An Integrated Landscape Modelling Tool for Simulating the Dispersal Syndromes of Invasive Plants

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EXTENDED ABSTRACT

Surveillance for newly detected serious weed incursions is expensive and resource limited, and is often done on an 'ad hoc' basis. A novel way to improve the efficiency of surveillance efforts is to concentrate surveillance in areas that are more likely to contain the weed, or are more susceptible to invasion. These areas can be identified by replicating the various dispersal syndromes (wind, water, and roads) and plant life history factors that influence the spread of invasive plants. This paper presents a simulation system that replicates invasive plant spread across real landscapes for identifying areas susceptible to invasion. These areas can then be targeted for surveillance, potentially improving the success of containment and eradication efforts.

The simulation system consists of a Python module that can be parameterised and executed from Arc Toolbox. The module consists of 25 Python functions that replicate elements of invasive plant establishment, growth and dispersal. These elements are placed in an iterative loop so the annual cycle of establishment, growth, and dispersal can be run for multiple years. The simulation system is integrated with ArcGIS for direct application to known spatial information on the weed incursion. Simulation outputs are written to the GIS for spatial interrogation and map preparation for rapid communication to land managers.

This paper presents the various design elements of the simulation system, from the selection of a stage matrix life-history model to the identification of kernel functions for various seed dispersal syndromes such as wind, water, and road. Population growth is tracked within raster cells, and the generalised kernel of Clark *et al*. (1999) was selected to replicate dispersal events. Wind dispersal of seeds was implemented using an Exponential kernel that could be weighted by wind strength, direction, and terrain influences. A linear Fat-tailed kernel was selected for seed dispersal along rivers and roads. Long distance dispersal events were modelled by sampling the distance parameter of kernel functions from a Lognormal distribution. This skewed long-tailed distribution results in rare long distance dispersal events when large distance parameters are sampled. The described simulation system is the basis of a GIS based decision support tool that can be used by managers to predict the spread of invasive plants for improved surveillance efforts.

1. INTRODUCTION

Consider the scenario of a newly detected weed incursion. If the weed is targeted for containment or eradication the first step for managing the incursion is to determine the spatial extent using surveillance around the known infestation (Panetta and Lawes 2005). Current surveillance methods are generally ad hoc, involving intensive survey in the vicinity of the known infestation, with sporadic efforts at greater distance. These surveillance efforts are invariably expensive and resource limited, so efforts that maximise the chance of detection are preferred. A novel approach to this problem is to simulate the various dispersal and life-history mechanisms that influence incursion spread and establishment, and concentrate surveillance efforts in areas most susceptible to invasion. The approach may improve efficiency, reduce wasted resources, and improve the success of management actions such as containment and eradication. This paper describes the development of an integrated landscape modelling tool for predicting incursion extent and spread using Python programming language and ArcGIS. The modelling system will form the foundation of a GIS based decision support tool that can be used by managers to guide surveillance efforts.

The real value of simulation systems is their ability to simulate and compare different management strategies that would not otherwise be possible. Simulation models allow available data to be integrated in a manner that is comprehensive, explicit and repeatable, which then allows a transparent assessment of the consequences of different management strategies (Higgins *et al.*, 2000). With a set of simulation tools integrated with a GIS, it is hoped that practitioners can quickly calibrate a simulation of plant invasion for evaluation of different surveillance and management strategies.

Previous simulation models for plant invasion have emphasised the critical influence that dispersal, and particularly the choice of kernel, has had on simulation outputs (Higgins *et al.* 2001). In the context of seed dispersal, a kernel can be defined as a mathematical function which for each spatial location around a parent plant, defines the probability distribution of seed dispersal. The shape of the kernel (particularly its tail), and whether it captures long distance dispersal, have been shown to be pivotal to predictions of invasion, and the inferred management recommendations (Clark *et al.* 2003, Buckley *et al.* 2005). The literature on modelling seed dispersal is diverse and expansive and can be categorised into wind, water and road mediated dispersal.

Wind-mediated seed dispersal is an important mechanism of spread and colonisation for invasive plants, and this has been recognised, with a proliferation of models for wind dispersal in the last decade. Modelling this mechanism is challenging; it varies with strength, duration and direction of wind, meteorological conditions, the nature of the terrain and the forest canopy, and seed morphology. Recently, complex models incorporating seed uplift processes, aerial transport processes, and atmosphere dynamics have been used to characterise long distance dispersal (Nathan *et al.* 2002, Katul *et al.* 2005). Despite these advances, model complexity and the required parameters restrict models to specific and detailed instances of wind dispersal rather than application at the landscape-level in a generalised simulation setting. The challenge is to simplify this complexity into simple but meaningful models of wind dispersal. For application at the landscape level, it is envisaged that a simple but flexible kernel will be parameterised for short and long distance dispersal and then weighted for wind strength, direction and terrain influences.

