Environmental Conservation **38** (3): 353–365 © Foundation for Environmental Conservation 2011 doi:10.1017/S0376892911000130

Introducing irrigation efficiencies: prospects for flood-dependent biodiversity in a rice agro-ecosystem

S. McINTYRE*, H. M. McGINNESS, D. GAYDON AND A. D. ARTHUR
CSIRO Ecosystem Sciences, PO Box 284, Canberra, Australian Capital Territory 2601, Australia
Date submitted: 20 July 2010; Date accepted: 17 November 2010;
First published online: 25 May 2011

SUMMARY

Worldwide, irrigation development has affected pre-existing natural habitats and created novel aquatic habitats, and future changes in management will continue to influence flood-dependent vegetation and fauna. Irrigated agriculture has had a profound influence on native biodiversity in the Riverina region of temperate Australia. Current irrigation practices provide large amounts of water to the landscape in the form of constructed wetland habitats: irrigation channels, impoundments and flooded crop-growing areas. Flooded rice bays support many species of native wetland plants, and 12 of the 14 species of frog recorded in the region. All constructed habitats provide a food resource for waterbirds, but not breeding habitat. While a species of tortoise benefits from the provision of constructed habitats, terrestrial reptiles and mammals are most abundant in remaining native vegetation. The climate is predicted to become increasingly hot and dry, with a reduced and more variable supply of irrigation water, thus placing increasing stress on farming and on natural ecosystems. The predicted reduction of constructed aquatic habitats may affect the native species using them, but may not have a major adverse impact on biodiversity regionally because the species recorded in constructed habitats tend be abundant and widespread, and such species also occur in natural wetland habitats. Sensitive species that depend on native vegetation persisting in reasonable amounts and in good condition are at greater risk. In the Riverina, the remaining native vegetation should be managed to protect and improve its condition, including appropriate managed inundation events for flood-dependent communities. The landscape should be managed to provide the best context for the function and health of existing vegetation including moderating the effects of soil disturbance, fertilizers and herbicides. The impacts of changed irrigation practices should be mitigated through managed flooding of remnant vegetation. In countries with more evolved, traditional rice-growing systems than the Riverina, there will be greater emphasis on biodiversity coexistence with cultivation. Nonetheless, in all settings there is value in jointly considering the role of both natural and constructed habitats in biodiversity research and conservation.

Keywords: amphibians, climate change, reptiles, vegetation, waterbirds, wetlands

INTRODUCTION

With 155 million ha under cultivation, rice is the second most important cereal crop globally (Van Nguyen & Ferrero 2006) and accounts for over a quarter of irrigation water used (Bouman *et al.* 2007). Flooded rice cultivation (paddy rice) creates around 130 million ha of human-created wetland habitat, a significant amount compared with the 570 million ha remaining natural freshwater wetlands (Yoon 2009). A worldwide trend influencing paddy rice is that water supplies are being increasingly appropriated for human use (Postel *et al.* 1996; Molden 2007) and there are ongoing pressures to use irrigation water more efficiently and productively (Kassam *et al.* 2007). Efficient irrigation essentially involves delivery of water for crop growth with minimal losses to the wider environment (Mateos 2008), and this may have important implications for biodiversity in rice growing regions.

In a geographical sense, flooded rice culture is intimately associated with natural wetland ecosystems in most regions where it is grown (Ferrero 2006). It may have displaced natural wetland habitats though recent development, for example in California (USA), Brazil and Australia (Stenert *et al.* 2009) or have evolved intimately with the flooded environment over periods of time up to 8000 years (Ellis & Wang 1997). In either case, changed cultivation and irrigation practices, and particularly increased intensification in traditional rice-growing areas are going to have impacts on ecosystems and the biodiversity associated with them (Rijsberman 2004; Miyamoto 2007). There is little known about the relationship between flooded rice habitats and surrounding landscapes in terms of biodiversity, but this is going to become an increasingly important issue for conservation given global trends of natural wetland loss and modernization, and intensification of paddy rice cultivation (Ferrero 2006; Miyamoto 2007; Stenert *et al.* 2009).

The Riverina bioregion of south-eastern Australia provides an example of an intensive flooded rice production system that has significantly displaced natural wetland ecosystems

*Correspondence: Dr Sue McIntyre e-mail: Sue.McIntyre@csiro.au

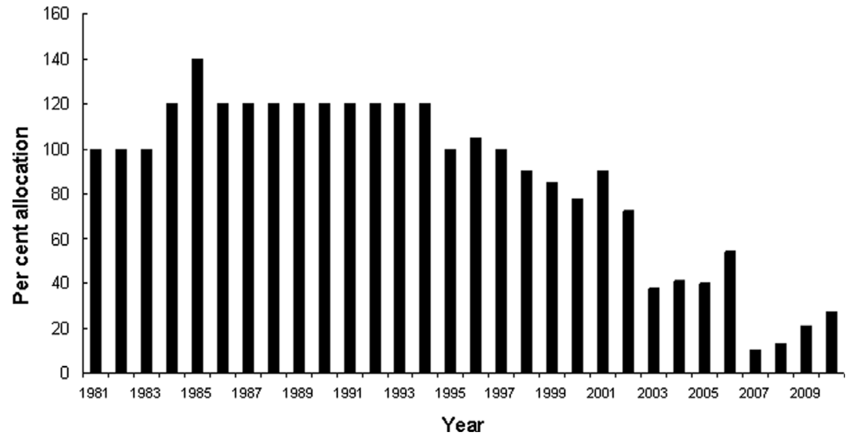

Figure 1 Irrigation water allocations (percentage of licensed quota) for Murrumbidgee Irrigation Area, 1980/1981–2009/2010 seasons. The trend of 100% or greater allocation extends unbroken back to 1914. Historical data source: NSW (New South Wales) Government, NSW Water Information (see http://waterinfo.nsw.gov.au/ac/alloc.xls). Recent data: Murrumbidgee Irrigation (see http://www.mirrigation.com.au/Water%20Info/season%20history-09-10.htm).

and which needs to respond to a diminishing water resource. Predictions of climate change indicate a strong warming and drying trend (Alexander & Arblaster 2009), affecting both the Riverina directly, and the broader Murray-Darling River system which provides flood and irrigation water to the Riverina. Diversion of stream flows for irrigated agriculture is placing natural flood-dependent ecosystems under additional stress (Kingsford 2000; Horner *et al.* 2009). Irrigators have already experienced a precipitous drop in irrigation water allocations over the last decade (Fig. 1), in stark contrast to over 80 years of receiving 100% or more of licensed allocations.

The purpose of this article is to review how changed management of rice cultivation may influence native biodiversity persistence in the region. To achieve this we firstly provide an account of the past impacts of pastoralism and irrigation development on the landscapes. We describe the constructed habitats and water regimes created by rice cultivation, and summarize likely changes in irrigation practices in response to water shortages. We then consider the effects on flora and fauna and discuss possible mitigation strategies. Finally, we consider the relevance of these strategies to other rice agro-ecosystems regions of the world.

PAST AND PREDICTED CHANGES

Prehistory

The Riverina bioregion straddles the Murray and Murrumbidgee Rivers, its central point being approximately 35°S and 145°E. The climate grades from temperate cool-season wet in the south, to Mediterranean and semi-arid in the north (Hutchinson *et al.* 2005). The region is dominated by a semi-arid outwash plain of alluvial fans, with sediments built up from a system of prior streams (Butler 1950). The present river systems have been cutting down through these sediments and are now at a lower level than the prior streams. Despite the relatively flat topography, a variety of plant communities occur in this bioregion, many having evolved in direct response to zones of flooding frequency (Beadle 1948). Historically, wetlands on the plain filled via flooding of the major rivers and streams, driven by upstream precipitation, or in some cases via local rainfall events. Floods would usually have occurred in late winter or spring every year, driven by snowmelt and rainfall in the headwaters. Aboriginal people lived in the region at least 40 000 years prior to the arrival of Europeans in the 19th century (Hope 1995). Their life centred on riverine and wetland sources of water, with occasional excursions into drier country.

