predicted that eradication is highly feasible for all but one species (*Alternanthera philoxeroides* (Mart.) Griseb.) and even this was only considered an unfeasible target at two sites (probability of eradication at these sites was 0.42, whereas probability of eradication at all other sites was 0.99) (Table 2).

Application of the WeedSearch model indicated that 24.4% ($n = 11$) of Class 1 taxa could be eradicated for less than $100 000 per taxon. An additional 43.9% ($n = 18$) could be eradicated for between $100 000 and $1M per taxon. Hence, 68.3% of Class 1 weed taxa ($n = 29$) could be eradicated for less than $1M per taxon. Eradication of 29.3% ($n = 12$) was predicted to cost more than $1M per taxon.

Discussion

Although eradication is predicted to be feasible for all but one Class 1 species, it is important to note that WeedSearch assumes that sufficient search hours can be

Table 2. Estimated mean costs of eradication for 41 weed taxa. Species are listed in order of decreasing program cost.

Taxon	Total search area (ha)	No. sites	Probability of eradication[A] (%)	Time to eradication (years)	Total cost ($000)	Cost per annum ($000)
Chromolaena odorata	14 776	n/a	99	24	47 812	1 992
Cylindropuntia prolifera	10 000	1	99	6	19 380	3 230
Nassella neesiana	14 000	1	99	16	14 780	924
Miconia calvescens	5 284	53	99	21	11 347	540
Gleditsia triacanthos	25 315	n/a	99	39	9 899	254
Acaciella angustissima	338	27	99	34	2 632	77.4
Alternanthera philoxeroides	91	115	42–99	50	1 994	39.9
Mimosa pigra	1 000	1	99	12	1 809	151
Gymnocoronis spilanthoides	172	19	99	22	1 462	66.4
Acaciella glauca	175	14	99	36	1 390	38.6
Nassella tenuissima	46	46	99	4	1 201	300
Cecropia spp.	625	50	99	11	1 185	108
Acaciella concinna (syn. *Acacia concinna*)	113	9	99	34	878	25.8
Gmelina elliptica	18 076	52	98	41	809	19.7
Hygrophila costata	240	12	99	9	798	86.7
Clidemia hirta	436	1	99	12	781	65.1
Acacia pennata	87	7	99	34	682	20.1
Neptunia oleracea and *N. plena*	15	15	99	10	446	44.6
Thunbergia laurifolia	500	1	99	9	382	42.4
Miconia nervosa	141	1	99	19	379	19.9
Mikania micrantha	183	3	99	19	357	18.8
Miconia racemosa	114	1	99	18	309	17.2
Pithecellobium dulce	250	1	99	13	270	20.7
Chrysanthemoides monilifera subsp. *rotundata*	448	7	99	5	221	44.2
Ulex europaeus	25	2	99	39	202	5.2
Acacia karroo	25	2	99	27	179	6.6
Opuntia leucotricha	38	3	99	14	172	12.2
Cylindropuntia tunicata	38	3	99	5	132	26.3
Prosopis laevigata	25	2	99	17	129	7.6
Asparagus asparagoides	75	3	99	7	121	17.3
Salix nigra	25	2	99	13	120	9.2
Acacia xanthophloea	12	1	99	21	79.5	3.8
Opuntia elata	50	1	99	13	71.8	5.5
Limnocharis flava	40	4	99	2	63.9	32.0
Chromolaena squalida	12	1	99	13	60.2	4.6
Salix cinerea	12	1	99	13	59.9	4.6
Opuntia dejecta	12	1	99	14	57.2	4.1
Opuntia elatior	12	1	99	14	57.2	4.1
Opuntia sulphurea	12	1	99	14	57.2	4.1
Opuntia microdasys	12	1	99	12	51.7	4.3
Piper aduncum	12	1	99	9	46.4	5.2

[A] Calculated as $[a/(n+1)] \times 100$, where a = number of iterations where eradication was achieved and n = total number of iterations.

committed to satisfy the input parameters. For example, the model predicts that to eradicate *Cylindropuntia prolifera* (Engelm.) F.M.Knuth. in six years, an average of 46 710 search hours per annum will be required. This is roughly equivalent to a full-time workforce of 26 people. Similarly, eradication of *N. neesiana* is predicted to require 28 000 hours search time per annum (roughly equivalent to a full-time workforce of 16 people). This demand for labour would not necessarily be evenly distributed through the year (more effort could be required during times of peak weed detectability and/or prior to seed production), meaning that at times even larger numbers of staff would be required. Hence practical considerations such as staff recruitment and management, and provision of equipment and facilities could have a major influence upon the chances of achieving eradication.

At first glance, the estimated cost for some species generally restricted to garden sites may appear excessive (e.g. $1 185 000 for *Cecropia* spp.). While removal of individual garden specimens is inexpensive, the model has assumed that a 200 m radius (equivalent to a 12.5 ha area) will be searched around each locality. This may be excessive under some circumstances, e.g. where aquatic weeds are restricted to small enclosures. On the other hand, some aspects of garden infrastructure, such as fencing, may substantially impede searching.

Validation of WeedSearch is difficult at present, particularly when total search area is neither consistently nor (often) accurately documented for completed eradication programs (Woldendorp and Bomford 2004, Panetta 2009). However, there is evidence that WeedSearch may underestimate total program costs, since the relationship between total search area and predicted cost is at best linear for infestations with search areas up to 1000 ha (Figure 1), in contrast to the findings of other work. Based on an analysis of eradication programs undertaken by the California Department of Food and Agriculture, comprising 18 species and 53 independent infestations, Rejmánek and Pitcairn (2002) found that mean eradication effort per infestation (work hours) increased exponentially over the same range of search area as that portrayed in Figure 1. In another application of WeedSearch (to an eradication program targeting *Sesbania punicea* (Cavanilles) Bentham) in northern California, Robison and Darin (2009) found that the estimated total program cost was low, after taking into account how much had already been spent on the program. They suggested that WeedSearch estimates might be more aligned with the costs of programs subsequent to initial control efforts.

