River red gum (*Eucalyptus camaldulensis*): a review of ecosystem processes, seedling regeneration and silvicultural practice

Julian Di Stefano

Forest Science Centre, Water St, Creswick, Victoria 3363, Australia
Email: julian.distefano@nre.vic.gov.au

Revised manuscript received 24 October 2001

Summary

This review brings together disparate information about the red gum ecosystem. The climate and soils of the Murray Valley are described, and I outline the impact of river regulation, as well as a number of other human activities, on some of the plants and animals of the region. The review illustrates the fundamental interconnectedness of ecosystem processes, especially in riparian systems. The ecology of red gum regeneration and current silvicultural practices are examined, and the likely future of the red gum ecosystem is discussed. On balance, it would seem that the greatest public good lies in re-establishing and maintaining the natural values of the red gum ecosystem.

Keywords: riparian forests; forest ecology; forest regeneration; flooding; water relations; silviculture; *Eucalyptus camaldulensis*; New South Wales; Victoria

Introduction

River red gum (*Eucalyptus camaldulensis*) is widely distributed throughout much of inland Australia. It often grows as isolated individuals, or as a line of trees along river banks and watercourses. The most prominent stands of red gum are found on the flood-plains of the Murray River in south-eastern Australia where the species forms large monospecific forests (Jacobs 1955). Areas of this forest in Victoria and southern New South Wales are shown in Figure 1.

Red gum communities of the Murray Valley have evolved in conjunction with the hydrology and climate of this flood-plain ecosystem. Due to low average rainfall and high evaporation rates (Dexter 1967), red gum forests require more water than is provided by rainfall alone. Under natural conditions, the extra water is generally supplied by flooding during winter and spring (Parsons *et al.* 1991). The extent, frequency, timing and duration of these floods impose major limitations on the distribution and quality of river red gum forests. For example, forested areas occupying higher ground (i.e. at the spatial limits of most floods) tend to be of relatively low quality due to high moisture stress during summer (Davies 1953; Jacobs 1955).

During the first part of the twentieth century, an increasing demand for water by human settlements in the Murray Valley led to the construction of the Hume Dam in 1934. Additional water storage and diversion facilities built in subsequent years (e.g. the Yarrawonga Weir in 1939 and the Dartmouth Dam in 1978) provided the capacity to store winter and spring river flows for release during summer and autumn (Dexter *et al.* 1986). The impact of these works (commonly known as river regulation) on the flooding regime of the Murray Valley has been investigated by a number of authors (e.g. Bren and Gibbs 1986; Dexter *et al.* 1986; Bren *et al.* 1987; Bren 1988, 1991; Close 1990; Maheshwari *et al.* 1995). A summary of their main findings is shown in Table 1.

In general, the research summarised in Table 1 indicates that river regulation has substantially altered the extent, frequency, timing and duration of floods in the Murray Valley. These changes to the natural flood regime may adversely affect the health of the red gum forests and associated ecosystems (Dexter *et al.* 1986; Parsons *et al.* 1991; Kingsford 2000). Effects noted include changes to understorey composition (Chesterfield 1986), reduced red gum growth rates, replacement of red gum by box eucalypt species at the margins of the forest (Bren 1991), increased insect damage (Campbell 1962; Stone and Bacon 1994, 1995), crown die-back and limited regeneration (Bacon *et al.* 1993a,b), and a reduction in the number of successful breeding episodes by some species of water bird (Leslie 2001). Other anthropogenic influences such as the introduction of rabbits, stock and domestic animals are likely to have precipitated a decline in the distribution and abundance of terrestrial mammals from the Murray Valley region (Chesterfield *et al.* 1984). In sum, human influences have resulted in a marked departure from the natural state of the red gum ecosystem.

Because of the risks posed by human activity, management practices in parts of the red gum ecosystem may need to change.

Table 1. The major impacts that river regulation has had on natural flood regimes in the Murray Valley

Impact of river regulation	Consequence
Flood frequency reduced	The time between floods has increased
Flood extent reduced	Less forest area is flooded
Flood timing altered	Fewer winter/spring floods and more summer floods
Flood duration reduced	Forests flooded for fewer months of the year

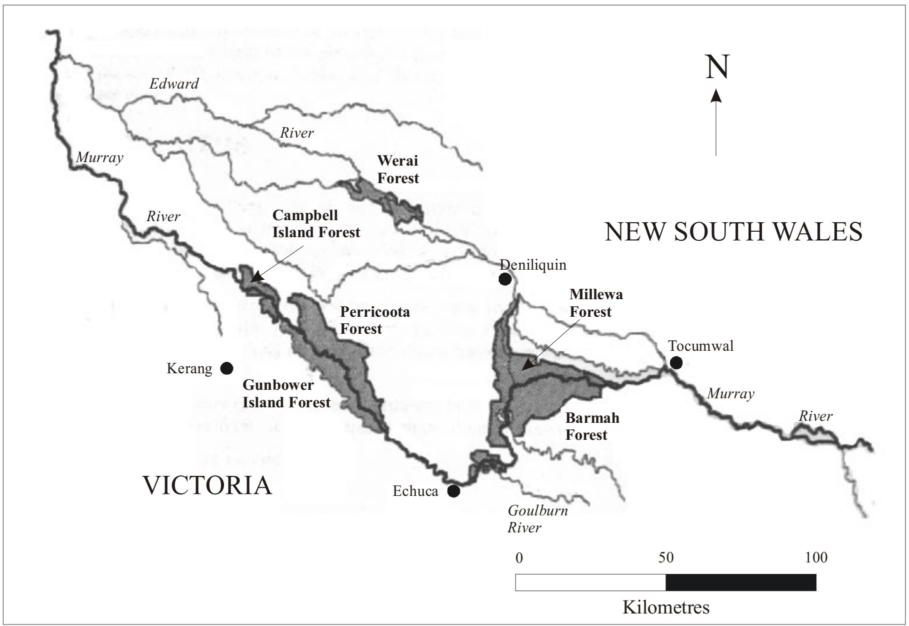

Figure 1. Major river red gum forests of Victoria and southern New South Wales

Consequently, it is the aim of this review to draw together information about the red gum ecosystem with a particular focus on seedling regeneration, and to discuss current and potential silvicultural practices. The focus is on flood-plain systems, as the bulk of published research has been conducted on the flood-plains of the Murray Valley.

