Cotton Catchment Communities CRC

FINAL REPORT

Part 1 - Summary Details

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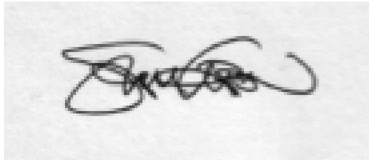

Part 3 – Final Report

Regeneration of floodplain vegetation
in response to large-scale flooding in the Condamine-Balonne and Border Rivers

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Background

Project background

This report presents the results of a collaborative research project between the Australian Rivers Institute (ARI) of Griffith University, the Cotton Catchment Communities Cooperative Research Centre (Cotton CRC), the NSW Office of Water (NOW) and the Queensland Department of Environment and Resource Management (DERM). Originally conceived as a pilot project for a larger research programme proposed under the Cotton CRC Extension bid, this project aimed to augment and strengthen research relationships between the partner organisations through the collaborative design and implementation of a research project to investigate floodplain vegetation responses to recent flooding in the Condamine-Balonne and Border Rivers catchments. The project also contributed to the obligation of the two State jurisdictions to implement the Integrated Environmental Flows Monitoring Program proposed under the NSW/Qld Intergovernmental Agreement for the Border Rivers and Intersecting Streams.

Floodplain vegetation dynamics in the Condamine-Balonne and Border Rivers catchments have received scant scientific attention, with the exception of a number of studies of iconic sites (e.g. Narran Lakes; Thoms et al., 2007), and watering requirements of wetland and floodplain vegetation within these rivers are poorly understood. This project addressed major knowledge gaps concerning the dynamics and resilience of key vegetation communities of floodplains within this region to provide information to improve decision making regarding water resources management and conservation in these ecologically and culturally significant landscapes. More specically, this project sought to provide ecological information of relevance to the monitoring and review of the NSW Water Sharing Plans and Queensland Resource Operation Plans for these catchments.

The overarching aim of the project was to determine the regeneration responses of key floodplain tree and shrub species to significant overbank flooding in the Condamine-Balonne and Border Rivers catchments following an extended period of drought, thereby contributing to an assessment of vegetation resilience in this region as well as the capacity to make predictions concerning the outcome of various hydrologic changes associated with climate change and water management scenarios for floodplain vegetation.

Project structure

The research undertaken in this project was led by staff of the Australian Rivers Institute. A project steering committee, comprising members of NOW, DERM and ARI, provided advice on the intital project design and the selection of appropriate field sites in particular. DERM staff, especially Andrea Prior, Tariq Kahn and Jacqui Lee, were also instrumental in undertaking the field surveys. The DERM contribution to this project was provided via this significant in-kind support as well as through alignment of this project with the National Water Commission funded project, *Riverine and floodplain ecosystem responses to flooding in the lower Balonne and Border Rivers*, undertaken by DERM in conjunction with ARI staff and completed earlier in 2012 (Woods et al., 2012).

Research background

Decline in the condition of riparian vegetation in semi-arid regions is a global phenomenon, typically attributed to flow regime alteration, invasive species and grazing (e.g. Stromberg, 2001; Thoms et al., 2007; Horner et al., 2009). Of particular concern, are observations of reductions in the successful recruitment of native woody species and the implication that many populations may not be self-sustaining (e.g. George et al., 2005). Given the importance of riparian canopies for aquatic and terrestrial ecosystems, there is significant impetus for research to identify factors limiting recruitment in these systems and inform their restoration and management.

Seedling establishment represents a major recruitment bottleneck influencing population and community structure amongst many plant species and vegetation types; from trees in tropical savanna (e.g. Lehman et al., 2009) and Mediterranean oak coppice forests (e.g. Espelta et al., 1995) to perennial meadow plants (e.g. Jongejans et al., 2006). Due to their reduced stature, seedlings tend to be more vulnerable to stresses than their mature counterparts, being more sensitive (e.g. to fire) or having a greater degree of exposure (e.g. light limitations in understorey) to these. Identifying recruitment bottlenecks and the mechanisms which underpin them is therefore critical to understanding vegetation dynamics of particular systems and their vulnerability to anthropogenic and non-anthropogenic disturbances and threats such as climate change.

In arid and semi-arid riparian and floodplain habitats, tree and shrub species often produce large numbers of widely dispersed seeds which typically germinate rapidly in response to favourable conditions such as light, warmth and soil moiture (e.g. Streng et al., 1989; Chong and Walker, 2005). Surival of emerging seedlings, however, is generally rare and recruitment of trees and shrubs in these heterogeneous landscapes tends to be sparse and patchy in both space and time (Streng et al., 1989; Hughes, 1990; Cooper et al., 1999; Horton and Clark, 2001). Consequently, seedling establishment is perceived as a major recruitment bottleneck for many arid and semi-arid riparian tree and shrub species (George et al., 2005; Capon et al., 2009).

The composition, structure and dynamics of vegetation in arid and semi-arid riparian and floodplain habitats are typically controlled predominantly by the unpredictable hydrological regimes which dominate these landscapes (e.g. Stromberg 2001; Brock et al., 2006). Hydrology also tends to have an overriding effect on seedling growth and survival in riparian habitats (e.g. Cooper et al., 1999; Horton and Clark, 2001; Gindaba et al., 2004; Capon et al., 2009). Seedlings can be influenced directly by flooding as a result of soil anoxia and toxicity associated with inundation, reductions in light, burial by sediment or hydraulically driven mechanical damage although the water column may also provide structural support for developing stems (Blom et al., 1990; 1996). The type and degree of these effects will depend on the size and developmental stage of seedlings as well as flood attributes including timing, depth, duration and rate of rise and fall (Brock et al., 2006; Capon et al., 2009). Flooding may also shape patterns of seedling establishment indirectly by influencing seed dispersal (i.e. via hyrochory; Nilsson et al., 1991) or through the creation of bare substrate for colonisation as a result of scouring (e.g. Stromberg 2001). Addionally, floodwaters provide an important source of soil moisture in arid regions which may favour seedling establishment during and following flood water recession (Capon et al., 2009). Seedling establishment initiated during such phases is likely to depend on the rate of drying and water table decline (Horton and Clark, 2011). Overall, variable flooding and drying regimes create heterogeneous habitat mosaics, reflected by dynamic vegetation communities (e.g. Stromberg, 2001; Brock et al., 2006).

The regeneration of trees and shrubs in arid and semi-arid riparian floodplain environments is promoted by a range of plant traits and response mechanisms (e.g. Brock et al., 2006; Capon et al., 2009). Recruitment by large numbers of seedlings, rapid establishment and growth, and growth variability and adaptation to local environmental conditions can all be considered as adaptations to the variable and unpredictable environmental conditions that characterise these habitats (Gibson et al. 1994). Rapid development of tap root systems which can track declining soil water tables has also been identified in some species (Kranjcec et al., 1998; Horton and Clark, 2001). This represents a possible example of morphological plasticity which may be a beneficial trait for plants inhabiting variable environments. However, in unpredictable arid systems, plasticity is neither likely to have evolved or necessarily be advantageous (Capon et al., 2009). Vegetative regeneration mechanisms and the capacity to resprout from woody stems, may also enable plants to respond to unpredictable flooding (Chong and Walker, 2005; Capon et al., 2009).

Most knowledge of riparian tree and shrub regeneration in arid and semi-arid regions comes from North American studies (e.g. Kranjcec et al., 1998; Cooper et al., 1999; Horton and Clark, 2001). Regeneration traits and mechanisms amongst many common Australian dryland riparian species, however, are poorly known (e.g. Roberts and Marston, 2011). Even amongst those speciees which have been relatively intensively studied, e.g. river red gum, the focus has been on populations and individuals from particular areas of their distribution, usually concentrated in the southern Murray-Darling Basin (e.g. Rogers and Ralph, 2010) and little is known, therefore, about possible variation within populations across their distribution. Since there is considerable concern regarding the health of mature riparian trees throughout the Murray-Darling Basin (e.g. Thoms et al., 2007; Cunningham et al., 2009; Horner et al., 2009), knowledge of vegetation regeneration patterns and the factors influencing these is critical for informing water resources planning and management to improve the conservation and restoration of these ecologically and culturally vital components of the landscape.

This project was designed to address major knowledge gaps concerning patterns of vegetation regeneration in riparian habitats of the Condamine-Balonne and Border Rivers in the northern Murray-Darling Basin. More specifically, the project sought to describe patterns in seedling establishment of key woody species in these riparian zones following flooding in early 2011 which was preceded by an extensive period of drought. We also sought to identify dominant drivers of these patterns with respect to both landscape-scale climatic and hydrologic variables as well as local-scale environmental characteristics, such as topography, canopy cover and soil character, and extant vegetation composition, including the presence of seeds. We predicted that flooding would have triggered a significant recruitment event amongst many common tree and shrub species in the study area and that patterns in seedling distribution would predominantly reflect interactions between hydrological factors and local habitat characterstics.

Objectives

The major objectives of this project were to:

1. describe spatial and temporal patterns in vegetation regeneration amongst key floodplain plant species (i.e. river red gum, coolibah, river cooba and lignum) following major flooding in the Condamine-Balonne and Border Rivers catchments;
2. identify major environmental factors influencing the success of vegetation regeneration in floodplains of the Condamine-Balonne and Border Rivers catchments; and
3. identify any thresholds (e.g. duration of dry spells) beyond which vegetation regeneration is sigificanlty hampered, even in response to large-scale flooding.

The project has clearly addressed the first and second of these objectives by conducting a thorough literature review pertaining to vegetation regeneration in Australia's dryland floodplains as well as via the design and implementation of a field research program. Observed spatial and temporal patterns in the regeneration of key floodplain plant species across selected sites of the Condamine-Balonne and Border Rivers between September 2011 and March 2012 are described in the Results section that follows as are the major environmental factors influencing these. We were not able to identify factors affecting recruitment success in all of the species considered since regeneration of some key species, most notably river red gum, was barely observed during this study.

We were unable to adequately address the third objective during the current project due to the relatively low number of seedlings observed and the high degree of spatial patchiness in their distribution. As a substantial pilot study, however, this project's findings indicate that identification of any such thresholds that do exist is likely to require systematic long-term monitoring of floodplain vegetation dynamics over successive periods of drying and flooding.

Methods

The project comprised two major components: 1.) a literature review and associated development of conceptual models, and 2.) a field study program. The approach and methods employed in each are described here.

Literature review and conceptual models

We conducted a thorough and comprehensive review of published literature pertainining to the regeneration of plant species common to Australia's inland arid and semi-arid floodplains. Over 130 published sources were located and used in this review. Questions asked of these sources to prepare the review included:

1. What are the constraints on plant regeneration in desert floodplains?;
2. What plant traits and mechanisms enable regeneration under hydrologic variability?; and
3. What regeneration strategies are exhibited by Australian desert floodplain plants?

The literature review contributed to the development of conceptual models for the regeneration of four selected floodplain tree and shrub species: river red gum (*Eucalyptus camaldulensis* Denhm.), coolibah (*E. coolabah* Blakely and Jacobs), river cooba *(Acacia stenopylla*) and tangled lignum (*Muehlenbeckia florulenta* Meisn). These species were chosen based on ecological assets identified within the *Condamine-Balonne Resource Operations Plan* and in consultation with the project steering committee. Conceptual models were developed for each of these species, based on the literature review and the expert advice of the project team and steering committee, to describe interactions between flow regime characteristics and major life history stages.

Field study sites

The study region for this project comprised the Border Rivers and Condamine-Balonne catchments that straddle the Queensland and New South Wales border in the northern Murray-Darling Basin (Figure 1). This region has a dry, sub-tropicl climate with highly variable rainfall, both spatially and temporally, though generally falling predominantly during summer months (Marshall et al., 2006). Mean annual rainfall in the eastern parts of these catchments can exceed 1 000 mm but is lower than 150 mm in western areas (Thoms 2003; Marshall et al. 2006). Lowland rivers in these catchments typically comprise meandering channels often associated with wide floodplains and a variety of wetland complexes (Kingsford, 1999; Thoms, 2003). Grazing and irrigated cropping are the major land uses in the area and these are supported by significant water resources developments in the region including dams, weirs, off-stream storage, extraction and levee bank construction (Kingsford, 1999). Woody riparian and floodplain vegetation along lowland reaches of these catchments typically comprises woodland communities with canopies dominated by *Eucalyptus camaldulensis* (river red gum), *E. coolabah* (coolibah) and *A. stenophylla* (river cooba) as well as shrubland and understoreys dominated by *Muehlenbeckia florulenta* (tangled lignum). Further upland, additional woody species are likely to be present in riparian zones of these catchments, e.g. *Casuarina cunninghamiana* (river she-oak; Roberts and Marston, 2011).

