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Invited Paper

Developing Indicators for Floodplain Wetlands: Managing Water in Agricultural Landscapes

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ABSTRACT

Floodplain wetlands in arid and tropical environments are intermittently or seasonally flooded, drying for months and up to years in arid wetlands between floods. Aquatic food webs in these systems are adapted to this variable water regime; pulsing in productivity and diversity after floods, yet dependent on nutrients generated during dry cycles. In floodplain wetlands, upstream dams and irrigated agriculture have reduced floods and extended drying, leading to changes to natural levels of productivity and diversity. Environmental flows can contribute to the sustainable management and restoration of degraded wetlands in agricultural landscapes. Decisions on the timing, frequency, duration and magnitude of environmental water allocations depend on sound knowledge of ecological thresholds, and indicators to measure success or failure of management interventions. Thresholds are discussed for concentrations of carbon, ecosystem metabolism and microinvertebrates in arid wetlands as indicators of key ecosystem functions. This approach is also relevant to floodplain wetlands in tropical climates where water managers must balance environmental and agricultural needs in the midst of the uncertainty of climate change.

Keywords: river regulation, water abstraction, environmental flows, ecosystem function.

1. INTRODUCTION

The variable water regime of floodplain wetlands in arid and tropical regions drives their characteristic biodiversity and ecological processes [1-3]. Intermittent or seasonal floods transport organic matter and biota, trigger the lifecycles of many aquatic and terrestrial organisms, and connect aquatic organisms over broad spatial scales [4-9]. Waterbirds and fish breed in tens to hundreds of thousands on arid and tropical wetlands after floods, building up body resources and feeding young on the abundant invertebrates, frogs, fish and plants [5, 10, 11]. Eventually ‘boom’ turns to ‘bust’ as wetlands dry and animals either move away, diapause or die [12, 13].

Wetting and drying are vital to the boom and bust cycles of floodplain wetlands. During dry phases, eggs and seeds of diapausing animals and plants remain in dry floodplain soils [14, 15]. Terrestrial microorganisms decompose organic matter from leaf litter and stranded aquatic plants and animals, adding nutrients and energy to floodplain soils

[16]. When flooding triggers the next aquatic boom phase, this conditioned organic reservoir supports emerging aquatic organisms and biota that arrive to colonise the newly inundated habitats [17]. Heterotrophic organisms, (bacteria, fungi, macroinvertebrates) assimilate these resources into aquatic food webs, directly linking detritus to higher trophic levels. The temporal dynamics of water drive this complexity, and are essential for the functioning of arid and tropical wetlands.

After floods, mobile fauna, such as waterbirds travel long distances to colonise these temporary habitats [18]. Microinvertebrates, algae and vascular plants can colonise from in situ propagules, but may also move over large spatial scales carried by waterbirds [19], wind [20] or large floods [6]. Fish, like waterbirds, are also capable of long distance movements, but are dependent on riverine connections to wetlands [8, 21]. Hence, interdependent components of aquatic food webs in these temporary wetland ecosystems must respond in different ways to the same patterns of wetland distribution and flooding [22]. The boom cycles in temporary wetlands play a critical role replenishing populations and are underpinned by the flow of energy from organic matter resources.

Almost half the world's land area lies in the arid-zone, where annual rainfall is low and variable [23], while 19 percent is in tropical climates [24], with high rainfall in the wet season juxtaposed with dry seasons. Despite the variable availability of water, arid and tropical regions support extensive wetlands and rivers [25, 26]. Many significant floodplain wetlands connect to rivers during floods, but these are becoming increasingly dry due to extraction for irrigation (for example, the Macquarie Marshes in Australia; the Aral Sea in central Asia and tropical floodplain throughout South America, Africa and Asia including the Chao Phrya in Thailand [25, 27-29]).

In the last 50 years freshwater biodiversity has plummeted with increasing human demands for water [30, 31]. Colonisation pathways for waterbirds and their food webs have become more disconnected with drying of wetlands and rivers [13, 32] and the strength of ecological connectivity, defined as the transfer of biota, materials and genotypes, has weakened and is likely to worsen with climate change [33]. Annual stream flow in the Murray-Darling Basin, Australia is predicted to decrease by 10-25% by 2050 and 18-48% by 2100, compounding the effects of increasing demand for water throughout the region [33, 34]. Globally, scientists and managers are striving to allocate environmental water to restore connectivity and biodiversity in floodplain wetlands. We need to identify critical ecosystem thresholds and refugia to design environmental flows as the water crisis and climate change reduce the frequency of boom periods and lengthen bust cycles [30, 35].

