# Weed surveillance using search theory

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**Summary** The success of a weed incursion response ultimately depends on the ability to find and kill individual plants. Understanding detectability will allow development of operational models to guide eradication efforts by allocating resources as efficiently as possible. We present the basics of search theory to show why obtaining a measure of detectability can help us develop effective tools for allocating surveillance resources. This is particularly important in the context of new methods of searching for weeds becoming available. The use of detector dogs, remote sensing, drones and other tools provide new opportunities to improve efficiency, but the right mix of methods will depend on the cost to achieve a given probability of detection. We use examples from existing weed eradication responses to show how detectability is affected by environment, search mode and life stage of the plant. We conclude by proposing ways of making these decision-analysis principles more accessible to practitioners.

**Keywords** Detection, eradication, decision analysis.

## INTRODUCTION

Invasive plant managers are required to design and implement strategies that use available budgets as efficiently as possible. Budgets are typically distributed between the treatment of known infestations, research to improve control methods and future management decisions, active surveillance, and community engagement to encourage the public to report infestations—passive surveillance. The decision problem faced by invasive plant managers is illustrated (Figure 1).

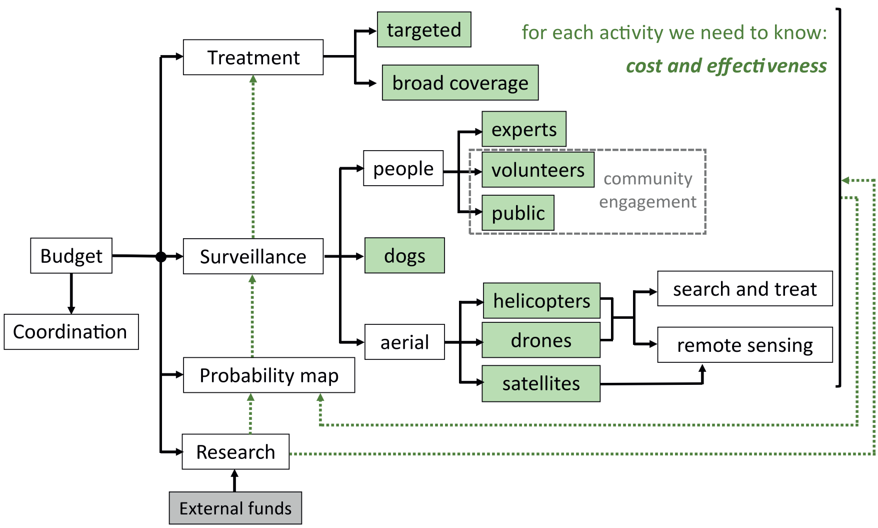


**Figure 1.** Conceptual model of the decision problem facing managers of eradication and containment programs. Dotted lines indicate transmission of information.

Within the expected budget, an agency must decide how to allocate resources to different forms of surveillance, treatment and research. Each of these actions can involve different activities. For example, in the case of treatment, targeted application of herbicide may be necessary in natural ecosystems whereas broad treatment is possible in cropping systems. Surveillance informs treatment (illustrated by a broken line in Figure 1) by assigning target areas. For surveillance in public lands, the typical case involves field officers (experts) searching for the weed in areas known or suspected to be invaded. Targeted treatment may occur simultaneously with surveillance, but it can also occur separately, as when contractors are sent later to spray. This form of surveillance may be supplemented by volunteers working under the guidance of field officers and, in some cases, informed by members of the public reporting sightings of the weed. Community engagement activities influence the effectiveness and cost of surveillance by attracting volunteers, and by enabling members of the public to recognise and report weeds (Hester and Cacho 2017). For large eradication efforts, a dedicated coordinator is required, and this is a significant fixed cost.

The use of detector dogs can be beneficial in situations where the weed is present at very low densities and/or is difficult to distinguish visually from the surrounding vegetation. Remote detection using satellites, drones or helicopters to collect photos or imagery can be used to pinpoint areas for treatment. Aerial surveillance is valuable when large search areas are involved, and for gaining access to inaccessible or remote sites. Aerial surveillance can also be combined with treatment when helicopters or drones apply herbicide directly to weeds as they are found (e.g. Leary *et al.* 2014).

