Integrating biological control and land management practices for control of *Ulex europaeus* in Hawai’i

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**Summary**

Despite our best efforts, most biological control programs do not adequately control target weeds. The number of “partially successful” programs in place around the world is legion. Recent advances in modelling allow us to simulate how biological control interacts with more traditional control techniques and with land-use choices, and to test scenarios for integrating control strategies to enhance the value of partially successful biological control projects. A comprehensive, integrated weed-management program for approximately 4000 ha of *Ulex europaeus* L. (gorse) at Humu‘ula, Hawai‘i, is under development. An existing, spatially explicit, population dynamics model created using *U. europaeus* population parameters from New Zealand predicts that long-term suppression of *U. europaeus* infestations is feasible within a range of combinations of seed predation, inter-specific seedling competition, and disturbance from fire or herbicides. Results from a field experiment at Humu‘ula will be used to re-parameterise the model for Hawaiian conditions, and test the predictions of the model. Several biological control agents have already been established there, and the seed-feeder *Cydia succedana* will be introduced. The insights gained from the field experiment and from modelling will be used to enhance biological control, by developing an array of integrated control tactics and incorporating these into long-term management plans for *U. europaeus* at a landscape level. Provenance trials are underway to test the feasibility of forestry in the area. Management plans will be prepared with local stakeholders, and will take into account the relative viability of alternative land uses such as forestry and grazing.

Keywords: gorse, Hawai‘i, integrated control, models, *U. europaeus*.

**Introduction**

In various estimates 50–83% of mature, well-resourced biological control of weeds projects mounted in countries across the world have provided economic benefits, or have contributed to environmental or social wellbeing (Hoffman 1995, McFadyen 1998, Fowler et al. 2000). In only 17–30% of these cases has complete control been achieved by biological control alone. For the rest, biological control is seen as valuable, but partial, or sporadic. One can look at this large bulk of partial successes either as an indictment of the success rate of such projects, or as a plethora of “near-successful” projects waiting to be realised.

One way to improve the value of such projects is to integrate the biological control system with other control techniques in a synergistic fashion (Syrett et al. 2000). Integrated weed management is a concept that is much discussed, but rarely implemented. Huwer et al. (2002) and Paynter & Flanagan (2003) have examined the results of the simultaneous application of alternative control tactics, but studies of this type are rare. More often, development of integrated weed manage-
ment has been brought up short by the complex interactions of weed and agent ecology, management strategies, and environmental influences.

Models can be used to describe weed population dynamics and inform decisions about biological control options (e.g. Hoffman 1990, Lonsdale et al. 1995, Shea and Kelly 1999). Models also provide the means to analyse relationships between weed populations and natural enemies, and how these are influenced by plant competition, environmental variables, and control tactics. They can therefore provide insights into the complexity of real weed management systems and identify promising avenues for improving weed control (McEvoy & Coombs 1999, Buckley et al. 2001, 2003).

Rees & Paynter (1997) developed a spatially explicit simulation model for population size and ground cover of *Cytisus scoparius* L. (Link) (broom). They found that insects that fed on seeds were most likely to have substantial impact on the equilibrium plant cover if the rate of disturbance was high and survival of seedlings was low. Simulated reduction in annual seed production of as little as 75% had a dramatic impact on broom abundance in their model. Rees & Hill (2001) applied this modelling approach to *U. europaeus*, and again found that disturbance and seedling survival were critical determinants of plant cover in simulations. As with *C. scoparius*, 75% reduction in annual seed production (originally set at 20,000 seeds m\(^{-2}\)) resulted in decline in *U. europaeus* cover under certain combinations of disturbance and seedling survival. They took the approach further and explored the effects of management tools such as herbicides, fire and over-sowing on the key population parameters, and simulated their effect on the equilibrium cover of *U. europaeus*. The model predicted that both treatments were capable of either further depressing equilibrium *U. europaeus* cover at a given level of seed predation or that a lower level of seed predation by biological control agents might still yield effective control.