The WeedSearch model suggests that eradication of several species found over considerable areas (*N. neesiana*, *G. triacanthos* and *C. odorata*) is theoretically feasible. However, this prediction is based on a number of significant assumptions. First, the model assumes that the target species' distribution has been effectively delimited. It assumes that the designated search area is searched methodically and that sufficient search effort is provided for each year that eradication is pursued. Finally, the assumption is made that reinvasion does not occur from existing invasion pathways (e.g. through the nursery trade). In reality, these assumptions are often violated. Effective delimitation of eradication targets is rare. Search areas can contain difficult terrain which hinders perfect search lines – areas inevitably get missed, or are omitted for other operational reasons. The annual investment required to meet modelled search effort may be difficult to acquire and maintain, especially over the considerable periods of time required to exhaust seed banks. Ongoing invasion, particularly where pathways remain open, can be difficult to stop.

It is also important to note that there is considerable uncertainty associated with the results. Apart from difficulties encountered in estimating search area, the main source of uncertainty was missing or incomplete data – basic biological data on most species was incomplete, despite a review of the literature. For example, data on seed longevity, seed production and juvenile mortality are rarely collected and published (but see Long *et al.* 2008 for a method to rapidly characterize seed longevity). Similarly, data on species distribution was often limited to herbarium records and lacked accurate measurements of area infested. In many cases input data had to be estimated by experts. Lastly, data on species detectability was almost always absent and had to be estimated, based on limited published data for a range of other plant species in other countries. These limitations aside, WeedSearch has a number of advantages that should encourage its wider use. It provides a transparent process for assessing feasibility of eradication (users can see what assumptions and data were used to generate the output), it provides a numerical ranking of candidate taxa that can be modified over time as new information is collected, and it is relatively easy and quick to use. Furthermore, the effects of varying parameter estimates can be determined readily through sensitivity analysis.

The appeal of eradication is that the need for long-term (ongoing) funding can be avoided at some point. However, eradication *per se* might be an unrealistic goal for many targets, for three reasons: (1) eradication of most weeds will require a 10–20 year commitment at best, (2) invasion pathways for the target may remain open so that additional incursions are possible, and (3) experience from current eradication campaigns indicates that detection of the last few individuals is very difficult, as is achieving complete delimitation. This indicates that, apart from its use as a ranking tool in situations where multiple targets are being assessed, WeedSearch might be most effectively applied to relatively small incursions, where most eradication success has been achieved to date (Panetta 2009).

Concluding remarks

Application of the WeedSearch model suggests that eradication is theoretically feasible for all 41 weed taxa, with the exception of *A. philoxeroides* at two sites. However, the total cost of eradication of all 41 weed taxa is substantial; the estimated cost of eradication in the first year alone is $8 618 000.

The predicted cost of a weed management strategy and the likelihood of its success are critical inputs in decision making. It is our view that whatever its shortcomings, WeedSearch has the potential to provide better estimates for these inputs than the informal approaches that have prevailed to date. Because WeedSearch assumes that weed incursions have been delimited, model outputs will obviously be more accurate if this is actually the case; in general, an increased allocation of effort is required to achieve delimitation of weed eradication targets (Panetta and Lawes 2005). To reduce uncertainty associated with the model, increased research effort needs to be directed at collecting basic biological data on Class 1 taxa, especially seed longevity and species detectability. The quality of predictive modelling and assessment cannot improve without such information.

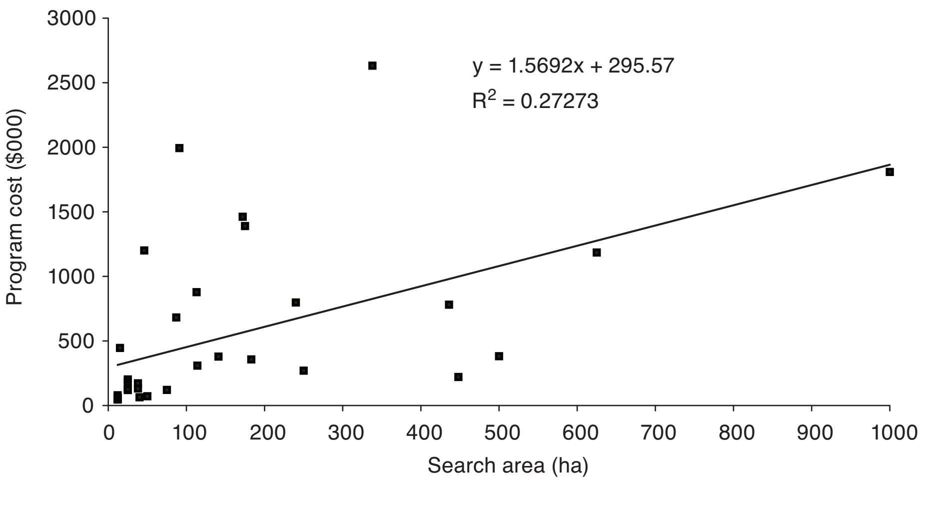

Figure 1. Relationship between predicted cost of eradication and total search area for Class 1 species with ≤1000 ha search area.

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