The red gum ecosystem

Climate

Rainfall in the Murray Valley ranges between about 350 and 700 mm per year, decreasing from the south-east (Benalla) to the north-west (Kerang). The area to the east of Echuca is described as a hot temperate zone, and receives more than 400 mm of rain per year. Areas west of Echuca receive less than 400 mm of rain, and are described as semi-arid. Across the whole region, rainfall is highly variable, and is substantially less than average rates of evaporation. About 60% of annual rainfall occurs in winter, and winter rainfall events are usually of low intensity. Summer rainfall is often of greater intensity (Land Conservation Council 1983).

Throughout the Murray Valley, average summer temperature ranges from 14 to 31°C and average winter temperature ranges from 3 to 13°C. About eight severe frosts are recorded between May and October each year (Land Conservation Council 1983). These frosts may have important implications for the survival of red gum germinants.

Soils

Most of the Murray Valley consists of broad, flat plains rising between 70 and 200 m above sea level. Red gum forests dominate the sections of these plains close to major streams. Soils in these areas are often silty gradational loams, and have developed from Quaternary alluvial deposits (Land Conservation Council 1983).

The soils upon which red gum populations grow are typically composed of a layer of anoxic clay overlying interleaved clay and sand strata. In some places, the overlying layer of clay is greater than 30 m thick (Dexter 1978; Bren 1988). At the surface, these flood-plain soils are structureless, and when dry form a hard layer that plants find difficult to penetrate (Land Conservation Council 1983). Groundwater may be found in sandy aquifers at depths greater than 10 m below flood-plain soils (Parsons *et al.* 1991).

Primary production

Changes to the natural timing and frequency of flood events can have marked effects on primary production in flood-plain ecosystems (Brinson 1990). Recent analysis of the red gum ecosystem lends support to this claim. Under experimental conditions, primary production by aquatic macrophytes and microbial mats (biofilms) was significantly greater during spring flooding than during summer floods. In addition, macrophyte communities were significantly more diverse during spring floods (Robertson *et al.* 2001). Consequently, reduction in the frequency and extent of spring floods resulting from river regulation is clearly detrimental to macrophyte communities and biofilm accumulation (Robertson *et al.* 2001). Glazebrook and Robertson (1999) also suggested that increased summer water levels may have an additional detrimental effect. Summer flooding results in rapid decomposition of forest floor litter, a process that facilitates the release of nutrients. As a consequence, there is less decomposition the following spring, and fewer nutrients are released at the time when they are most critical for macrophyte and biofilm development. Reduced production by macrophytes and biofilms contributes to lower overall primary production, and may have direct effects on other organisms. Aquatic macrophytes, for example, are eaten by waterbirds living in flood-plain wetlands (Kingsford and Porter 1994).

Flora and fauna

Documentation of the flora and fauna of red gum ecosystems is poor. Much of the information reviewed here has been drawn from Land Conservation Council (1983), Chesterfield *et al.* (1984) and Chesterfield (1986).

The main vegetation association in river red gum ecosystems contains *E. camaldulensis* in conjunction with a monocotyledonous understorey, composed mainly of grasses, sedges and rushes. Successful understorey species are resistant to both inundation and moisture stress and include Moira grass (*Pseudoraphis spinescens*), swamp wallaby-grass (*Amphibromus neesii*), Warrego summer-grass (*Paspalidium jubiflorum*), terete-culm sedge (*Carex tereticaulis*) and common spike rush (*Eleocharis acuta*). Grasslands, composed mainly of Moira grass, and rushlands, composed mainly of the giant rush (*Juncus ingens*), also cover small areas of the flood-plain landscape. Shrubs are generally absent from the understorey in red gum stands.

On the higher ground, red gum stands grade into a box-eucalypt woodland. The main species is grey box (*E. microcarpa*) which is often associated with gold dust wattle (*Acacia acinacea*). Yellow box (*E. melliodora*) and black box (*E. largiflorens*) are also present in some areas. A few shrubs adapted to low rainfall environments grow in the box-eucalypt woodland, although most have a restricted distribution.

Based on analysis of historical documentation, Chesterfield (1986) suggested that vegetation patterns in the red gum forests have changed during the last 150 years. It is likely that these changes were precipitated by a number of human-induced factors, including reduced burning, the introduction of rabbits and domestic stock and river regulation. The cessation of burning by Aboriginal groups facilitated increased red gum regeneration during the last part of the nineteenth century, although increasing numbers of rabbits in the early years of the twentieth century probably had the opposite effect (Jacobs 1955). Increased summer flooding resulting from river regulation has killed trees in some low-lying areas of the forest, while reduced spring flooding has resulted in the invasion of red gums into areas previously too wet for them to survive (Chesterfield 1986). The latter phenomenon has been analysed in detail by Bren (1992). In addition, tree density in box woodlands has declined due to clearing and grazing associated with European settlement of the Murray Valley. The contraction of reedbeds to poorly drained sites and a decline in the extent of grassy plains has also been observed (Chesterfield 1986).

Mammal populations in red gum ecosystems include terrestrial, arboreal, aerial and aquatic species. Arboreal, aerial and aquatic species are relatively common, although notable exceptions are sugar gliders (*Petaurus breviceps*) and yellow-footed antechinus (*Antechinus flavipes*) whose populations were found to be low in a survey conducted in the Barmah State Forest during 1978–79 (Chesterfield *et al.* 1984). Yellow-footed antechinus, however, was the only native mammal found in Elliot traps during a recent survey (Mac Nally *et al.* 2001). This indicates that the distribution and abundance of some small mammal species may have changed during the last 20 years.

