# Optimal frequency for woody weed management for North Queensland grazing properties: an economic perspective

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**Summary** Once invasive species have colonised a landscape, they require frequent management to preserve the lands' productive capacity. However, weed management is costly, and tradeoffs exist between the frequency of weed management and the productive capacity of the landscape. We construct an analytical framework that synthesises the complex relationships between the weed's population dynamics, imposed weed costs, and benefits and costs of management strategies to determine the optimal frequency of managing *Ziziphus mauritiana* (chinee apple). Model output suggests it is uneconomic to manage chinee apple by mechanical means in the upland zones with current management cost. We show that management decisions are more sensitive to changes in control costs than they are to grazing returns and we estimate the relationship between control costs and the optimal frequency of management.

**Keywords** Benefit-cost analysis, stage matrix, management frequency, NPV, woody weeds.

## INTRODUCTION

Invaded landscapes must be managed continually to ensure they remain productive; ecological frameworks have been developed to determine which populations should be managed (Moody and Mack 1988). However, many of these frameworks assume eradication of the weeds from the location. In reality, this is rarely the case, and ongoing weed management is required.

In the Australian rangelands weed management is infrequent because management must be carried out across vast areas. Additionally, woody weeds are slow growing and long lived, thus, a single management action generates benefits for a number of years. Furthermore, the cost of a single weed management intervention is high relative to annual grazing returns.

Although weed density will impact on landholders' decisions of when to manage an infestation, the actual cost of weed management in the rangelands is rarely influenced by the weed's population density as the activity (eg burning or bulldozing) is either undertaken or not. Other management techniques such as herbicide application, which are influenced by density, have not been considered due to their high labour costs relative to grazing returns per unit area.

The management of woody weeds is a long-term investment, where benefits and costs are accrued over a number of years. The most efficient management frequency can be derived from net present value (*NPV*) analysis of benefits and costs.

## MATERIALS AND METHODS

To determine the optimal frequency of weed management we use the *NPV* for the different management frequency regimes. The *NPV* is defined as the discounted sum of the difference between the benefits $B_t$ and costs $C_t$, that are attributed to weed management, that occur in each period *t* over the timeline *T*. The *NPV* is given by:

$$NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1+r)^t} \quad (1)$$

where *r* is the time discount rate.

The current annual benefit-cost of each management frequency can be estimated with the equivalent annual value (EAV) method as:

$$EAV = \frac{r\ NPV}{1 - \dfrac{1}{(1+r)^t}} \quad (2)$$

The cost of management $C_t$ is defined as:

$$Ct = (\beta_t \times p) \quad (3)$$

where the decision to manage in year *t* is represented by the dummy variable $\beta_t$ The actual cost of each management is *p*. The benefits of management are given by:

$$B_t = (d - D_t)^* y_{wf} \quad (4)$$

which is the reduction of the steady state yield loss from *d* to $D_t$ (the damage after management at time *t*), as a result of a reduction in weed density. The financial value of management is derived for the weed free yield ha$^{-1}$ ($y_{wf}$).

The relationships between weed density and yield loss (damage) can be explained with a rectangular hyperbolic function (Cousens 1985):

$$D_t = \frac{\psi\, x_t}{1 + \dfrac{\psi\, x_t}{\tau}} \quad (5)$$

$\mathbf{x}_t$ is the weed density, $\psi$ is a damage vector index for yield lost per weed in each life stage. The maximum possible yield loss is $\tau$.

To model weed density $\mathbf{x}_t$ over time we used a stage projection matrix. For further explanation of this technique see Caswell (2001). The population state transition is:

$$\mathrm{x}_{t+1} = \mathrm{H}\mathrm{x}_t - \beta_t \nu \circ \mathrm{x}_t \qquad (6)$$

where $\nu$ is the efficacy of weed management, and $\mathbf{H}$ is the annual stage projection matrix with dimensions $n \times n$; where $n$ is the number of life cycle stages. $\mathbf{x}_t$ is the population vector for the number of individuals in each life stage. The four main life cycle stages of woody weeds are new seeds (*NS*), seed bank (*SB*), juveniles (*J*), and adults (*A*). The juvenile and adult stages are broken down into sub stages ($J_1, J_2, \ldots, J_m$) and ($A_1, A_2, \ldots, A_q$), based on the time required to reach maturity and plant longevity (Figure 1).