European settlement and agricultural development

The first major impact of European settlement in the area was the establishment of pastoralism in the mid-1800s, which resulted in clearing and overgrazing throughout the region (Beadle 1948). The second major phase was the establishment of extensive irrigation schemes, with the creation of the Murrumbidgee Irrigation Area starting in 1914, followed by the Murray Valley Irrigation Districts in the 1940s, and the Coleambally Irrigation Area in the 1960s. Other less intensive developments occur to the west of the Murrumbidgee Irrigation Area. These schemes have resulted in the conversion of 456 000 ha of the Riverina to intensively managed irrigation land with considerable expansion of European settlement and influence (Leigh & Noble 1972). Floodplain agricultural development and upstream water resource development have resulted in much of the floodplain area being replaced by agriculture or isolated from natural inundation (Kingsford 2000). For example, in the western Riverina, the maximum period between Murrumbidgee River floods has more than doubled (from 4 to 10.5 years) while the average annual flooding volume has more than halved (CSIRO 2008).

Establishment of irrigation infrastructure involved the creation of supply and drainage channels, storage dams, and associated roads and settlements. Horticultural crops and broad-acre row crops (such as maize) have been generally watered by flooding furrows, while rice, wheat and pasture have been grown in levelled bays that are completely flooded. These activities involve significant and ongoing earthworks (contour banks, levees and ditches) and altered flow and drainage patterns across the landscape. Channels and flooded rice bays have provided large areas of free water continuously over the warmer months, in a landscape that would have been mainly dry in summer.

Changes to native vegetation communities

We reviewed major vegetation communities in the Riverina bioregion , and both past impacts of agricultural development on vegetation extent and ongoing threats (summarized in Table 1). Together, these communities supported the full range of the area's native fauna and flora. Virtually all community types have been seriously affected by agricultural development, either directly by clearing, or indirectly through changed flooding regimes, weed invasions and grazing by livestock. The woodlands of *Eucalyptus*, *Acacia* and *Callitris* that once dominated the bioregion have been subject to the greatest amount of clearing. Wetlands in the Riverina were most commonly found interspersed with woodlands and forests dominated by either river red gum (*Eucalyptus camaldulensis*) or black box (*E. largiflorens*). Understorey species composition and responses vary according to flooding regime (Williams 1955, 1956; Paijmans 1978; McIntyre & Barrett 1985; McIntyre *et al.* 1988). Wetlands lacking a tree layer may take the form of reed beds, rushlands and grasslands. Lignum (*Muehlenbeckia* spp.) shrubs dominate wetlands with or without a tree layer.

Most of the wetlands are impermanent, are fed by local rainfall or channel flooding, and are variable in size, depth and flood regime. Since river regulation, they have suffered from insufficient flooding, particularly those distant from the main river channels. Many are so altered that they are no longer recognized as wetlands. Others have been artificially flooded for too long or at inappropriate times, their altered hydrology being indicated by dead and unhealthy trees, and invasion of species tolerant to long-term inundation (Roberts 2005).

While the conservation management of all remaining native vegetation is critical for the region, we focus here on: (1) river red gum forests, woodlands and associated wetlands; and (2) black box woodlands and associated wetlands. These communities have been subject to the greatest impact of irrigation development and activities, and have a strong dependence on flooding. They form most of the small remnants of vegetation in the intensive irrigation areas and are therefore directly affected by changes in management.

Constructed habitats resulting from irrigation development

Two major habitats for native biota have been artificially created by irrigation development, namely irrigation channels and flooded bays in which broad acre crops are grown. Other habitats associated with farming in general are dams and impoundments that are generally permanently flooded but occupy a relatively small area.

Large open earth supply channels (7–30 m wide and up to 3 m deep) distribute water from the Murrumbidgee and Murray Rivers to the irrigation areas. These channels are nearly permanently inundated. Similar open earth drainage channels have been created to manage used and excess water. These include modified pre-existing creek lines, and many eventually empty into dams, rivers or low-lying land. Smaller shallow open earth channels (usually <5 m wide and <1 m deep) distribute water across each farm. Most irrigation canals are drained periodically for dredging and vegetation control by direct removal or use of herbicides. This dumping of sediment and mechanical disturbance results in exotic species dominating the adjoining terrestrial vegetation. Native vegetation is highly susceptible to this combination of soil disturbance and nutrient enrichment (McIntyre & Lavorel 2007).

Rice and terrestrial crops are grown in levelled bays separated by earth contour banks with a fall of approximately 7 cm between them. For rice production, bays are continuously flooded from spring to early autumn. Terrestrial crops such as wheat and pasture are often grown in the contoured paddocks during winter generally in rotation with rice. Rice bays have rapidly changing moisture conditions favourable to mobile and opportunistic organisms that are able to exploit temporary resources, such as some aquatic invertebrate species (Bambaradeniya *et al.* 2004; Wilson *et al.* 2008), some frog species (Wassens *et al.* 2004; Doody *et al.* 2006) and plants with large seed banks (McIntyre 1985).

Predicted changes to water regimes and irrigation practices

Changes in irrigation practices stem from reduced availability of water, resulting in the development of water conservation strategies and fewer areas under irrigated broad acre crops. Although Riverina irrigators have a history of increasing water-use efficiency (Humphreys *et al.* 2006), current and forecast circumstances will require even greater levels of ingenuity. Projected changes have been identified by the authors through information synthesis and consultation with the industry (see Gaydon *et al.* 2010) and include:

(1) A further general reduction of flows in rivers. Climate change is expected to result in reductions in Murray–Darling stream-flows of 16–25% by 2050 and 16–48% by 2100 (Christensen *et al.* 2007).
(2) Changes in water regimes for some natural habitats, associated with changes in management of drainage and surplus irrigation water (i.e. water rejected due to natural rainfall events). For example, surplus water may be stored for later use in crops rather than being discharged onto wetlands.
(3) Reductions in area under irrigated agriculture in a higher proportion of seasons, including reductions in the area of paddy rice.
(4) Methods of water application to reduce water use, such as increased adoption of efficient lateral move, centre pivot and drip irrigation technology on lighter soils, and

Table 1 Major vegetation formations and plant communities of the Riverina bioregion in New South Wales. Formations, community ID and status are from Benson *et al.* (2006); additional notes from Cunningham *et al.* (1981).

Formation (group acronym)	*Major communities in the Riverina (ID numbers)*	*Approximate % of pre-European extent remaining*	*Condition*
River red gum (*E. camaldulensis*) forests and woodlands of watercourses and flood plains (EIW)	Tall forests in frequently flooded areas adjacent to watercourses, woodlands on higher less flooded ground (2, 5, 7, 8, 9, 10, 11)	Taller forests logged and grazed with less clearing (> 60% remaining); on higher ground there is more clearing for agriculture (30–60%)	Moderate to poor, threats from changed flood regimes, salinity, grazing, timber removal
Black box (*E. largiflorens*) woodlands of watercourses and flood plains (EIW)	Extensive, associated with watercourses, wetlands and flood plains, less regularly flooded (13, 15, 16)	Wetter communities impacted by cropping, horticulture and grazing (30–50%) elsewhere (30–60%)	Mostly poor but recoverable condition resulting from grazing, changed water regimes and rising water tables. More impacted in the irrigation areas
Freshwater wetlands, regularly flooded (FWI)	Herblands and *Muehlenbeckia* shrublands of floodplain depressions (12,17); shallow sedgeland associated with flood plains or local drainage (53)	Cleared for crops and horticulture (40–80%). Shrublands most heavily impacted.	Moderate, though *Muehlenbeckia* shrubland poor. Threats from stock trampling, altered flood regimes and weed invasions
Freshwater wetlands, (semi-) permanently flooded (FWI)	*Typha* rushlands (182) of streams, ox-bow lakes and flood plains; forblands and sedgelands of lakes (238)	Drainage and river regulation have displaced communities (40–75%)	Moderate condition. Altered flooding, pollution and salinity
Grasslands of freshwater aquatic habitats or periodically flooded soil (GFAPF)	Tussock grasslands of drainage depressions and plains, dominated by *Eragrostis australasica* (24) and *Lachnagrostis* (47)	*Lachnagrostis* (47) most affected by clearing for agriculture (50%) *Eragrostis* (24) less cleared due to unsuitable soils (80%).	Moderate condition. Grazing, altered flood regime and weed invasion are ongoing threats
Eucalypt grassy woodlands (EBWP)	Combinations of *E. microcarpa*, *E. melliodora*, *Callitris glaucophylla* on lighter soils (75, 76, 80)	Cleared for cropping, horticulture, grazing (<30%)	Very poor, composition and structure altered, highly fragmented by clearing, natural regeneration not possible in some cases
Grey box (*E. microcarpa*) grassy woodlands (EIW)	Limited to grey clays on rises in flood plains dominated by river red gum forests along the Murray and Murrumbidgee Rivers (237)	Thinned for timber and grazing, cleared for dryland cropping and horticulture (<50%).	Poor, as structure and/or composition significantly altered. But sufficient biota remain for restoration
White cypress pine (*Callitris glaucophylla*) woodlands (CPW)	Open woodland of sand plains, prior streams and dunes (028)	Cleared for agriculture and intensive grazing (<30%)	Poor due to lack of tree and shrub recruitment, erosion, weed invasion. Highly fragmented
Weeping myall (*Acacia pendula*) open woodland (ASI)	On brown clays and loams on alluvial plains (026)	Cropping and horticulture; grazing has converted large areas to grassland (<30%)	Poor, structure and/or composition significantly altered. But sufficient biota remain for restoration
Casuarina woodlands (CCI)	Black Oak Western Rosewood (*Casuarina cristata Alectryon oleifolius*) open woodland on deep sandy loams (058)	Cleared for cropping and horticulture, used for grazing and timber production (30–60%)	Poor, structure and/or composition significantly altered. But sufficient biota remain for restoration
Chenopod shrublands (CHS)	Numerous community types on a range of soils *Maireana*, *Atriplex*, *Bassia*, *Nitraria* (153, 157, 159, 163, 164, 166, 216, 236)	Estimates of original extent and remaining areas vary greatly within and across communities	Grazing has converted shrubland to annual grasslands in many cases
Grasslands on fine-textured soils (GFTI)	(*Chloris*, *Danthonia* and *Stipa*) Widespread on clays and clay-loams (44–46)	Cleared for cropping, horticulture, used for grazing. Remaining extent varies greatly with community type from <30 to >60%	Generally poor condition. Some grasslands some converted from perennial annual. Potential for improvement with change in grazing practice