The goal of this paper is to examine the dual impacts of regulation (constant flows) and loss of flooding on key indicators of floodplain wetland health in the Macquarie Marshes, in arid Australia. We examined sediments from two distinct flood regimes ranging from moderate (4 years since last inundated) to prolonged dry (14 years). We tested whether increased drying reduced soil organic matter and viable invertebrate egg banks. We also compared macroinvertebrate communities in regulated creeks with those in inundated intermittent floodplain to assess the potential for regulated creeks to act as refugia for key floodplain biota. Finally we discuss the implications of prolonged drying and regulation on floodplain wetland ecosystems, and the role of increased environmental flow allocations for restoration of degraded floodplains.

2. MATERIALS AND METHODS

2.1 Study Area and Hydrological Change

The Macquarie Marshes is a large floodplain wetland (about 200,000 ha after regulation, Kingsford and Thomas 1995) on the downstream end of the Macquarie River in central western New South Wales, Australia (Figure 1). During floods, numerous channels connect a complex of wetland habitats comprising scattered areas of open water, lignum (*Muehlenbeckii florulenta*), common reed (*Phragmites australis*), cumbungi (*Typha orientalis*), water couch (*Paspalum paspaloides*), and extensive floodplain eucalypts including river red gum (*Eucalyptus camaldulensis*), coolibah (*E. coolibah*) and blackbox (*E. largiflorens*). An area of 19,443 ha is contained in the National Parks and Wildlife Service Nature Reserve, divided between the southern and northern Nature Reserves and another newly acquired area (Figure 1). The Nature Reserve and part of the property 'Wilgara' is listed under the Ramsar convention [36] due to their significance as habitat for waterbird breeding.

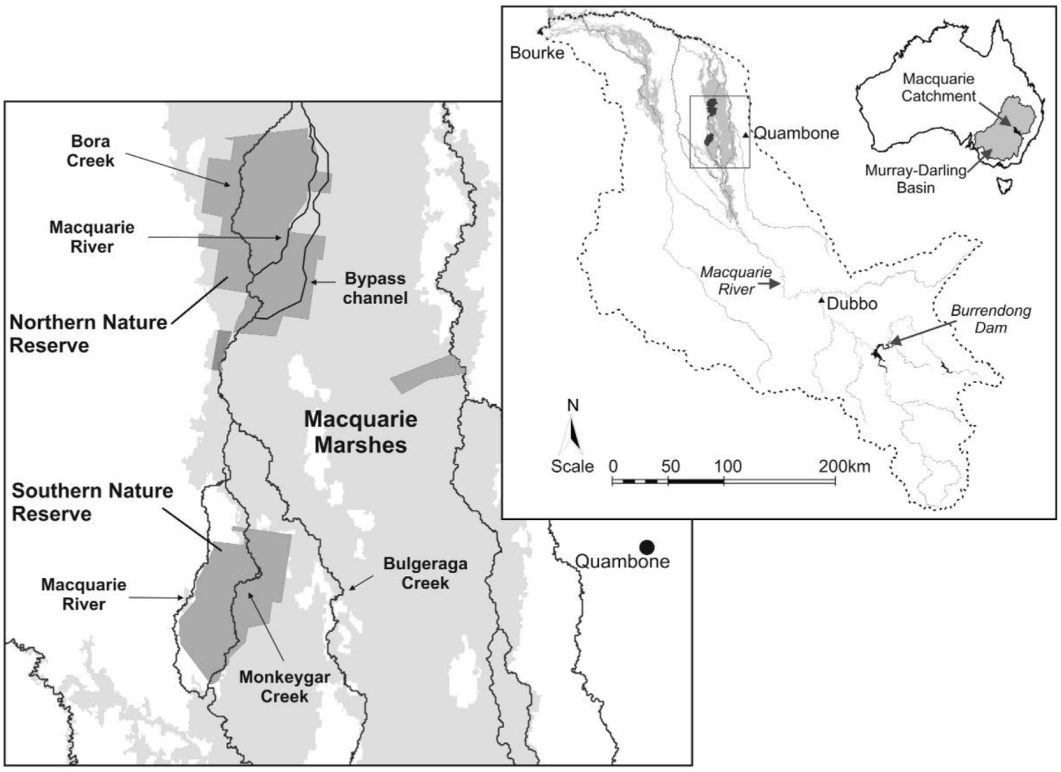

Figure 1. Locations of the Macquarie River catchment within the Murray-Darling Basin, Australia and the Macquarie Marshes and Nature Reserves within the catchment.