Historical information indicates that since 1900, four species of terrestrial mammal have disappeared from the Barmah forest (Chesterfield *et al.* 1984). These are the rufous bettong (*Aepyprymnus rufescens*), the bridled nailtail wallaby (*Onychogalea fraenata*), the western barred bandicoot (*Perameles bougainville*) and the lesser stick-nest rat (*Leporillus apicalis*). These four species are all medium-size terrestrial mammals with a heavy dependence on understorey vegetation. It is likely that destruction of understorey strata by sheep and cattle, as well as the introduction of exotic predators such as foxes and cats, has contributed to the decline of these species. The only terrestrial mammal inhabiting the red gum ecosystem that has resisted this demise is the eastern grey kangaroo (*Macropus giganteus*), whose numbers remain high.

Temporary wetlands formed by the periodic flooding of red gum stands provide habitat for over 50 species of waterbirds. These wetlands are important breeding areas for a number of species including ibis (*Threskiornis aethiopica* and *T. spinicollis*) and egrets (*Egretta alba* and *E. garzetta*). Leslie (2001) lists waterbirds that breed colonially in the Barmah–Millewa forest.

Although the impact of river regulation on waterbird populations is not well understood, a growing body of evidence suggests that past management decisions have adversely affected waterbird populations that live and breed in the red gum ecosystems. Leslie (2001) suggests that river regulation is linked with the loss of breeding colonies of at least eight formerly abundant species, a substantial decline in the numbers of at least 11 others and the abandonment of many traditional nesting sites. Further, the analysis presented by Leslie indicates that river regulation has reduced the frequency of successful breeding episodes by more than 80%. Briggs and Thornton (1999) suggested that reductions in the duration and frequency of flooding are most likely to affect those species which require long time periods to reach peak breeding following flooding. Egrets, for example, require wetlands to be inundated for up to 10 months if reproduction is to be successful (Briggs and Thornton 1999). Egrets no longer inhabit wetlands along the Murray River to the extent that they once did, and this decline has been attributed to a reduction in the extent of winter/spring flooding (Chesterfield *et al.* 1984). In addition, a case study of Moira Lake, a wetland within the Barmah–Millewa red gum forest, suggested that a number of other species of water bird which formerly bred in the region (e.g. glossy ibis, *Plegadis falcinellus*, and whiskered terns, *Chlidonias hybrida*) no longer do so (Leslie 1995). Kingsford (2000) provides a recent review of the impact of river regulation on flood-plain wetlands in Australia.

Many birds live in drier sections of red gum forest. A survey of Barmah State Forest reported by Chesterfield *et al.* (1984) found three numerically dominant species; white-plumed honeyeater (*Lichenostomus penicillatus*), striated pardalote (*Pardalotus striatus*) and brown treecreeper (*Climacteris picumnus*). A recent study (Mac Nally *et al.* 2001) confirmed the high abundance of these species, and recorded relatively high numbers of the superb fairy-wren (*Malurus cyaneus*), sulphur-crested cockatoo (*Cacatua galerita*), weebill (*Smicrornis brevirostris*) and buff-rumped thornbill (*Acanthiza reguloides*). The rarest bird utilising red gum forests is the superb parrot (*Polytelis swainsonii*). Reduction in the health of red gum trees as a result of river regulation (Bacon *et al.* 1993b) may adversely affect this species which breeds in large, healthy red gums (Webster 1988).

Fifteen reptile and eight amphibian species (Land Conservation Council 1983) have been observed in red gum forests and associated wetlands, although there is evidence that the diversity of reptiles may be decreasing (Mac Nally *et al.* 2001). Numerous aquatic plant species (Roberts and Ludwig 1991) and invertebrate species (Boulton and Lloyd 1991) have also been recorded.

In a study that encompassed Barmah State Forest, Gunbower State Forest and the Ovens River flood-plain, Mac Nally *et al.* (2001) found reduced density and diversity of native homeothermic vertebrates in areas with lowered structural diversity. In addition, these authors noted that structural diversity (measured as the mass of coarse woody debris) has decreased markedly since European settlement. Available evidence suggests that human impacts (including burning by Aboriginal people, timber harvesting, the introduction of rabbits and foxes, grazing and, in particular, river regulation) have changed the distribution and abundance of plant and animal species in red gum ecosystems (Chesterfield *et al.* 1984).

Red gum regeneration

Much of what we know about red gum regeneration is derived from the work of Barrie Dexter in the Barmah State Forest during the 1960s. Although many of Dexter's experiments were poorly replicated (e.g. Dexter 1970), further research and experience during the subsequent three decades support most of his findings.

Seedcrop development and dispersal

Red gum generally flowers between late spring and mid-summer (November–January). Seeds fall around 9 to 12 months later during the following spring or summer. About 25% of seeds generated by a particular flowering event are retained, and thus small amounts of seed are also shed during autumn and winter (Dexter 1970). Although red gum produces large quantities of seed (Jacobs 1955), production is highly variable and is influenced by losses of buds and immature capsules during spring and summer. Heavy seedcrops are sometimes followed by light ones (Dexter 1970).

Compared with many other species of eucalypt, the viability of red gum seed is high. In a test of 41 seedlots, Grose and Zimmer (1958) found that the mean viability of red gum seed was 622 160 viable seeds kg^{-1}, although the variance between seedlots was high. The most viable seedlot recorded contained 3 111 500 viable seeds kg^{-1} (Boland et al. 1980).

In red gum ecosystems, seed dispersal is aided by the movement of floodwaters. Laboratory tests indicate that red gum seed floats for up to 36 h. Consequently, the movement of water may deposit seed many kilometres from the parent tree (Dexter 1970).

Seed germination

Temperature, moisture and the condition of the seedbed play major roles in determining the success of seed germination. Laboratory studies by Grose and Zimmer (1958) established that the optimum temperature for the germination of red gum seed was about 35°C. Subsequent field trials, however, showed that red gum seed will readily germinate at lower temperatures as long as sufficient moisture is available (Dexter 1970). In flooded areas, germination in late spring and summer was linked to the recession of winter/spring floods and increasing temperatures. Nevertheless, germination was poor when flood waters did not recede until late summer, due to above-optimal temperatures at the soil–water interface. In non-flooded areas, most seeds germinate between May and August in response to heavy rain (Dexter 1970; Edgar 1977).