reductions and increased efficiency in the use of flood irrigation techniques.

(5) Changes in the methods of delivering water to reduce leakage and evaporative losses. This could include sealed lining of earthen irrigation channels and the piping of water which has previously been carried in open channels. Under current water prices, economics dictate that these changes are likely to be limited to locations where channels or drains cross highly permeable soils. Increasing costs of water could result in more widespread piping and lining.

(6) Increases in herbicide use may occur, because the use of ponded water has been the primary method for controlling weeds in rice crops.

(7) Adjustments to farming practices and associated changes to farm layout are likely. For example recycling of water will involve increasing on-farm water storages and associated engineering works.

If correct, these predictions will create further challenges to a biota that has already been dramatically perturbed by pastoralism and irrigation development. In the following sections, we draw on available information on species and community response to consider how the predicted changes may further affect flora and fauna conservation in the Riverina.

EFFECTS OF CHANGES IN IRRIGATION PRACTICE ON FLORA

Wetland flora

The creation of constructed habitats such as rice bays, channels and roadside ditches has provided habitat permitting native herbaceous wetland plants to persist long after their associated trees and shrubs have disappeared from these habitats (McIntyre *et al.* 1988). Unlike their terrestrial native counterparts, wetland species appear to have been pre-adapted to productive highly disturbed situations (McIntyre & Barrett 1985; McIntyre *et al.* 1988). The largest threat to this assemblage in constructed habitats will be lining and piping of channels, and reduced areas of paddy rice production. This will certainly reduce population sizes of some species. In the case of channels, where diversity is limited by deep water and the effects of dredging and herbicides, a reduction in area or impermeable lining will pose little threat. Rice bays are potentially of more concern, as a survey comparing flooded bays with natural swamps found 11 native species to be found only in rice bays compared with 29 species restricted to swamps (McIntyre *et al.* 1988). This situation would need to be reassessed to identify the current threats more precisely, as the diversity status of both habitats may have changed over the 30-odd years since this survey. The fate of wetland species is linked with that of their associated woodlands, as discussed below.

Woodlands

Notwithstanding any effects of climate change on rainfall and natural water flows, the major issues for flood-dependent woodlands are those resulting from local management of irrigation water. Irrigation infrastructure has interfered with natural drainage patterns, and where 'waste' water may have previously been applied to woodland remnants, there is a trend toward more careful recycling and storage of water on-farm in dams and channels. This could have positive effects on flood-dependent woodlands by avoiding prolonged waterlogging, or could have negative effects, due to induced drought compounding the effects of loss of natural flooding. More broadly, irrigation and tree clearing in the Riverina have caused water tables to rise, with associated increases in soil and water salinity. The recent drought, together with changes in infrastructure and management, has lowered the water table, and these factors have combined to reduce the urgency of this problem, at least in the short term. Changes in irrigation practices in the future may further reduce the amount of water reaching the water table; this issue requires ongoing monitoring and management.

Removal of paddock trees is a conservation issue with potential to escalate under changing irrigation techniques, as installation of lateral move and centre pivot irrigation systems requires large treeless areas to operate. Isolated paddock trees in intensively farmed landscapes are increasingly recognized as irreplaceable habitat elements for native fauna (Manning *et al.* 2006). Retained paddock trees are typically mature and bear hollows upon which native fauna rely for breeding and shelter (Gibbons & Boak 2002). Isolated trees may also act as 'stepping stones' or provide some form of connectivity across the agricultural landscape. They can also provide a feeding resource for fauna such as bats, birds and mammals (Gibbons & Boak 2002; Lumsden & Bennett 2005).

River red gum (Eucalyptus camaldulensis) forests and woodlands

River red gum communities are widely distributed in the Riverina and grow under a range of flood regimes (Benson *et al.* 2006) as well as accessing groundwater (Mensforth *et al.* 1994; Thorburn & Walker 1994). Communities near major rivers are generally adapted to flooding every 1–3 years, but tolerate dry or wet periods of up to two years (Bren & Gibbs 1986; Bren 1987, 1988; Robertson *et al.* 2001). Large areas are managed for grazing and forestry (Bacon *et al.* 1993; Jansen & Robertson 2005). These modifications have a range of effects upon the vegetation community, including poor tree health leading to compositional and structural change (Briggs & Thornton 1999; Robertson *et al.* 2001; George *et al.* 2005; Horner *et al.* 2009). Current responses to water shortages include substituting natural flooding in some areas with managed water allocations to restore the condition of tree and fauna populations (Nias *et al.* 2003).

https://doi.org/10.1017/S0376892911000130 Published online by Cambridge University Press

Table 2 Frogs recorded in the Riverina. Summary of historic records and recent habitat records in the irrigation areas as collated and reported by: 1 = Ehmann (1996); 2 = Wassens *et al.* (2004); 3 = Doody *et al.* (2006); and 4 = Wassens *et al.* (2008).

Name	*River red gum*	*Black box*	*Dams*	*Rice bays*	*Channels*
Plains froglet (*Crinia parinsignifera*)	2, 3	2, 3	2, 3	2, 3	2, 3
Sloane's froglet (*C. sloanei*)	–	–	2	–	–
Barking marsh frog (*Limnodynastes fletcheri*)	2, 3	2, 3	2, 3	2, 3	2, 3
Spotted marsh frog (*L. tasmaniensis*)	2, 3	2, 3	2, 3	2, 3	2, 3
Giant bullfrog (*L. interioris*)	2	–	2	–	–
Eastern banjo frog (*L. dumerilii*)	–	–	–	–	–
Peron's tree frog (*Litoria peronii*)	2	2	2	2	2
Broad-palmed frog (*L. latopalmata*)	2	–	–	–	–
Southern bell frog (*L. raniformis*)	1	1	1	1, 4	1, 4
Green tree frog (*L. caerulea*)	–	–	–	–	–
Sudell's frog (*Neobatrachus sudelli*)	–	2	2	2	2
Wrinkled toadlet (*Uperoleia rugosa*)	2	2	2	2	–
Bibron's toadlet (*Pseudophryne bibronii*)	–	2	–	–	–
Crucifix toad (*Notaden bennetti*)	–	2	2	–	–

Black box (Eucalyptus largiflorens) woodlands

Despite broad-scale clearing (Table 1), black box woodlands remain widespread (Benson *et al.* 2006). These communities have been commonly used for grazing and disposal of irrigation drainage and escape water (Harrison & Roberts 2005), and their condition is often compromised as a result (Eldridge *et al.* 2003, 2007). It is thought that natural flood events occurred in 10–50% of years, for periods of 2–6 months (Jolly *et al.* 1996; Akeroyd *et al.* 1998; Slavich *et al.* 1999). Access to groundwater is important for tree survival during dry periods. Although relatively tolerant, black box trees will succumb to too little, or too much, flooding (George *et al.* 2005). Understorey composition and structure are also altered, and this affects fauna such as waterbirds breeding in reed beds, although very few data are available to identify specific links between water regime and biodiversity status of these communities.