Flows in the Macquarie Marshes are influenced by a large catchment covering 75,000 square kilometers to the southeast of the Marshes and west of the Great Dividing Range [37]. Since 1968 flows to the Macquarie Marshes have been regulated by Burrendong Dam (1,189,000 ML plus 489,000 ML in the flood mitigation zone) on the headwaters. The dam captures most of the water and then releases more than half the water for irrigation (365,341 ML/year) [36, 38]. Water is released from Burrendong Dam for high security irrigation and town water supply (26,539 ML/year), stock and domestic supply to properties along the river (22,423 ML/yr) and for replenishment flows to distributory creeks [36].

An environmental water allocation (160,000 ML general security), is available annually (if the main storages are full) for the Macquarie Marshes and the ecological needs of the main Macquarie River channel [36]. This is the maximum volume when there is 100% allocation but when dams are only half full, all users receive a 50% allocation including the environmental allocation which concomitantly reduces to 80,000 ML [36]. Located at the lower end of the Macquarie River, some water (~5%) flows through the Macquarie Marshes to the Barwon-Darling River System.

Before river regulation (1944-1953), 51% of water passing Dubbo each year reached the Macquarie Marshes, but this declined to 21% by 1984-1993 and the areas flooded by large floods contracted by at least 40-50% [39]. Now the median annual modeled flow is only 43% of the natural flow and the area inundated is 59% of the natural area [40]. Channel and wetland habitats flood less often and flow variability is drastically reduced [39, 41]. Constant low flows have increased in some channels due to stock and domestic supply and irrigation releases.

2.2 Dry Sediment Sampling Design and Procedures

The floodplain was sampled in two flood history groups on the basis of time since the last flood pulse (14 and 4 years). Flood history grouping was based on anecdotal records and Landsat images. Floodplain that was dry for 14 and 4 years was last inundated in large floods that occurred in 1990 and 2000 respectively. The recently flooded floodplain also flooded in the 1990 flood. Three floodplain patches (1000×1000m) were nested within each level of flood history and were haphazardly dispersed throughout the Marshes to maximise the geographic spread. Three randomly located sites (20×20 m) were nested within each floodplain patch. A composite sediment sample comprising four subsamples was collected from each of the three sites within each floodplain patch.

Sediment was collected from 0-1 cm depth using a quadrat and dustpan or spade with care taken to preserve the soil profile. At each subsample point, an adjacent subsample was collected to quantify levels of organic matter and soil nutrient status. A separate composite sample was collected and inundated for each experimental flood day in the laboratory (sampled without replacement on days 1, 3, 7, 14, 28 and 56). Floodplain sediments were collected in September and October 2004 and were flooded in a glasshouse from January to February 2005 in three blocks (A to C) of 6 samples, with treatments haphazardly dispersed. Samples from blocks A to C were flooded with 3300ml of deionised water and subsequently processed on sequential days within the same week. Flooding and sample processing procedures followed Jenkins and Boulton [6]. Dissolved oxygen (DO) concentrations and temperature were measured in all samples for a 24-26 hour period preceding days 1, 3, 7, 14, 28 and 56 after flooding, at which point invertebrates were sampled without replacement from each microcosm.

Organic matter and organic carbon were measured in soils prior to flooding. Replicate soil samples from patches within each flood history were analysed for total C and percent organic matter through determination of Ash Free Dry Mass. Total C was determined using Heanes Wet oxidation [42]. Percent organic matter was determined gravimetrically by drying soil sediments at 80^{o}C, then ashing at 500^{o}C.

2.3 Macroinvertebrate Sampling in Regulated Creeks

Macroinvertebrates were collected during spring 2005 (flooded) and 2006 (low flow) with a 250 μm sweep net over an area of 2×1 m in benthic and pelagic habitats. One to eight replicate samples were collected from two to three sites in regulated creeks (Macquarie, Bulgeraga, Monkeygar, Bora), temporary creeks (Gum Cowal and Ginket) and inundated floodplain habitats (Bora and Gum Cowal). Samples were preserved in 70% ethanol and were counted and identified in the laboratory using microscopes (Zeiss Stemi DV4×32 magnification; Kyowa Medilux-12×100 magnification).

