

Spatial modelling of new weed incursions in cropping systems

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Summary A mathematical model incorporating weeds growth, dispersal and control is developed to represent the spread of a weed on a large regional scale. Four case study weed spread simulations were undertaken to demonstrate the model's applicability to different weed incursions and to demonstrate the effects of weed search and control effort.

Keywords Weeds population growth, dispersal, spread, mathematical modelling.

INTRODUCTION

Invasions by non-indigenous plant species pose serious economic threats to Australian agricultural industries (Sinden *et al.* 2004). When a new invader is identified a rapid response is critical, particularly if the invasive plant has the ability to spread rapidly. The first step in developing strategies to optimally manage a new incursion is the realistic modelling of the spread of a weed.

The aim of this paper is to present a flexible modelling approach that can incorporate the key processes that determine the spatial population dynamics of an invading plant species in a large area cropping system.

MATERIALS AND METHODS

A raster-based approach was used to represent a large region as a grid of neighbouring cells. The model uses an annual time step and a two-dimensional grid of sites representing space. It follows three stages; population growth, dispersal processes to represent the spread of a weed from a point source, and weed control effort. The region at risk of invasion is divided into an $n \times m$ array (grid) of rectangular cells of equal size.

Population growth The first part of the model comprises a population growth sub-model which describes the weeds population growth using a discrete version of the logistic equation model. Letting r denote the intrinsic growth rate, $X(t)$ the size of the weed population at time t , and K the environmental carrying capacity or saturation level, the growth model is given by

$$X(t+1) = X(t) + rX(t)(1 - X(t)/K) \quad (1)$$

with the constraint that $0 \leq X(t) \leq K$. Expressing $X(t)$ as a percentage infestation (corresponding to the percentage of a grid cell occupied by the weed) at

time t , K is taken to be 100 to denote the possibility of 100% infestation.

Using equation (1), weed population size $X(t)$ can be computed for different values of the intrinsic growth rate parameter r and $X(0)$. Conversely, this equation can be used to determine a r value for a particular case study weed spread scenario in the field. Depending on the initial size of the invasion and number of years a weed may take to reach a 95% spread level in one grid cell, the corresponding r parameter value can be obtained.

To denote the infestation level post growth but prior to dispersal, for each cell across the $n \times m$ array equation (1) can be written as

$$X_{ij}^{pd}(t+1) = X_{ij}(t) + r_{ij}(t)X_{ij}(t)(1 - X_{ij}(t)/100) \quad (2)$$

where ij denotes the cell at i th row and j th column of the hypothetical grid field with the constraint that $X_{ij}^{pd}(t) \in [0, 100]$. Here $r_{ij}(t)$ is set up to allow dependence on both cell and time. Replacing $r_{ij}(t)$ with r would have the growth parameter independent of both space and time. The superscript *pd* denotes 'prior to dispersal'.

When modelling $X_{ij}^{pd}(t)$ above we restrict percentage intensity to the nearest decimal place. Hence the unit of infestation is 0.1% and each cell can be considered to have an integer number of infestation units between 0 and 1000 inclusive.

Dispersal The second part of the model comprises a dispersal processes sub-model. In addition to growth within each time interval, weed dispersal takes place with a proportion $P_{ij}^{j'}$ of the weed intensity in the (i, j) th cell dispersed to the (i', j') th cell. Hence, after growth and dispersal the weed intensity in the (i, j) th cell is given by

$$X_{ij}^{pc}(t+1) = \sum_{i'j'} P_{i'j'}^{ij} X_{i'j'}^{pd}(t+1) \quad (3)$$

where superscript *pc* denotes 'prior to control'. Again the $X_{ij}^{pc}(t)$ values are restricted to $[0, 100]$.

In modelling dispersal it is assumed all weed units are independently dispersed. Next, weed dispersal is separated into two components, local or short distance dispersal and long distance dispersal. Long distance dispersal represents rare events in the dispersal process and therefore involves only a small proportion (e.g. ≤ 0.001).