Black box trees themselves are regionally significant in providing nesting hollows and supplying nectar for fauna (Gates 1996; Eldridge *et al.* 2003). However, in many remnants mature hollow-bearing trees have been removed, and the understorey has little fallen timber, few perennials and is dominated by exotic plants (Eldridge *et al.* 2003, 2007; Eldridge & Lunt 2010). Even under these circumstances, rice farms with black box vegetation support more fauna than farms without (Doody *et al.* 2006). As in other Australian agricultural landscapes, fauna occurrence varies with proximity of a vegetation remnant to other vegetation, as well as patch size and condition (see for example Wassens *et al.* 2004, 2005*a*, *b*; Brown *et al.* 2008).

EFFECTS OF CHANGES IN IRRIGATION PRACTICE ON FAUNA

Faunal surveys in the Riverina have included both native vegetation and constructed habitats such as irrigation channels, and constitute the main source of information in considering vulnerabilities to future changes. We consider four vertebrate groups (frogs, reptile, birds and mammals).

Amphibians (frogs)

Of the 14 species of frog that have been historically recorded in the Riverina, 12 have been recorded in irrigation areas in recent years (Table 2). The two unaccounted for, namely the green tree frog (*Litoria caerulea*) and eastern banjo frog (*Limnodynastes dumerilii*), are more likely to be detected in periods of several successive wet years. There appear to be no species restricted to rice bays or irrigation channels, though one species, the endangered southern bell frog (*Litoria raniformis*) may now rely on permanently flooded channels or dams for over-wintering and dry-season persistence (Wassens *et al.* 2007, 2008).

In general, black box depressions in the Riverina have slightly greater frog species richness (eight spp.) than river red gum wetlands (six spp.), rice bays (six spp.) and channels (five spp; Wassens *et al.* 2004). One species (the broad-palmed frog, *Litoria latopalmata*) appears to be restricted to river red gum billabongs. Dams with abundant vegetation support the highest number of species (nine spp.). We interpret this to be because of the density and diversity of fringing vegetation and number of microhabitats, which are elements of favourable frog habitat elsewhere in Australia (Hazell *et al.* 2004).

The changes in irrigation practice that are most likely to affect amphibian diversity in the Riverina are those relevant to dams, and those affecting the condition of black box depressions. While there is some chance that unpredictability in water supply may lead to construction of more dams to increase water security over time, the value of both new and old dams will depend on maintaining a variety of vegetation in and around dams (Hazell *et al.* 2001). Amphibian habitat quality of both dams and black box remnants may also be affected by agro-chemical usage. In the Riverina, organically grown rice was found to have more diverse macro-invertebrate communities than rice bays treated with agrochemicals (Wilson *et al.* 2008), which may affect the quality, if not the quantity of food supply for frogs in channel, dams and rice bays.

Reptiles

Reptile abundance and diversity are low in the Riverina compared with other sites in south-eastern Australia (Wassens *et al.* 2005*b*; Brown *et al.* 2008). Although 29 species have been recorded in vegetation remnants of the Murrumbidgee Irrigation Area (Wassens *et al.* 2005*b*), other studies in the Riverina have located far fewer species (AMBS [Australian Museum Business Services] 2005; Doody *et al.* 2006; Brown *et al.* 2008). Only four species were considered both abundant and widespread in the southern Riverina (Herring *et al.* 2006*a*, *b*, *c*, *d*): Boulenger's skink (*Morethia boulengeri*), Carnaby's wall skink (*Cryptoblepharus carnabyi*), the southern marbled gecko (*Christinus marmoratus*) and the eastern brown snake (*Pseudonaja textilis*).

In irrigation areas, reptiles are more abundant in black box remnants than in other rice farm habitats such as rice bays, dams, dry crops or river red gum woodland (Doody *et al.* 2006; Brown *et al.* 2008). Ten species have been found in black box remnants of the Murrumbidgee Irrigation Area, compared to six species in river red gum (Wassens *et al.* 2005*b*). Numbers of reptiles in river red gum communities are thought to be limited by long periods of flooding, though the habitat is important for skinks, geckos and carpet pythons. Resident species are commonly large mobile generalists, or arboreal in habit. The highest richness, abundance and frequency of reptiles have been recorded in roadside remnants of black box, possibly reflecting greater structural complexity due to protection from grazing (Brown *et al.* 2008). Overall, species richness varies with grazing pressure, fallen timber and connectivity between patches of vegetation (Sass *et al.* 2004; Wassens *et al.* 2005*b*).

Most reptile species in the Riverina are restricted to terrestrial habitats or the margins of wet areas, though they may be attracted to and benefit from the higher abundances of frogs and insects associated with irrigation waters. However, Doody *et al.* (2006) found no difference in diversity or abundance between rice bays and dry crops, except for tortoises. The eastern long-necked tortoise (*Chelodina longicollis*) uses large irrigation channels, with feeding forays into rice bays during the irrigation season (Doody *et al.* 2006). Loss of these habitats would negatively affect tortoise populations in localized areas, but being an abundant and widespread species, such changes would not greatly reduce reptile diversity in the Riverina. Improving the condition of remnant vegetation would provide significantly greater long-term benefit.

Birds

The Riverina provides internationally significant habitat for waterbirds (Kingsford & Thomas 2004) and supports a range of rare and threatened terrestrial birds (Jansen & Robertson 2005). Many Riverina bird species have suffered regional and national population declines in the last 25 years (Kingsford *et al.* 1999; Ford *et al.* 2001; Porter *et al.* 2006). Successful breeding by waterbirds in the region has been linked to the water regime required to produce suitable habitat (Briggs *et al.* 1997; Briggs & Thornton 1999) and in many sites water regimes have been changed by irrigation practices. Clearing and grazing have also affected species composition and abundance in the region (Jansen & Robertson 2001). In recent years, surveys have found that black box communities generally have had higher terrestrial bird diversity and abundance than several other major vegetation types in the region (Antos & Bennett 2005; Herring *et al.* 2006*a*, *b*, *c*, *d*).

Constructed habitats associated with irrigation have the potential to increase resources for birds (for example herons and egrets in southern Europe), but also create hazards, for example through pesticide use (Czech & Parsons 2002). A wide range of Australian birds use rice bays, irrigation channels and water storages for foraging. These habitats can partially substitute for lost or altered habitat; in the rice growing regions of Italy, Spain and California, irrigation channels (canals and ditches) and their margins provide nesting and foraging habitat for waterbirds (Czech & Parsons 2002; Taft & Elphick 2007). In general, terrestrial bird and waterbird diversity associated with irrigation channels is greatest when channels are large and have extensive complex vegetation, both inside and outside the channel itself (Herzon & Helenius 2008). Irrigation channels in the Riverina rarely have these characteristics. Lining channels with concrete further reduces habitat value (Lane & Fujioka 1998; Maeda 2001). In Australia, there is evidence of ducks and egrets foraging in channels (Frith 1957*a*, *b*; Richardson & Taylor 2003) but there are no records of associated breeding.

Waterbirds exploit rice crops for their food resources worldwide (Frith 1957*b*; Richardson *et al.* 2001; Czech & Parsons 2002; Taft & Elphick 2007). Ducks have had minor economic impacts in Australian crops through feeding on grain and young plants in the establishment phase. This was found by Frith (1957*b*) to be offset to some extent by their consumption of seed from the major grass weed *Echinochloa*, and the damage was usually confined to those areas in crops where growth was unsatisfactory for other reasons. Australian egrets (*Ardea alba* and *Egretta intermedia*) have been recorded foraging in rice during their breeding season but shifted to natural wetlands as the crops matured and chick rearing took place. In contrast the introduced cattle egret (*Bubulcus ibis*) foraged in rice fields until after their chicks had fledged, leading to speculation that this invasive species may have some advantage over the native egrets in the irrigated agricultural landscape (Richardson & Taylor 2003).

Targeted management practices can be important for improvement of food availability for birds in irrigation areas that have replaced natural wetland habitats. For example, in the USA, stubble management, shallow winter flooding, reduced use of pesticides, fallow and secondary crop rotation practices that encourage seeding plants are beneficial (Taft

& Elphick 2007). In the Riverina, reports indicate that terrestrial birds and waterbirds increase around rice bays following flooding and decrease after draining (Doody *et al.* 2006).