Dexter (1970) examined the effect of five different seedbed types on the germination of red gum seed. In both winter and summer, seeds under dense swards of grass, and seeds covered with ash-bed material or soil, germinated more rapidly than exposed seed. In general, seedbeds that protected seed from desiccation facilitated germination. These findings prompted Dexter (1970 p. 56) to conclude that 'Moisture is one of the most critical factors controlling germination in the red gum forest type…'.

Seedling survival and establishment

A number of factors influence the survival and establishment of red gum seedlings. Most are related to the availability of moisture, especially for the first few years before taproots reach subterranean water sources (Jacobs 1955; Dexter 1967, 1970). Consequently, increases in the initial rate of growth facilitate survival and establishment. Dexter (1967, 1970) noted that the growth rate of red gum seedlings was faster on deep ash beds and heavily cultivated soils than on hard bare surfaces and on grassy sites. Eight to ten months after germination, for example, the height of seedlings growing on ash beds averaged 60 cm while the height of seedlings growing on hard bare earth averaged 10 cm. The physical state of the seedbed is one of the few factors that can be controlled to enhance water acquisition by red gum seedlings (Dexter 1970).

While winter and spring floods usually aid the survival and establishment of red gum seedlings, prolonged flooding can clearly have an adverse effect. In Victoria, there is anecdotal evidence that summer rain rejection floods[1] inhibit regeneration and damage mature trees. Frosts and high temperatures at the soil–air interface also inhibit the survival and establishment of red gum seedlings (Dexter 1970).

The impact of insects and mammals on red gum regeneration

Campbell (1962) found that the gum leaf skeletonizer moth, *Uraba lugens*, caused substantial damage in red gum forests, and suggested that non-flooded areas were more susceptible because flooding facilitated the spread of an entomogenous fungus that kept insect populations low. In addition, trees in non-flooded areas often suffer from a lack of water and produce relatively sparse crowns with smaller leaves. These responses to water stress may further exacerbate the impact of insect herbivory on red gum forests (Stone and Bacon 1994, 1995).

Damage caused by herbivorous insects may be influenced by management action to some degree. Thinning red gum stands to less than 750 trees ha^{-1} significantly reduced defoliation caused by an outbreak of *U. lugens* (Harris 1975). In addition, Stone and Bacon (1994) suggested that red gums with a higher foliar content of terpenoids and cineoles were subject to significantly less insect herbivory than trees with low concentrations of these compounds.

---

[1]In the River Murray system water takes about 2 d to travel from an irrigation dam to the point of diversion. To ensure that there is adequate flow to sustain their diversions, irrigators have to 'order' their water 2–3 d before they wish to use it. If, however, rain falls in that 2–3 d they may not need the water. They have the right to 'reject' it, which means it continues in the channel until someone else diverts it. The result of heavy rain is that 'rain rejection' flows accumulate and push the river flow over the 12 000 ML d^{-1} flow limit for the Barmah Forest. The result is unseasonal flooding.

These authors proposed that selection of trees with high cineole content may ameliorate the impact of insect herbivory.

Dexter (1967, 1970) found that cattle, kangaroos and rabbits had a minor effect on seedling survival and form, except during drought years when their impact could be substantial. More recent research on the flood-plain of the Murrumbidgee River (Jansen and Robertson 2001) suggested that cattle can have a marked negative impact. Jansen and Robertson measured ecological condition using six macro-variables, each describing a different part of the red gum forest. These variables were (a) habitat continuity and extent, (b) vegetation cover and structural complexity, (c) bank and soil structure and stability, (d) standing and fallen debris, (e) dominance of natives versus exotics, and (f) the presence of indicative species. The results suggested that ecological condition declined significantly as the density of cattle increased. At low stocking rates (5–10 dry sheep equivalents (DSE) ha^{-1} y^{-1}; 8 DSE are equivalent to one cow), negative impacts of cattle were few. However, Jansen and Robertson (2001) note that stocking rates as high as 20 DSE ha^{-1} y^{-1} are present in some sections of the Murrumbidgee River flood-plain, and ecological condition in these areas is correspondingly poor.

The study by Jansen and Robertson (2001) raises issues regarding the measurement of ecosystem state. Using categorical variables (as Jansen and Robertson have done) will result in a somewhat subjective evaluation of ecosystem state, although due to the ease of data collection, measurements can be conducted over a large area. The use of continuous variables will result in more accurate data, but complexity of measurement techniques will reduce the spatial coverage. Future assessments of ecosystem state will need to consider the relative importance of accuracy versus spatial coverage for the particular hypotheses being tested.

The impact of river regulation on red gum regeneration

The effect of river regulation on red gum regeneration has not been recorded directly. However, river regulation has clearly reduced the extent of flooding, and stands of red gum on higher ground are notably affected. Prior to river regulation, high ground areas regenerated only after major floods (Jacobs 1955). At present, regulation ensures that major floods almost never occur, and thus regeneration on higher ground is most unlikely.

River regulation has also affected the frequency and duration of flooding. In Barmah State Forest, for example, flooding frequency of some red gum stands (site quality two) has fallen by 36% since regulation, and the number of months that these stands are flooded has fallen by 50% (Maunsell 1992). Such changes have undoubtedly reduced availability of water in large areas of red gum forest. Although it is difficult to specify the impact on red gum regeneration, it is logical to expect a negative effect. In contrast, river regulation may facilitate red gum regeneration in some low-lying sections of the forest (Jacobs 1955). Prior to regulation, it is likely that regeneration failed in some areas due to frequent inundation — conditions were not dry enough for germination and subsequent survival. There is no direct evidence to support this hypothesis, except that some low-lying areas contain only old red gum trees (Jacobs 1955).

Red gum silviculture

Promoting regeneration

Due to the complex nature of the interactions influencing red gum regeneration, it is unlikely that conditions favouring regeneration will occur frequently. Between 1900 and 1965, extensive natural regeneration occurred only six times in the Barmah State Forest (Dexter 1970). Because natural regeneration is infrequent, and because activities such as river regulation have limited regeneration in some areas (Bacon *et al.* 1993a,b), it is important for forest managers to develop techniques that promote regeneration events in harvested areas.