This paper describes a new project that aims to develop an integrated control program for *U. europaeus* in Hawai‘i. The core of the program will be two models. The first will extend the exploratory power of the model developed by Rees & Hill (2001) to predict changes in *U. europaeus* cover under various management regimes. The second will be a process-driven model developed to further explore the impact of weed management practices.

*Ulex europaeus* L. is a spiny leguminous shrub that can grow to over 3 m tall, and has a life span of 20–30 years. Its natural range is western Europe, where it occurs singly or in small clumps on sandy heathland soils; but where it has colonised new environments it forms dense impenetrable thickets (Richardson & Hill 1998). It is regarded as a weed in New Zealand, Australia, Chile, Iran, Italy, Poland (Holm et al. 1979) and elsewhere. It first became naturalised in Hawai‘i before 1910 (Wegner et al. 1990). It can be found on approximately 4000 ha of rangeland on the island of Hawai‘i, on the flanks of Mauna Kea in a parcel of land called Humu‘ula, where it forms dense thickets on 60% of this land. Some has been colonised relatively recently, but *U. europaeus* may have been present for over 80 years. The infestation is barely contained, but could potentially occupy an area at least 20 times larger than its current distribution. The affected land could be grazed by cattle, and annual production losses are estimated to be $US1.8million. *U. europaeus* also threatens the landscape and conservation values of the Hakalau National Wildlife Refuge, which invests at least $50,000 annually in preventing *U. europaeus* invasion, and is also invading open land and watercourses in neighbouring forests. It is also present on the islands of Maui and Molokai.

**Key principles for sustainable management of *U. europaeus***

*U. europaeus* is a large, long-lived shrub that is difficult to kill and has a persistent soil seed bank. Its populations are therefore resilient, and achieving sustained management of an infestation is difficult. As with other woody weeds, successful management requires a long-term, coherent, and painstaking approach. Effective management over large areas requires clear understanding of the extent of the problem, the economic and environmental capacity of the area, and the preferred land uses for the infested area. This understanding is important because the level of control required, and hence the tactics employed, may vary with preferred land use, and at a landscape level, there may be a mosaic of land uses. For example, in heavily infested areas where the economic or environmental future of the land is uncertain, no weed management may be a valid option. To manage this complexity requires effective GIS-based mapping of the infestation, definition of its distribution, and an estimate of weed density. This allows subdivision into areas for which practical management plans can be developed. Control of woody weeds is expensive, and setting priorities for resource allocation is important. Containment of the infestation should be the most important priority, followed by action that will limit future costs. In particular, control of outlying or low-density infestations will be more effective in the long term than control of dense thickets.

It is likely that effective management of such weeds over a range of land uses, topography, and weed densities will require the full range of appropriate and practical biological, chemical and mechanical control tactics available, integrated to provide the best and most cost-effective management strategy. Population models now allow us to explore the effects of control-tactic combinations on future infestation levels, without having to rely heavily on experimentation. Modelling suggests that biological control is likely to have an important role to play in reducing the maximum age of
plants (an important determinant of cover in both *U. europaeus* and *C. scoparius*), possibly increasing seedling mortality, and perhaps making weeds seed-limited (Rees & Paynter 1997, Rees & Hill 2001).

For a weed like *U. europaeus*, seeds in the soil are capable of reestablishing a population for at least 20 years after plants are removed (Hill *et al.* 2001). Long-term management plans based on land-use aspirations and on optimal control strategies must be developed for each management unit. Failure to plan on this scale risks wasting the resources expended in the early stages of weed management, and rapid reinvasion by the weed. Operational plans therefore need to transcend changes in personnel and land tenure, and to be resourced for the long term. For this reason, all potential stakeholders need to agree to the plans, and commit to maintaining operations. Finally, the long-term management plan needs to be continually reviewed and refocused as circumstances change.

**Operational planning for *U. europaeus* management at Humu‘ula**

Long-term management plans were developed by August 2003. In preparation for this, aerial photographs of the infested area were taken at a scale of 1:24 000, scanned at 15 µ, and assembled as small .tif images. “Farmdata” (www.farmdata.com) has been selected as the mapping package. It is a simple GIS and GPS-capable package that will be used for defining and locating management areas, and for long-term record keeping.