Although constructed habitats in irrigation areas may provide some resources for native birds, large regional declines in the populations of many waterbird species have coincided with irrigation development (Kingsford & Thomas 2004). So while we do not understand the net population effects of particular constructed habitats on birds, it would appear that irrigation development overall has not been able to do more than partially substitute for the alterations and losses of the natural habitats and resources that have ensued. Consequently the impacts of further change to water availability in the Riverina via changes in irrigation practice are difficult to estimate.

Mammals

Many mammal species present in the Riverina in the past are now rare. The only abundant and widespread native mammals are bats, the eastern grey kangaroo (*Macropus giganteus*) and the brush-tailed possum (*Trichosurus vulpecula*). Currently the greatest diversity of mammals appears to be in river red gum forests (Herring *et al.* 2006*a*, *b*, *c*, *d*), which contain several species of bats, as well as yellow-footed antechinus (*Antechinus flavipes*), water rats (*Hydromys chrysogaster*), black wallaby (*Wallabia bicolour*), sugar glider (*Petaurus breviceps*) and platypus (*Ornithorhynchus anatinus*). Black box woodland also supports bats, eastern grey kangaroos and brush-tailed possums, and the presence of these species is dependent on specific landscape and woodland characteristics, for example landscape complexity, shrub and log cover, presence of hollow-bearing trees and woodland patch size (Lewis 2006).

The use of constructed irrigation habitats by mammals is poorly known, both in Australia and overseas. There are potential benefits of habitat in close proximity to a water source such as an irrigation channel. However in the Riverina this seems to be offset by the loss of adjacent native vegetation due to channel maintenance activities. The introduced house mouse (*Mus domesticus*) was the only mammal recorded in a large survey (45 000 trap-nights) adjacent to irrigation channels and in fields in the Riverina (Brown *et al.* 2004). House mice are usually the most abundant mammals in rice bays (Brown *et al.* 2004; Doody *et al.* 2006). In tropical rice systems overseas, these may attract carnivores such as mongoose, wild cats, otter and civet cats (Bambaradeniya *et al.* 2004); in the Riverina they may attract introduced predators such as cats and foxes as well as provide food resources to some native raptors (Sinclair *et al.* 1990). One native mammal that might be expected to occur is the water rat; however a recent survey in the Murrumbidgee Irrigation Area failed to find water rats in or near irrigation channels (Lewis 2006) even though they occasionally use rice bays (Scott & Grant 1997). Overall, constructed habitats offer poor habitat for native mammals, which appear to be more dependent on native vegetation than the other fauna groups. Therefore changes in the availability of constructed habitats and water sources are unlikely to significantly change abundance or diversity of mammals in the Riverina.

MITIGATION AND ADAPTATION

We can summarize the effects of the previously listed potential changes in irrigation supply and management on biodiversity and discuss appropriate response strategies as follows.

A further general reduction of flows in rivers

A further general reduction of flows in rivers will reduce the frequency and magnitude of flooding events, which will affect natural water regimes of river red gum and, to a lesser extent, black box communities. All components of biodiversity will be affected by these changes. The Murray-Darling system is highly controlled and, except in exceptionally wet years and in circumstances of local flooding, flooding events will be explicitly controlled. There is an acute awareness of the trade-off between environmental uses of water (such as to flood wetlands) and its use for human purposes, and the issue is currently being debated at the Australian national level. It is likely that flooding regimes approximating pre-European conditions will be restored for a limited number of wetlands in the Murray-Darling system.

Changes in water regimes for some natural habitats

On-farm management of irrigation waters is important for the remnant flood-dependent woodlands that exist within the rice agro-ecosystem. For this reason, all components of biodiversity are subjected to the vagaries of individual irrigation decisions and managed flooding will become even more important in the face of more generally dry conditions due to climate change. There is great scope for refining management in ways that can benefit remnant native vegetation. The New South Wales Murray Wetlands Working Group has successfully inundated many wetlands in southern NSW, and such cooperation between irrigation companies, landholders, government departments and catchment management groups can be effective (Nias *et al.* 2003). Even partial rehabilitation of a wetland can provide multiple benefits to both irrigators and the environment. For example, Barren Box Swamp, an intermittent wetland in the Murrumbidgee Irrigation Area, was permanently inundated by irrigation drainage for about 50 years, killing most of the black box trees. Restoration consisted of splitting the area into three cells, including a deep storage cell, resulting in more efficient storage (less evaporation) and restoration of 1650 ha of the wetland to an intermittent regime (Murrumbidgee Irrigation 2009). The extent to which these habitats can be maintained, when overall water availability is likely to decline, will be driven by political and economic imperatives.

Reductions in area under irrigated agriculture

As well as reducing the average area of flooded rice bays, this may reduce the total average amount of free water in supply and irrigation channels. These are discussed under the following two headings.

Irrigation techniques for reduced water use

Future reduction in area and duration of flooding in irrigation bays is highly likely, and this will reduce a previously extensive habitat for a range of species in the warm season. As for channels, the local abundance of some frogs and waterbirds may be reduced, but these changes will not necessarily be deleterious in terms of total biodiversity in the region, providing natural habitats are maintained. The situation is less clear for wetland plants, which appear to have some dependence on flooded rice bays, but it could be argued that the improved management of natural wetlands would compensate for reduced areas of flooded rice.

Reducing leakage and evaporative losses in water delivery

In Japan, concrete lining and piping of irrigation channels has resulted in loss of habitat for aquatic invertebrates, amphibians and some waterbirds (Fujioka & Lane 1997; Lane & Fujioka 1998). If such engineering modifications are widely implemented within Australia, the likely result will be reductions in abundance of species that exploit channels (such as frogs and turtles) and possibly sedentary terrestrial species from the surrounding landscape that obtain food resources from them. However, many species associated with channels are relatively common, and while channels provide additional habitat, refuge during unfavourable seasons and connectivity of aquatic habitat across the landscape, there is no evidence that they provide habitat that cannot be maintained with appropriate management of remaining native vegetation, natural watercourses and wetlands.

Increases in herbicide use

Herbicides and fertilizer are important in rice cultivation, but there are significant contributions from flooding in suppressing some major weeds (McIntyre *et al.* 1991). Dependence on herbicides is likely to increase with reduced flooding depth or duration. While discharging drainage water on native vegetation could provide beneficial watering, residual chemicals and nutrients could be detrimental. Strategies to control these, such as retention and recycling, need to be integrated into any recommendations for changed practices to reduce water use.

Adjustments to farm layout

While most constructed aquatic habitats are likely to decline in the future, the number of dams will most likely increase to conserve and recycle water on-farm. This has the potential to benefit a range of common species, most notably frogs and turtles. There will be options to improve habitat for fauna within irrigation areas by creating physical variability within and among dams, excluding livestock and restoring vegetation (Hazell *et al.* 2001; Jansen & Healey 2003; Hazell *et al.* 2004; Jansen & Robertson 2005).

It is likely that changed farm layout will further threaten remnant vegetation with earthworks during the construction process. Modified irrigation techniques may also threaten remnant vegetation. For example, efficiency practices such as laser levelling and centre pivot irrigation may affect critical landscape elements such as isolated mature native trees, which may have otherwise persisted in paddocks. There is scope for strategies that mitigate for these effects, as well as more proactive approaches to farming that could result in better prospects for biodiversity.

CONCLUSIONS AND GLOBAL PERSPECTIVE

Summary of impacts

In the Riverina, the general reduction in water availability associated with constructed wetland habitats will have some local impacts on biodiversity. However, this is not necessarily a major problem as the plants and vertebrate fauna of such habitats tend to be common, generalist and are necessarily tolerant of some human disturbance. The population sizes of common species are likely to be reduced rather than local extinctions occurring. It should be noted that there may be more vulnerable species that are dependent on the productivity of constructed habitats that may not have been identified with the available information. The question of importance is whether there are still sufficient natural or alternative constructed habitats to support viable populations of both these 'common' and vulnerable species after the changes have taken place. This seems likely for some groups (for example frogs and invertebrates), but to understand the impacts, comparative studies of the range of possible habitats would be needed to clarify the situation for aquatic plants, mammals and birds, and for particular species (such as the southern bell frog). The scenario for waterbirds is difficult to comprehend owing to their nomadic movements and dependence on a range of alternative wetlands that may be affected by changes to water management. Scientific understanding of these dynamics is rudimentary. Locally occurring birds will be threatened by changed farming practices that result in the loss of mature trees in paddocks, further loss of native vegetation and unfavourable flooding practices.