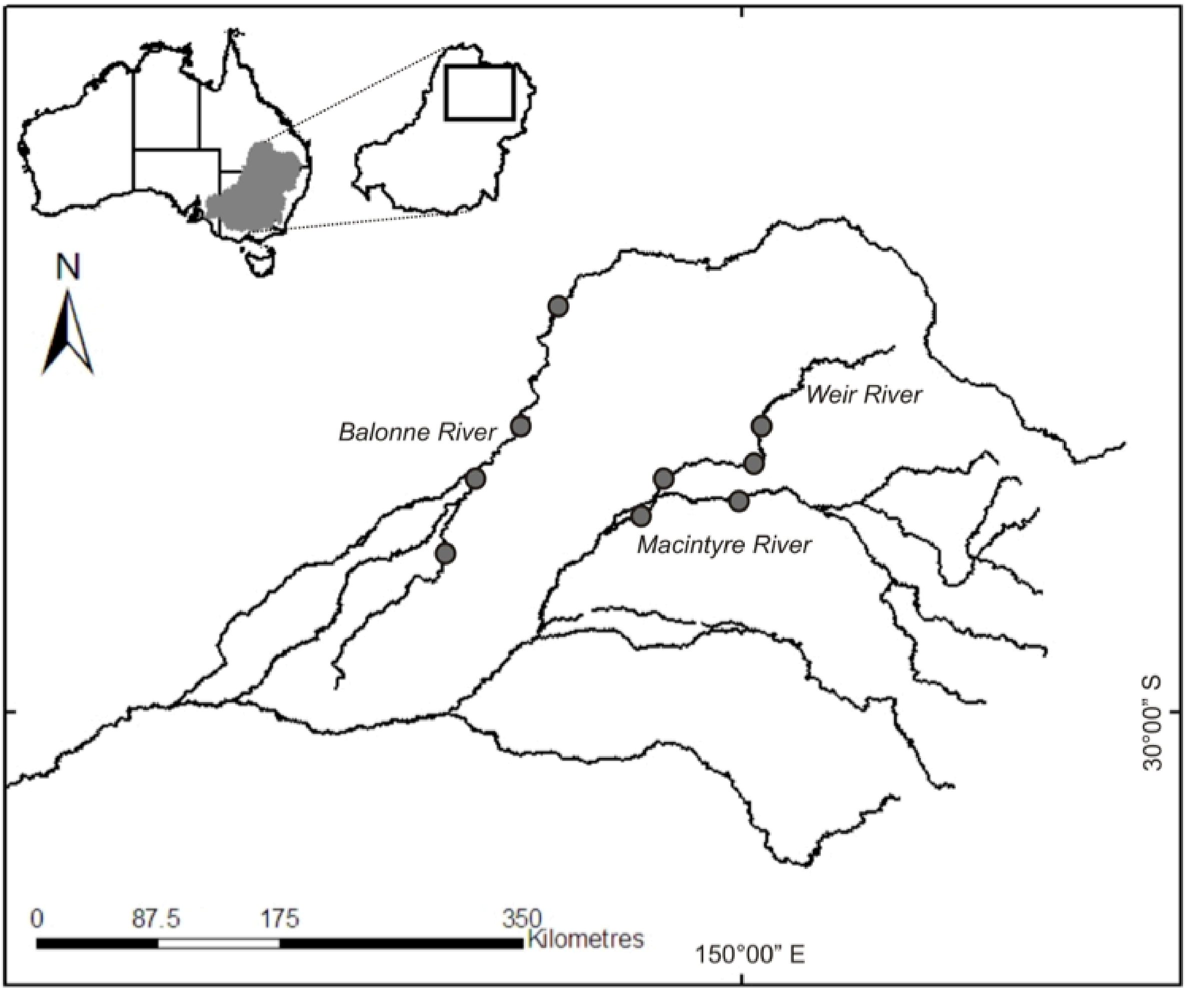

Figure 1. Map of the study region showing the distribution of field survey sites across the three catchments. Inset shows location of study region in the Murray-Darling Basin.

Nine sites across the Border Rivers and Condamine-Balonne catchments were selected for inclusion in the field study (Figure 1). A preliminary list of fifteen sites was prepared but had to be pared down due to logistical constraints associated with field work. The final nine sites included five sites used for the waterhole study component of the aligned DERM project *Riverine and floodplain ecosystem responses to flooding in the lower Balonne and Border Rivers*, which were selected as representative of a gradient of floodplain width and inundation extent (Woods et al., 2010). The other four sites were included based on the experience and recommendation of the steering committee and to represent a spread of sites geographically. Where possible, additional sites were chosen in close proximity to stream gauging stations. Site details are provided in Table 1 and a description of each is also provided below.

Table 1. Field sites with location, survey details and nearest gauge.

River	Site Name	Latitude (south)	Longitude (east)	# Transects surveyed	River bank surveyed	Nearest stream gauge	Trips surveyed
Weir	Talwood*	28.4958	149.4906	3	Left bank	416202 Weir River at Talwood	All
	Giddi Giddi South*	28.4027	150.0485	3	Left bank	416204 Weir River at Gunn Bridge	Sept 2011 Mar 2012
	Gunn Bridge	28.1556	150.1014	3	Left bank	416204 Weir River at Gunn Bridge	All
Balonne	Weribone	27.3081	148.8379	3	Left bank	422213 Balonne River at Weribone	Sept 2011 Nov 2011
	St George*	28.0722	148.5733	3	Left bank	422201 Balonne River at St George	Sept 2011
	Whyenbah Bridge*	28.3754	148.3397	3	Right bank	422204 Culgoa River at Whyenbah	Sept 2011
(Narran)*	Booligar*	28.9252	148.0800	2	Left bank	422206 Narran River at Dirranbandi-Hebel Road	Sept 2011
MacIntyre	Stuartville	28.6132	149.9325	3	Left bank	416047 MacIntyre River at Terrewah	Sept 2011 Mar 2012
	Kanowna	28.6930	149.3896	2	Left bank	416048 MacIntyre River at Kanowna	Sept 2011 Mar 2012

** indicates sites also used for waterhole study (see Woods et al., 2012)*

Weir River at Gunn Bridge

This site is located downstream of the Gunn Bridge gauging station weir on the left bank. The riparian canopy here was dominated by river red gum, coolibah, river cooba, whitewood and other *Acacia* species. The majority of the site was fenced but two transects extended into a neighbouring paddock by around 10 m.

Weir River at Giddi Giddi South

This site is located on the left bank of the Weir River. The riparian canopy here comprised river red gum, coolibah, river cooba and *Eremohpila* spp. with an understorey during September 2011 of dry grass and *Wahlenbergia* spp. This site is not in close proximity to a gauging station. The river banks here were less stee than those at Gunn Bridge.

Weir River at Talwood

This site is located on the left bank of the Wier River on both sides of the Talwood-Boonanga Road. Two transects at this site were positioned near the gauging station on the western side of the road while the other transect was located on the eastern side of the road. The riparian canopy cover here was relatively low and comprised coolibah, river cooba and river she-oak. A shrubby undertorey comprising tangled lignum, *Eremohpila* spp., chenopods and grasses was also present in September 2011.

Balonne River at Weribone Station

This site is located next to the Weribone gauging station (422213) on the left bank of the Balonne River. The riparian canopy cover comprised regrowth but mature trees were lacking. Dominant tree species included river red gum, coolibah, river cooba, whitewood and *Melaeuca bracteata*. The understorey comprised tangled lignum, grasses and herbs including emu-foot (*Psoralea tenax*). This site was accessible by livestock.

Balonne River at St George

Site selection in this reach was constrained by considerable disturbance to riparian and floodplain vegetation. The chosen site is on the left bank of the river, approximately 4.4 km downstream of the site used in the aligned waterhole study (Woods et al., 2012), where considerable narrowing of the Balonne River is apparent. Riparian canopy cover here was relatively high with even-aged stands of tree species suggesting previous flood-related colonisation events. The canopy mainly comprised coolibah and *Acacia* species and the understorey consisted of patchy grass and other herbaceous vegetation with much bare substrate. This site was aslo accessible by livestock.

Balonne River at Whyenbah Bridge

This site is located on the right bank of the Balonne River. The riparian canopy comprises river red gum, river cooba, *Eremophila* spp., whitewood and other *Acacia* spp.. A shrub layer of tangled lignum and *Eremophila* spp. was also present but understorey vegetation was scant during September 2011. The site was also accessible by livestock.

Narran River at Booligar

This site is located next to a ring tank on the left bank of the Narran River. The site is dominated by river cooba and tangled lignum with little or no understorey vegetation present during September 2011. This site was accessible by livestock. The Booligar site was counted as belonging to the Balonne catchment for the purposes of the data analyses conducted in this project.

MacIntyre River at Stuartville

This site is located upstream of the Terrewah guage (416047) by approximately 10 river kilometres. The riparian canopy here comprised river cooba, coolibah and whitwood. A shrub layer of tangled lignum, *Swainsonia* sp., black roly-poly (*Sclerolaena quinquecuspis* var. *quinquecuspis*) and prickly Acacia (*Acacia paradoxa*) was also present during September 2011.

MacIntyre River at Kanowna

This site is located next to the Kanowna gauging station on the left bank of the MacIntyre River. The riparian canopy here included river red gum, river cooba, *Melaleuca bracteata*, whitewood and *Eremophila* spp.. In September 2011, a shrub layer dominated by tangled lignum and *Eremophila* spp. was present with ground cover including grasses and bare ground.

Field survey methods

Seedling transects

At each site, we selected up to three 50 m long transects running perpendicular to the river channel based on the presence of visible patches of seedlings, as determined by an extensive visual inspection. This approach, rather than random selection of transects, was taken to ensure that at least some seedlings were encountered given their clearly sparse and patchy distribution. At two sites (Booligar and Kanowna; see Table 1), only two transects were delineated due to the rarity of seedlings. In all but one case (i.e. Talwood), transects were positioned on the same river bank with at least 50 m intervening. Trasects were marked with wooden stakes at the bankfull point of the river channel, taken as the break in slope, and at their 50 m end points, with GPS coordinates recorded at both ends to enable mapping and location of transects during future surveys.

Seedlings were recorded within contiguous 1m^2 quadrats along each transect. In each quadrat the number and type of seedlings were recorded where seedlings included all trees or shrubs up to 1 m in height. For each species present, the height (mm), recruit type (i.e. asexual or sexual), the distance to nearest adult plant, the number of stems and the % greenness were also recorded for no more than 10 individuals along with any evidence of mechanical damage or grazing. Recruit type was judged by inspecting seedlings below the soil surface to identify the presence of clear tap roots (indicating a sexually produced seedling) or suckers, rhizomes or stolons (indicating an asexual recruit). The % greenness was recorded as an indication of plant health, particularly in relation to moisture stress.

Seedling transects were initially surveyed at all sites in September 2011. A second field trip was commenced in November 2011 but only three sites (Talwood, Gunn Bridge and Werribone) were able to be completed because of the inaccessibility of sites due to flooding in the region. A final field trip was conducted in March 2012. Again, only the five sites on the Weir and MacIntyre rivers were able to be surveyed at this time due to extreme flooding in the Balonne catchment (Table 1).

Extant vegetation and propagule supply

The extant vegetation canopy was surveyed at all sites during the September 2011 field trip within 10 contiguous 5 m^2 quadrats centred along the seedling transects. Within each 5 m^2 quadrat, riparian canopy cover was measured using a spherical densiometer (Lemmon, 1956) and the percentage contribution to overall cover of each woody species present estimated. The percent covers of woody shrubs and groundcover were also recorded within the 1 m^2 quadrats used in the seedling transects on each survey occasion. We also recorded the presence of seeds of major woody species present both in the canopy and on the surface within each 5 m^2 quadrat during the September 2011 field survey.

Environmental variables

A number of environmental variables with the potential to influence germination and seedling establishment were also recorded during field surveys or calculated from available data sources. These included % bare ground and % leaf litter cover, visually estimated for each 1 m ^{2} quadrat along the seedling transects on each survey occasion, and soil composition (i.e. % mud-clay, % silt, % fine sand, % coarse sand and % fine gravel) also recorded based on inspection of surface sediments in 1 m^2 quadrats but only during the first survey (Table 2).

Relative elevation of each 1 m ^{2} quadrat, with respect to the start and end of transects as well as river level, was also recorded using a staff and dumpy since this is likely to influence the occurrence, depth and duration of inundation. Topographic surveys were conducted during the November 2011 and March 2012 field trips. Consequently, relative quadrat elevations were not obtained at sites only visited in September 2011 (see Table 1).

Table 2. An overview of field survey data measured in 1m² and 5m² quadrats on each transect.

Component	Measurements	1 m²	5 m²
Vegetation recruits	Number of recruits	x	
	Height (mm)	x	
	Nearest potential parent tree (m)	x	
	Origin of recruit (sexual/asexual)	x	
	Number of stems per recruit	x	
	Greeness (%)	x	
	Evidence of mechanical damage (Y/N)	x	
	Evidence of grazing (Y/N)	x	
Environmental and extant vegetation characteristics	Soil composition (% mud-clay, % silt, % fine sand, % coarse sand, % fine gravel)	x	
	Cover elements (% shrub cover, % leaf litter, % ground cover, % bare ground)	x	
	Riparian canopy cover (%)		x
	Proportion of canopy cover contributed by individual tree species		x
	Relative elevation of quadrat (m)	x	
	Presence of seeds on ground (Y/N)		x

Rainfall data for each site was obtained from the Bureau of Meteorology (BOM ; Table 3). Streamflow data for gauges associated with sites (Table 1) were obtained from DERM and NOW.

Table 3. Bureau of Meteorology (BOM) sites used to obtain rainfall data for field survey sites.

Survey site	BOM Station
Gunn Bridge	41112 Giddi Giddi South TM
Giddi Giddi South	41112 Giddi Giddi South TM
Talwood	42027 Talwood State School
Weribone	43101 Werribone TM
St George	43109 St George Airport
Whyenbah Bridge	44154 Whyenbah
Booligar	48168 Angledool Station
Stuartville	52004 Boomi (Barwon Street)
Kanowna	52004 Boomi (Barwon Street)

Tagged seedlings

In addition to the seedling transects, further individual seedlings were located, tagged (with labelled cabel ties) and measured so that their growth could be monitored over the survey period (Table 4). Seedlings were tagged at four sites: Talwood, South Giddi Giddi, Weribone and Kanowna. The following variables were recorded for each tagged seedling: height (mm), recruit type (i.e. asexual or sexual), distance to nearest adult plant, number of stems, % greenness and evidence of mechanical damage and/or grazing.

Table 4. Details of tagged seedlings.

Survey site	Species	Number tagged	Dates surveyed
South Giddi Giddi	*Atalaya hemiglauca* (F. muell.) F.Muell. ex Benth (whitewood)	10	Sept 2011 Mar 2012
Talwood	*Eucalyptus coolabah*	11	Sept 2011 Nov 2011 Mar 2012
	Acacia stenophylla	10	Sept 2011 Nov 2011 Mar 2012
Kanowna	*Atalaya hemiglauca*	10	Sept 2011 Mar 2012
	Acacia stenophylla	10	Sept 2011 Mar 2012
Weribone	*Eucalyptus coolabah*	10	Sept 2011 Nov 2011

Data anlayses

Landscape-scale variation

Variation in hydrology and rainfall preceding vegetation surveys were investigated using data obtained from DERM, NOW and BOM. Much of this work was done as part of the aligned DERM project and is report in Woods et al. (2012) accompanying this report.

Spatial and temporal variation in the abundance and composition of seedlings was explored using field data from all available survey dates converted to counts of seedlings along each transect, square-root transformed to reflect patterns in dominance of each species and compared using the Bray-Curtis similarity measure.

Permutational Analysis of Variance (PERMANOVA; Anderson 2001) was used to test differences in seedling assemblages at a site level, with transects as replicates, using a three-factor mixed model design; Rivers (Fixed: Weir v Macintyre v Balonne), Sites (Random, Nested in "River") and Time (Fixed: September v November v March). Variance components of each level of the statistical test were examined to aid in interpretation of the relative importance of each factor and interaction term. Because significance levels (P values) are arbitrary without being based on power analysis, data were interpreted as significant at $P<0.1$ due to the high variation in the data (and hence limited ability to detect real changes). SIMPER analysis was used to identify species that were contributing to significant differences identified using PERMANOVA.