Vegetation studies along watercourses and roads have indicated an enhanced presence of invasive plants; these conduits act as corridors for rapid dispersal, and often provide suitable habitat for germination (Parendes and Jones 2000). In a rare study where the water column of a stream was sampled for seeds, Boedeltje *et al.* (2003) observed aquatic dispersal events of almost 1 km for species with limited normal dispersal. Similar results have been observed elsewhere, with experimentally released rhizomes retrieved 1.5km downstream for an aquatic plant (Johansson and Nilsson 1993), and 90% of seeds for two floodplain trees being retrieved 1800 metres downstream (Schneider and Sharitz 1988)

Studies of the material attached to vehicles (primarily mud attached to mudguards) indicated a surprising diversity of flora (Hodkinson & Thompson 1997). Distances associated with vehicular dispersal may be several orders of magnitude greater than other dispersal syndromes (Hodkinson & Thompson 1997) and have been estimated to be 3 to 40 km, with longer distance dispersal over several hundred kilometres. The challenge is to adequately characterise a highly stochastic mechanism in a relative simple kernel.

2. METHOD

An integrated GIS and simulation system has several advantages. Simulations can be applied to real incursions in real landscapes inclusive of terrain, hydrological, and wind models, and geographic layers describing roading and vegetation. GIS packages are designed for the creation and display of geographic information. In the instance of a weed incursion, the spatial accuracy of information on location and areas vulnerable to invasion is paramount for containment efforts. Likewise, the spatial accuracy of simulation outputs that lead to decisions on surveillance is also paramount. Using an integrated system of GIS and simulation tools, the spatial accuracy of the inputs will be maintained in model outputs and will follow through to decisions on surveillance and containment. As new information on the incursion extent becomes available, an integrated system can be rapidly updated for new spatial information, and simulations rerun for new surveillance recommendations.

The simulation consists of a series of scripts written in Python that implement various dispersal syndromes and a life-history model placed in an iterative loop that can be run for the desired number of years. Python is an object-oriented programming language developed in the 1990s as a platform for non-programmers to quickly and easily write complex programs. Python is open source software and is portable to a wide range of hardware and software platforms, programs can therefore be deployed unrestricted by licensing issues and preferred user platforms. The Numerical Python Module provides a range of mathematical and numerical functions used in the simulation system. There also exist a range of Python functions for manipulating GIS data layers in their various formats. However, most important of all, Python has been adopted as the scripting language in the ArcGIS 9 Geoprocessing Framework. Python scripts can be called from ArcGIS resulting in the GIS and the developed simulation tools being truly integrated

3. RESULTS AND DISCUSSION

With elements of simulation design selected, models of plant life-history and dispersal needed to be identified. Selected models are described below.

3.1. Modelling plant life-history

The life-history component of the simulation model drives plant germination, growth, fecundity and mortality. A stage matrix approach was used to track the movement of individuals through the various life stages, with the survival, growth, and reproduction of each life stage summarised in the columns of a stage matrix. This is consistent with the raster based approach, as the number of individuals in each life stage can be summarised at the raster cell level, and simple matrix multiplication can be used to project the population into the next time step. The stage matrix approach is the underpinning of population viability analysis, a tool used for assessing populations under threat in conservation biology (Burgman *et al.* 1993). The approach is also widely used in population models for invasive plants (Buckley *et al.* 2003).

An example matrix (A) is shown below (1) for a hypothetical perennial herbaceous or woody weed with high fecundity (1500) and short seed longevity (0.25).

$$\mathbf{A} = \begin{vmatrix} 0.25 & 0 & 1500 \\ 0.0375 & 0 & 14 \\ 0 & 0.1 & 0.5 \end{vmatrix} \qquad (1)$$

The three columns represent three basic life stages, seed, seedling, and adult, whilst the rows represent fecundity and survivorship for seeds, seedlings and adults into the next time period. Plant life-history can either be modelled deterministically using matrix A, or demographic stochasticity can be incorporated by sampling matrix A from a standard deviation matrix of the same dimension. Matrices can be viewed as life cycle diagrams, Figure 1 is the life cycle diagram for the matrix above.

