Applying a re-emergence model to inform weed monitoring visitation rates

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Summary To eradicate an invasive plant species from a site it is necessary to destroy all individuals and monitor the site to prevent re-establishment from the soil seed bank or other populations. Quantifying re-establishment potential after control works can help to allocate monitoring resources and determine when to declare a monitored site eradicated. We propose using a recurrent event analysis to model the potential for individual re-emergence at controlled sites. This approach is applied to the monitoring program for controlled hawkweed (*Pilosella* spp.) infestation sites at Falls Creek, Victoria. We use the re-emergence model to guide decisions on reducing monitoring frequency for sites with low re-emergence probability. The decision criteria to reduce visitation of sites are presented as simple, conservative rules of thumb. We simulate these stopping rules using historical observation data to assess the accuracy of decisions. We found that 52% of all sites being monitored in the 2012/2013 season satisfied the reduced visitation criteria, which could have produced a resource saving of 154 person days if the monitoring frequency was reduced from once per week to once per month. Simulations show that re-emergence can occur outside the predictive capabilities of the model, although the accuracy of decisions improves with longer monitoring periods.

Keywords Eradication, resource efficiency, monitoring effort, weed re-emergence, hawkweeds, recurrent event analysis.

INTRODUCTION

To eradicate a weed species all individual plants must be discovered and successfully controlled (destroyed). After the control treatment, infestations must be monitored to ensure that any plants that re-emerge are discovered and destroyed before they reach reproductive maturity (Panetta 2007). The monitoring component of weed eradication programs can be highly resource intensive when the target species has short times to maturity and is difficult to detect in the landscape. As more sites are discovered the monitoring requirements of a project increases, reducing the resources available to survey for unknown infestations.

To achieve an efficient monitoring program, the costs of monitoring should be weighed against the risks and consequences of untreated re-emerged infestations (Regan *et al.* 2006). Some sites could have lower re-emergence potential than others and therefore may not require as much effort to monitor. If we can determine the probability of plants re-emerging at sites after control, sites with low re-emergence probability can be visited at reduced rates. Resources can then be prioritised to searching for unknown infestations and monitoring controlled sites with a high probability of re-emergence.

Three species of hawkweeds are currently targeted for eradication from the Falls Creek Alpine Resort and adjacent Alpine National Park in Victoria, Australia: orange hawkweed (*Pilosella aurantiaca* (L.) F.W.Schultz & Sch.Bip); king devil hawkweed (*P. piloselloides* subsp. *bauhinii* (Schult.) S.Braut. & Greuter); and mouse-ear hawkweed[A] (*P. officinarum* Vaill). Like all weed control programs, the Hawkweed Eradication Project faces the challenge of allocating resources between monitoring and surveillance activities. As more sites are discovered and controlled each season the monitoring requirement increases, reducing the available resources for surveillance.

Hawkweeds are perennial, herbaceous members of the Asteraceae (daisy) family that grow as basal rosettes (Williams and Holland 2007). Native to Europe, members of the recently reclassified *Pilosella* genus (N. Walsh pers. comm. 2013) are stoloniferous and some have become serious environmental and agricultural weeds (Williams and Holland 2007). We used a recurrent event analysis to model the re-emergence probability of orange (OHW) and king devil hawkweed (KDHW) infestation sites at Falls Creek after control works. We then used the results of the analysis to formulate simple rules of thumb to designate sites with low estimated re-emergence potential for reduced visitation. This paper describes this process and the application of these rules to monitoring data collected during the eradication project.

[A] Mouse-ear hawkweed was only recently discovered in the study area (2011) and lacked the data needed for the analysis.

METHODS

Data Hawkweed infestation sites are defined as the location of an infestation to a radius of 2 m; larger infestations are compartmentalised into multiple sites. After discovery, sites are treated with herbicide and then visited weekly during the summer months. Currently, two teams of two people monitor sites and search for re-emergent plants. They record whether hawkweeds are present or absent from the site, numbers of rosettes, buds, flowers and stolons, and the condition of plants previously discovered and treated. By the end of the 2012/2013 monitoring season there were 546 sites dispersed over an area of 1181 ha.

A re-emergence event was defined as any live plant discovered when hawkweed was previously considered to be absent from the site. The criteria we used for absence was that a site must have two absent observations after treated plants have perished and are no longer visible. Furthermore, any absent observation recorded within four observations (approximately one month) of a live plant presence is considered false, as plants take approximately four weeks to perish. We prepared the data by combining the time-independent site data and the time-dependent event data to create a monitoring profile of the sites' history. All modelling, analysis and simulations were performed using R statistical software.