Stream flow data, floodplain inundation levels from rating curves (see Woods et al., 2012) and BOM rainfall data was then used to determine whether landscape-scale variation in seedling patterns related to inundation history or rainfall. Patterns in species abundances identified by SIMPER analysis as driving assemblage level variation in seedling composition were further investigate using univariate regression tree analysis (De'ath and Fabricius 2000) to determine how variation in environmental variables (i.e. time since overbank flooding, frequency of overbank flooding, total rainfall since last overbank inundation and rainfall in the month preceding sampling) were associated with patterns in the abundance of separate species (i.e. the summed number of recruiting seedlings of each species from each site and sampling time). Data were analysed using the RPART package in R v2.14 (R Core Development Team, 2011; Therneau and Atkinson, 2011).

Local-scale variation

Patterns in seedling assemblages at a local scale and identification of environmental variables influencing these were approached using multivariate regression trees using the MVPART package in R 2.14. Predictor variables used were percentage cover of leaf litter, shrubs, ground cover and bare ground, along with distance along the transect (0m: closest to river, 50m: furthest away), site name, river and month of sampling. Three response variables were used; the composition of sexually recruited seedlings, composition of asexually recruited seedlings, and the composition of all seedlings (i.e. total sexual and asexual seedlings for each species). Data from the November 2011 field trip were excluded from this analysis. Indicator species analysis (Dufrene and Legendre 1997) was used to identify species that were unique to each terminal group, using the LABDSV package in R (Robert 2010).

Partial least squares projection to latent structures (PLS) modelling was also used to examine the September 2011 field survey data and relate total seedling density and the density of *Muehlenbeckia florulenta*, *Acacia stenophyll* and *Eucalyptus coolabah* recruits (standardised to 100 m^2) to environmental predictor variables. PLS models were fitted using the pls package for R (Wehrens and Mevik 2009; R Development Core Team 2011) and the orthogonal scores algorithm.

Results

Here we present key results of the field study program with respect to the two major research objectives addressed by the project (above). A bibliography of relevant published references compiled during the literature review component of the project is provided as an appendix to this report (Appendix 1) as are the conceptaual models for the four key floodplain asset species and supporting literature review (Appendix 2).

Objective 1. Spatial and temporal patterns in floodplain vegetation regeneration

Overview of seedling assemblages

More than 800 seedlings were measured in transects over the three field trips representing at least nine tree and shrub species: *Muehlenbeckia florulenta* (tangled lignum), *Acacia stenophylla* (river cooba), *Eucalyptus coolabah* (coolibah), *Atalaya hemiglauca* (whitewood), *Eremophila bignoniiflora* (Benth.) F.Muell. (creek wilga), *Casuarina cunninghamiana* Miq. (river she-oak), *Acacia* spp., *Eucalyptus camaldulensis* (river red gum) and *Geijera parvilfora* Lindl. (wilga). *Acacia stenophylla* seedlings were the most frequently encountered species at all survey times, accounting for over half of the seedlings measured overall (Figure 2). *Muehlenbeckia florulenta* recruits were also frequently encountered. Seedlings of *Eremophila bignoniiflora, Casuarina cunninghamiana, Eucalyptus camaldulensis* and *Geijera parvilfora* were extremely rare and only observed in the final field survey (Figure 2). Species with seedlings present in low to moderate numbers included *Eucalyptus coolabah* and *Atalaya hemiglauca* (Figure 2).

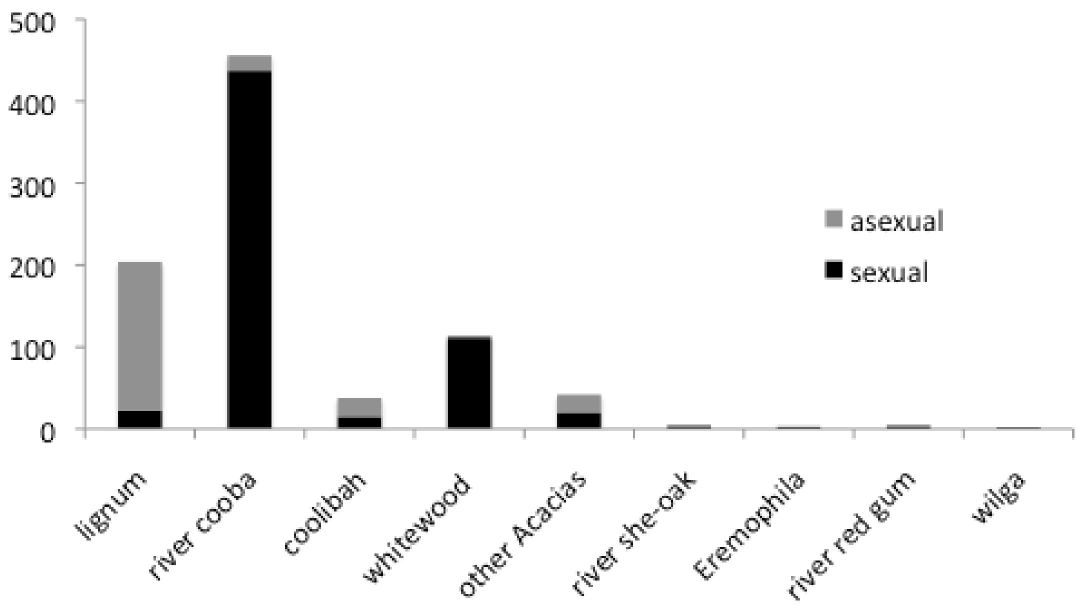

Figure 2. Total number of asexual and sexual recruits recorded in transects for each species across all field surveys.

Over 400 seedlings were recorded during the first field trip in September 2011 alone mainly consisting of the four most common species, i.e. *Muehlenbeckia florulenta, Acacia stenophylla*, *Atalya hemiglauca* and *Eucalyptus coolabah*. No seedlings of *Eucalyptus camaldulensis* were observed at this time at any of the selected sites. At this survey time, which was the sole trip on which all nine sites were able to be surveyed, *Acacia stenophylla* seedlings were observed at all sites and *Muehlenbeckia florulenta* seedlings at all sites except one (St George). Although *Eucalyptus coolabah* seedlings were relatively rare at this time, accounting for under 6% of all observed, they were widely distributed being recorded at six of the nine sites.

Sexual recruits were observed for all species and asexual recruits were also identified for five species but were only abundant amogst three (Figure 2). Asexual recruits of *Muehlenbeckia florulenta* included sprouting fragments and clones sprouting from arching stems as well as rhizomes and comprised almost 90% of all recruits recorded for this species. Asexual *Acacia stenophylla* recruits included suckers but accounted for just under 5% of seedlings recorded for this species. Resprouting individuals of *Eucalyptus coolabah* were also denoted asexual so that they could be distibutished from younger seedlings, and tended to be larger, both in terms of height and girth, than those of other species. These accounted for around 6% of all *E. coolabah* recruits recorded.

The distribution of heights amongst seedlings observed during the September 2011 field trip indicates that regeneration in the three selected species observed to be reruiting is likely to have been triggered by different processes (Figures 3, 4 and 5). Both *Eucalyptus coolabah* and *v*observed recruitment may have been triggered by a single event, although this event was probably different for each of the two species. The recruitment trigger for *Eucalyptus coolabah* was probably earlier than that for *Acacia stenophylla* since *Eucalyptus coolabah* recruits were considerably larger and no recruits less than 100 mm in height were observed (Figures 3 and 5). In contrast, the relatively consistent spread of heights observed amongst *Muehlenbeckia florulenta* recruits suggests that more sustained regeneration had occurred in this species over a continuous period prior to the first field survey (Figure 4).

Changes in the height distribution of seedlings over time also suggest different growth patterns amongst the selected species. For instance, the lack of taller *Acacia stenophylla* recruits observed during March 2012 suggests that many of the seedlings observed during Septeber 2011 are likely to have died and that the seedlings observed during the last field survey represent an additional, more recent germination event (Figure 3). This is supported by the results of the tagged seedling survey in which none of the smaller *Acacia stenophylla* seedlings tagged at Kanowna in Septebmer 2011 could be relocated in March 2012 suggesting mortality or removal by flood scour (Figure 6). In contrast, most of the larger *Acacia stenophylla* recruits tagged at Talwod exhibited substantial gains in height over the same period (Figure 6).

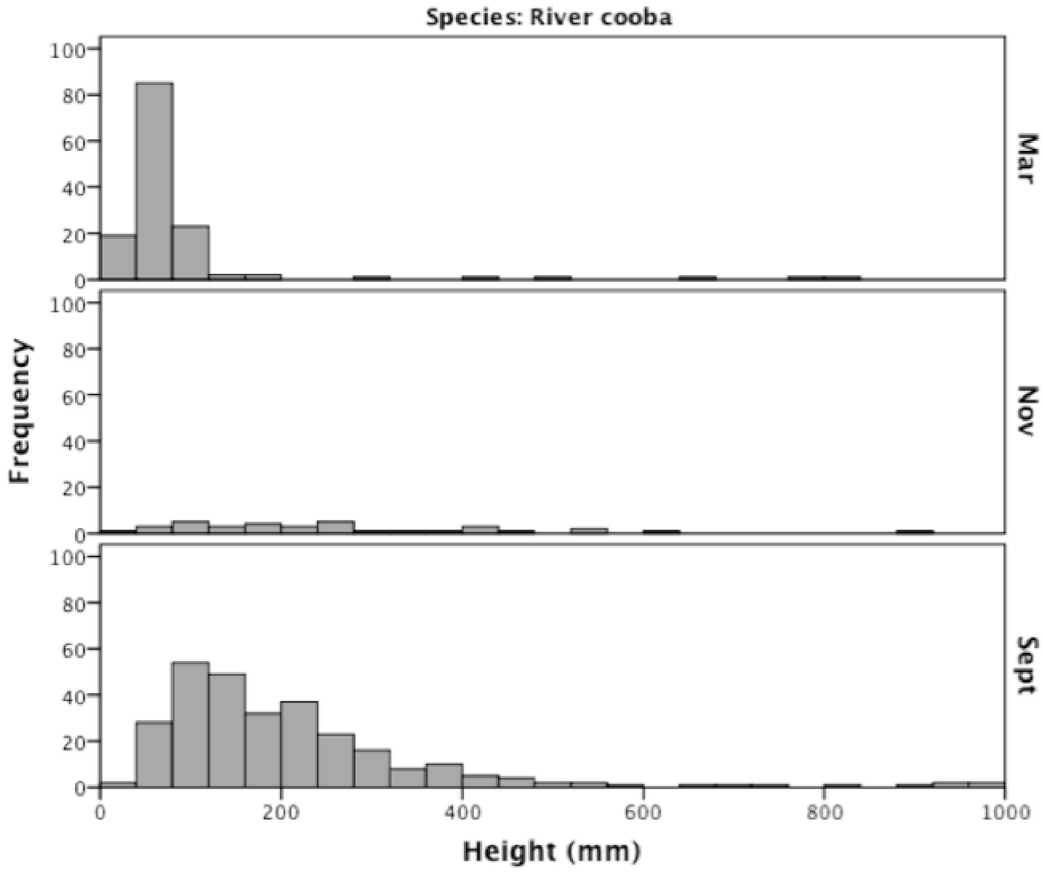

Figure 3. Histograms illustrating the distribution of heights (mm) of *Acacia stenophylla* recruits recorded on transects during each field trip. (N.B. Most recent survey date shown at top).

Tagged *Eucalyptus coolabah* recruits at Talwood displayed a mixed response in terms of height over the study period with some gains and some losses observed, the latter perhaps in response to flooding stress (Figure 7). Increased height was recorded amongst all except one tagged *Atalaya hemiglauca* seedling over the study period although growth rates in these species appear to be somewhat slower than amongst surviving tagged *Acacia stenophylla* seedlings (Figures 6 and 8).

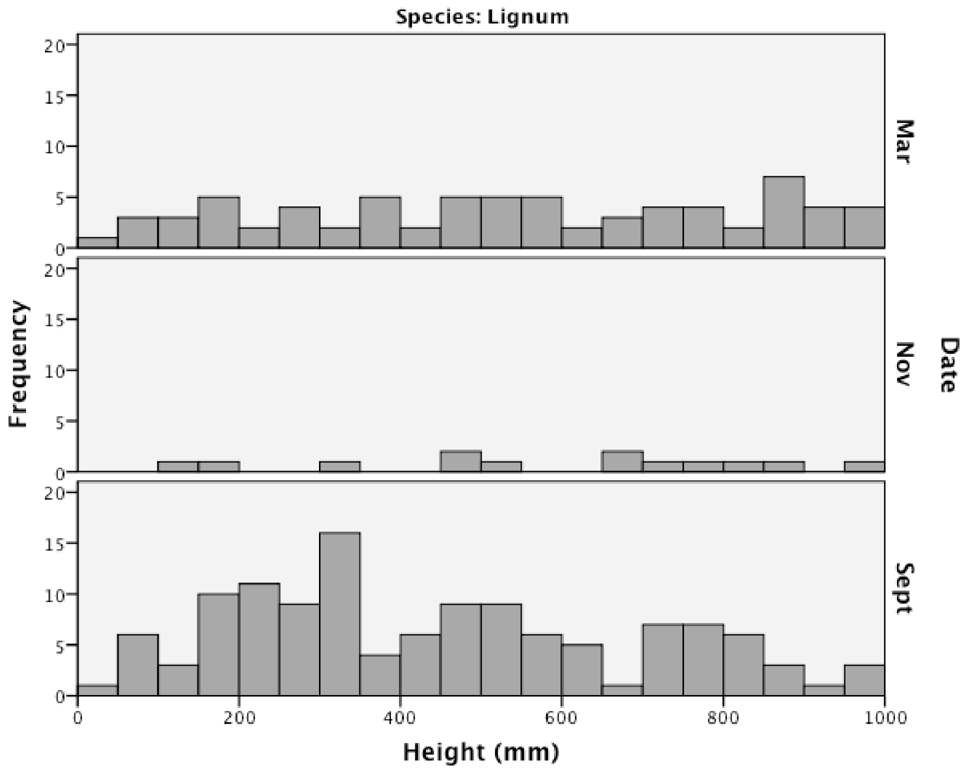

Figure 4. Histograms illustrating the distribution of heights (mm) of *Muehlenbeckia florulenta* recruits recorded on transects during each field trip. (N.B. Most recent survey date shown at top).