The elements $h_{ij}$ of $\mathbf{H}$ represent the probability of moving from stage $i$ to stage $j$, except for the first row, where $h_{ij}$ represents the fecundity of stage $j$ (new viable seeds produced per plant). The stage matrix for a new invasion is denoted by $\mathbf{H_0}$. Repeated application of this operation results in exponential growth. To account for density dependence a steady state matrix $\mathbf{H}_\infty$ was established. Cacho and Spring (2004) offer a plausible transition between these two states with a rectangular hyperbola formula, resulting in a sigmoid population growth curve. The stage projection matrix $\mathbf{H}_t$ at time $t$ is given by:

$$\mathbf{H}_t = \frac{\gamma \mathbf{H}_0}{\gamma + \left( \dfrac{\mathbf{H}_0}{\mathbf{H}_\infty} - 1 \right) W_t} \qquad (7)$$

Competition for resources is based on 'gap theory' which uses the plant's crown diameter as an indicator of plant competition for area and resources. This provides a plausible mechanism of weighting the impact of individual plants on population structures that is density dependent in terms of both quantity and size. As the population grows it will tend towards the maximum carrying capacity ($\gamma$) which is set at 10,000 to represent $\mathrm{m}^2\ \mathrm{ha}^{-1}$. The total area used ($W_t$) by the population is calculated as $W_t = \omega' \mathrm{x}_t$. Where $\omega$ is a vector of areas occupied by plants in each life stage.

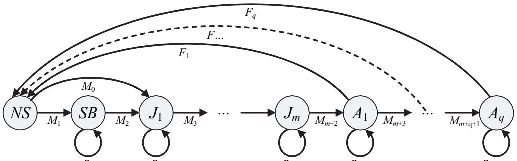


**Figure 1.** Life cycle diagram for woody weeds.

RESULTS

The following simulation is based on a single hectare in the Australian rangelands upland zone and assumes the weed will not invade neighbouring areas. It takes chinee apple a minimum of five years to reach maturity, therefore $m$ = 4. The adult population is divided into four sub-stages based on its physical attributes, so $q$ = 4. There are two additional life cycle stages being new seeds and seedbank, therefore, $n = 1 + 1 + m + q = 10$. For the non-zero elements of $\mathbf{H_0}$ and $\mathbf{H}_\infty$ in Eq. (7), see Table 1. The elements for the area vector $\omega$ to derive $W_t$ are given in Table 2, $\tau$ in Eq. (5) is set at 0.899.

Zull *et al.* (2006) showed that the targeting of adult chinee apple has the greatest effect on population growth. The Elliott® blade plough removes nearly all of them, therefore $\nu$ in Eq. (6) is set at one for all adults stage and zero for other life stages in the years of management. The initial population $\mathbf{x_1}$ is set at steady state.

The annual returns for grazing a weed-free hectare ($y_{wf}$), Eq. (4), in the Charters Towers (North Qld) is up to \$13.25 $\mathrm{ha}^{-1}$ for good condition land (Neil MacLeod pers. comm). As future profits are unknown it is assumed that real returns are constant over time. The cost of managing the weeds ($p$), Eq. (3), with blade-ploughing costs between A\$100 and A\$200 $\mathrm{ha}^{-1}$ (Landsberg pers. comm). Assuming a 30% tax rate, the after tax cost to graziers is between A\$76.92 and A\$153.84 $\mathrm{ha}^{-1}$. It is also assumed that real management costs are constant over time. The discount rate ($r$) for graziers'

**Table 1.** Parameters for chinee apple model.

| | Stage transition | Element $\mathbf{h}_{ij}$ | New infestation $\mathbf{H}_0$ | Steady state $\mathbf{H}_\infty$ |
|---|---|---|---|---|
| New seeds (*NS*) | $M_0$ | $h_{3,1}$ | 0.003 | 0.002 |
| | $M_1$ | $h_{2,1}$ | 0.600 | 0.484 |
| Seed bank (*SB*) | $R_1$ | $h_{2,2}$ | 0.600 | 0.484 |
| | $M_2$ | $h_{3,2}$ | 0.003 | 0.002 |
| Juvenile small ($J_1$) | $R_2$ | $h_{3,3}$ | 0.100 | 0.074 |
| | $M_3$ | $h_{4,3}$ | 0.200 | 0.147 |
| Juvenile medium ($J_2$) | $R_3$ | $h_{4,4}$ | 0.100 | 0.081 |
| | $M_4$ | $h_{5,4}$ | 0.500 | 0.403 |
| Juvenile large ($J_3$) | $R_4$ | $h_{5,5}$ | 0.100 | 0.086 |
| | $M_5$ | $h_{6,5}$ | 0.800 | 0.690 |
| Juvenile largest ($J_4$) | $R_5$ | $h_{6,6}$ | 0.100 | 0.093 |
| | $M_6$ | $h_{7,6}$ | 0.850 | 0.787 |
| Adults small ($A_1$) | $R_6$ | $h_{7,7}$ | 0.720 | 0.679 |
| | $M_7$ | $h_{8,7}$ | 0.100 | 0.094 |
| | $F_1$ | $h_{1,7}$ | 5 | 5 |
| Adults medium ($A_2$) | $R_7$ | $h_{8,8}$ | 0.770 | 0.739 |
| | $M_8$ | $h_{9,8}$ | 0.100 | 0.096 |
| | $F_2$ | $h_{1,8}$ | 750 | 750 |
| Adults large ($A_3$) | $R_8$ | $h_{9,9}$ | 0.900 | 0.889 |
| | $M_9$ | $h_{10,9}$ | 0.035 | 0.035 |
| | $F_3$ | $h_{1,9}$ | 2 000 | 2 000 |
| Adults largest ($A_4$) | $R_9$ | $h_{10,10}$ | 0.960 | 0.958 |
| | $F$ | $h$ | 3 000 | 3 000 |