Recurrent event analysis To model the probability of re-emergence at a site, we used a Cox Proportional Hazards model (Cox PH; Therneau and Gambsch 2000) that allows for multiple events (re-emergences; Prentice *et al.* 1981). It features a hazard function $\lambda_{ij}(t)$, which gives the instantaneous potential for the jth re-emergence event at site i given the covariate set:

$$\lambda_{ij}(t) = \lambda_{0j}(t) \exp(X_i(t)\beta_j)$$

where β_j is an estimated regression coefficient.

We used step-wise regression with a large set of theoretically suitable covariates following Mills (2011). For a description of variables used, diagnostics and goodness-of-fit see Primrose (2013). Fitted models and event probabilities are often expressed in terms of the cumulative hazard function:

$$\Lambda(t) = \int_0^t \lambda(u)\, du$$

i.e. the expected number of events occurring from time 0 to time t. This notation can be extended to accommodate the baseline cumulative hazard $\Lambda_0(t)$, and the cumulative hazard for any indexed site i or ordered event j as $\Lambda_{ij}(t)$.

Developing the decision framework The monitoring visitation schedule is based on the probability of re-emergence for each site over 1 year from the time of observation. This probability can be calculated from the hazard function as:

$$1 - \exp[\Lambda_{ij}(t) - \Lambda_{ij}(t+365)]$$

for the jth event experienced at site i, given that the site was observed without re-emergence to time t. However it can be difficult to perform the cumulative hazard integration over time-varying predictors. Therefore we approximate the probability of re-emergence by holding the time-varying predictors constant:

$$1 - \exp\{\Lambda_{0j}(t)\exp[X_i(t)b] - \Lambda_{0j}(t+365)\exp[X_i(t+365)\, b]\}$$

We specify a threshold probability of re-emergence (15% for OHW, 10% for KDHW) for the rules of thumb. When the probability of re-emergence in the next year is below the threshold, the site can be visited less often (monthly), while the probability is above the threshold the site must be visited at the current frequency (weekly).

We calculated the re-emergence probabilities for all historical observations and determined which combinations of covariate values fell within the acceptable threshold for all possible values of base hazard rate. These values were the criteria for reduced visitation.

Simulating the monitoring schedules The decision framework was applied to every observation in the historical data to determine if the site would have been monitored the following week. To simulate a data set under the recommended visitation schedule, three out of four observations for sites which met the criteria were assessed for re-emergence but recorded as un-visited.

To estimate resource savings we calculated the average number of observations made by two teams of two people in a day, which incorporates travel and breaks as well as unpredictable factors such as inclement weather. This team set visits an average of 108 sites per day (S.D. 84, n = 178).

RESULTS

Significant predictor variables in the models predicting re-emergence are: (1) *the number of rosettes at first discovery,* a measure of the original infestation size (KDHW only); (2) *the prior density* of live hawkweeds within the surrounding UTM zone 55 1 ha grid; and (3) *the duration since last observed presence,* representing the diminishing influence of processes on the occurrence of a re-emergence event (Primrose, 2013).

Reduced visitation criteria were covariate sets that fell within the designated probability thresholds for all values of base hazard (Figure 1). In the 2012/2013 season, 52% of all sites monitored met the reduced visitation criteria: 63% (204/326 sites) of OHW sites and 37% (74/200 sites) of KDHW sites. This proportion was reduced in earlier seasons when sites had been monitored for less time, and in the 2009/2010 season only 5% (14/286) of OHW and zero (0/130) KDHW sites met their respective criteria (Figure 2). Some re-emergence was expected to occur at sites with probabilities within thresholds, and re-emergence events are known to occur outside the predictive capabilities of the models. The OHW rule of thumb returned the lowest re-emergence events with a minimum of 1% (3/216 sites in 2012/2013) and a maximum of 3% (4/119 sites in 2011/2012). The KDHW rule of thumb performed less accurately with a minimum of 16% (12/74 sites) designated for reduced visitation but experiencing an event in the 2012/2013 season, and a maximum of 50% (4/8 sites) with re-emergence in 2010/2011.