The short-distance dispersal modelling is based on the approach used in Auld and Cooté (1990). Each unit dispersed locally has a probability equal to p_0, p_1, \dots, p_w , of being dispersed to a 'ring' 0, 1, ..., w cells away respectively from the dispersing cell. Within a ring each cell is equally likely to be selected. The units falling outside the grid are lost to the system. Weed units dispersed long distance are dispersed to non-local cells with the probability inversely proportional to the squared distance the cell is from the dispersing cell. These probabilities approximate the probabilities for a Cauchy distribution in the tails and hence the long distance dispersal approximates a radial Cauchy distribution.

The probability of detection Cacho *et al.* (2006) modelled detection curves representing the proportion of targets detected (p_d), or the probability of detecting a single target, as a function of coverage (c) defined as the ratio of the area actually searched over the total area of the invasion

$$c = S \times T \times R / A \quad (4)$$

where A is the total area (km^2) at risk of invasion, S is the speed of search (km h^{-1}), T is time spent searching (hours) and R is the effective sweep width (km). R is a measure of the detection capability of the searcher taking into account target characteristics and environmental conditions, and is referred to as the detectability of the weed. The numerator of equation represents the area searched (km^2) as the product of search effort in terms of distance traversed ($S \times T$) times the detectability of the weed (R).

The proportion of targets detected (p_d) for random sweeping is given by

$$p_d = 1 - e^{-c} \quad (5)$$

Once detection is made, it is assumed that an attempt is made to kill all weeds found, subject to the effectiveness of the control method used. The mortality (D) caused by the search and control effort is

$$D = p_d p_k \quad (6)$$

where p_k is the probability that a target organism will die when a control is applied.

Re-infestation from the soil seed bank Though individual plants can be killed after applying 'search and control effort', there is always the possibility of re-infestation occurring from the soil seed bank. The mortality caused by the search and control effort (D) is readjusted to accommodate re-infestation of weeds from the soil seed bank

$$M = D(1 - \theta) \quad (7)$$

where M is mortality caused by the search and control effort after adjusting for the seed bank re-infestation rate (θ).

We have adopted a method to allocate search and control effort proportionately into each grid cell based on the weed densities in those cells in different years. This approach implicitly assumes that individual farmers in the large region are accurate in observing the weed densities and thus focus their search and control effort on those locations. Therefore T for each (i, j) th cell across the $n \times m$ array at time t , is set proportional to $X_{ij}^{pc}(t)$ so that $\sum_{ij} T_{ij}(t) = T$.

To denote the M for each (i, j) th cell across the $n \times m$ array at time t , equation (7) can be written as

$$M_{ij}(t) = D_{ij}(t)[1 - \theta_{ij}(t)] \quad (8)$$

Here $\theta_{ij}(t)$ is set up to allow dependence on both cell and time. Replacing $\theta_{ij}(t)$ with $\theta(t)$ would have the re-infestation parameter independent of space. This $M_{ij}(t)$ is then applied to the equation (3) to obtain

$$X_{ij}(t+1) = X_{ij}^{pc}(t+1) [1 - M_{ij}(t)] \quad (9)$$

Data for case study simulations Equation (1) is used to determine different values of intrinsic growth rate parameter r . This value was computed for four hypothetical case study spread scenarios, being 4, 7, 10 and 15 years to reach a 95% infestation level, starting with a 0.1% infestation in a 1 km^2 area. Parameter values are given in Table 1.

The conditional short distance probabilities p_0, p_1, \dots, p_w of being dispersed to 0, 1, ..., w cells away are given in Table 1. The parameters p_k and θ vary each year representing climatic variability. The parameters S and R vary for each grid cell and year, representing variability of search parameters on individual localities or search operations and the climate. Random variation is incorporated into these four parameters in the form of a triangular probability distribution (Table 1). The time spent searching, as denoted by T in equation (4), was the decision variable on the weed control strategy and is expressed in 'man days' assuming seven hours of search and control time spent per man day in the field.