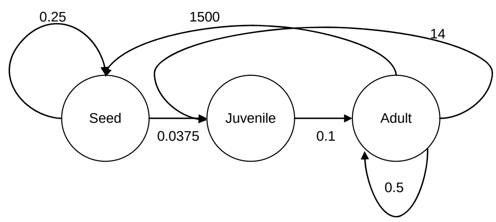

Figure 1. Life cycle diagram for a perennial herbaceous or woody weed with high fecundity (1500) and short seed longevity (0.25).

3.2. Modelling seed dispersal

For our models we require a general dispersal kernel that can be parameterised for a suite of dispersal syndromes under different conditions operating at a landscape scale. Therefore a model that has been shown to fit actual seed dispersion data, and has the flexibility to assume a variety of shapes is preferred. Given these criteria, the generalised model of Clark *et al.* (1999) was selected. This generalised dispersal kernel has been adopted in several recent studies (e.g. Dick *et al.* (2003), Austerlitz *et al.* (2004), Robledo-Arnuncio and Gil (2005), and Grevstad (2005)).

Clark *et al.* (1999) describe a family of dispersal kernels in the functional form

$$SD(x,y) = \frac{c}{2\pi\alpha^2\Gamma(2/c)}\exp\left[-\left(\frac{r}{\alpha}\right)^c\right] \quad (2)$$

where *SD(x,y)* is seed density per square metre for a cell with coordinates *x,y* at distance *r* from the source, Γ is the classical gamma function, α is distance parameter, and *c* is dimensionless shape parameter.

The generalised kernel is flexible and results in a Fat-tailed kernel when the shape parameter (*c*) is less than 1, an exponential kernel when *c* equals 1, and a Gaussian kernel when *c* equals 2 (Nathan *et al.* 2003). For our purposes we require models that can be simply parameterised based on a limited understanding of the dispersal agents. In the study of Clark *et al.* (1999) the generalised model form was found to fit a range of animal and wind dispersed species.

3.3. Applying the dispersal kernel

The generalised kernel of Clark *et al.* (1999) was adapted to distribute seeds in a raster based GIS. This was done by calculating the dispersal into a raster cell based on the Euclidian distance of the cell centroid from the source, and the size of the cell. Clark's model calculates the seed deposition for a 1 by 1 cell unit; therefore we need to scale deposition to the cell size as described below;

To sum all seeds for a cell size with centroid distance *r* from the source

$$\text{Seeds}*(\text{cellsize}^2)*\frac{c}{2\pi\alpha^2\Gamma(2/c)}\exp\left[-\left(\frac{r}{\alpha}\right)^c\right] \quad (3)$$

Using the solutions for the Gamma function (Γ) and the formulation above, the dispersal kernel can be estimated as a fat-tailed (4), exponential (5), or Gaussian (6) kernel;

$$\text{Seeds} * (\text{cellsize}^2) * \frac{1}{24\pi\alpha^2}\exp\left[-\left(\frac{r}{\alpha}\right)^{1/2}\right] \quad (4)$$

$$\text{Seeds} * (\text{cellsize}^2) * \frac{1}{2\pi\alpha^2}\exp\left[-\left(\frac{r}{\alpha}\right)\right] \quad (5)$$

$$\text{Seeds} * (\text{cellsize}^2) * \frac{1}{\pi\alpha^2}\exp\left[-\left(\frac{r}{\alpha}\right)^2\right] \quad (6)$$

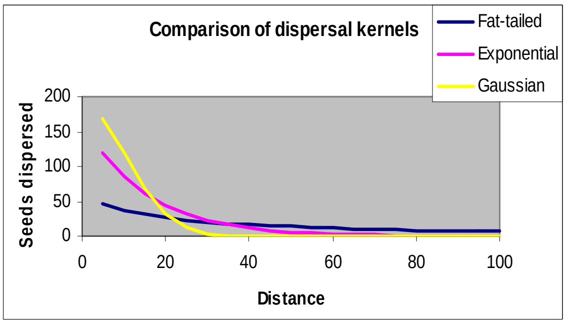

Figure 2. Graphically, the three kernels are shown above with a fixed distance parameter of 15. It can be observed that the Gaussian kernel distributes most seeds close to the parent plant, whilst the Fat-tailed kernel distributes seeds further from the parent. The total number of seeds dispersed is equivalent for the three kernels.

The parameterised kernel is used to distribute seeds from each source cell to surrounding cells on an annual basis. In the programming, this occurs in reverse, i.e. dispersal is calculated from each source cell into the analysis cell based on the Euclidian distance, and all dispersal events into the analysis cell are summed.