A number of factors influence the germination, establishment and survival of red gum. Dexter (1970) identified eight important variables.

- Seed supply;
- Incidence of flooding;
- The time of flood recession;
- Duration and depth of flooding in the season following germination;
- Seedbed type;
- Availability of water in the sub-soil;
- Distribution and abundance of summer rainfall; and
- Insects, livestock and other animals.

All are interrelated to some degree, with water availability being the most important factor. Seed supply, seedbed type, competition for water, the extent of browsing, and flood duration and timing can all be manipulated to facilitate red gum regeneration. Formal regeneration activities, however, are rarely performed. The most pro-active step towards promoting red gum regeneration in recent times has been the allocation of water to red gum forests for environmental purposes.

It is clear from the discussion earlier in this paper that altered flood regimes resulting from river regulation have negative impacts on red gum regeneration. To address these problems, the respective State land management agencies and the Murray Darling Basin Commission (MDBC) aim to manage red gum forests as a single ecosystem by adopting flow regimes that mimic patterns of flooding prior to river regulation (MDBC 2000). As progress towards this goal, 100 GL of water under a high-security entitlement has been allocated for environmental uses in the Barmah–Millewa Forests.

A committee established by the Victorian Government to allocate Victoria's share of available water between irrigation and environmental uses recommended the allocation of an additional 50 GL of lower-security entitlement water for the Barmah–Millewa Forests (MWEC 1997). Detailed water management plans are also being prepared for other areas, including Gunbower State Forest, Bruces Bend State Forest, Lake Moodemere and Hattah Lakes (DNRE 2001).

Although land management agencies in both Victoria and NSW have made firm commitments to environmental water allocations, the impacts of these actions are unclear. Many years of monitoring will be required to determine the effect of environmental floods on red gum ecosystems. It is likely, however, that artificial flooding of red gum forests at the right time and for the right duration will increase the frequency of regeneration events.

Planting and machine-based direct seeding are two other techniques used to regenerate red gums on non-forest rural land. A widely accepted planting technique involves planting seedlings in ripped lines between September and December. The use of gypsum and herbicides, and the addition of water at the time of planting, can also enhance the chance of seedling survival (P. Haw, *pers. comm.*). Successful machine-based direct seeding requires viable seed, a receptive seedbed, warmth and sub-soil moisture. A comprehensive account of direct seeding techniques, including discussion on methods, timing, weed and pest control and the use of machinery, can be found in Dalton (1993).

The efficacy of planting and machine-based direct seeding techniques for regenerating red gum in forest environments has not been tested. In some situations, these techniques may be useful complements to natural regeneration processes, although protocols for their use in red gum forests remain to be developed.

Current red gum silviculture

Documents that outline silvicultural practice in red gum forests in Victoria and NSW include Woodward (1993) and DNRE (2001) in Victoria and Forestry Commission of NSW (1984) and State Forests of NSW (2001) in NSW. In both States, these documents refer to harvesting systems that should be employed, promotion of tree growth by thinning, and the retention of trees for wildlife habitat. In the Victorian literature, however, there is additional discussion about the promotion of red gum regeneration through seedbed creation, artificial seeding and the use of formal regeneration surveys. There is little focus on these practices in the NSW literature.

The published silvicultural notes, however, do not reveal the nuances of silvicultural practice. The following discussion outlines operational red gum silviculture as practised in both Victoria and NSW. The information presented is based on discussions with people who actively work in the field or have an interest in red gum silviculture, along with the author's own experience.

The harvesting system used most frequently in both Victoria and NSW is single-tree selection, although small-group selection is used in some areas. These systems create small gaps in the forest, a practice that has received some criticism. As noted in the literature (e.g. DNRE 2001), the size of the gap created by harvesting has implications for the success of regenerating seedlings. Mature red gums have a large zone of influence (Dexter 1967; Opie 1969) which affects the survival and growth rate of nearby seedlings. The creation of small gaps results in a large percentage of regenerating seedlings being close to mature trees, and thus adversely affects their viability.

Under natural conditions, red gums often regenerate along the edge of receding floodwaters (Dexter 1970), a pattern of regeneration that commonly results in even-aged clumps or strips of trees. Examples of this phenomenon are large even-aged red gum stands that regenerated after floods in the late nineteenth and early twentieth centuries (Jacobs 1955). To maintain the natural structure of red gum forests, harvesting systems should be coherent with natural patterns of regeneration. The generation of small gaps, however, promotes the development of uneven-aged stands, a structure that differs from naturally occurring red gum in frequently flooded areas. In such areas, the creation of larger gaps during harvesting would help maintain the natural structure of the forest. B. Dexter (*pers. comm.*) believes that gaps of 5 to 10 ha would be appropriate in most cases.

The retention of trees for wildlife habitat is an important aspect of the balance between wood production and biodiversity conservation. In the Victorian General Management Zone (the general harvesting area), 40 habitat trees (20 between 50 and 100 cm dbh and 20 between 100 and150 cm dbh) must be retained in every 10 ha of harvested forest, as well as all trees over 150 cm dbh. Alone, the 40 trees comprise 20%–25% of the post-harvest basal area (DNRE 2001). In Gunbower State Forest, all trees larger than 100 cm dbh must be retained in addition to the required quota of smaller habitat trees (M. Thorson, *pers. comm.*). In NSW general harvesting areas, habitat tree prescriptions are much less stringent. The same number of habitat trees must be retained as in Victoria (4 ha^{-1}), but their size is not specified. In addition, large veteran trees do not have to be kept for wildlife habitat (G. Rodda, *pers. comm.*). These prescriptions provide NSW silviculturalists with much more flexibility than their Victorian counterparts.