RESULTS

Dividing space into discrete units (grid of 100×100 cells equivalent to 10,000 km^2), the spread model was run for 50 years starting with a 10% infestation in the central cell of the grid space. Four case-study scenarios were run by varying the intrinsic growth rate parameter r . The model counts the number of grid cells that have weed infestations above a threshold level of 1% and reports the proportion of grid cells infested out of the

Table 1. Parameters used in the spread model.

| Variable | Value |
|---|--------|
| Total area at risk of invasion (km ²) grid of 100 × 100 cells (<i>A</i>) | 10,000 |
| Intrinsic growth rate when <i>X</i> years taken to reach 95% infestation in 1 km ² grid cell: (<i>r</i>) | |
| <i>X</i> = 15 | 0.80 |
| <i>X</i> = 10 | 1.35 |
| <i>X</i> = 7 | 2.38 |
| <i>X</i> = 4 | 9.12 |
| Probability of long distance dispersal (%) | 0.1 |
| Conditional short distance dispersal probabilities (%): | |
| probability of dispersal: | |
| within the dispersing cell itself | 95.0 |
| among the 8 cells lying around one cell away | 2.0 |
| among the 16 cells lying around two cells away | 1.5 |
| among the 24 cells lying around three cells away | 1.0 |
| among the 32 cells lying around four cells away | 0.5 |
| Speed of search (<i>S</i>) (km/h) | |
| minimum value | 0.95 |
| mode value | 1.00 |
| maximum value | 1.05 |
| Effective sweep width (<i>R</i>) (km) | |
| minimum value | 0.018 |
| mode value | 0.020 |
| maximum value | 0.021 |
| Probability of kill (<i>p_k</i>) each time control is applied (%) | |
| minimum value | 90.0 |
| mode value | 95.0 |
| maximum value | 97.0 |
| Re-infestation rate (<i>θ</i>) from the soil seed bank (%) | |
| minimum value | 20.0 |
| mode value | 25.0 |
| maximum value | 30.0 |

total number of grid cells in the cropping area for every year of the simulation. This is termed the ‘infestation level’, and is presented in Figure 1 for different levels of search and control effort and values of *r*.

DISCUSSION

The four simulations shown in Figure 1 indicate the relationship between the weeds intrinsic growth rate *r*, its spread in the field and the search and control effort required in the total cropping region of 10,000 km². With an *r* parameter of 0.80 (where it takes 15 years to reach 95% infestation level in a 1 km² area starting with a 0.1% infestation), the whole region reaches 100% infestation by year 34 without any search and control effort. With control effort, the infestation curves are pushed to the right thus slowing the weed population spread rate in the region. With around 400 man days per annum input in search and control effort it seems possible to maintain a near zero infestation level in the region for the full 50 year period. When the *r* parameter is 1.35, the time taken to reach 100% infestation in the region is shortened for both with and without control scenarios. With an *r* parameter of 2.38, full infestation

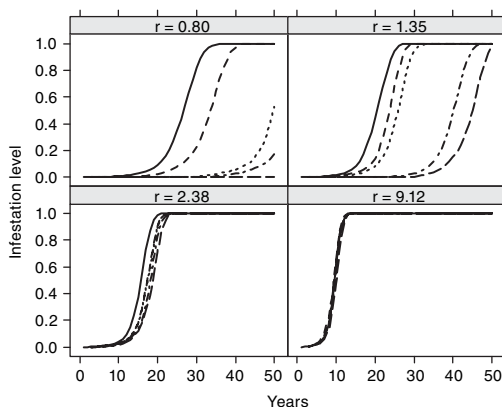


Figure 1. Weed spread under different *r* values and with different levels of control (—) no control, (— —) 100 man days *y*⁻¹, (----) 200 man days *y*⁻¹, (- - -) 300 man days *y*⁻¹, (— — —) 400 man days *y*⁻¹.

is reached by year 20 without a search and control effort. None of the search and control scenarios evaluated would be adequate in suppressing weed spread, thus requiring a much higher level of search and control effort. Finally, with a very high *r* value of 9.12 (where it takes only four years to reach 95% infestation level in a 1 km² area), it takes only 12–13 years for the particular weed to spread into the entire region of 10,000 km², regardless of the search and control scenarios evaluated. This model could be applied to large area cropping systems when a single grid cell can be equivalent to the size of an individual farm and where long distance weed spread can occur due to vehicles, farm machinery, flood or by animals such as bird dispersal.

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