General principles for conservation in face of water shortage

The best investment for the future will be to increase current efforts to protect and improve the condition of existing native vegetation of all community types in the irrigation areas and the region more widely. There are large areas

https://doi.org/10.1017/S0376892911000130 Published online by Cambridge University Press

of native vegetation that are in need of improvement in ecosystem condition (Table 1). This will require managed inundation events for flood-dependent communities, and actions to increase habitat complexity such as controlled grazing, retaining fallen timber and conserving standing timber. Recognizing the importance of preventing nutrient enrichment and inappropriate soil disturbance is also vital for function and diversity (McIntyre & Lavorel 2007).

Landscape-scale management is particularly important in times of change. By applying established principles for conservation, a risk-based approach can be used with a modest investment in new information. For example, maintaining a mosaic of heterogeneous habitats at multiple spatial scales (site, farm and region), retaining bigger patches of vegetation and less isolated patches of habitat are all appropriate general strategies for the Riverina landscape. Addressing more detailed questions of landscape design that need to take into account possible dependencies of vulnerable species to both constructed habitats and native vegetation will require considerably more knowledge.

In summary, while there are some issues that are currently intractable to address (for example direct climate change effects on ecosystems and management of nomadic fauna) there are local and regional strategies that could be implemented or investigated. Even with major knowledge gaps in the systems, action can be taken immediately to improve habitats using strategies that are derived from an existing body of knowledge in conservation biology. While details of management responses may be specific to the Riverina (for example flooding regimes for different vegetation types), we suggest that conservation strategies at the landscape and patch level should be no different to any recommended in an intensively managed agricultural landscape worldwide, namely maintain and improve natural vegetation and where possible increase its total area and connectivity (see Lindenmayer *et al.* 2008).

The global perspective

The Riverina rice growing system has considerable similarities to that of the Central Valley of California in terms of time of establishment of the industry, agronomic methods, the temperate climate and the predominantly native weed flora (McIntyre & Barrett 1985). In California, biodiversity management in the rice agro-ecosystem is focused on off-season watering of rice fields for waterbirds as a surrogate for the loss of natural wetlands in the region, these having been reduced to 5% of their original area (Sterling & Buttner 2009). In contrast, Riverina wetlands still persist in significant amounts (30–60% remain, depending on the community; Table 1). The Californian rice industry shares with Australia the problem of diminishing water supply and management of water quality (Hill *et al.* 2006), which may put pressure on environmental watering practices.

A key factor setting both Californian and Australian systems apart from many other regions is the longer cultural history of rice growing in Asia and Africa, measured in thousands of years rather than the tens of years marking rice cultivation in Australia and USA (Ellis & Wang 1997; Miyamoto 2007). In areas with a long cultural history of rice growing, it is to be expected that there has been a degree of adaptation of species to the cultivation system. In this setting, management of traditional rice growing systems will assume high importance for local biodiversity conservation compared with regions where agriculture is novel in an evolutionary sense. It should be noted that in these densely settled, long-established agro-ecosystems, species unable to adapt will have disappeared long ago from the transformed landscapes, and would no longer be considered lost. Rice fields should therefore not be considered a complete surrogate for natural wetlands in any region (Stenert *et al.* 2009). They are essentially simplified agricultural systems that provide some of the needs of some species, and which are highly vulnerable to changed economic and social settings (Czech & Parsons 2002). Rice cultivation throughout the world is subjected to the pressures of declining water supply and increased productivity, regardless of cultural history (Molden 2007; Lee 2009). Although details differ from region to region, reduced flooding and intensification of production systems are pervasive (Ellis & Wang 1997; Miyamoto 2007) and threaten biodiversity, even in traditional systems (Bambaradeniya & Amarasinghe 2003; Rijsberman 2004). Consideration of all flood-dependent biota and all habitats in the wider landscape is essential for biodiversity management in rice growing systems worldwide. This is a largely undeveloped area of research in a system where there has been an understandable focus on production. However, the links between sustainable agriculture and natural resource management, including biodiversity, are starting to be recognized (see for example Ferrero 2006; Stenert *et al.* 2009). Whether the pressures be direct climate change effects, water shortages or changes in farming practice, the essential approach to the conservation of biodiversity and ecosystem function will be to understand the ecosystem linkages between the paddy, wetlands and the wider landscape.

ACKNOWLEDGEMENTS

This work was supported by the Department of Agriculture, Forests and Fisheries, Land and Water Australia (Project CSE5029) and the Ricegrowers' Association of Australia. We also thank M. Pisasale, J. McGufficke, S. Tijs and K. McCann for discussion and information about the Riverina environment, irrigation practices and issues for biodiversity management, and J. McGufficke, A. House and N. Marcar for comments on the manuscript.

References

Akeroyd, M.D., Tyerman, S.D., Walker, G.R. & Jolly, I.D. (1998) Impact of flooding on the water use of semi-arid riparian eucalypts. *Journal of Hydrology* **206**: 104–117.

Alexander, L.V. & Arblaster, J.M. (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *International Journal of Climatology* **29**: 417–435.

AMBS (2005) *Biodiversity monitoring of the Coleambally and Kerarbury Irrigation Areas 2004*. Sydney, Australia: Australian Museum Business Services.

Antos, M.J. & Bennett, A.F. (2005) How important are different types of temperate woodlands for ground-foraging birds? *Wildlife Research* **32**: 557–572.

Bacon, P.E., Stone, C., Binns, D.L., Edwards, D.E. & Leslie, D.J. (1993) Inception report on development of watering strategies to maintain the Millewa group of river red gum (*Eucalyptus camaldulensis*) forests. Technical Publication No. 56. Forestry Commission of New South Wales, New South Wales, Australia.

Bambaradeniya, C.N.B. & Amarasinghe, F.P. (2003) Biodiversity associated with the rice field agro-ecosystem in Asian countries: a brief review. Working Paper 63. International Water Management Institute, Colombo, Sri Lanka.

Bambaradeniya, C.N.B., Edirisinghe, J.P., De Silva, D.N., Gunatilleke, C.V.S., Ranawana, K.B. & Wijekoon, S. (2004) Biodiversity associated with an irrigated rice agro-ecosystem in Sri Lanka. *Biodiversity and Conservation* **13**: 1715–1753.

Beadle, N.C.W. (1948) *The Vegetation and Pastures of Western New South Wales*. Sydney, Australia: Department of Conservation of New South Wales.

Benson, J.S., Allen, C.B., Togher, C. & Lemmon, J. (2006) New South Wales vegetation classification and assessment: Part 1 Plant communities of the NSW Western Plains. *Cunninghamia* **9**: 383–450.

Bouman, B.A.M., Humphreys, E., Tuong, T.P. & Barker, R. (2007). Rice and water. *Advances in Agronomy* **92**: 187–237.

Bren, L.J. (1987) The duration of inundation in a flooding river red gum forest. *Australian Forest Research* **17**: 191–202.

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

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

Briggs, S.V., Lawler, W.G. & Thornton, S.A. (1997) Relationships between hydrological control of river red gum wetlands and waterbird breeding. *Emu* **97**: 31–42.

Brown, G.W., Bennett, A.F. & Potts, J.M. (2008) Regional faunal decline – reptile occurrence in fragmented rural landscapes of south-eastern Australia. *Wildlife Research* **35**: 8–18.

Brown, P.R., Davies, M.J., Singleton, G.R. & Croft, J.D. (2004) Can farm-management practices reduce the impact of house mouse populations on crops in an irrigated farming system? *Wildlife Research* **31**: 597–604.

Butler, B.E. (1950) A theory of prior streams as a causal factor of soil occurrence in the Riverine Plain of south-eastern Australia. *Australian Journal of Agricultural Research* **1**: 231–252.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., Jones, R., Kolli, R.K., Kwon, W.K., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., Arritt, R., Benestad, R., Beniston, M., Bromwich, D., Caya, D., Comiso, J., de Elia, R., Dethloff, K., *et al.* (2007) IPCC WG1 Chapter 11. Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor & H. Miller, pp. 849–926. Cambridge, UK: Cambridge University Press.

CSIRO (2008) Water availability in the Murrumbidgee. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Canberra, Australia.

Cunningham, G.M., Mulham, W.E., Milthorpe, P.L. & Leigh, J.H. (1981) *Plants of Western New South Wales*. New South Wales, Australia: New South Wales Government Printing Office.

Czech, H.A. & Parsons, K.C. (2002) Agricultural wetlands and waterbirds: a review. *Waterbirds* **25** (Suppl. 2): 56–65.