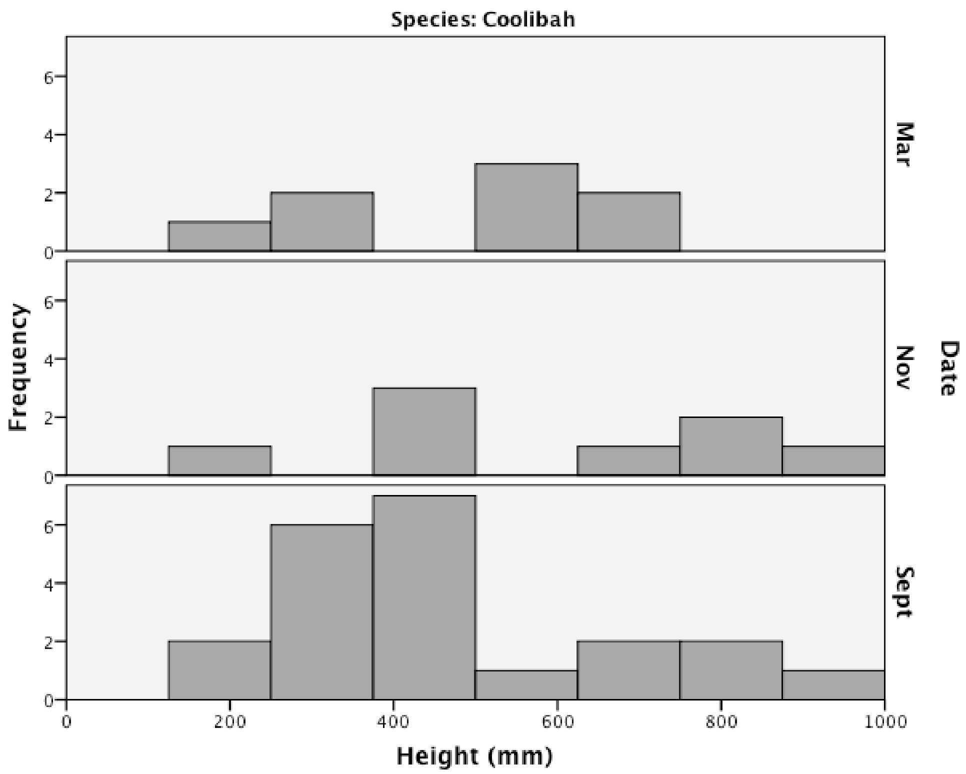

Figure 5. Histograms illustrating the distribution of heights (mm) of *Eucalyptus coolabah* recruits recorded on transects during each field trip. (N.B. Most recent survey date shown at top

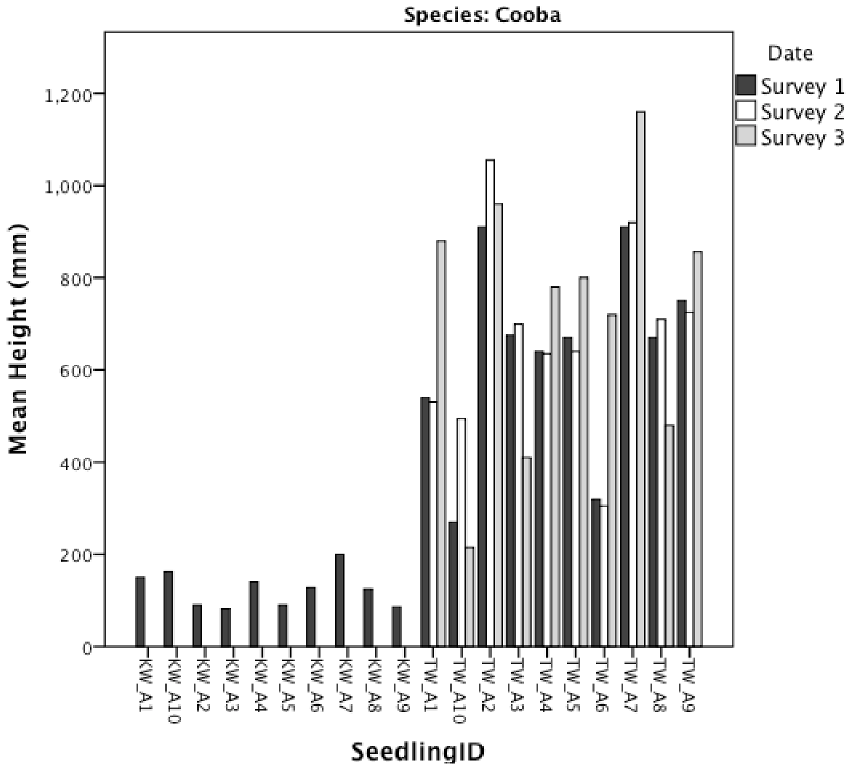

Figure 6. Height of individual taagged seedlings of *Acacia stenophylla* at each survey date. KW and TW indicates seedlings tagged at Kanowna and Talwood respectively

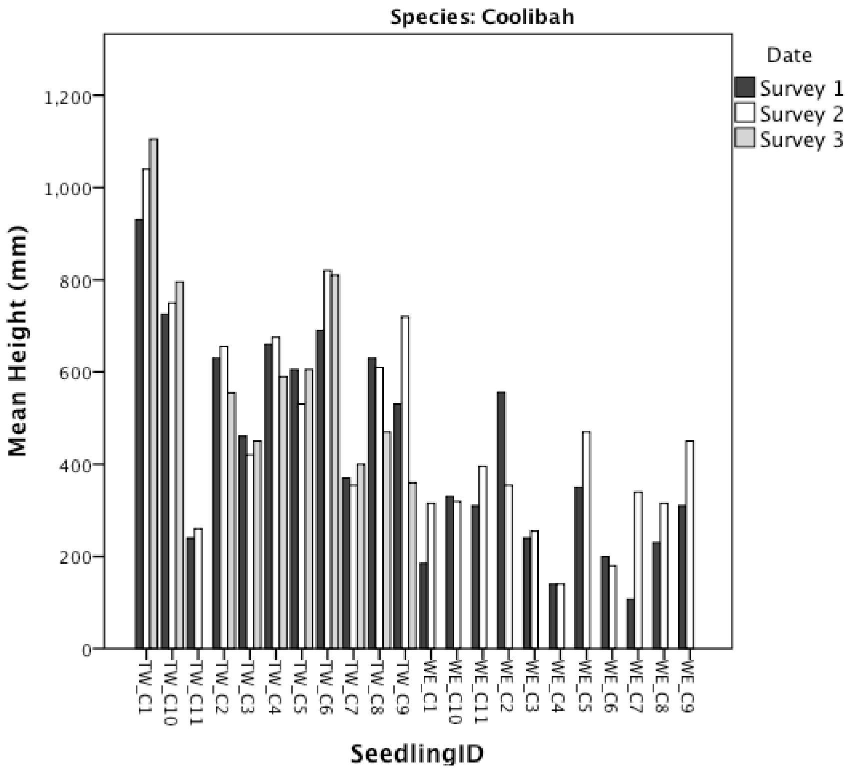

Figure 7. Height of individual taagged seedlings of *Eucalyptus coolabah* at each survey date. WE and TW indicates seedlings tagged Talwood and Weribone respectively.

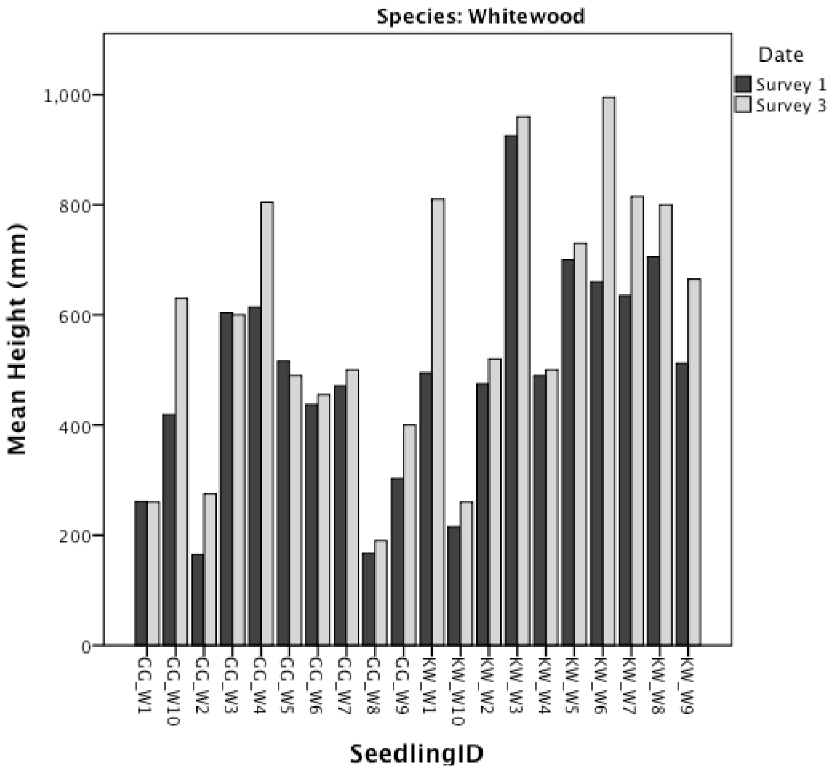

Figure 8. Height of individual taagged seedlings of *Atalaya hemiglauca* at each survey date. KW and GG indicates seedlings tagged at Kanowna and South Giddi Giddi respectively.

Landscape-scale variation in seedling assemblages

Large and significant differences in the abundance and composition of seedlings at the site scale were apparent between the three river catchments (i.e. Balonne, Weir and MacIntyre; Figure 9). The abundance and composition of seedling assemblages broadly differentiated between rivers in the MDS plot along a rough longitudinal gradient (Figure 9). This pattern was largely driven by variation in the abudance of *Acacia stenophylla* seedlings (Table 6). Sites also exhibited significant differences within each river catchment (Table 5) indicating that local-scale geographic, climatic, hydrologic and local variables are likely to have contributed to variation in seedling assemblages.

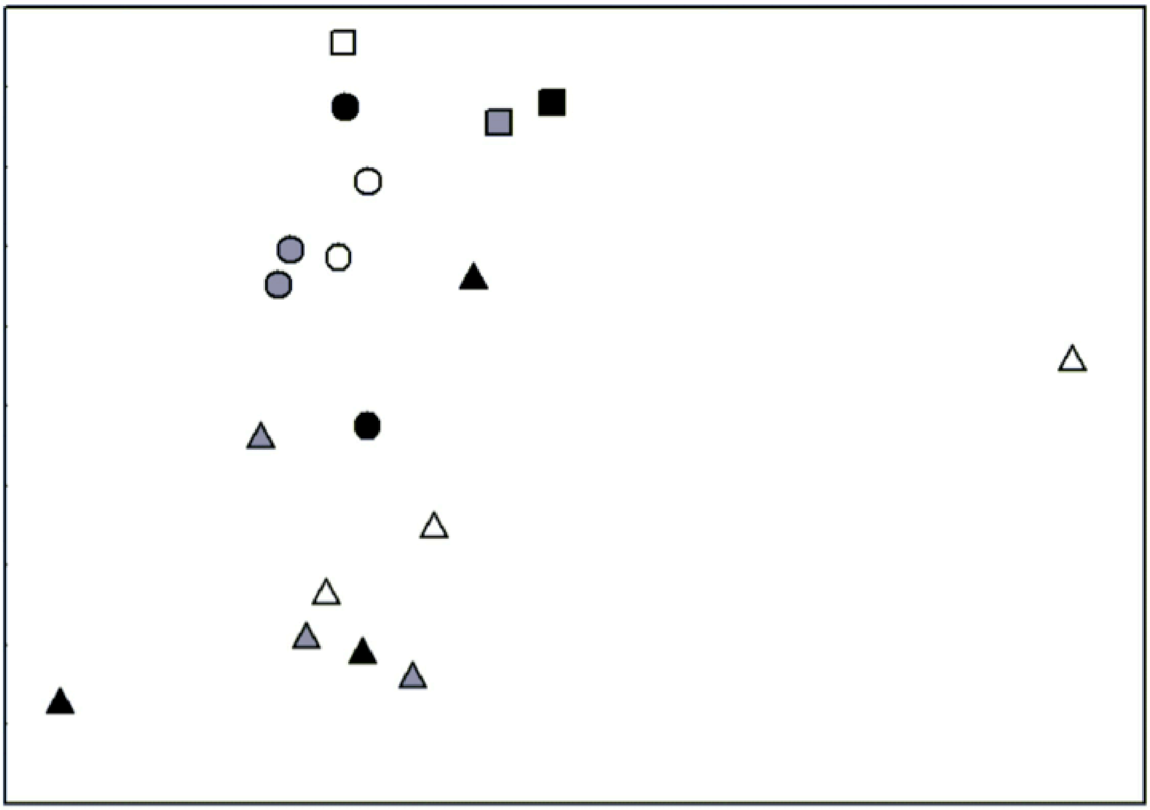

Figure 9. Two-dimensional MDS plot indicating variation in composition of recorded seedlings in survey sites across three rivers (Balonne: Squares, Macintyre: Circles, Weir: Triangles) over the survey period (September 2011: White, November 2011: Grey, March 2012: Black). Stress: 0.14.

Table 5. PERMANOVA results identifying patterns in the composition of recorded seedlings.

Source	Df	MS	F	P	VC
River	2	14342	2.66	0.075	22.5
Time	2	610.09	0.33	0.878	0.0
Site(River)	3	7182.8	4.99	0.001	20.8
River x Time	4	653.4	0.317	0.959	0.0
Site(River) x Time	6	2341.1	1.63	0.077	9.8
Error	30	1437.7			46.8

Table 6. Mean abundance (square-root) of species contributing to significant variation among the Weir, Macintyre and Balonne Rivers.

Species	Weir River	Macintyre River	Balonne River
Mean similarity (within river)	31.57	62.05	72.75
Cooba	0.72	3.54	7.56
Lignum	1.06	1.72	1.05
Coolibah	0.72	0.53	0
Whitewood	0.9	0	0
Acacia spp.	0.25	0.5	0

The abundance of seedlings varied substantially both between and within sites and over survey times (Figure 10). Species richness was quite even spatially and temporally due to the dominance and wide distribution of the commonly observed recruiting species (Figure 11). Kanowna had both the highest number of seedlings and most recruiting species observed during the survey period.