The retention of habitat trees, especially those with large diameters, has implications for the production of merchantable timber (DNRE 2001). Habitat trees occupy growing space and compete with merchantable trees for water, light and nutrients. As a consequence, they reduce the probability of successful regeneration events, and reduce the growth rate of nearby merchantable trees. Using Opie's (1969) zone of influence estimates for site-quality-two red gum stands, a single tree of 100 cm dbh will have some influence on 829 m^2 of ground area, and a tree 150 cm dbh will have some influence on 1863 m^2. Clearly, the retention of large habitat trees substantially increases competitive interactions, and probably reduces the growth potential of a site.

At present, there are no quantitative data that relate current habitat tree prescriptions to the persistence of hollow-dependent fauna (Bennett *et al.* 1994). Consequently, current prescriptions are compromises between conservation and timber production values. While the requirements of hollow-dependent fauna remain unknown, it seems prudent to retain high numbers of trees for wildlife habitat, regardless of the impact this has on wood production. Elucidation of the density, distribution, size and form of trees required for wildlife habitat is needed.

Seedbed creation, artificial sowing and the use of formal regeneration surveys are rarely practised in either Victoria or NSW. An exception is in the non-riverine red gum forests of south-western Victoria (Woohlpooer State Forest), where mechanical seedbed creation is routinely employed (Lutze *et al.* 1999). In other areas, it is assumed that natural processes will facilitate regeneration in harvesting gaps. Considering the small size of these gaps, the dependence of seedling survival on adequate water, and the reduction in the extent and frequency of flooding that has occurred since the 1930s, this assumption may not always be justified. In both Victoria and NSW, the use of techniques that promote red gum regeneration, along with the consistent use of formal regeneration surveys, should be seriously considered.

The major difference in red gum silviculture between Victoria and NSW is the importance placed on thinning, or stand improvement as it is sometimes called. In NSW there is a long history of stand improvement dating back to the early nineteen hundreds. In particular, the removal of large veteran trees during the middle years of the nineteen hundreds (Jacobs 1955) increased the growth rate of smaller, potentially merchantable stems. Although some veteran trees were removed in Victoria, the extent of the operations was relatively small. Removal of veteran trees in NSW has resulted in a greater number of potentially merchantable trees, a condition that facilitates the management of the forest for wood production (G. Rodda, *pers. comm.*).

At present, NSW invests more into stand improvement than Victoria (G. Rodda and M. Thorson, *pers. comm.*). In part, this is due to Victorian habitat tree requirements which restrict stand improvement operations. Nevertheless, Victorian silviculturalists recognise the growth benefits that result from stand improvements in red gum forests, and are committed to such operations in the future.

In Australia, the responsibility for land management lies with the States, thus ecosystems that straddle State boundaries will be subjected to different management practices. This is the case for major red gum forests in south-eastern Australia. Although they are a single ecological entity, sections of forest in Victoria and NSW are being managed differently. Ideally, forest management should be based on ecological principles, and not be influenced by arbitrary political boundaries. More dialogue and co-operation between management agencies in Victoria and NSW is needed to achieve this goal.

Managing the forest for multiple uses

In recent years, forest management agencies have moved towards a more inclusive form of management. The emerging rhetoric is that forests will be managed for ‘multiple uses’. For example, the *Proposed Forest Management Plan for the Mid-Murray Forest Management Area* (DNRE 2001) contains sections discussing biodiversity conservation, water management, hardwood production, the protection of forested areas from pests and diseases, cultural heritage and recreation. Managing the forests for multiple uses, however, is difficult. One example, discussed in the previous section, is the incompatibility between stand improvement and the retention of hollow-bearing trees. Another is the conflict between maintaining aesthetic values by using small-gap harvesting systems and promoting more natural patterns of red gum regeneration by harvesting in larger gaps.

Rather than trying to manage forests for multiple uses (an exercise that may, in fact, be impossible — Wagner 1994), forest managers should aim to maximise ecosystem health. Ecosystem health is a value-laden term (Lackey 2001), and thus must be carefully defined before becoming a goal of management. The major assumption underlying the use of this term here is that ecosystems in their natural state (i.e. ecosystems that are changing in response to naturally occurring environmental impacts and interactions between their components) are more desirable than ecosystems that have been altered by major human influences. Major human influences (such as Aboriginal burning practices, river regulation and timber harvesting in the case of red gum forests) are expected to result in (a) unnatural patterns of change and (b) relatively rapid change, both of which are likely to precipitate substantial ecosystem alteration relatively quickly. Ecosystems altered in this way are interpreted as less healthy than natural ones.

Regardless of the difficulties with definition, the principle of managing forests to maximise ecosystem health is quite clear. A healthy forest ecosystem provides the basis for all anthropogenic forest uses — without a healthy forest ecosystem, timber production, recreational use, etc., will suffer. More generally, ecosystem health provides the foundation for human social and economic systems (Rapport 1998), and thus must be maintained. To this end, forest managers should work towards an acceptable definition of ecosystem health, focusing as much as possible on biological principles, and then manage the forests to achieve this goal. Other forest uses should be acceptable only if they do not jeopardise the health of the forest ecosystem.

The future of the red gum ecosystem

There is no doubt that red gum forests are changing. Factors as varied as Aboriginal burning practices, river regulation, early silvicultural treatment, modern timber harvesting practices, recreational activities and the introduction of exotic animals have caused major alterations in structure, distribution and growth patterns. Other identified changes (outlined earlier in this paper) include variation in the distribution and abundance of understorey species, increased insect herbivory, a reduction in the number of terrestrial mammals, degradation of waterbird habitat, a possible decline in the abundance of reptiles and a reduction in the amount of coarse woody debris on the forest floor.

The future impact of these changes is difficult to predict. If high-ground sections of the forest continue to be deprived of water, it is likely that these areas will be invaded by species of box eucalypts (Jacobs 1955). This would result in a reduction in the size of red gum forests, and would change the quality of the resource available for timber production. In addition, higher quality sections of red gum forests receive less water than they would under natural conditions (Maunsell 1992). If this state is maintained into the future, patterns of regeneration and growth will be affected, and the structure of the forest will continue to change.

It is clear that changes to the distribution and structure of the forest will result in changed biological and physical associations. Some associations (e.g. between wetlands and the regeneration success of some waterbirds) will be broken and others will be formed. The end result will be a suite of organisms that differs from the one that currently exists. Ecosystem change, however, is not necessarily a negative phenomenon — natural ecosystems are constantly in a state of flux (Connell and Sousa 1983).