**Biological control of *U. europaeus* at Humu‘ula**

Biological control, particularly of seed production, is predicted to be a critical factor in suppressing *U. europaeus* at Humu‘ula. The seed-feeding moth *Cydia succedana* may be introduced from New Zealand where it was released in 1992 (Hill & Gourlay 2002). Twenty-seven valued Hawaiian plant species bearing flowers and pods will be sent to New Zealand, where experiments will assess the susceptibility of these plants to *Cydia* attack before permission is sought to release the moth in Hawai‘i. Other biological control agents have already been released at Humu‘ula (Markin *et al.* 1996). It is thought that further control agents for *U. europaeus* exist in Spain and Portugal. Two surveys will be conducted in southern Europe to seek additional potential control agents (A. Sheppard, CSIRO Montpellier, pers. comm.).

**Parameter determination, and modelling integrated control at Humu‘ula**

The recent model of *U. europaeus* population dynamics prepared by Rees & Hill (2001) showed that three key determinants of its cover are the rate of disturbance of the environment, the rate at which seedlings are successfully recruited from the seed bank, and seed production. The size of the seed bank is also important. These ecological characteristics can be manipulated using biological control, herbicides, fire, and over-sowing (Paynter & Flanagan 2003). The Rees–Hill model was compiled using parameter estimates from New Zealand. The following experiment will measure those parameters at Humu‘ula to validate the model for Hawaiian conditions.

Four similar blocks (250 m × 30 m) were selected at four accessible sites at Humu‘ula. Blocks are oriented across the prevailing wind to assist management operations. Firebreaks (10 m wide) were cut around each block and through the blocks to create eight identical treatment plots in each. Blocks were fenced to minimise unplanned disturbance. In each block, eight combinations (presence/absence) of herbicide, fire, and over-sowing (+H+/F–O etc.) were randomly assigned to produce a standard randomised block design, replicated four times.

Prior to treatment, *U. europaeus* stem and seed bank density were estimated at each end of every plot. At the time of peak growth, herbicide was applied by air to the four assigned plots in each block. After 3 months, each assigned plot was individually fired. Measurement areas (5 m × 5 m) were established 5 m from each end of each plot and equidistant from the sides (128 areas in total). For unburnt plots (four per block) this involved cutting access into the *U. europaeus*. A mixture of *Holeus lanatus* (velvet grass, fog), *Dactylis glomeratus* (orchard grass, cocksfoot), *Lolium multiflorum* (annual ryegrass) and *Pennisetum clandestinum* (kikuyu) seed (at a rate of 2.6:10:1 kg/ha) was sown onto the measurement areas in plots assigned for over-sowing (as opposed to treating the whole plot).

Two permanent quadrats (40 cm × 40 cm) were selected within 1 m of a random point within each measurement area. Seedling emergence from the seed bank is measured by serial removal of seedlings from one quadrat, and in the other, the survival of cohorts of individual seedlings is monitored (128 measures). These measurements will be made monthly for 16 months. We have labelled 10 randomly selected plants or crowns in each treatment plot, and will monitor the survival of mature plants following each treatment combination (320 plants).

At the same random point in each measurement plot, two seed traps measure the amount of seed that falls under intact plants, and pod infestation rate is monitored (initially monthly, then twice annually). These
There will be 25–30 treatments (seed sources) in a 5-plot design at Humu’ula. Different species and which seed sources within species will be selected, fenced, and protected by firebreaks. A range of tree species are being planted in a randomised complete block experiment at Humu’ula. Two-hectare plots have been provided, which will be representative of the land available for forestry control. We are looking at both approaches.

These measurements will provide reliable estimates of the key population parameters for U. europaeus at Humu’ula and allow us to better calibrate the model (Rees & Hill 2001) for local conditions. We will check the validity of the model by comparing model predictions with real measures of seedling recruitment under the different disturbance (treatment) regimes. After 2 years, the plots will also provide a statistically sound assessment of the role that each of the control tactics plays in limiting recruitment of U. europaeus seedlings at Humu’ula. This will assist the development of long-term plans for sustainable management of the weed.