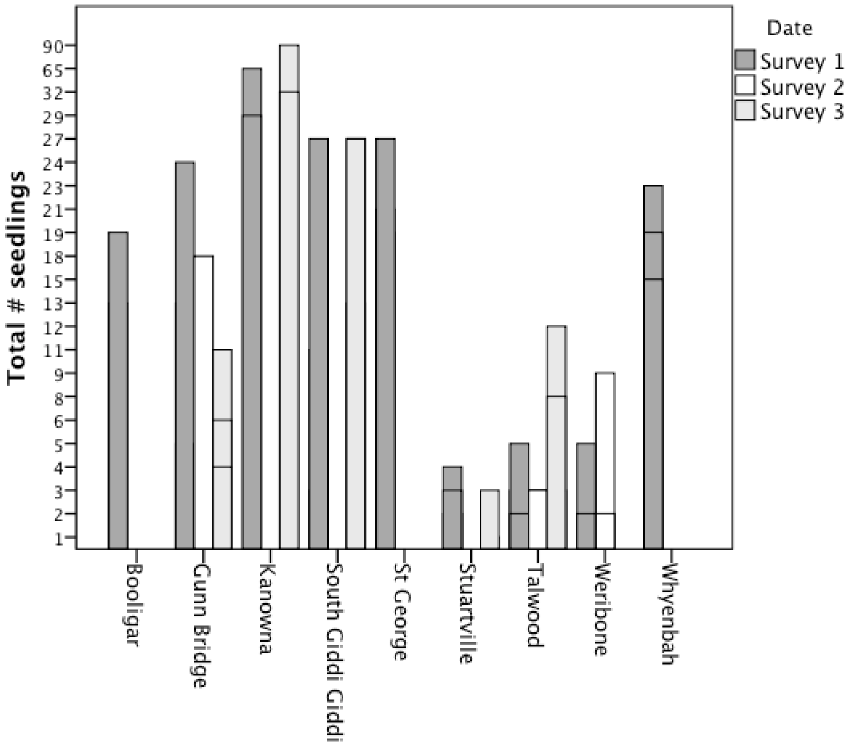

Figure 10. Total abundance of seedlings recorded at each site at each survey date. Lines in bars distribution of seedlings numbers across transects at each time. N.B. The only sites surveyed during November 2011 were Talwood, Stuartville and South Giddi Giddi.

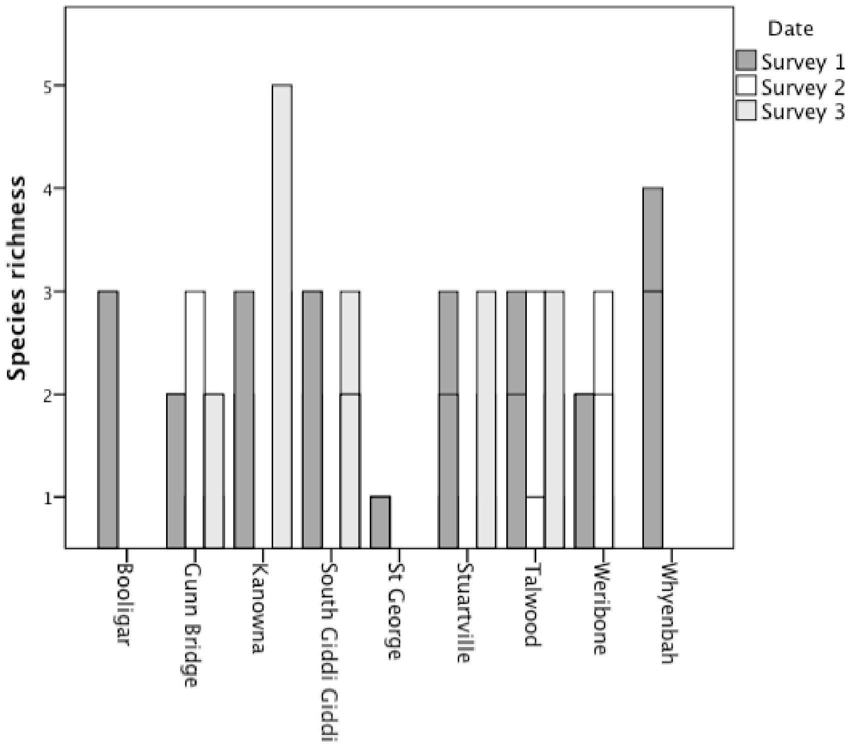

Figure 11. Total number of species of seedlings recorded at each site at each survey date. Lines in bars distribution of seedlings numbers across transects at each time. N.B. The only sites surveyed during November 2011 were Talwood, Stuartville and South Giddi Giddi.

Objective 2. Environmental factors influencing floodplain vegetation regeneration

Landscape-scale variation between sites

Analyses of hydrologic and rainfall data obtained for survey sites indicated that all sites experienced overbank flooding to some degree during the summer preceding the first field survey (i.e. 2010 to 2011). At most sites, annual discharge in 2010 and 2011 was around two to three times greater than the long-term average (i.e. calculated between 1967 and 2011; Figure 12). Prior to this, flow records indicate that there was a relatively prolonged period of low flow between 2000 and 2009 (Figure 12). Time since last floodplain inundation was also calculated for all sites and exceeded 221 days in all cases except St George on the Balonne River which had experienced high flows during autumn (Table 7). Rainfall at BOM stations near survey sites in the months preceding the first vegetation survey are given in Table 8. Rainfall was lowest near the Booligar site and highest near Kanowna and Stuartville sites.

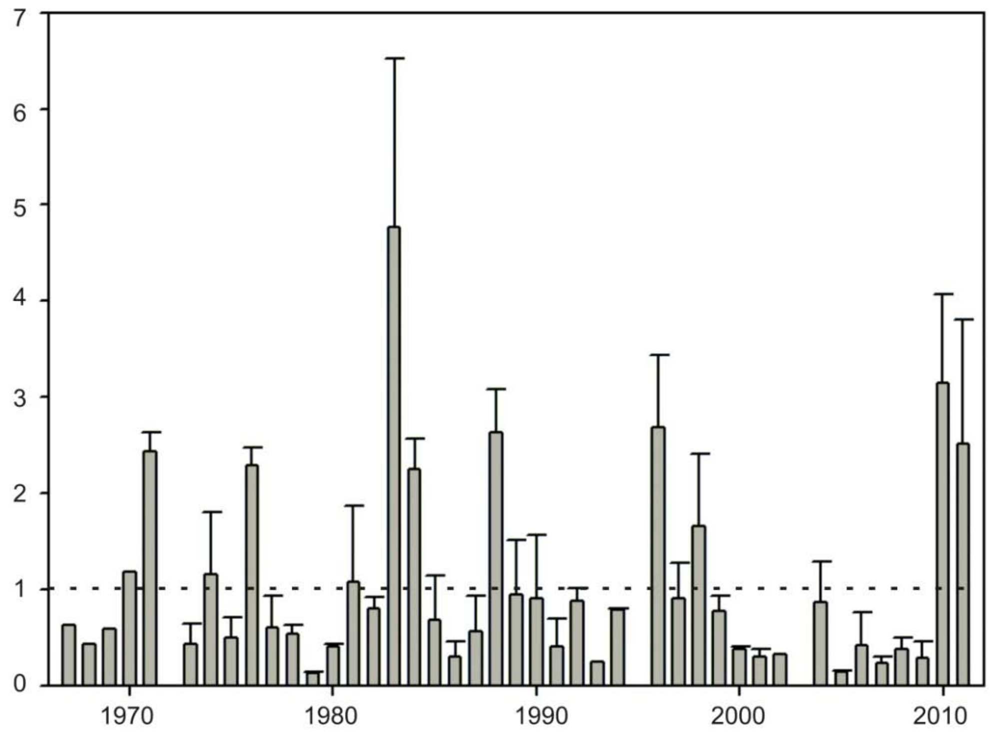

Figure 12. Standardised mean (+SD) annual discharge in the Weir, Macintyre and Balonne River 1967-2011. Data for each site are standardised to the mean discharge for each of five gauges throughout the study region from 1967-2011. A value of 1 indicates that annual discharge was average. >1 indicates above average and <1 indicates lower mean annual discharge. Gaps in the plot occur when no complete annual data was available.

Table 7. Days since floodplain inundation at field survey sites prior to first survey.

Survey site	Days since floodplain inundation prior to first field survey
Gunn Bridge	244
Giddi Giddi South	238
Talwood	231
Weribone	240
St George	146
Whyenbah Bridge	230
Booligar	228
Stuartville	221
Kanowna	222

Table 8. Monthly rainfall at BOM stations near field survey sites preceding the first survey.

Site	Station	June Total Rainfall (ml)	July Total Rainfall (ml)	August Total Rainfall (ml)
Weribone	Weribone TM	10	20	33
St George	St George Airport	22	19	25
Whyenbah	Whyenbah	20	19	28
Booligar	Angledool	19	14	9
Talwood	Talwood State School	13	21	23
Giddi Giddi South, Gunn Bridge	Giddi Giddi South	10	20	33
Kanowna, Stuartville	Boomi (Barwon St)	10	25	43

There was some variation in the composition of riparian canopy cover between sites although species dominating canopy cover across most sites included river red gum, coolibah and river cooba (Table 9). Whitewood (*Atalaya hemiglauca*) also occurred relatively frequently in the canopy at these sites. Seeds of woody species were recorded during the September 2011 field trip at all sites, both in the canopy and on the soil surface (Table 10). *Eucalyptus camaldulensis* seeds were present at six of the nine sites, *E. coolabah* at all but one (Whyenbah) and *Acacia stenophylla* at all sites (Table 10). The site with the greatest richness of observed seeds was Kanowna.

Table 9. Woody riparian canopy cover present at each of the field survey sites.

Site	River red gum	Coolibah	River cooba	*Acacia* spp.	*Eremo-phila* spp.	*Melaleuca* spp.	White-wood	River she-oak
Gunn Bridge	X	X	X	X			X	
Talwood	X		X					X
Giddi Giddi	X	X	X	X	X		X	
Weribone	X	X	X			X		
St George	X	X		X				X
Whyenbah	X		X	X	X		X	
Booligar		X	X					
Stuartville		X	X				X	
Kanowna	X		X		X	X	X	X

Table 10. Seeds present in the canopy and on the ground at each of the field survey sites in September 2011.

Site	River red gum		Coolibah		River cooba		*Eremo-phila* spp.		*Melaleuca* spp.		White-wood		River she-oak	
	Canopy	Ground	Canopy	Ground	Canopy	Ground	Canopy	Ground	Canopy	Ground	Canopy	Ground	Canopy	Ground
Gunn Bridge		X		X		X								
Talwood			X	X	X									
Giddi Giddi	X	X	X	X	X	X								
Weribone	X	X	X	X	X	X			X	X				
St George	X		X	X										
Whyenbah	X	X			X	X	X	X			X			
Booligar			X	X	X	X		X						
Stuartville			X	X	X	X								
Kanowna	X	X		X	X	X	X	X	X	X			X	X

Factors driving landscape-scale variation in seedling assemblages

Since landscape-scale variation in seedling assemblages detected between rivers were driven by patterns of *Acacia stenophylla* seedling abundance (see Table 6), we investigated relationships between this pattern and a range of hydrological and rainfall factors. The maximum mean abundance of *Acacia stenophylla* seedlings occurred at three sites where the frequency of overbank flooding was relatively low, i.e. < 3.6 times in 10 years (Figure 13). In the remaining sites, i.e. those that flood more than 3.6 times in 10 years, a secondary split in *Acacia stenophylla* seedling abundance was identified at 10.1 inundation events in every 10 years. Sites that experience intermediate frequencies of flooding (ie. <10.1 but > 3.6) had the lowest mean abundances of *Acacia stenophylla* seedlings (0.66) compared with sites with the greatest inundation frequencies (Figure 3).

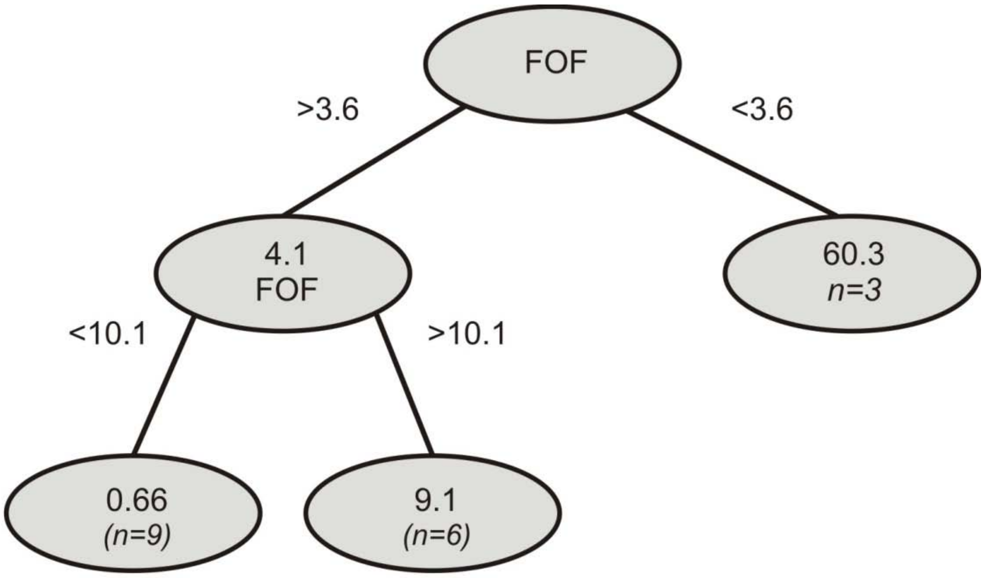

Figure 13. Regression tree plot indicating shifts in the abundance (summed counts from three transects per site) of *Acacia stenophylla* associated with variation in environmental predictor variables. The model explained 78.4% of the variance in the data. FOF: Mean frequency of overbank flooding over a 10 year period.

Factors driving site-scale variation in seedling assemblages

At a local scale, the abundance and composition of both asexual and sexual recruit assemblages varied in relation to site (Figure 14). Multivariate regression tree analysis for the entire data set (i.e. all sites and survey times) identified two groups of asexual recruit assemblages, one dominated by *Muehlenbeckia florulenta* and one dominated by *Acacia stenophylla*. The first assemblage type dominated Booligar, Giddi Giddi, Kanowna, Talwood and Stuartville while the latter was predominant at Gunn Bridge, Whyenbah and Weribone. With respect to sexual recruit asseblages, two primary groups were identified (Figure 14). The first, dominated by *Atalaya hemiglauca* seedlings, distinguished Giddi Giddi, Kanowna and Stuartville. A secondary split was evident in the other group distinguishing between sites dominated by other *Acacia* spp. seedlings, i.e. Gunn Bridge and Whyenbah, and those with *Eucalyptus coolabah, Eremophila* spp. and *Muehlenbeckia florulenta* seedlings, i.e. Talwood and Weribone (Figure 14). The latter sites also fell into separate groups in this analysis (Figure 14).

Aside from these site scale differences, no significant relationships between measured and calculated local-scale environmental variables and seedling assemblages were detected. Such absence of fine-scale spatial structuring may indicate that variation in the composition of recruiting seedlings is driven primarily by large-scale environmental variation, possibly large-scale variation in flooding extent and frequency.

