Using networks to understand source and sink relationships to manage weeds in a riparian zone

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Summary In riparian zones weeds spread through the landscape along the water course. Streams and rivers are interconnected. The connectivity between streams is influenced by the amount of water flowing through each point. In this study we estimate the strength of the connection between two points or nodes, based on the volume of water passing from one point to the next. These connectivities are subsequently used to determine the most likely location of weed sources and weed sinks. Weed sources are the areas most likely to contribute to an invasion downstream, while weed sinks are the areas most likely to be invaded. We use a network approach to describe the connectivities between successive nodes of the Burdekin catchment and classify each node into a source or sink based on a water accumulation index. In general, sources were located in the upper portions of the catchment and sinks were located in the medium to lower reaches of the catchment. Some of the minor streams were neither sources nor sinks. We then consider possible management strategies for each of these regions.

Keywords Connectivity, network, riparian zone.

INTRODUCTION
Local government encourages land managers faced with weed problems to develop management plans for invasive species. To achieve this, land managers need to determine the spatial extent of species and plan follow up treatments. Additional landscape information on connectivity and habitat suitability would allow managers to identify regions most likely to be invaded (weed sinks) and determine the areas contributing to invasions elsewhere (weed sources).

Many theoretical frameworks have been developed to explore components of an invasion (e.g. Moody and Mack 1988). Others have been able to explore invaded landscapes using datasets that partly describe the demography and dispersal of a species (e.g. Buckley et al. 2004). The arrangement of habitat and connectivity between suitable habitats has also been explored in a theoretical sense by Cumming (2002). However, methodologies that allow managers to quickly evaluate habitat connectivities and determine the locations of potential sources and sinks have not been developed.

In riparian zones managers can safely assume that flooding, or at least the movement of seed from one part of the catchment to another by water, will affect the likelihood that an area of the catchment will be invaded. Riparian zones in the rangelands are considered more vulnerable to invasion than the other parts of the landscape due to their elevated water and nutrient status (Grice et al. 2000). In essence, every tributary of a riparian zone is connected and the habitat, at least within the riparian zone, can be treated as uniform from the weed’s perspective.

The process of seed dispersing down a catchment is complicated by the underlying nature of the riparian system. Some species are wind dispersed, while others are dispersed by water. Inland ephemeral streams, such as the Sandover River in Central Australia, rarely flow and may be comprised of one major river with few or no tributaries entering the stream. Other river systems, such as the Burdekin in north Queensland, are over 800 m wide and have many tributaries, or second order streams that flow into them. These second order streams may also have tributaries, or third order streams flowing in to them. The streams are all connected and a weed invasion may start in any one of these streams. However, the connectivities between the riparian zones are likely to vary and will be influenced by the volume of water likely to flow from one stream to the next. This variation in flow may be used to identify parts of the catchment that act as a weed source and those that form sinks for water dispersed weeds.

Recent statistical analyses of spatial datasets of woody weeds suggest the potential for the weed to spread is influenced by its geographic location in the catchment (Lawes and Grice in press). While these empirical studies are useful in highlighting the potential process, they do not allow managers to evaluate a landscape and determine which components of a riparian system, once invaded, pose the greatest threat to the remainder of the landscape.

In this study we develop a method to explore the connectivities between different stream orders...
of a riparian zone in the Burdekin catchment using network theory. We use connectivity to identify the sources and sinks within the catchment. We demonstrate how connectivity may be represented and discuss the importance of managing sources and sinks in the landscape. Using network theory, we are able to ascertain the cumulative flow for each tributary and determine its contribution to an invasion in the landscape. When combined, these algorithms can be used to determine the locations in the catchment that act as a weed source and threaten other areas in the catchment. They also determine which areas of the catchment act as sinks and are most at risk from other areas in the catchment.

MATERIALS AND METHODS

In this study we evaluated the southern component of the Burdekin river system and its associated tributaries in Northern Australia. We were primarily interested in the movement of water across the landscape and down the riparian zone. Therefore, the study area included the riparian zone and the upland areas where water flows into the riparian zone. This includes all rivers, streams and gullies that flow directly or indirectly into the waterway, and the land that feeds these systems. We assume that if water can flow across the landscape, then it has the capacity to move seed across the same landscape.

The landscape was represented as a network using a 250 × 250 m GIS Digital Evaluation Model (DEM). We use ArcInfo to calculate water flow direction and water flow accumulation. The accumulation index was converted to ASCII raster format as a 250 × 250 m grid, essentially a text-file grid covering the catchment, where each value indicates how much water passes through that position. We defined each grid cell as a node and link each node to its neighbour(s) with the greatest accumulation index. For each node in the landscape we calculated an index for source and sink. A sink index for a node in the network is the probability that that node will experience an infestation from other network nodes. A source index for each is the expected number of subsequent nodes infested by introducing the local infection.

To calculate these indices we simulated the transmission of weeds throughout the riparian network after introducing a weed infestation into every node of the network.