Reducing visitation of sites which met the criteria could have resulted in a saving of 154 person days in the 2012/2013 season. The potential resource savings were decreased in earlier seasons with shorter monitoring times, only 2.5 person days could have been saved in the 2009/2010 season.

DISCUSSION

The results of the decision framework simulations show there is the potential for resource savings if the proposed protocol is applied. We found re-emergence potential to be largely dependent on time. The duration since last presence had a strong negative relationship with re-emergence probability. Consequently, the number of sites which met the criteria for reduced visitation increased in the later seasons, and there was a lower instance of un-predicted re-emergence with greater monitoring time. These findings concur with recent research demonstrating that the soil seed bank of hawkweeds is short lived (Bear *et al.* 2012).

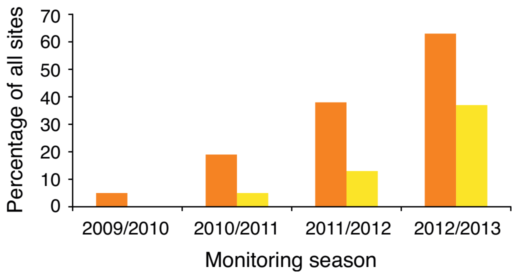

Figure 2. Percentage of OHW (■) and KDHW (■) sites meeting the reduced-visitation decision criteria.

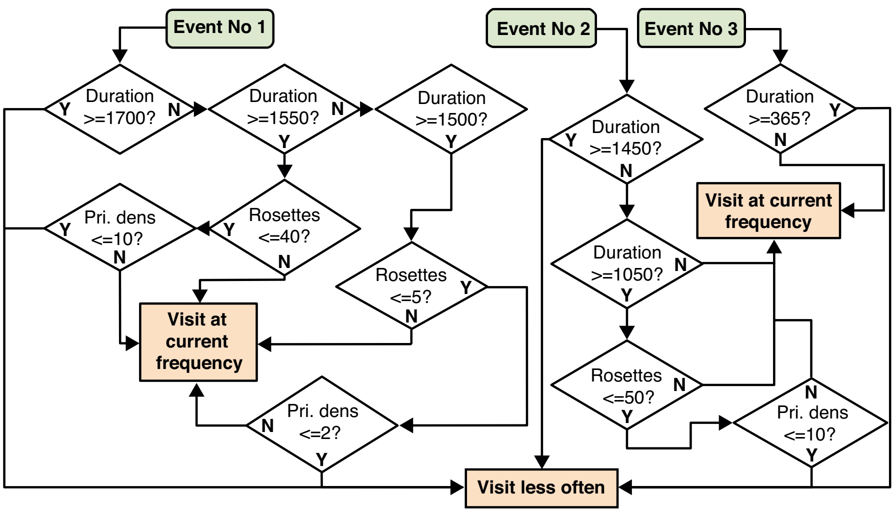

Figure 1. Decision tree illustrating the KDHW 10% probability threshold rule of thumb. The starting points are represented by rectangles containing event numbers; diamonds represent binary decisions based on covariate values; pathways that result in decreased visitation lead to a rectangle labelled 'visit less often'. Failure to meet the decision criteria results in visitation at the current frequency.

Increased monitoring time also represents greater search effort. Detection of hawkweeds is highly variable, with a requirement for greater effort in some situations (Moore *et al.* 2011). In particular, KDHW can be difficult to detect in the presence of other yellow flowering species compared to OHW which has more visible flowers (Hauser *et al.* 2012, unpublished results). This phenomenon can also be observed in the results whereby OHW sites designated for reduced visitation demonstrate a lower rate of re-emergence than the probability threshold. KDHW sites however show more re-emergence than estimated, this could be due to nearby flowering individuals going undetected. The models we present use the number of sites active the previous season located within the 1 ha grid as a measure of local propagule potential. This is a very coarse measure and could be improved to decrease un-modelled risk of re-emergence. A more precise parameter to use is the number of sites within a 50 m proximity. This parameter has been developed and will be used for application in the field.

With this study we have developed a method of using recurrent event analysis to guide monitoring effort of an ongoing eradication program. The model we present uses data collected for management purposes, the decision framework is formulated as simple decision rules that can be applied at the on-ground level. The results of simulations have shown that with further refinement these methods could improve the efficiency of eradication efforts whilst reducing risk of re-emergent plants being un-detected. This methodology could be adapted for other terrestrial plant species that have discrete areas of infestation and adequate modelling data.

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