PLS models calculated for the September 2011 field data detected two hydrological variables influencing the total density of recurits as well as the density of *Acacia stenophylla* and *Eucalytus coolabah* recruits, but none for *Muehlenbeckia florulenta* (Table 11). A negative relationships between the number of days since inundation and total recruit density was found (Table 11). The duration of the last inundatoin event (i.e. Time.Start.End; Table 11) was positively related to *Acacia stenophylla* density but negatively related to *Eucalyptus coolabah* density. The % cover of groundcover was also positively associated with *Acacia stenophylla* recruit density (Table 11).

Table 11. Unstandardised regression coefficients for PLS models calculated for recruit density (recruits per 100 m^2) and environmental variables. Significance: * P<0.05; ** P<0.01. Only significant coefficients shown.

Environmental variable	Total recruit density	Lignum density	Cooba density	Coolibah density
Days.Since.Inund	-0.024 ± 0.009*	---	---	---
Time.Start.End	---	---	0.177 ± 0.041**	-0.017 ± 0.007*
Ground.cov	---	---	0.027 ± 0.007**	---

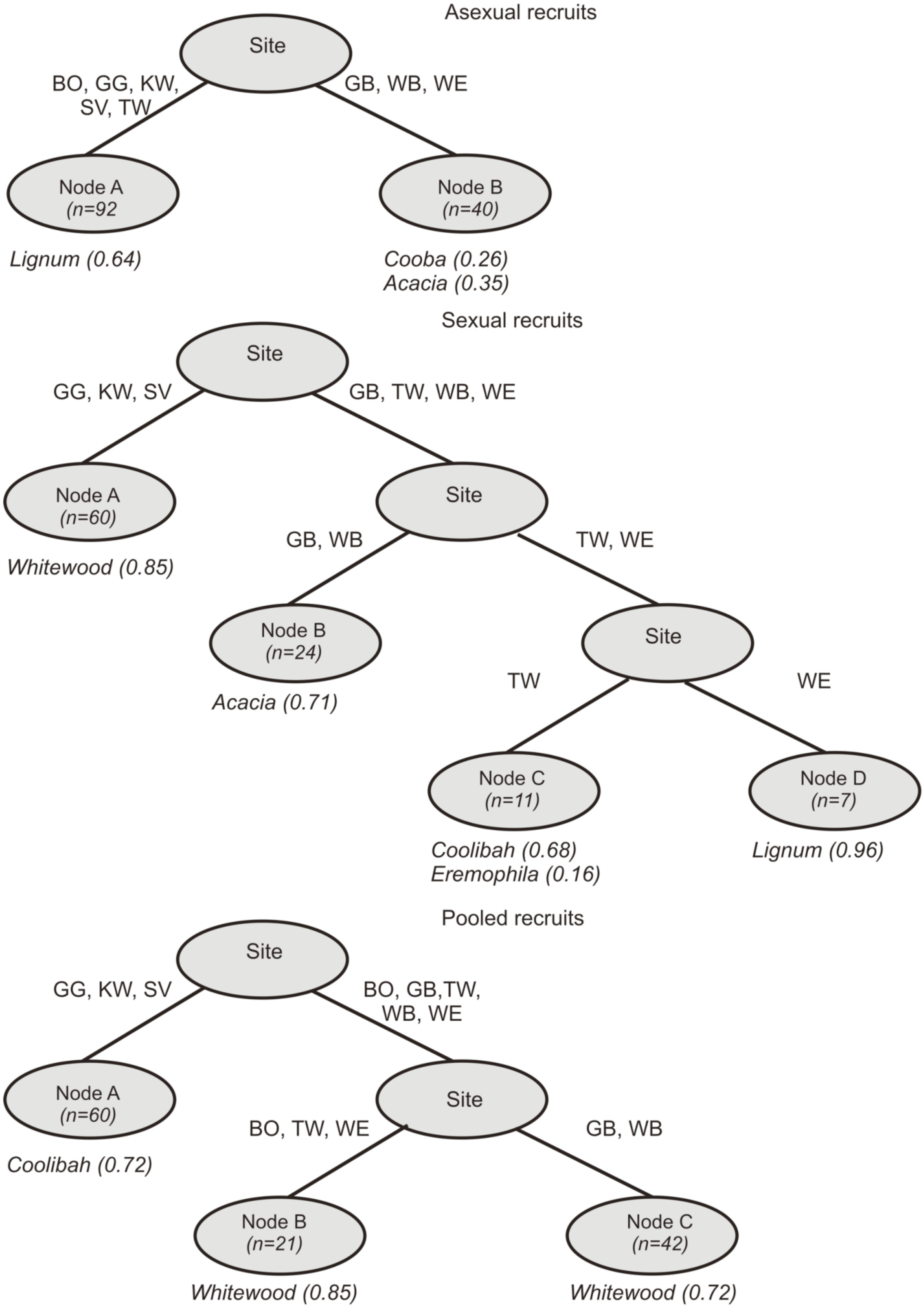
Asexual recruits
Site
BO, GG, KW, SV, TW
GB, WB, WE
Node A
(n=92
Lignum (0.64)
Node B
(n=40)
Cooba (0.26)
Acacia (0.35)
Sexual recruits
Site
GG, KW, SV
GB, TW, WB, WE
Node A
(n=60)
Whitewood (0.85)
Site
GB, WB
TW, WE
Node B
(n=24)
Acacia (0.71)
Site
TW
WE
Node C
(n=11)
Coolibah (0.68)
Eremophila (0.16)
Node D
(n=7)
Lignum (0.96)
Pooled recruits
Site
GG, KW, SV
BO, GB,TW, WB, WE
Node A
(n=60)
Coolibah (0.72)
Site
BO, TW, WE
GB, WB
Node B
(n=21)
Whitewood (0.85)
Node C
(n=42)
Whitewood (0.72)

Figure 14. Multivariate regression trees describing relationships between the composition of asexual recruits (16% variance explained), sexual recruits (57% variance explained) and all recruiting seedlings (54% variance explained) in the northern MDB in September 2011-February 2012. Species discriminating between terminal groups identified by indicator species analysis are presented, including their indicator value.

Outcomes

The planned scientific outcomes for this project, as stated in the project application were:

- greater understanding of dispersal and regeration mechanisms in floodplain vegetation species;
- improved understanding of the role of large flood events in floodplain vegetation dynamics; and
- greater understanding of floodplain vegetation resilience and likely response to future climatic and hydrological conditions.

The main management outcome expected from this project, as stated in the project application was:

- improved information for the establishment and review of environmental flow provisions for the mainteance of floodplain vegetation and wetlands.

This project has achieved these scientific outcomes by providing information about very poorly known species and processes, particularly with respect to the study area. Although this study did not detect a large recruitment event amongst riparian eucalypts in response to flooding, as was initially expected, this finding is interesting in itself since our results indicate that regeneration of these significant species is far more patchy and limited than might be assumed. In particular, this project has demonstrated that large flood events do not necessarily trigger recruitment amongst dominant riparian species in these habitats and that conditions for successful germination and seedling establishment therefore entail more specific requirements than simply the occurrence of inundation. These conditions may involve particular flooding attributes, e.g. flood timing, duration, rate of fall, etc., or relate to weather, e.g. rainfall and temperature following flooding, or other aspects, e.g. absence of herbivory.

Overall, our results indicate that long-term and large-scale monitoring of recruitment is necessary to adequately determine flow provisions for the maintenance of floodplain vegetation in the study region. The extreme patchiness in the distribution of seedlings highlighted by our results suggests that such a research program would be best served initially by covering a broader area than was achieved here with but less effort allocated at a site scale. Given the significance of landscape-scale factors to recruitment processes detected in this study, an appropriate future field study program might aim to identify critical drivers of these patterns over a larger area and with a greater number and diversity of sites. Examining spatial patterns in recruitment at sites related to stream gauging stations across the northern Murray-Darling Basin, for instance, would be an excellent next step towards better understanding hyrologic influences on vegetation regeneration in these habitats.

Conclusion

It is widely assumed that large flood events trigger recruitment of key tree and shrub species of riparian and floodplain habitats in arid and semi-arid catchments of inland Australia (e.g. Roberts and Marston, 2011). This project has demonstrated that whilst flooding may be such a requirement for seedling germination and establishment in many species, not all floods will result in a significant regeneration response amongst all species. Consequently, our findings indicate that regeneration of important riparian eucalypts in these habitats, i.e. river red gum and coolibah, is likely to occur in response to a much more specific suite of conditions that may include particular flood characteristics (i.e. depth, duration, timing etc.) and/or other criteria such as weather before, during and following flooding.

The results of this study also indicate that seedling establishment in riparian habitats of the study region is extremely patchy spatially with some sites supporting relatively dense regeneration of numerous tree and shrub species and other sites only having few seedlings present. Evidence of ongoing recruiment may therefore be useful in prioritising investment in riparian restoration activities, e.g. fencing.

Overall, our findings imply that an understanding of riparian and floodplain tree and shrub regeneration sufficient to ensure appropriate water resources management in these catchments for the maintenance of vegetation diversity and dynamics, requires long-term monitoring over a large spatial scale. We recommend that such monitoring should include a greater number and diversity of riparian sites than included here but with less effort in sampling at each. These sites should ideally be associated with stream gauging stations across the region so that hydrological influences on patterns of seedling establishment can be determined.

Extension Opportunities

The dissemination and uptake of this project's findings will best be achieved by publication of its results in the peer-reviewed scientific literature. As detailed below, at least two manuscripts are in preparation and expected to be ready for submission to journals by the end of June 2012. On publication, these papers will be widely disseminated to the project's partners and other interested organisations, e.g. the Murray-Darling Basin Authority. Presentation of this project's results at this year's Australian Society for Limnology conference (see below), will also reach a wide variety of researchers and managers for whom our findings are likely to be of interest.

Publications

<u>Peer reviewed articles / books</u>

Two draft manuscripts are in preparation based on the results of this project and are intended to be ready for submission to peer-reviewed international journals by the end of June 2012 . The first article presents the results of the literature review and will be entitled "Regeneration strategies of arid and semi-arid floodplain trees and shrubs: constraints and strategies". The second paper presents the results of the field study.

<u>Non-peered reviewed articles / books</u>

Five chapters were contributed to the final report for the aligned DERM project *Riverine and floodplain ecosystem responses to flooding in the lower Balonne and Border Rivers* accompanying this report (Woods et al., 2012). These chapters presented the conceptual models for the regeneration of key species and supporting literature review as well as methods and results of field surveys from September and November 2011.

An article based on the preliminary findings of this project was also submitted for the Cotton CRC's *Cotton Water Story* document in preparation by Jane MacFarlane in early April 2012.

<u>Presentations (conference, field days, workshops etc)</u>

It is anticipated that results from this project will be presented at the 2012 Australian Society for Limnology conference to be held in Armidale in November.

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Part 4 – Final Report Executive Summary

The project, *Regeneration of floodplain vegetation in response to large-scale flooding in the Condamine-Balonne and Border* Rivers, was a collaboration between the Cotton CRC, QLD DERM, NSW Office of Water and the Australian Rivers Institute of Griffith University. The aims of the project were to i) describe spatial and temporal patterns in the regeneration of major riparian tree and shrub species in the Condamine-Balonne and Border Rivers following the major floods of early 2011 and ii) identify key factors, particularly hydrological, influencing these patterns.

The project comprised two major components: i) a literature review and associated development of conceptual models for key riparian tree and shrub species of Australian arid and semi-arid catchments and ii) a field study program. The field study program involved surveying up to twenty-five 50m long transects across nine sites along the Weir, MacIntyre and Balonne rivers on three occasions: September and November 2011 and March 2012. Prior to the first survey all sites received significant overbank flows preceded by an extended period of drought (c. 10 yrs). Further flooding also occurred during the study period prohibiting repeated surveys at several sites. During each survey, all woody seedlings (< 1 m) present in transects were recorded and measured. Relevant environmental characteristics were also measured (e.g. soil characteristics, canopy cover, elevation etc.) and the composition of the canopy and presence of seeds recorded. Additionally, a further 70 seedlings across four sites, including *Eucalyptus coolabah* (coolibah), *Acacia stenophylla* (river cooba) and *Atalaya hemiglauca* (whitewood) were tagged and measured to monitor survival and growth during the study period.

Seedling establishment was found to be sparse and spatially patchy. Over half of seedlings recorded during each trip were *Acacia stenophylla* seedlings and these were present at all sites. *Muehlenbeckia florulenta* (lignum) seedlings were also relatively common and widely distributed. *Eucalyptus coolabah* seedlings were comparatively rare but were present at six of the nine sites. *Atalaya hemiglauca* (whitewood) seedlings were also encountered relatively frequently. Only two *Eucalyptus camaldulensis* (river red gum) seedlings were observed in the entire field study. The range of seedling sizes present at each time suggest that the *Acacia stenophylla* seedlings observed represented single germination events on each occasion with the tagged seedling study also suggesting limited survival of small seedlings between September and March. *Eucalyptus coolabah* seedling sizes were also indicative of a single, but considerably earlier, establishment event. In contrast, *Muehlenbeckia florulenta* appears to be recruiting continuously in these habitats. Larger tagged *Acacia stenophylla* seedlings exhibited rapid growth over the survey period while *Atalaya hemiglauca* displayed slower growth and *Eucalyptus coolabah* seedlings showed a mixed growth response.

Significant variation in the composition and density of seedling assemblages was detected between the major river catchments, driven by the abundance of *Acacia stenophylla* seedlings, with strong variation at the site-scale also apparent. For the September 2011 observations, total seedling density was negatively related to the time since inundation and the duration of the last flood event positively related to *Acacia stenophylla* seedling density and negatively related to *Eucalyptus coolabah* density.

The results of this project indicate that large floods do not necessarily trigger major recruitment events amongst key riparian tree and shrub species in this region. Recruitment of key species (e.g. *Eucalyptus camaldulensis* and *E. coolabah*) does not appear to be limited by seed availability as seeds were observed in the canopy and on the soil surface at all sites.

Consequently, germination and seedling establishment in these species are likely to require floods with particular attributes (e.g. duration, timing etc.) possibly in combination with a suite of other conditions (e.g. rainfall, temperature). Understanding vegetation regeneration in these significant habitats to better inform water resources management will depend on the establishment of a well-designed long-tem monitoring program that captures recruitment patterns over a large and diverse array of sites.