Changing ecosystems may also provide benefits for some sections of the community. For example, Jacobs (1955) suggested that the transformation of high-ground red gum forests to box woodland would have positive outcomes for the timber industry due to the high quality of box timbers. However, the current rate of change in red gum forests is fast compared with pre-European standards, and many of the values associated with red gum ecosystems may be lost as a direct result of human activities. It is the author's opinion that this is not desirable. Thus tree species other than red gum should not be used as 'replacements', even though conditions in some sections of the forest are suitable for a number of other dry-land eucalypts. The decision to regenerate these sites with other species would be an implicit acknowledgment by forest managers that major human-induced changes to red gum ecosystems are acceptable. Although the use of red gum ecosystems by human populations means that some change is inevitable, every attempt should be made to keep our impact as small as possible.

Red gum forests will not disappear in the foreseeable future. They will, however, continue to change in both predictable and unpredictable ways. Forest managers could and perhaps should act to reduce, as much as possible, human impacts on red gum ecosystems, and thus minimise the rate of human-induced ecosystem change.

Acknowledgements

Thanks to Rob Campbell, Peter Fagg, Peter Rutherford, Martin Woodward, Barrie Dexter and Mark Adams for commenting on drafts. Discussions with Barrie Dexter, Murray Thorson (DNRE, Cohuna) and Gary Rodda (State Forests of NSW, Deniliquin) greatly enhanced this paper. Two anonymous reviewers also provided comments that improved the quality of this work. This work is part of a larger project funded by Forestry Victoria, a business unit of the Department of Natural Resources and Environment (DNRE). The views and opinions expressed, however, are those of the author and do not necessarily reflect those of DNRE.

References

Bacon, P.E., Stone, C., Binns, D.L., Edwards, D.W. and Leslie, D.J. (1993a) *Inception Report on Development of Watering Strategies to Maintain the Millewa Group of River Red Gum (*Eucalyptus camaldulensis*) Forests*. Technical Paper No. 56. Forestry Commission of NSW, Sydney.

Bacon, P.E., Stone, C., Binns, D.L., Leslie, D.J. and Edwards, D.W. (1993b) Relationships between water availability and *Eucalyptus camaldulensis* growth in a riparian forest. *Journal of Hydrology* **150,** 541–561.

Bennett, A.F., Lumsden, L.F. and Nicholls, A.O. (1994) Tree hollows as a resource for wildlife in remnant woodlands: spatial and temporal patterns across the northern plains of Victoria, Australia. *Pacific Conservation Biology* **1,** 222–235.

Boland, D.J., Brooker, M.I.H. and Turnbull, J.W. (1980) *Eucalyptus Seed*. CSIRO, Australia.

Boulton, A.J. and Lloyd, L.N. (1991) Aquatic macroinvertebrate assemblages in floodplain habitats of the lower River Murray. *Regulated Rivers* **6,** 183–201.

Bren, L.J. (1988) Effects of river regulation on flooding of a riparian red gum forest on the River Murray, Australia. *Regulated Rivers: Research and Management* **2,** 65–77.

Bren, L.J. (1991) Modelling the influence of River Murray management on the Barmah river red gum forests. *Australian Forestry* **54,** 9–15.

Bren, L.J. (1992) Tree invasion of an intermittent wetland in relation to changes in the flooding frequency of the River Murray, Australia. *Australian Journal of Ecology* **17,** 395–408.

Bren, L.J. and Gibbs, N.L. (1986) Relationships between flood frequency, vegetation and topography in a river red gum forest. *Australian Forest Research* **16,** 357–370.

Bren, L.J., O'Neill, I.C. and Gibbs, N.L. (1987) Flooding of the Barmah forest and its relation to flow in the Murray–Edward River system. *Australian Forest Research* **17,** 127–144.

Briggs, S.V. and Thornton, S.A. (1999) Management of water regimes in river red gum *Eucalyptus camaldulensis* wetlands for waterbird breeding. *Australian Zoologist* **31,** 187–197.

Brinson, M.M. (1990) Riverine forests. In: Lugo, A.E., Brinson, M. and Brown, S. (eds) *Forested Wetlands. Ecosystems of the World*, Vol. 15. Elsevier, Amsterdam, pp. 87–142.

Campbell, K.G. (1962) The biology of *Roeselia lugens* (Walk.), the gum-leaf skeletonizer moth, with particular reference to the *Eucalyptus camaldulensis* Dehn. (river red gum) forests of the Murray Valley region. *Proceedings of the Linnean Society of New South Wales* **87,** 316–338.

Chesterfield, E.A. (1986) Changes in the vegetation of the river red gum forest at Barmah, Victoria. *Australian Forestry* **49,** 4–15.

Chesterfield, E.A., Loyn, R.H. and Macfarlane, M.A. (1984) *Flora and Fauna of the Barmah State Forest and their Management*. Research Branch Report No. 240. Forests Commission of Victoria, Melbourne.

Close, A. (1990) The impact of man on the natural flow regime. In: Mackay, N. and Eastburn, D. (eds) *The Murray*. Murray-Darling Basin Commission, Canberra, pp. 61–74.

Connell, J.H. and Sousa, W.P. (1983) On the evidence needed to judge ecological stability or persistence. *The American Naturalist* **121,** 789–824.

Dalton, G. (1993) *Direct Seeding of Trees and Shrubs — A Manual for Australian Conditions*. Primary Industries (SA), Adelaide.

Davies, N. (1953) *Investigations on the Soil and Water Relations of the River Red Gum Forests*. Final Report by Murray Management Survey. Resources Branch Report No. R. 124.

Dexter, B.D. (1967) *Flooding and Regeneration of River Red Gum,* Eucalyptus camaldulensis*, Dehn*. Bulletin No. 20. Forests Commission of Victoria, Melbourne.

Dexter, B.D. (1970) Regeneration of river red gum *Eucalyptus camaldulensis* Dehn. Masters Thesis, University of Melbourne.