The incursion response is guided by a 'probability map' (Figure 1) based on the best information available. Ideally, the map would show likelihood of weed presence in space, based on habitat suitability, proximity to known infestations and other factors (Hauser and McCarthy 2009). This information would guide surveillance and treatment efforts. The probability map can be improved over time as new surveillance and treatment information is incorporated. The feedback from surveillance to the probability map can be improved through additional research that combines data on the incursion with other information (e.g. biology/ecology of the target weed).

## DETECTABILITY AND SEARCH THEORY

To solve the allocation problem, we need to know the effectiveness and cost of each mode of surveillance and treatment. Effectiveness is measured as the probability that a weed will be found when present ($P_D$) and the probability that a treated weed will be killed ($P_K$), in the case of surveillance and treatment respectively. The probability that a weed will be extirpated from an area can be expressed as:

$$P_E = P_D \times P_K. \quad (1)$$

For a random search path:

$$P_D = 1 - \exp(-RSW) \qquad (2)$$

Where $R$ = detectability (m); $S$ = speed of search (m/s); $W$ = search effort (s m$^{-2}$). The term within brackets is also called coverage ($c$). The variables that determine coverage are related to costs, so expressing the problem in this way allows us to come up with realistic estimates of what is possible with a given budget or, conversely, to justify budget requests for a target outcome (Cacho *et al.* 2007).

The detectability of a target can be calculated based on the detection profile, a representation of the searcher's performance showing the probability that the target will be detected as a function of its lateral distance from the searcher (Figure 2). The efficiency of search per unit of distance covered is given by the area under the lateral range curve, which is equivalent to the area of the rectangle in Figure 2.

In practice, the two key probabilities ($P_D$ and $P_K$) are dependent on the resources available and their allocation. The WeedSearch model (Cacho and Pheloung

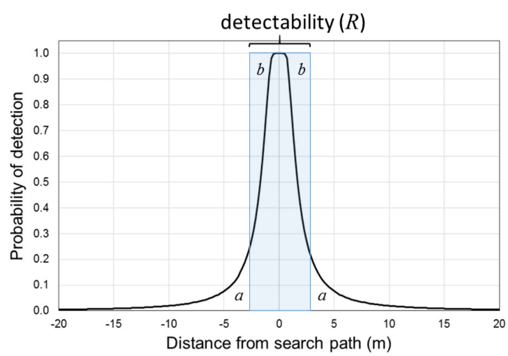


**Figure 2.** Lateral range curve (LRC) showing the probability that a target will be detected depending on its distance from the search path. Detectability ($R$) is calculated as the width of a rectangle with area equal to the area under the LRC. The areas labelled $a$ equal the areas labelled $b$. See Cacho *et al.* (2006) for details.

2007) provides a simple tool to assess eradication feasibility based on a small number of parameters related to biological and logistical aspects of the weed and the environment it invades (Panetta *et al.* 2011), but more work is needed to understand how detectability is affected by surveillance method.

## APPLYING THE MODEL

To solve the allocation problem we need estimates of weed detectability (*R*). The ability to detect a weed for a given search effort depends on the weed's visibility, experience of the searcher, and search method. Weed visibility is as much a function of the vegetation and terrain in which it occurs as of the characteristics of the target weed, which vary with phenology and growth stage. This means our detectability parameter needs to account for search mode, environment, and plant characteristics as they change seasonally and with life stage. These factors are combined to illustrate how the problem could be tackled (Table 1). Numerical values are not available, but we indicate the relative detectability of selected weeds depending on life stage and surveillance method.