Doody, J S., Osborne, W., Bourne, D., Rennie, B. & Sims, R.A. (2006) *Vertebrate Biodiversity on Australian Rice Farms: An Inventory of Species, Variation among Farms, and Proximate Factors Explaining that Variation*. Publication W05/198. Canberra, Australia: Rural Industries Research and Development Corporation.

Ehmann, H., ed. (1996) *Threatened Frogs of New South Wales: Habitats, Status, and Conservation*. Sydney, New South Wales: Frog and Tadpole Study Group of New South Wales Inc.

Eldridge, D., Harrison, L., Parker, L. & Milligan, A. (2003) Condition and biodiversity of vegetation remnants: Murrumbidgee Irrigation Area. *Natural Resource Management* **6**: 63–66.

Eldridge, D., Koen, T.B. & Harrison, L. (2007) Plant composition of three woodland communities of variable condition in the western Riverina, New South Wales, Australia. *Cunninghamia* **10**: 189–198.

Eldridge, D.J. & Lunt, I.D. (2010) Resilience of soil seed banks to site degradation intermittently flooded riverine wetlands. *Journal of Vegetation Science* **21**: 157–166.

Ellis, E.C. & Wang, S.M. (1997) Sustainable traditional agriculture in the Tai Lake region of China. *Agriculture, Ecosystems and Environment* **61**: 177–193.

Ferrero, A. (2006) Challenges and opportunities for a sustainable rice production in Europe and Mediterranean area. *Paddy and Water Environment* **4**: 11–12.

Ford, H.A., Barrett, G.W., Saunders, D.A. & Recher, H.F. (2001) Why have birds in the woodlands of Southern Australia declined? *Biological Conservation* **97**: 71–88.

Frith, H.J. (1957*a*) Breeding and movements of wild ducks in inland New South Wales. *CSIRO Wildlife Research* **2**: 19–31.

Frith, H.J. (1957*b*) Wild ducks and the rice industry in New South Wales. *CSIRO Wildlife Research* **2**: 32–50.

Fujioka, M. & Lane, S. (1997) The impact of changing irrigation practices in rice fields on frog populations of the Kanto Plain, central Japan. *Ecological Research* **12**: 101–108.

Gates, J.A. (1996) The use of hollows by birds and mammals in dead river red gum and black box trees at Disher Creek, Murray River National Park, South Australia. *South Australian Ornithologist* **32**: 65–75.

Gaydon, D., Beecher, H.G., Reinke, R., Crimp, S. & Howden, S.M. (2010) Rice. In: *Adapting Australian Agriculture to Climate Change*, ed. C.J. Stokes & S.M. Howden, pp. 67–83. Melbourne, Australia: CSIRO Publishing.

George, A.J., Walker, K.F. & Lewis, M.M. (2005) Population status of eucalypt trees on the River Murray floodplain, South Australia. *River Research and Applications* **21**: 271–282.

Gibbons, P. & Boak, M. (2002) The value of paddock trees for regional conservation in an agricultural landscape. *Ecological Management and Restoration* **3**: 205–210.

Harrison, L. & Roberts, J. (2005) *Inventory of Wetlands in the Eastern Murrumbidgee Irrigation Area*. Griffith, Australia: Murrumbidgee Irrigation Ltd.

Hazell, D., Cunnningham, R., Lindenmayer, D., Mackey, B. & Osborne, W. (2001) Use of farm dams as frog habitat in an Australian agricultural landscape: factors affecting species richness and distribution. *Biological Conservation* **102**: 155–169.

Hazell, D., Hero, J.-M., Lindenmayer, D. & Cunningham, R. (2004) A comparison of constructed and natural habitat for frog conservation in an Australian agricultural landscape. *Biological Conservation* **119**: 61–71.

Herring, M., Webb, D. & Pisasale, M. (2006*a*) *Cadell Wildlife – Murray Land and Water Management Plan Wildlife Survey 2005–2006*. Griffith, Australia: Murrumbidgee Irrigation Ltd.

Herring, M., Webb, D. & Pisasale, M. (2006*b*) *Denimein Wildlife. Murray Land and Water Management Plan Wildlife Survey 2005–2006*. Griffith, Australia: Murrumbidgee Irrigation Ltd.

Herring, M., Webb, D. & Pisasale, M. (2006*c*) *Murray Wildlife. Murray Land and Water Management Plan Wildlife Survey 2005–2006*. Griffith, Australia: Murrumbidgee Irrigation Ltd.

Herring, M., Webb, D. & Pisasale, M. (2006*d*) *Wakool Wildlife. Murray Land and Water Management Plan Wildlife Survey 2005–2006*. Griffith, Australia: Murrumbidgee Irrigation Ltd.

Herzon, I. & Helenius, J. (2008) Agricultural drainage ditches, their biological importance and functioning. *Biological Conservation* **141**: 1171–1183.

Hill, J.E., Williams, J.F., Mutters, R.G. & Greer, C.A. (2006) The California rice cropping system: agronomic and natural resource issues for long-term sustainability. *Paddy and Water Environment* **4**: 13–19.

Hope, J. (1995) Aboriginal burial conservation in the Murray Darling Basin. *Historic Environment* **11**: 57–60.

Horner, G.J., Baker, P.J., MacNally, R., Cunningham, S.C., Thomson, J.R. & Hamilton, F. (2009) Mortality of developing floodplain forests subjected to a drying climate and water extraction. *Global Change Biology* **15**: 2176–2186.

Humphreys, E., Lewin, L.G., Khan, S., Beecher, H.G., Lacy, J.M., Thompson, J.A., Batten, G.D., Brown, A., Russell, C.A., Christen, E.W. & Dunn, B.W. (2006) Integration of approaches to increasing water use efficiency in rice-based systems in southeast Australia. *Field Crops Research* **97:** 19–33.

Hutchinson, M.F., McIntyre, S., Hobbs, R.J., Stein, J.L., Garnett, S. & Kinloch, J. (2005) Integrating a global agro-climatic classification with bioregional boundaries in Australia. *Global Ecology and Biogeography* **14**: 197–212.

Jansen, A. & Healey, M. (2003) Frog communities and wetland condition: relationships with grazing by domestic livestock along an Australian floodplain river. *Biological Conservation* **109**: 207–219.

Jansen, A. & Robertson, A.I. (2001) Riparian bird communities in relation to land management practices in floodplain woodlands of south-eastern Australia. *Biological Conservation* **100**: 173.

Jansen, A. & Robertson, A.I. (2005) Grazing, ecological condition and biodiversity in riparian river red gum forests in south-eastern Australia. *Proceedings of the Royal Society of Victoria* **117**: 85–95.

Jolly, I.D., Walker, G.R., Hollingsworth, I.D., Eldridge, S.R., Thorburn, P.J., McEwan, K.L. & Hatton, T.J. (1996) The causes of decline in eucalypt communities and possible ameliorative approaches. In: *Salt and Water Movement in the Chowilla Floodplain*, ed. G.R. Walker, I.D. Jolly & S.D. Jarwal, pp. 119–50. CSIRO Division of Water Resources: Canberra, Australia.

Kassam, A.H., Molden, D., Fereres, E. & Doorenbos, J. (2007) Water productivity: science and practice: introduction. *Irrigation Science* **25:** 185–188.

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. & Thomas, R.F. (2004) Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee River in arid Australia. *Environmental Management* **34**: 383–396.

Kingsford, R.T., Wong, P.S., Braithwaite, L.W. & Maher, M.T. (1999) Waterbird abundance in eastern Australia, 1983–92. *Wildlife Research* **26**: 351–366.

Lane, S.J. & Fujioka, M. (1998) The impact of changes in irrigation practices on the distribution of foraging egrets and herons (Ardeidae) in the rice fields of central Japan. *Biological Conservation* **83**: 221–230.

Lee, H.-L. (2009) The impact of climate change on global food supply and demand, food prices, and land use. *Paddy and Water Environment* **7**: 321–331.

Leigh, J.H. & Noble, J.C. (1972) *Riverine Plain of New South Wales: its Pastoral and Irrigation Development*. Canberra, Australia: CSIRO Division of Plant Industry.

Lewis, B.D. (2006) Biodiversity benchmarking survey of the Murrumbidgee Irrigation Area: mammals. Murrumbidgee Irrigation Ltd, Griffith, NSW, Australia.