Dexter, B.D. (1978) Silviculture of the river red gum forests of the central Murray floodplain. *Proceedings of the Royal Society of Victoria* **90,** 175–192.

Dexter, B.D., Rose, H.J. and Davies, N. (1986) River regulation and associated forest management problems in the River Murray red gum forests. *Australian Forestry* **49,** 16–27.

DNRE (2001) *Proposed Forest Management Plan for the Mid-Murray Forest Management Area*. Department of Natural Resources and Environment, Victoria.

Edgar, J.G. (1977) Effects of moisture stress on germination of *Eucalyptus camaldulensis* Dehn. and *E. regnans* F. Muell. *Australian Forest Research* **7,** 241–245.

Forestry Commission of NSW (1984) Notes on the silviculture of major NSW forest types. 5. River red gum types. In: *Silvicultural Notes*. Forestry Commission of NSW, Sydney.

Glazebrook, H.S. and Robertson, A.I. (1999) The effect of flooding and flood timing on leaf litter breakdown rates and nutrient dynamics in a river red gum (*Eucalyptus camaldulensis*) forest. *Australian Journal of Ecology* **24,** 625–635.

Grose, R.J. and Zimmer, W.J. (1958) Some laboratory germination responses of the seeds of river red gum *Eucalyptus camaldulensis* Dehn., syn. *Eucalyptus rostrata* Schlecht. *Australian Journal of Botany* **6,** 129–158.

Harris, J.A. (1975) *The Influence of Thinning upon Defoliation by the Gum Leaf Skeletonizer in River Red Gum Forests*. Forestry Technical Papers No. 22. Forests Commission, Melbourne.

Jacobs, M.R. (1955) *Growth Habits of the Eucalypts*. Commonwealth Government Printer, Canberra.

Jansen, A. and Robertson, A.I. (2001) Relationships between livestock management and the ecological condition of riparian habitats along an Australian floodplain river. *Journal of Applied Ecology* **38,** 63–75.

Kingsford, R.T. (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25,** 109–127.

Kingsford, R.T. and Porter, J.L. (1994) Waterbirds on an adjacent freshwater lake and salt lake in arid Australia. *Biological Conservation* **69,** 219–228.

Lackey, R.T. (2001) Values, policy, and ecosystem health. *BioScience* **51,** 437–443.

Land Conservation Council (1983) *Report on the Murray Valley Area*. Land Conservation Council, Melbourne.

Leslie, D.J. (1995) Moira Lake — a case study of the deterioration of a River Murray natural resource. MSc Thesis, University of Melbourne.

Leslie, D.J. (2001) Effect of river management on colonially-nesting waterbirds in the Barmah–Millewa forest, south-eastern Australia. *Regulated Rivers: Research and Management* **17,** 21–36.

Lutze, M.T., Campbell, R.G. and Fagg, P.C. (1999) Development of silviculture in the native State forests of Victoria. *Australian Forestry* **62,** 236–244.

Mac Nally, R., Parkinson, A., Horrocks, G., Conole, L. and Tzaros, C. (2001) Relationships between terrestrial vertebrate diversity, abundance and availability of coarse woody debris on south-eastern Australian floodplains. *Biological Conservation* **99,** 191–205.

Maheshwari, B.L., Walker, K.F. and McMahon, T.A. (1995) Effects of regulation on the flow regime of the River Murray, Australia. *Regulated Rivers* **10,** 15–38.

Maunsell Pty Ltd (1992) *Barmah–Millewa Forest Water Management Plan*. Murray-Darling Basin Commission, NSW.

MDBC (2000) *The Barmah–Millewa Forest Water Management Strategy.* Barmah–Millewa Forum and Murray-Darling Basin Commission, Canberra.

MWEC (1997) *Sharing the Murray. Proposal for Defining People's Entitlements to Victoria's Water from the Murray.* Murray Water Entitlements Committee, Melbourne.

Opie, J.E. (1969) The individual tree as a sampling unit. PhD thesis, University of Melbourne.

Parsons, M., Bren, L.J. and Dexter, B.D. (1991) Riverine forests of the central Murray Valley. In: McKinnell, F.H., Hopkins, E.R. and Fox, J.E.D. (eds) *Forest Management in Australia*. Surrey Beatty, Chipping Norton, pp. 271–283.

Rapport, D.J. (1998) Defining ecosystem health. In: Rapport, D.J., Costanza, R., Epstein, P.R., Gaudet, C.L. and Levins, R. (eds) *Ecosystem Health*. Blackwell Science, Malden, pp. 18–33.

Roberts, J. and Ludwig, J.A. (1991) Riparian vegetation along current-exposure gradients in floodplain wetlands of the River Murray, Australia. *Journal of Ecology* **79,** 117–127.

Robertson, A.I., Bacon, P. and Heagney, G. (2001) The response of floodplain primary production to flood frequency and timing. *Journal of Applied Ecology* **38,** 126–136.

State Forests of NSW (2001) *Native Forest Silviculture Manual*. State Forests of NSW, Sydney (unpublished).

Stone, C. and Bacon, P. (1994) Relationships among moisture stress, insect herbivory, foliar cineole content and the growth of river red gum *Eucalyptus camaldulensis*. *Journal of Applied Ecology* **31,** 604–612.

Stone, C. and Bacon, P.E. (1995) Leaf dynamics and insect herbivory in a *Eucalyptus camaldulensis* forest under moisture stress. *Australian Journal of Ecology* **20,** 473–481.

Wagner, M.R. (1994) The healthy multiple-use forest ecosystem: An impossible dream. In: Covington, W.W. and DeBano, L.F. (eds) *Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management.* USDA Forest Service, Fort Collins, pp. 185–188.

Webster, R. (1988) *The Superb Parrot. A Survey of the Breeding Distribution and Habitat Requirements*. Australian National Parks and Wildlife Service Report Series No. 12. Australian National Parks and Wildlife Service, Canberra.

Woodward, M. (1993) Red Gum Timber Management Procedures Manual. Department of Natural Resources and Environment, Victoria (Unpublished).