Treatments were completed in October 2002, and measurements were conducted in December, January and March. Unseasonal drought since October 2003 resulted in poor germination of over-sowing treatments and this will profoundly affect the experiment. It is too early to draw any other conclusions from this experiment.

Forestry and agro-forestry

Afforestation can enhance sustainable management of U. europaeus by shading out germinating seedlings until the seed bank is effectively exhausted, or by providing sufficient cash flow to justify intensive weed control. We are looking at both approaches.

Three uniform sites have been selected that are broadly representative of the land available for forestry operations at Humu’ula. Two-hectare plots have been selected, fenced, and protected by firebreaks. A range of trees are being planted in a randomised complete block or eight-tree-row plot designs to assess which tree species and which seed sources within species will be most successful operationally at Humu’ula. Different assemblages of trees are being planted at each site. There will be 25–30 treatments (seed sources) in a 5 x 5 configuration, at 2-m spacing within the row and 3 m between rows. There will be 4–6 replications per treatment per trial. Tree performance will be assessed by analysing differences in tree survival, growth rate, and stem diameter increment at 6, 12, 18 and 24 months. The trees selected for evaluation are Acacia koa, Cryptomeria japonica (Sugi), Eucalyptus spp., Pinus spp. and Pseudotsuga menziesii (Douglas fir). Data will also be collected on the costs of establishment and maintenance of forestry operations at Humu’ula.

Over 250,000 Christmas trees are imported into Hawai’i annually. We will examine the feasibility of growing such trees at Humu’ula to substitute for imports, and to provide short-rotation revenue to improve the economics of long-term U. europaeus control. The tree species selected for assessment are P. menziesii, Abies concolor (Concolor fir), A. fraseri (Fraser fir), and A. procera (Noble fir). The design is the same as for the provenance trial, and will be replicated twice. Trees will require periodic shearing and fertilisation, and this site-intensive management regime will be combined with tight control of U. europaeus among the trees.

A 2-ha silvo-pastoral agro-forestry trial will demonstrate how trees can be integrated with livestock grazing and forage operations in this environment. Examples may include forest grazing amongst low-density plantings, or fence-line plantations. Such systems can provide greater income per acre than either forestry or grazing alone. Grazing can also provide weed control in such systems, further enhancing sustainability. Related research has demonstrated that, if properly managed, forage production can be maintained while producing high-value timber. There is significant potential for this agro-forestry system to become widely adopted in rangelands across Hawai’i. The trees will be established in single-, double- and triple-row sets planted along the contour. The stocking rate for trees will vary from 60 to 160 trees per hectare depending on the number of rows planted. The pasture alley will be over-sown with the same grass mixture that will be utilised in the agronomic trials and the pasture alley width will be 15 m. The forest tree species chosen will be a sub-set of those included in the forestry trials. U. europaeus density and growth rates will be assessed within and around all trials to measure the effectiveness of these treatments in suppressing infestations. The area around each trial will be monitored to check whether any of the tree species are spreading. Potentially invasive species will be removed from the trials.

Discussion

Knowledge of population dynamics is important for evaluating control, especially where control is costly or risky or where eradication is not possible. Timing of control strategies can be important due to density dependence or interactions with other control methods (Buckley et al. 2001). We model interacting control strategies in two ways. The first approach uses DYMEX™ and incorporates process-based sub-models (driven by environmental variables) to describe how control strategies affect population dynamics and weed management options. The second approach uses a simple, spatially explicit population model and incorporates the effects of integrated control options by the estimation of how those integrated strategies affect the population parameters in the model. The experiment described in this paper will provide new estimates of population parameters under different integrated...
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control regimes, which will then be used in the models. The use of this approach will enable us to compare our results with those from the original population model (Rees & Hill 2001).

Modelling the effects of combinations of control methods allows the evaluation of far more strategies than can be tested in the field, providing an objective method for narrowing down a wide range of options (Buckley et al. 2003).

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References


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