In its most basic form dispersal will occur concentrically around the source cell. Additional information on the dispersal event such as wind direction, strength and terrain effects are incorporated using weights. The application of weights results in anisotropic dispersal, however, the average of all weights for a particular influence is always one, thus ensuring that the overall magnitude of dispersal from each source cell is unchanged. For example, a weight for the influence of wind results in values less than one for areas upwind of the source and values greater than one for areas downwind of the source. Thus when the function is applied, more seeds are dispersed to locations downwind than upwind.

Dispersal is a highly stochastic event, and the deterministic kernel needs to be modified to reflect this. To generate more realistic stochastic dispersal events, the distance parameter can be randomly sampled from a designated distribution. This is similar to the 2Dt mixture kernel of Clark *et al.* (1999). Distance parameters can be sampled from different distributions dependent on the dispersal syndrome. Stochastic short dispersal events can be realised by sampling a normal distribution with mean as the average expected dispersal distance, and a standard deviation to control the stochastic variation. For incorporating rare long distance dispersal events the Lognormal distribution can be sampled. Using a skewed long-tailed Lognormal distribution, rare long distance dispersal events will be represented when large distance parameters are sampled. At the commencement of the dispersal function the chosen distribution was sampled for each source cell, and sampled values were stored in an array. During implementation of the kernel, dispersal from each source cell will use the sampled value in the array. Therefore each time the dispersal function is called, a new set of random values will be sampled from the distribution. Distributions are truncated to ensure the sampled distance parameters are positive.

3.4. Wind dispersal kernel

The analysis of Clark *et al.* (1999) suggested that an exponential kernel (4) provided the best fit to observed wind-mediated seed dispersal. This is a good starting point for a simple model of wind dispersal.

Modelling the influence of wind direction and strength

A python function was written to determine the bearing, in radians from north, for dispersal from the source cell to the analysis cell. The prevailing wind direction was then subtracted from this bearing and subject to the following formulation:

$$WindWt = WindStrgth^{\left(\left(1-\left(\frac{(1-\cos(CellDir-WindDir))}{2}\right)^{0.75}\right)-0.5\right)} \quad (7)$$

where *WindWt* is the weight applied to the kernel, *WindStrgth* makes the ellipse more oblique, *CellDir* is the bearing from the source cell to the analysis cell, and *WindDir* is the bearing of the prevailing wind

The function results in values greater than one when cell direction and wind direction are in agreement, and less then one when they oppose. The weights average to one across all directions, thus the total dispersal is not altered due to the weight. The variable '*WindStrgth*' makes the ellipse more oblique, and concentrates dispersal in the direction of the prevailing wind.

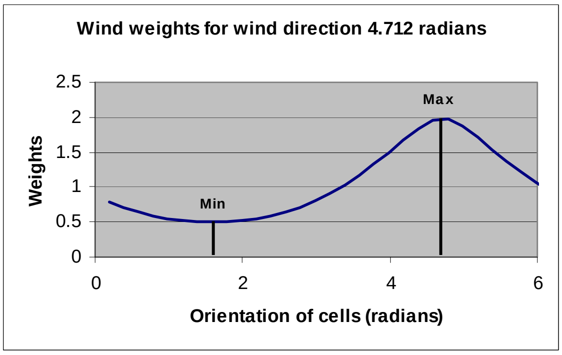

Figure 3 demonstrates the calculated WindWt values for a wind direction of 4.712 radians (270 degrees) with a WindStrgth of 4. It can be observed that when the orientation of cells is against the wind (1.571 radians) the magnitude of dispersal is halved, whilst when the orientation is aligned with the wind the magnitude of dispersal is doubled.

Modelling terrain influences on wind dispersal

A python function was written that determines the angle due to difference in terrain (elevation) between the analysis cell and the cell from which dispersal is occurring. This function is intended to capture the influence of terrain on wind dispersal. The angle is determined as described in equation 8:

$$Angle = a\tan\left(\frac{elev_a - elev_s}{Dis}\right) \quad (8)$$

where $elev_a$ and $elev_s$ are elevation of the analysis and source cells respectively, and *Dis* is the Euclidian distance between analysis and source cells

The terrain weight is then calculated by dividing the *Angle* by pi/2 (90 degrees) to give a unit-less ratio between 0 and 1. For upslope dispersal the quantity is subtracted from 1 to provide a unit-less ratio between 0 and 1;

$$TerrWght = \left[1 - \frac{Angle}{1.571}\right]^4 \quad (9)$$

For downslope dispersal the quantity is added to 1 to provide a unit-less ratio greater than 1;

$$TerrWght = \left[1 + \frac{Angle}{1.571}\right]^4 \quad (10)$$

A power factor of 4 is applied to increase the influence of terrain on dispersal.