The visibility of weeds across different life stages has a significant impact on appropriate surveillance techniques. For example, mature bitou bush (*Chrysanthemoides monilifera* subsp. *rotundata* (DC.) Norl. is easy to spot, especially when flowering, but a seedling or juvenile is not. The pink bark of cherry guava trees (*Psidium cattleianum* Afzel. ex Sabine), more prevalent on mature plants, and the new growth which flushes with a pink/reddish tinge contribute to its visibility. Cherry guava in a shrubland/heathland situation occurs on the upper slopes and edges of cliffs of Lord Howe Island (LHI). In these cases, the plant will form part of the canopy; combined with the flushing foliage this is a key to spotting, and treating, the target from a helicopter (AH, Table 1). Orange hawkweed (*Hieracium aurantiacum* L.) resembles a number of other native and introduced species, and is most detectable at flowering. However, it flowers and sets seed within several weeks, meaning that timely detection is critical (Constantine *et al.* 2016). The duration of maximum visibility during the year influences the temporal allocation of search effort, requiring periods of intense activity by staff and volunteers.

**Table 1.** Detectability of weeds depending on growth form, habitat type and growth stage. Estimates are approximations based on Harris et al. (2001) and authors' experience. Life stages: seedlings (S); juveniles (J); mature (M); and mature flowering or with flushing foliage (MF). Surveillance methods applicable for each life stage (see Figure 1): people: PE (experts); PV (volunteers-trained); PP (public -untrained); D (detection dogs)[a]; aerial: AH (helicopter – human visual sighting); AD (drones – remote imagery/video/photos); and AS (satellites – remote imagery/photos)[b]. For these methods L, M, H and N refer to low, medium, high and no potential for detection.

| **Weed growth form** (*examples*) | **Habitat type** | **Life stage** | **Surveillance mode and level of detectability** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | PE | PV | PP | D | AH | AD | AS |
| Tree or tall shrub *Psidium cattleianum* (cherry guava) | Forest | S | H | L | L | M | N | N | N |
| | | J | H | L | L | M | L | L | L |
| | | M | H | M | L | M | M | M | ? |
| | | MF | H | H | M | M | M | M | ? |
| Shrub *Chyrsanthemoides monilifera* (bitou bush) | Shrubland – including coastal dune habitat | S | M | M | L | M | N | N | N |
| | | J | M | M | L | M | L | L | L |
| | | M | H | H | L | M | H | H | M |
| | | MF | H | H | H | M | H | H | M |
| Annual or herbaceous perennial *Hieracium aurantiacum* (orange hawkweed) | Open habitat* | S | M | L | L | M | N | N | N |
| | | J | H | M | L | M | L | L | L |
| | | M | H | M | L | M | L | L | L |
| | | MF | H | H | M | M | M | M | L |

* Open habitat includes grassland, river beds, sand dunes and other natural and induced open habitats.

[a] Detectability estimates for dogs are based on olfactory (rather than visual) detection.

[b] Detectability estimates for aerial surveillance (AH, AD and AS) are based on scenarios where the weed has emergent foliage either above or in canopy).

Use of dogs in detection of weeds (D, Table 1) can increase our ability to detect plants before flowering, which reduces the risk of reproductive escape. McLean and Sargisson (2017) show that dogs can be effectively trained to discriminate specific weed species, and indeed trials in Kosciuszko National Park on detection of hawkweeds by dogs show promise. The reliance on olfactory detection could be particularly useful in the understory where dense vegetation hinders visual detectability.

An interesting case of public detections (PP, Table 1) occurs in LHI, where 80–90% of the local population (350 inhabitants) would be able to detect a cherry guava. Long-term inhabitants of LHI have grown up with this plant, and have been involved in the campaign to eradicate the plant, but detectability could be lower among others.

Regarding aerial surveillance, drones (AD, Table 1) are proving useful in some situations. For example, the visibility of mature bitou bush by drones can be high, as the plant has a distinct leaf shape and colour, and it is highly detectable using aerial photographs when in full flower. Drones in combination with automatic image recognition are being used for orange hawkweed detection in Kosciuszko National Park (Hamilton *et al.* 2018). As this technology improves it will increase the effectiveness and reduce costs of remote area surveillance and monitoring. While remote sensing may pick up sizeable infestations of weeds, it is unlikely to detect very small numbers of plants, particularly if these occur in the understory (Panetta and Timmins 2004). However, multispectral imagery collected from drones and satellites may enable detection of small patches (~ 1 $m^2$) if the target weed has a unique spectral signature to other species in the invaded environment.