value of time, in Eq. (1) and (2), is set at 5%. *T* in Eq. (1) was set at 1000 years.

The estimated *EAV*s for the different management frequencies are based on low and high management costs (Figure 2).

A sensitivity analysis was based on a 10% change in both the average management cost (A\$115.30) and weed free yield (A\$13.25) with management every 10 years. This resulted in total losses changing by 11.5% and 5.5%, respectively.

The optimal frequencies for different management costs are presented in Figure 3.

**Table 2.** Height, area and damage for the different life cycle stages.

| | | Weed height $m$ | Area $m^2$ $\omega_i$ | Damage index $\psi_i$ |
|---|---|---|---|---|
| New seeds | ($NS$) | 0 | ∞ | 0 |
| Seed bank | ($SB$) | 0 | ∞ | 0 |
| Juvenile small | ($J_1$) | < 0.2 | 0.004 | 0.000,001 |
| Juvenile medium | ($J_2$) | 0.2 – 0.4 | 0.073 | 0.000,027 |
| Juvenile large | ($J_3$) | 0.4 – 0.7 | 0.283 | 0.000,106 |
| Juvenile largest | ($J_4$) | 0.7 – 1.0 | 0.715 | 0.000,268 |
| Adults small | ($A_1$) | 1 – 2 | 2.326 | 0.000,873 |
| Adults medium | ($A_2$) | 2 – 3 | 6.610 | 0.002,480 |
| Adults large | ($A_3$) | 3 – 5 | 17.136 | 0.006,429 |
| Adults largest | ($A_4$) | > 5 | 52.952 | 0.019,868 |

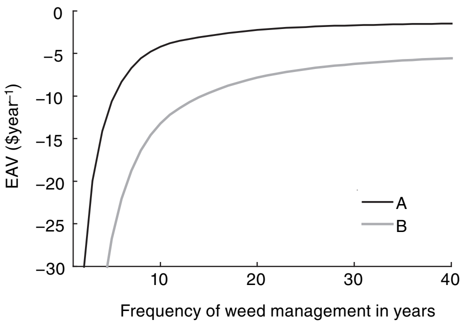


**Figure 2.** Expected annual values for the different management frequencies – results are based on low (A) \$76.92 or high (B) \$153.84 management costs ha$^{-1}$ and \$13.25 weed free yields ha$^{-1}$.

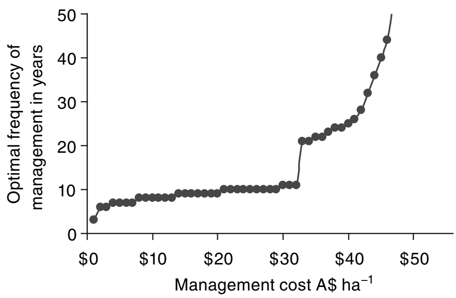


**Figure 3.** Optimal frequency of management for given control costs of chinee apple in upland zones.

## DISCUSSION

As the *EAV*s of all management frequencies are negative it is uneconomic to manage heavily infested areas of chinee apple with current management costs and grazing returns (Figure 2). However, the losses incurred from weed management decrease significantly with management frequencies greater than 15 years, being between A\$2.93 and 9.65 ha$^{-1}$ EAV for low and high management costs.

Management becomes economically viable when the cost of management is reduced to A\$49 ha$^{-1}$ (Figure 3) with weed free yields of A\$13.25 ha$^{-1}$. There is also a switching point for management costs between A\$33 and 32 ha$^{-1}$ where management frequencies changes from 21 to 11 years.

Management decisions are more susceptible to changes in management costs than to changes in the grazing revenues. Therefore, greater emphasis is needed to find more efficient methods of management. The modelled costs ha$^{-1}$ did not account for the cost of other areas being infested, their management, or environmental costs. The inclusion of these costs would shift the curves in Figure 2 and Figure 3 upwards, i.e. making the threshold for intervention occur at a higher management cost and the frequency of management more often.

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