After introducing a weed to a node we calculated the probability of transmission to all linked nodes, for up to 100 links along the network. An introduced weed infestation was transmitted to a subsequent connected node based on a sigmoidal distribution so the probability of transmission from node \( i \) to the connected node \( j \) is,

\[
p_{i,j} = \frac{f_i^k}{a^k + f_i^k}
\]

where \( f_i \) refers to the accumulation flow index for node \( i \), and \( a \) and \( k \) are shape parameters of the sigmoidal distribution equal to 200 and 5, respectively. Therefore the chance of a node transmitting weeds to other nodes decreases as the distance between the source increases. Assuming nodes \( i \) to \( s \) form a path within a network then,

\[
\hat{p}_{i,s} = \sum_{z=2}^{100} (p_{z-1,z} \cdot p_{z,z+1})
\]

where \( \hat{p}_{i,s} \) is the probability of node \( i \) infecting \( s \) which are not directly connected.

We simulated weed introduction at every point, so it is likely that a given point has some probability of being infected from multiple sources, in which case the probabilities are cumulative. We used the cumulative probabilities that a node will be infected as the sink index, while the expected number of node infestations that occurred from a source node is our source index,

\[
\sum_{z=2}^{100} p_{z-1,z}
\]

where nodes \( i \) to 100 form of a linked path within a network.

The probability that a node was infected was primarily a function of infestation from other nodes. The probability of initial introduction into the network was not explored in this system. In all situations, we therefore assume the probability of weed invasion was 10% (from Eq. 2, \( p_{i,s} = 0.1 \)).

For display purposes we classified the source and sink index into four categories based on whether a node is a source or not (above or below its median) and sink or not (above or below its median). The categories were therefore: 1) source and sink; 2) source but not a sink; 3) sink but not a source; and 4) not a source or sink.

RESULTS

The structure of the catchment was viewed as a network, where nodes were connected by the movement of water across the landscape (Figure 1 and 2). There were similar numbers of sources and sinks in the catchment (3014 and 3015). 2669 of these nodes were members of category 1 and acted as a source and a sink. Despite these similarities the geographic location of sources and sinks did vary and a large number of nodes (2669) were members of category 4, neither a source nor sink (Figure 2b, Table 1). Source nodes, category 1 or 2, were situated in the upper portion of
the main tributary (Figure 1a). Sinks, category 1 or 3, were more widely distributed along the entire length of the main tributary and some of the secondary streams (Figure 1b). The 3rd and 4th categories were generally present in distant parts of the catchment that included 2nd or 3rd order streams (Figure 2a).

Table 1. Number of nodes in the catchment identified as sources and sinks.

<table>
<thead>
<tr>
<th></th>
<th>Source</th>
<th>Not source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sink</td>
<td>2,669</td>
<td>346</td>
</tr>
<tr>
<td>Not sink</td>
<td>345</td>
<td>2,669</td>
</tr>
</tbody>
</table>

**Figure 1.** Geographic location of weed sources (a) and weed sinks (b) in the lower portion of the Burdekin catchment.

**Figure 2.** Geographic location of weed sources that are not weed sinks (a) and areas that are neither sources nor sinks (b) in the lower portion of the Burdekin catchment.
DISCUSSION
The use of network theory analysis of a riparian flow gave insights into weed invasion and provides an explanation behind the commonly observed phenomena that more weeds accumulate close to the river mouth, downstream. The four categories of the riparian zone may be used by managers to plan regional weed control strategies. Each category should be managed with a different objective.

The first category, sources and sinks, were the most numerous and may experience further invasions as they are connected to other sources. All sinks have high cumulative flows and by default are highly connected. It is difficult to isolate them from other areas of the catchment. Thus management effort should only be expended in this category if other areas have been controlled or constant follow up treatment is planned. This category acts as a source, so there is some benefit for other locations downstream in controlling weeds from this category.

The second category, sources but not sinks are arguably the most important categories in the catchment. They are not at risk of invasion and it should be possible to manage them and keep them weed free. This group contributes extensively to flows experienced by the remaining categories with invasion sinks. If this category were effectively managed, the probability of water driven invasions would be reduced throughout the catchment.

The third category, sinks but not sources, with high cumulative flows were highly connected. They were located on the main tributary in the lower part of the catchment. They are under constant threat of invasion from other areas of the catchment and should only be managed if extensive follow up treatment is planned or the remainder of the catchment is relatively weed free.

The fourth category, neither source nor sink and found in second or third order tributaries, could be managed relatively easily as the movement of water into and out of these nodes is minimal. Therefore if weeds are removed from these areas, the chance of re-infestation is lower than other parts of the catchment.

In this study the application of network theory to a riparian zone enabled us to determine critical source/sink relationships important for weed management. The methodology used here may be incorporated into more elaborate models of weed management that use the source/sink indices as continuous rather than categorical variables to develop catchment scale weed management strategies.

REFERENCES