Lindenmayer, D., Hobbs, R.J., Montague-Drake, R., Alexandra, J., Bennett, A., Burgman, M., Cale, P., Calhoun, A., Cramer, V., Cullen, P., Driscoll, D., Fahrig, L., Fischer, J., Franklin, J., Haila, Y., Hunter, M., Gibbons, P., Lake, S., Luck, G., MacGregor, C., McIntyre, S., Nally, R.M., Manning, A., Miller, J., Mooney, H., Noss, R., Possingham, H., Saunders, D., Schmiegelow, F., Scott, M., Simberloff, D., Sisk, T., Tabor, G., Walker, B., Wiens, J., Woinarski, J. & Zavaleta, E. (2008) A checklist for ecological management of landscapes for conservation. *Ecology Letters* **11**: 78–91.

Lumsden, L.F. & Bennett, A.F. (2005) Scattered trees in rural landscapes: foraging habitat for insectivorous bats in south-eastern Australia. *Biological Conservation* **122**: 205–222.

Maeda, T. (2001) Patterns of bird abundance and habitat use in rice fields of the Kanto Plain, central Japan. *Ecological Research* **16**: 569–585.

Manning, A.D., Fischer, J. & Lindenmayer, D.B. (2006) Scattered trees are keystone structures: implications for conservation. *Biological Conservation* **132**: 3111–3321.

Mateos, L. (2008) Identifying a new paradigm for assessing irrigation system performance. *Irrigation Science* **27**: 24–35.

McIntyre, S. (1985) Seed reserves in temperate Australian rice fields following pasture rotation and continuous cropping. *Journal of Applied Ecology* **22**: 875–884.

McIntyre, S. & Barrett, S.C.H. (1985) A comparison of weed communities of rice in Australia and California. *Proceedings of the Ecological Society of Australia* **14**: 237–250.

McIntyre, S. & Lavorel, S. (2007) A conceptual model of land use effects on the structure and function of herbaceous vegetation. *Agriculture, Ecosystems and Environment* **119**: 11–21.

McIntyre, S., Finlayson, C.M., Ladiges, P.Y. & Mitchell, D.S. (1991) Weed community composition and rice husbandry

practices in New South Wales. *Agriculture, Ecosystems and Environment* **26**: 27–45.
McIntyre, S., Ladiges, P.Y. & Adams, G. (1988) Plant species-richness and invasion by exotics in relation to disturbance of wetland communities on the Riverine Plain, NSW. *Australian Journal of Ecology* **13**: 361–373.
Mensforth, L.J., Thorburn, P.J., Tyerman, S.D. & Walker, G.R. (1994) Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia* **100**: 21–28.
Miyamoto, K. (2007) Harmonization of irrigation system development and ecosystem preservation in paddy fields. *Paddy and Water Environment* **5**: 1–4.
Molden, D. (2007) Water responses to urbanization. *Paddy and Water Environment* **5**: 207–209.
Munack, A. (2003) Paddy and water environment: opening new opportunities for cooperation and discussion in the specific topic of sustainable paddy farming. *Paddy and Water Environment* **1**: 1.
Murrumbidgee Irrigation (2009) Licence Compliance Report 2008/09 [www document]. URL http://www.mirrigation.com.au/ReportsAR/EnvironmentalReports/LCR_2009.pdf
Nias, D.J., Alexander, P., & Herring, M. (2003) Watering private property wetlands in the Murray Valley, New South Wales. *Ecological Management and Restoration* **4**: 5–12.
Paijmans, K. (1978) A reconnaissance of four wetland pilot study areas. Technical Memorandum No. 78/3.CSIRO Division of Land Use Research, Canberra, Australia.
Porter, J.L., Kingsford, R. & Hunter, S.J. (2006) Aerial surveys of wetland birds in eastern Australia: October 2003–2005. Occasional Paper No. 37. Department of Environment & Conservation, New South Wales, Australia.
Postel, S.L., Daily, G.C. & Ehrlich, P.R. (1996) Human appropriation of renewable fresh water. *Science* **271**: 786–788.
Richardson, A.J. & Taylor, I.R. (2003) Are rice fields in southeastern Australia an adequate substitute for natural wetlands as foraging areas for egrets? *Waterbirds* **26**: 353–363.
Richardson, A.J., Taylor, I.R. & Growns, J.E. (2001) The foraging ecology of egrets in rice fields in southern New South Wales, Australia. *Waterbirds* **24**: 255–264.
Rijsberman, F. (2004) Growing more rice with less water. *Paddy and Water Environment* **2**: 181–183.
Roberts, J. (2005) *An Audit of Wetlands in the Eastern Murrumbidgee Irrigation Area*. Griffith, Australia: Murrumbidgee Irrigation Ltd.
Robertson, A.I., Bacon, P. & Heagney, G. (2001) The responses of floodplain primary production to flood frequency and timing. *Journal of Applied Ecology* **38**: 126–136.
Sass, S., Wassens, S., Swan, G. & Thompson, L.A. (2004) Reptile diversity in the Murrumbidgee Irrigation Area: a baseline survey. Environmental Consulting Report No. 69b. Johnstone Centre for Research in Natural Resources and Society, Charles Sturt University, Wagga Wagga, Australia.
Scott, A. & Grant, T. (1997) Impacts of water management in the Murray-Darling Basin on the platypus (*Ornithorhynchus anatinus*) and the water rat (*Hydromys chrysogaster*). Technical Report 23/97. CSIRO Land and Water, Canberra, Australia.
Sinclair, A.R.E., Olsen, P.D. & Redhead, T.D. (1990) Can predators regulate small mammal populations – evidence from house mouse outbreaks in Australia. *OIKOS* **59**: 382–392.
Slavich, P.G., Walker, G.R., Jolly, I.D., Hatton, T.J. & Dawes, W.R. (1999) Dynamics of *Eucalyptus largiflorens* growth and water use in response to modified watertable and flooding regimes on a saline floodplain. *Agricultural Water Management* **39**: 245–264.
Stenert, C., Bacca, R.C., Maltchik, L. & Rocha, O. (2009) Can hydrologic management practices of rice fields contribute to macroinvertebrate conservation in southern Brazil wetlands? *Hydrobiologia* **635**: 339–350.
Sterling, J. & Buttner, P. (2009) *Wildlife Known to use California Ricelands*. Sacramento, California, USA: California Rice Commission.
Taft, O.W. & Elphick, C.S. (2007) Waterbirds on working lands: literature review and bibliography development. Technical Report, National Audubon Society [www document]. URL http://www.audubon.org/bird/waterbirds/downloads.html
Thorburn, P.J. & Walker, G.R. (1994) Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water. *Oecologia* **100**: 293–301.
Van Nguyen, N. & Ferrero, A. (2006) Meeting the challenges of global rice production. *Paddy and Water Environment* **4**: 1–9.
Wassens, S., Car, C. & Jansen, A. (2005*a*) *Murrumbidgee Irrigation Area Invertebrate Biodiversity Benchmark*. Griffith, Australia: Murrumbidgee Irrigation Ltd.
Wassens, S., Roshier, D.A., Watts, R.J. & Robertson, A.I. (2007) Spatial patterns of a southern bell frog *Litoria raniformis* population in an agricultural landscape. *Pacific Conservation Biology* **13**: 104–110.
Wassens, S., Sass, S. & Swan, G. (2005*b*) Reptile communities in vegetation remnants of the Murrumbidgee Irrigation Area, New South Wales. *Herpetofauna* **35**: 66–72.
Wassens, S., Sass, S., Swan, G. & Thompson, L.A. (2004) Frog diversity in the Murrumbidgee Irrigation Area: a baseline survey. Griffith, Australia: Murrumbidgee Irrigation Ltd.
Wassens, S., Watts, R.J., Jansen, A. & Roshier, D. (2008) Movement patterns of southern bell frogs (*Litoria raniformis*) in response to flooding. *Wildlife Research* **35**: 50–58.
Williams, O.B. (1955) Studies in the ecology of the Riverine Plain. I. The gilgai microrelief and associated flora. *Australian Journal of Botany* **3**: 99–109.
Williams, O.B. (1956) Studies on the ecology of the Riverine Plain. II. Plant-soil relationships in three semi-arid grasslands. *Australian Journal of Agricultural Research* **7**: 127–139.
Wilson, A.L., Watts, R.J. & Stevens, M.M. (2008) Effects of different management regimes on aquatic macroinvertebrate diversity in Australian rice fields. *Ecological Research* **23**: 565–572.
Yoon, C.G. (2009) Wise use of paddy rice fields to partially compensate for the loss of natural wetlands. *Paddy and Water Environment* **7**: 357–366.