Appendix 1. Bibliography of references pertaining to the regernation of Australia's inland floodplain trees and shrubs

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Appendix 2. Conceptual models

Here, we provide conceptual models developed during this project for four selected tree and shrub species common to the study region illustrating relationships between flow regime attributes and plant life history stages. For each species, a table giving a summary of life history requirements best on the literature review is also provided.

Table A2.1 Summary table of relationships between life history stages of *Eucalyptus camaldulensis* (river red gum) and flow regime attributes.

Attribute	Comments
Description & Habitat	• A large, long-lived tree to a height of 45 m, more commonly to 20 m. Height may be related to flood frequency and duration [2]. This species is widely distributed in semi-arid regions of Australia, in riparian zones and on floodplains, in areas subjected to frequent or periodic flooding [5,6]. • It forms forests in frequently flooded areas, and occurs as a riparian fringe or woodland in more arid areas [2,?].
Reproduction and Dispersal	• Flowers late spring to summer [2, 5], but flowering times and intensity can be variable [6]. Seed production may be high [6]. • Flowering occurs every two years [7]. • Seed fall occurs nine months after flowering, with maximum seed fall in spring [2]. • Seed production dependent upon health of the parent tree [7]. • Healthy trees may be able to adjust the timing of seed fall in response to environmental conditions such as rainfall [7]. • Seeds held in aerial seed banks [7]. • Seeds can float for up to 36 hours and hence may be deposited many kilometres from the parent tree [Dexter 1970, in 10]. • Seed viability is high for Eucalypts, 620 000 viable seeds per kg has been recorded [10].
Germination and Establishment of Seedlings	• Seedling establishment (particularly survival to the next summer) is the key stage in stand regeneration [2]. Access to subterranean moisture via taproot extension important [10]. • Flooding is not required for germination if winter is wet but germination and establishment is enhanced if suitable flooding conditions occur [2,8]. • Seedling densities can be very high after flooding. Seedling density can be sufficiently high to form “impenetrable thickets” [6]. • Flooding followed by a mild summer is necessary for survival of seedlings – competition from grasses for water has been documented as a significant cause of seedling mortality [11]. • Ideal hydrologic condition for seedling establishment is floodwater recession during spring-early summer [2]. • Seedlings are susceptible to heat stress and immersion [2]. Heat stress is overcome by allocating resources to root elongation and shedding leaves, with recovery from axillary buds [2]. • Seedlings will tolerate brief inundation only, but tolerance to inundation increases with seedling age [2]. • Seedlings can survive soil anoxia resulting from immersion by adventitious roots and development of aerenchymatous tissue [2,8].
Maintenance and Survival	• Maintenance and survival is strongly dependent upon the availability of water. • River red gum is an opportunistic water user – transpiration will occur at the maximum rate until moisture is unavailable [4]. • Floodwaters, streamwater, groundwater and rainfall are the key water sources of water for River Red Gums [2]. The relative importance of each source may vary through time and with the location of trees on the floodplain [2]. • Crown condition closely linked with hydrologic regime [3]. • Crowns become denser and turn dark green in colour during flooding. Leaves are shed during flood recession. Crowns thin substantially during drought. Moisture-stressed trees may have yellow-green leaves [11]. • River Red Gum forests can survive for long periods without inundation but the growing season may be reduced [11].

	• Requires periodic inundation (3-5 years) for a duration of up to 64 days to be in moderate to good condition on the lower Murrumbidgee floodplain [3]. • Will shed leaves to reduce water stress [2]. • Published water requirements [1] suggest an ideal flood frequency of 1-3 years, flood duration of 2-8 months, an inter-flood dry period of 5-15 months (maximum of 36-48 months), depending on whether trees can access permanent water. River Red Gum forests may also have higher water requirements than river red Gum woodlands. • Can tolerate continuous flooding for up to 2 years and survive without surface flooding for at least 18 months [2].
Summary of Critical Links to Flow	• **Flowering:** No specific hydrologic requirements for flowering, but flowering enhanced by flooding, especially after a dry period. Trees that are continuously wet do not flower as well as trees subjected to dry-wet phases [Biggs and Maher, in 2]. Seed production is associated with the health of the parent tree, which is in turn associated with moisture availability. • **Germination and establishment**: Flooding is not essential for germination but suitable flooding conditions enhance germination. Flood recession during spring-summer is ideal for prolific germination. • **Maintenance**: Requires periodic inundation (3-5 years) for a duration of up to 64 days to be in moderate to good condition on lower Murrumbidgee floodplain [3]. Flood frequency and duration are known to be important for growth [2]. Does not tolerate permanent inundation (i.e. inundation of 3 years or more, but can die after 18 months inundation) [9].
Other Comments	• This species has a high growth rate, and can reach a height of 12-15 m within several years [6]. • Saplings are not often grazed by stock, except if other foliage is unavailable [6]. • Forms a straight trunk in frequently flooded areas, and a gnarled trunk in arid areas [6]. • Occurs on sandy and heavy clay soils [6]. • Access to groundwater important in absence of other water sources during extended dry periods. Leaf shedding is an important mechanism to reduce transpiration losses [2]. • Tolerant of salinity [12]. • This species is expected to be impacted by flow regime changes, particularly changes to flood frequency, flood duration and flood timing, at all stages of the life cycle.
Knowledge Gaps	• Factors that influence seed viability. • Biology of the species in the northern MDB.
Metrics for Assessing Regeneration	• Crown condition. • Seedling density. • Presence of flowers, buds in adult trees. • Soil type. • Air temperature. • Riparian canopy cover.
References	[1] Rogers (2011); [2] Roberts and Marston (2000); [3] Wen et al. (2009); [4] Bren (1988); [5] Boland et al. (2006); [6] Cunningham et al. (1992); [7] George (2004); [8] van der Moezel (1988); [9] Briggs et al. (1997); [10] Di Stefano (2002); [11] Bren (1988); [12] Akilan et al. (1997).

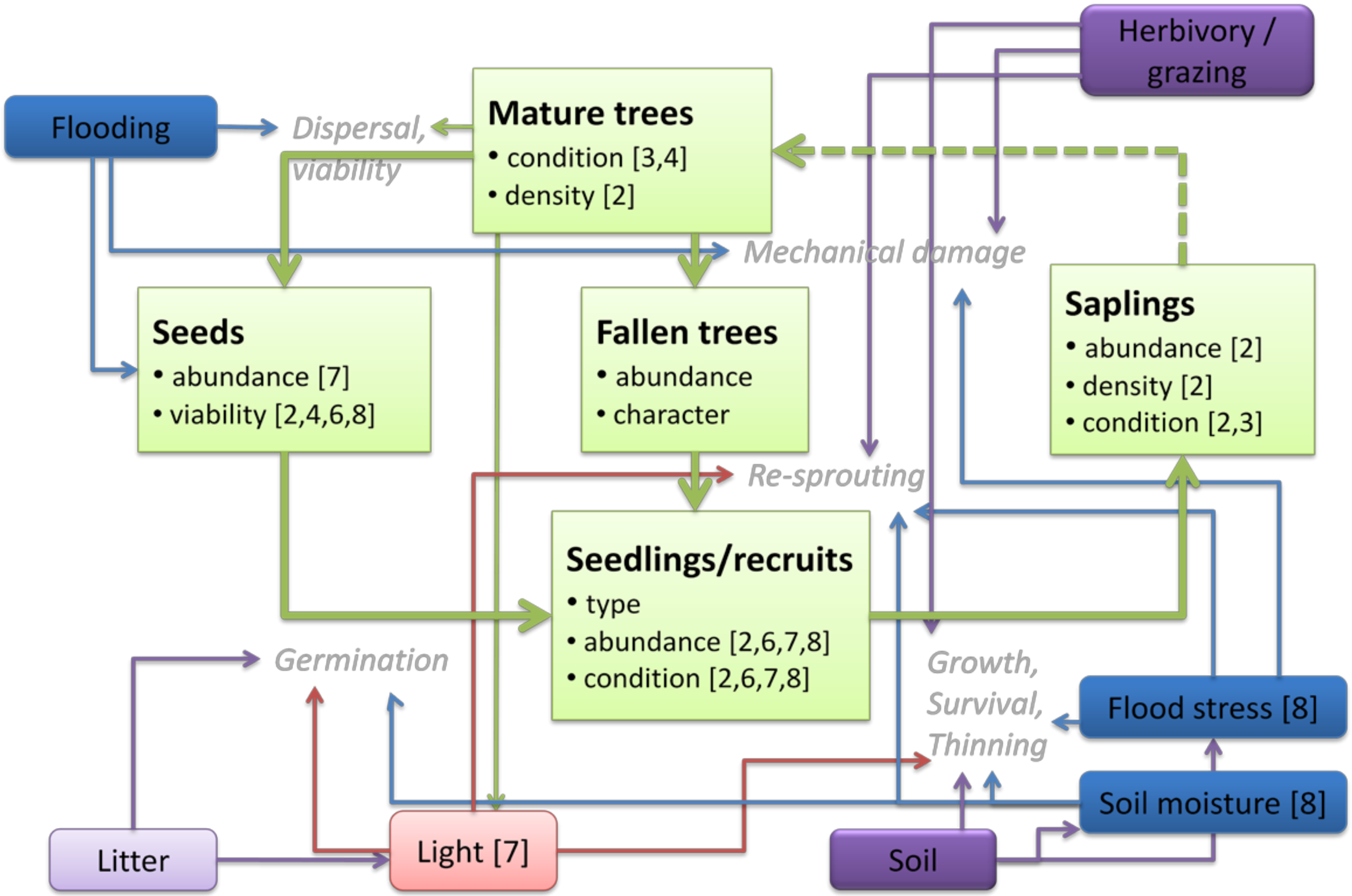

Figure A2.1. Conceptual model of links between environmental variables, biotic processes and life history stages of *Eucalyptus camaldulensis* (river red gum). Green lines indicate links between life history stages. Solid green lines indicate links between life history stages relevant to this study, dashed green lines indicate links between life history stages that were not be investigated in this study. Other links indicate relationships between abiotic variables and life history attributes. Numbers refer to references in the preceding table.

Table A2.2 Summary table of relationships between life history stages of *Eucalyptus coolabah* (coolibah) and flow regime attributes.

Attribute	Comments
Description & Habitat	• A medium sized tree to 20 m high, occurring as a smaller, poorly-formed tree in drier areas. Occurs along watercourses or seasonally inundated areas in arid and semi-arid regions [1,2,3]. • Occurs near permanent or regular water supplies [2,3].
Reproduction and Dispersal	• Coolibah flowers December to February [1]. Roberts [2] recorded trees with flowers in spring (Cooper Creek, South Australia). • Fruits mature January-April [1]. • Since fruit maturation is relatively quick it is unlikely that Coolibah has an aerial seed bank i.e. stores seed in the canopy [3]. • A soil seed bank is unlikely as seeds require temperatures of 3-5^{o}C for long term storage [3].
Germination and Establishment of Seedlings	• Soil moisture may be important for germination and seedling establishment [3]. • Roberts and Marston [3] suggest that Coolibah may be adapted to regenerate after late summer flooding as it has been shown that germination rates are high at high temperatures (optimal temperature for germination 35^{o}C [references in 3,4]).
Maintenance and survival	• Rogers [3] suggest an “ideal” flood frequency of 1 in 10-20 years, ideal flood duration of 2-5 weeks and flood timing summer-autumn. Inter-flood period 10-20 years. • The range of conditions this species has been recorded in suggests tolerance to a range of flood frequencies and inter-flood periods [3]. • Coolibah is intolerant of waterlogged soils or permanent flooding [4].
Summary of Critical Links to Flow	• **Flowering:** No known flow requirements for flowering. • **Germination and establishment**: Coolibah may be adapted to late summer flooding [3]. Soil moisture may be important for successful germination [2,3]. • **Maintenance**: Flood frequency of 1 in 10-20 years, ideal flood duration of 2-5 weeks and flood timing summer-autumn. Inter-flood period 10-20 years.
Other Comments	• Occurs on soils of alluvial origin, particularly heavy, cracking soils [1]. • Has some tolerance to salinity [4]. • Dense stands sometimes regenerate after floods [4].
Knowledge Gaps	• Water requirements throughout entire life cycle are a significant knowledge gap for this species.
Metrics for Assessing Regeneration	• Crown condition. • Seedling density. • Soil moisture [2,3]. • Soil texture [5]. • Presence of flowers and buds. • Air temperature.
References	[1] Boland et al. (2006); [2] Roberts (1993); [3] Rogers (2011); [4] Roberts and Marston (2000); [5] Pollock et al. (2004).

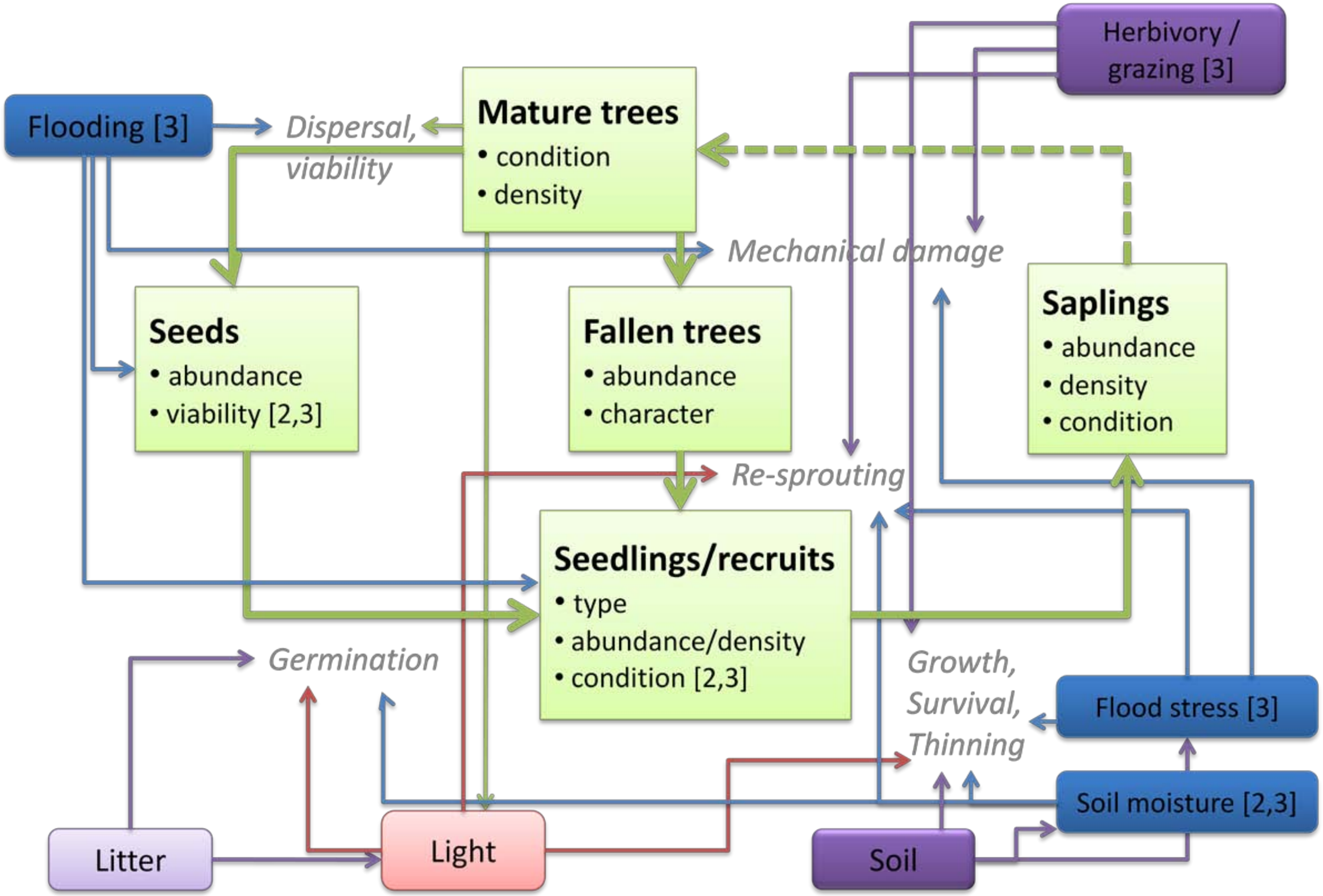

Figure A2.2. Conceptual model of links between environmental variables, biotic processes and life history stages of *Eucalyptus coolabah* (coolibah). Green lines indicate links between life history stages. Solid green lines indicate links between life history stages relevant to this study, dashed green lines indicate links between life history stages that were not be investigated in this study. Other links indicate relationships between abiotic variables and life history attributes. Numbers refer to references in the preceding table.