Research plays a critical role in the management of the weeds considered (Table 1). In the case of hawkweeds, considerable investment has enabled research on modelling and prioritising surveillance, developing effective herbicide techniques, and understanding the ecology and biology of the weed (Moore *et al*. 2011, Caldwell and Wright 2014). It should be possible to create tables of detectability parameters for some of the major weeds based on search theory concepts. This would be the first step towards making the allocation model outlined in Figure 1 operational.

There has been considerable progress since Panetta and Timmins (2004) noted the lack of quantitative approaches available to assess the feasibility of eradication. The probability that a plant invasion will be eradicated is strongly correlated to its detectability. It follows that understanding detectability is the key to developing operational models that can guide eradication efforts by allocating resources as efficiently as possible.

## REFERENCES

Cacho, O.J., Spring, D., Pheloung, P. and Hester, S. (2006). Evaluating the feasibility of eradicating an invasion. *Biological Invasions* 8, 903-17.

Cacho, O.J., Hester, S.M., and Spring, D. (2007). Applying search theory to determine the feasibility of eradicating an invasive population in natural environments. *Australian Journal of Agricultural and Resource Economics* 51, 425-33.

Cacho, O. and Pheloung, P. (2007). WeedSearch: Weed Eradication Feasibility Analysis Software Manual. CRC for Australian Weed Management Project 1.2.8.

Caldwell, J. and Wright, G. (2014). Orange hawkweed control program report 2013/14. Office of Environment and Heritage, NSW National Parks and Wildlife Service, Hurstville.

Constantine, A., Hauser, C.E., Primrose, K. and Smith, N. (2016). Hawkweed (*Hieracium* spp.) surveillance: Development of a targeted and robust plan for the Victorian Alps. *Plant Protection Quarterly* 31, 28-32.

Hamilton, M.A., Matthews, R. and Caldwell, J. (2018). Needle in a haystack – detecting hawkweeds using drones. Proceedings of the 21st Australasian Weeds Conference, 9–13 September, Sydney, New South Wales, eds S. Johnson, L. Weston, H. Wu and B. Auld, pp. 126-30. (Weed Society of New South Wales).

Harris, S., Brown, J. and Timmins, S.M. (2001). Weed surveillance–how often to search. Science for Conservation 175. Department of Conservation, Wellington, New Zealand. 27 pp.

Hauser, C.E. and McCarthy, M.A. (2009). Streamlining 'search and destroy': cost-effective surveillance for invasive species management. *Ecology Letters* 12, 683-92.

Hester, S.M. and Cacho, O.J. (2017). The contribution of passive surveillance to invasive species management. *Biological Invasions* 19, 737–48.

Leary, J., Mahnken, B.V., Cox, L.J., Radford, A., Yanagida, J., Penniman, T., Duffy, D.C. and Gooding, J. (2014). Reducing nascent Miconia (*Miconia calvescens*) patches with an accelerated intervention strategy utilizing herbicide ballistic technology. *Invasive Plant Science and Management* 7, 164-75.

McLean, I.G. and Sargisson, R.J. (2017). A dog as a generalist plant detection tool. *Weed Research* 57, 287-92.

Moore, J.L., Hauser, C.E., Bear, J.L., Williams N.S.G. and McCarthy, M.A. (2011). Estimating detection–effort curves for plants using search experiments. *Ecological Applications* 21, 601-7.

Panetta, F.D. and Timmins, S.M. (2004). Evaluating the feasibility of eradication for terrestrial weed incursions. *Plant Protection Quarterly* 19, 5-11.

Panetta, F.D., Csurhes, S., Markula, A. and Hannan-Jones, M. (2011). Predicting the cost of eradication for 41 Class 1 declared weeds in Queensland. *Plant Protection Quarterly* 26, 42-6.