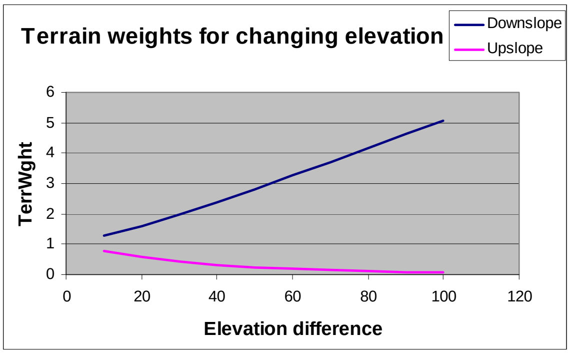

Figure 4 demonstrates calculated TerrWght values for upslope and downslope wind dispersal for a constant distance between cells of 100m, but subject to increasing elevation difference.

Modelling dispersal along roads and rivers

Initially, the dispersal kernel is modified so that dispersal occurs along a linear path rather than in all directions.

Clark (1998) describes a linear dispersal kernel as:

$$\frac{c}{2\alpha\Gamma(1/c)}\exp\left[-\left(\frac{r}{\alpha}\right)^{c}\right] \qquad (11)$$

where α is distance parameter, and c is dimensionless shape parameter

Based on available literature, a Fat-tailed kernel was selected for dispersal along rivers and roads as dispersal events further from the parent plant are better represented by the fatter tail of the distribution. Using the solution to the Gamma function, the Fat-tailed kernel is

$$\text{Seeds} * \text{cell\_length} * \frac{0.5}{2\alpha}\exp\left[-\left(\frac{r}{\alpha}\right)^{1/2}\right] \qquad (12)$$

Quantifying dispersal based on the Euclidian distance between two points rather than the actual distance along a road or watercourse is inexact. An improvement on this is to use network theory and apply the kernel along the stream or road represented as a network (Lawes and McAllister 2006). This is a more accurate method for stream and road dispersal.

For dispersal along watercourses the Hydrology tools in the ArcGIS Toolbox are used to estimate stream location, and calculate distances along streams from a DEM. By deciding on a cut-off, a Flow Accumulation layer was used to define potential watercourses, and Flow Length estimated dispersal distances along water courses. Linear dispersal along the river network occurred between two points on a watercourse when the source cell was located upstream relative to the analysis cell.

For dispersal along roads, tracks, etc, a GIS layer of tracks and their usage rates is used. Cells that intersect with roads are then assigned the usage rate. A buffering algorithm was used to determine cells in proximity to roads. Linear dispersal along the network occurs between two points on a road when the usage rate is the same (i.e., the same road). The weight on dispersal is a function of the usage rate, i.e., more dispersal along roads that are used often versus less dispersal along roads that are rarely used.

Multiple dispersal events

Studies have indicated that polychory is common in the dispersal biology of plants (Nathan & Muller-Landau (2000), Boedeltje *et al.* (2003), Bullock *et al.* (2006)), i.e., seed dispersal occurs by several mechanisms such as combinations of wind, water, and animal mediated dispersal. In the instance where seeds are subject to several alternative dispersal modes, seeds available for dispersal at the source can be proportioned and dispersed according to the each kernel. Seeds arriving at a source from several different modes are additive to provide a total for a particular species (Higgins *et al.* (2003), Bullock *et al.* (2006)). This is realised in simulations as follows: Initially, seeds available for dispersal are divided among the applicable mechanisms. Each mechanism then disperses its quota of seeds. The final dispersal into each cell is the sum of dispersal due to each mechanism.

4. CONCLUSION

The described simulation system is the basis of a GIS based decision support tool that can be used by managers to guide surveillance efforts. A Python module contains all the scripts necessary to run simulations, which is parameterised and called from an ArcGIS tool. Default values and acceptable ranges are provided to guide users in parameter selection. The interface provided by the ArcGIS Geoprocessing feature allows managers to parameterise and run complex simulations without exposure to the underlying script. The decision support tool has been parameterised for an incursion of Chilean needle grass (*nassella neesiana*) in south-east Queensland, and has been used to improve surveillance and eradication efforts. The ability to simulate seed dispersal in real landscapes is important for devising surveillance strategies for invasive plants that have been targeted for containment or eradication.

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