Table A2.3 Summary table of relationships between life history stages of *Acacia stenophylla* (river cooba) and flow regime attributes.

Attribute	Comments
Description and Habitat	• A tall shrub or tree commonly to 15 m, occurring along river and creek banks and floodplains [1], usually close to a river channel [2].
Reproduction and Dispersal	• The main period of flowering is winter, but is known to flower throughout the year [1]. Described as flowering mostly summer-early autumn by [2]. • Fruits mature September to May [1], seeds mature October-December [5]. • Can reproduce through suckering [1].
Germination and Establishment of Seedlings	• Flooding apparently increases the likelihood of germination [5]. • Growth of seedlings impaired by top-flooding in experimental trials – unable to adjust morphologically to top-flooding [3]. Reduced leaf development and photosynthetic activity results from continued inundation [3].
Maintenance and Survival	• Flood and drought tolerant [5].
Summary of Critical Links to Flow	• **Flowering:** No known requirements. • **Germination and establishment**: No known requirements. Seed maturation coincides with peak flood timing in Murray-Darling Basin [5]. • **Maintenance**: No known requirements.
Other Comments	• Occurs on heavy clay soils [4]. • The growth strategy for this species may be related to nutrient and water capture, as opposed to light capture [3]. • Low growth rate [3]. • Some tolerance to salinity [3]. • Transpiration rates may be related to location of trees on floodplain [6]
Knowledge Gaps	• Reproductive phenology and growth strategies [3]. • Water requirements at all stages of this species life cycle.
Metrics for assessing regeneration	• Depth to groundwater. • Soil moisture content. • Soil texture. • Crown condition.
References	[1] Boland et al. (2006); [2] Roberts and Marston (2000); [3] Gehrig (2010); [4] PlantNET; [5] Rogers (2011); [6] Doody et al. (2009).

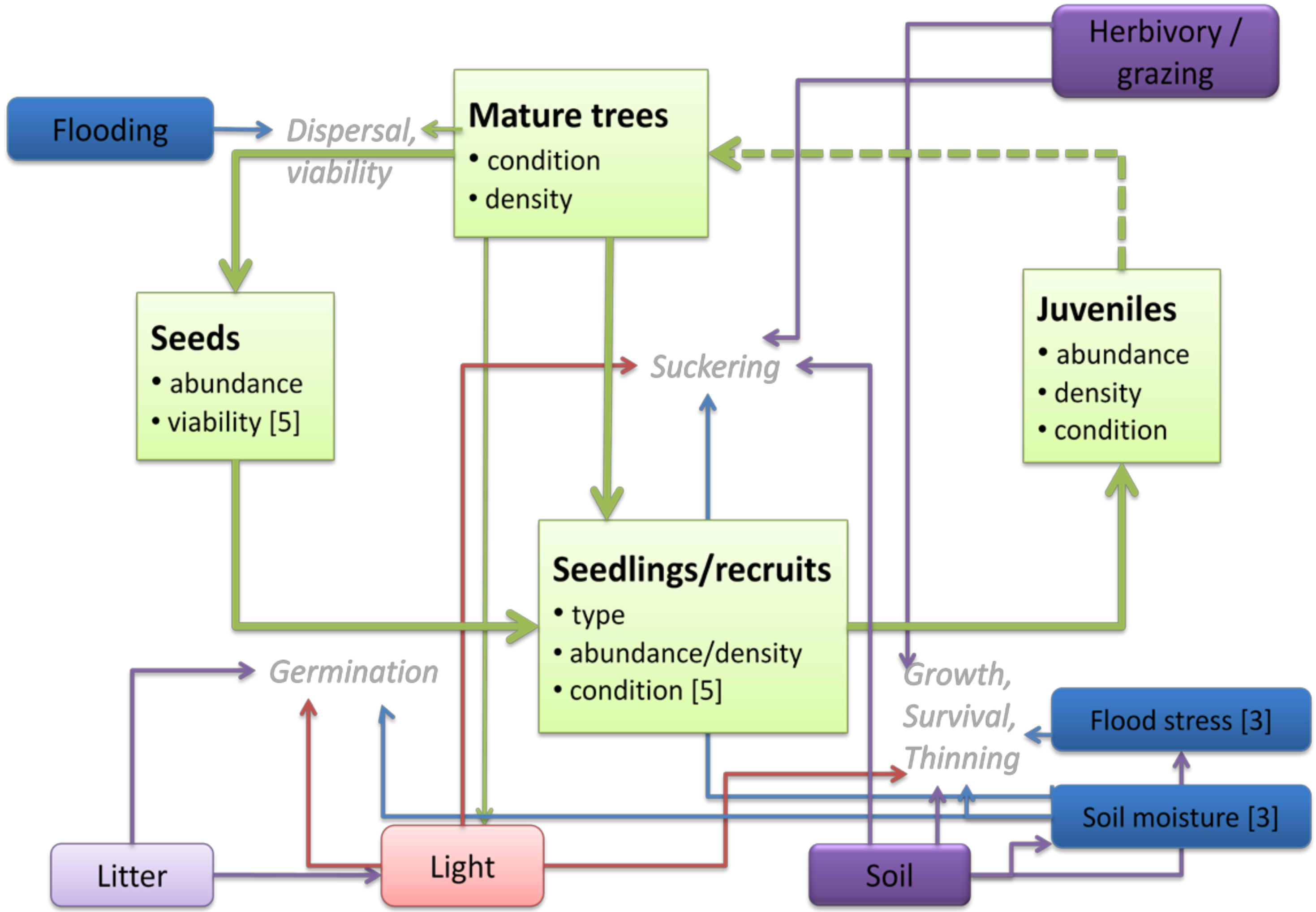

Figure A2.3. Conceptual model of links between environmental variables, biotic processes and life history stages of *Acacia stenophylla* (river cooba). Green lines indicate links between life history stages. Solid green lines indicate links between life history stages relevant to this study, dashed green lines indicate links between life history stages that were not be investigated in this study. Other links indicate relationships between abiotic variables and life history attributes. Numbers refer to references in the preceding table.

Table A2.4 Summary table of relationships between life history stages of *Muehlenbeckia florulenta* (tangled lignum) and flow regime attributes.

Attribute	Comments
Description and Habitat	• A highly variable multi-stemmed shrub ranging from small, short and leafless brown stems to relatively large clumps several metres in diameter and up to 3 m in height [1, 3]. • Dominates extensive areas of low-lying swamps as well as forming an understorey to riparian woodland [1, 3].
Reproduction and Dispersal	• Dioecious, i.e. separate male and female plants [2, 4]. • Flowers opportunistically in response to rainfall and flooding [2, 4]. • Can also reproduce vegetatively via stem layering [1] as well as re-sprouting from broken stem fragments [unpublished data, Capon and Murray]. • Seeds dispersed by floodwaters and are buoyant for at least 5 days [2]. • Does not form persistent soil seed bank and seeds lose viability relatively quickly [2].
Germination and Establishment of Seedlings	• Germination impeded by constant temperatures but no light requirement [2]. • Low temperatures appear to suppress germination [2]. • Growth of seedlings impaired by flooding and drought in experimental trials and favoured by damp and waterlogged conditions. Seedlings able to withstand considerable periods of both submergence and drought however though limited more by the former. No morphological plasticity amongst seedlings detected [4]. • Seedlings observed only after summer floods [5].
Maintenance and Survival	• Flood and drought tolerant to some degree though likely to be impeded by frequent, deep flooding of long duration [1, 2, 4 and 5].
Summary of Critical Links to Flow	• **Flowering:** No known requirements. • **Germination and establishment**: No known requirements. Likely to be favoured by moist conditions during periods of moderate temperatures [4]. • **Maintenance**: No known requirements. Typically absent form permanently waterlogged or deeply and frequently inundated sites and stunted in rarely flooded sites [5].
Other Comments	• Occurs on heavy clay soils [1]. • The growth form of this species varies with flood history with sparsely distributed and stunted shrubs occurring in rarely flooded areas compared with large, leafy clumps dominating relatively frequently flooded swamps [3, 5]. • Likely to be significant nurse plant species influencing diversity of understorey vegetation [unpublished data James and Capon].
Knowledge Gaps	• Quantifying limits of growth and both ends of flood frequency gradient. • Factors influencing successful establishment of seedlings.
Metrics for assessing regeneration	• Crown condition. • Seedling density. • Soil moisture. • Soil texture. • Presence of flowers and buds.
References	[1] Craig et al. (1991); [2] Chong and Walker (2005); [3] Thoms et al. (2007); [4] Capon et al. (2009); [5] Roberts and Marston (2000).

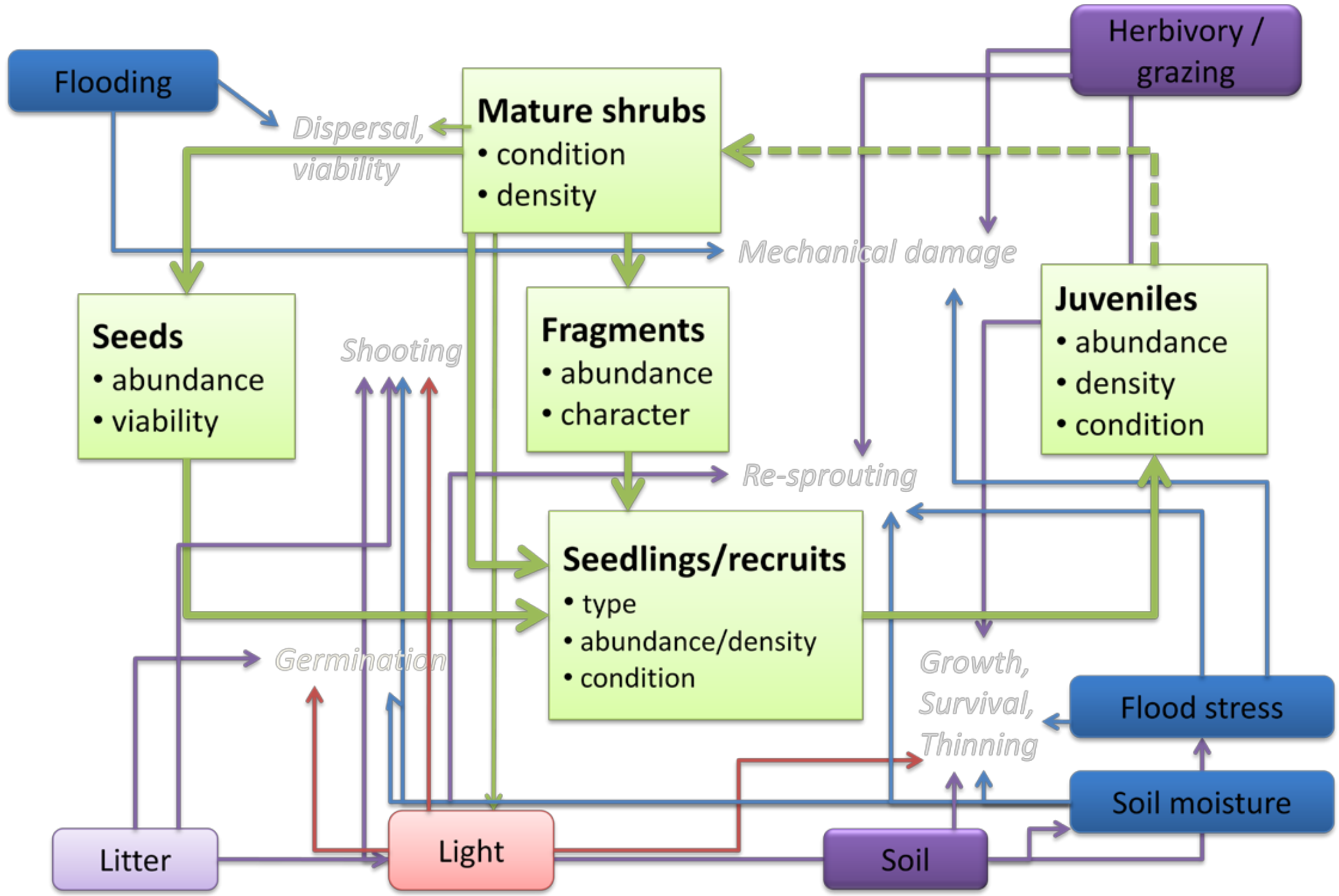

Figure A2.4. Conceptual model of links between environmental variables, biotic processes and life history stages of *Muehlenbeckia florulenta* (tangled lignum). Green lines indicate links between life history stages. Solid green lines indicate links between life history stages relevant to this study, dashed green lines indicate links between life history stages that were not be investigated in this study. Other links indicate relationships between abiotic variables and life history attributes. Numbers refer to references in the preceding table.

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