2.4 Statistical Analysis

Means were taken of sites (n=3) and then patches (n=3) to pool data prior to doing one-way ANOVAs to test for differences in total carbon, percentage organic matter, and number of invertebrate taxa between the two flood histories (dry 4 versus 14 years). All variables were checked for normality by viewing residual plots [43]. Number of invertebrate taxa were log x+1 transformed prior to analysis. Statistical analyses were performed using SYSTAT for Windows version 9.0 (SYSTAT, Evanston, Illinois, USA). Diurnal patterns in dissolved oxygen results are shown only for 28 days after samples were inundated. Community compositions of macroinvertebrate samples were compared using non-metric multidimensional scaling (NMDS) computed with Primer [44] on a Bray–Curtis similarity matrix of fourth-root transformed data. Composite samples of the abundances for each taxon from all samples in sites were analysed, reducing the data set. Coordinates of each composite sample were plotted in chronological order, generating succession trajectories (cf. Boulton and Lake [45]) to assess change in community composition over time.

3. RESULTS

ANOVA results for total carbon show significantly higher concentrations in sediments flooded 4 years compared to 14 years ago (Figure 2, p=0.008). Samples from the floodplain dry for 14 years were also significantly lower in percent organic matter (Figure 2, p=0.002) than samples from sediments dry for 4 years.

On day 28 after inundation, dissolved

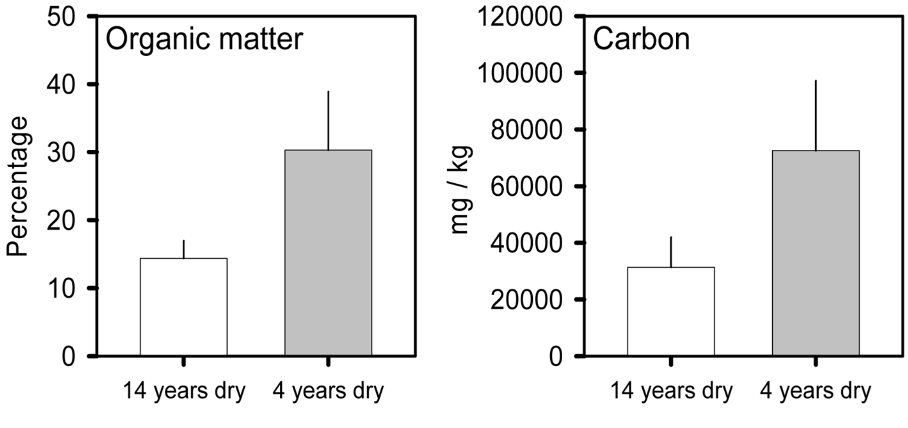

Figure 2. Percentage organic matter (left) and total carbon (right) in floodplain sediments last flooded 14 (white) and 4 (shaded) years earlier. Data are means of three patches in each flood history and error bars are standard errors.

oxygen concentrations showed a strong diurnal pattern with peak concentrations during the day and troughs at night. The rate of increase, peak in daytime oxygen concentration, and range of concentrations was greatest from sediments last flooded 14 years earlier (Figure 3). The lower oxygen levels during the day in sediments last flooded 4 years earlier indicates elevated respiration processes due to increased organic matter decomposition or reduced photosynthesis in these samples.

The number of microinvertebrate taxa after 56 days of inundation was significantly higher in sediments last flooded 4 years earlier, compared to those dry for 14 years (Figure 4, p<0.001). Multivariate analysis showed that macroinvertebrate communities differed between temporary floodplain habitats compared to regulated creeks with constant flows (Figure 5).

4. DISCUSSION

This study contributes understanding required to successfully manage environmental flow allocation and delivery, and their interaction with freshwater organisms and ecological function in space and time. The viability of native species depends on the good health of rivers and wetlands [30, 46]. Too often, we have witnessed the decline of waterbird populations as water allocations are uncoordinated and wetlands remain dry for extended periods, beyond the life spans of many organisms and recovery thresholds for ecosystem functions [13, 32, 47]. Degradation of floodplain rivers costs millions of dollars in remedial work and ineffective use of environmental water [35, 48]. Costs could be reduced by the solid knowledge base provided for resource management decisions by scientific studies. Investigating the functional role of biological communities, and targeting some activities towards the re-establishment

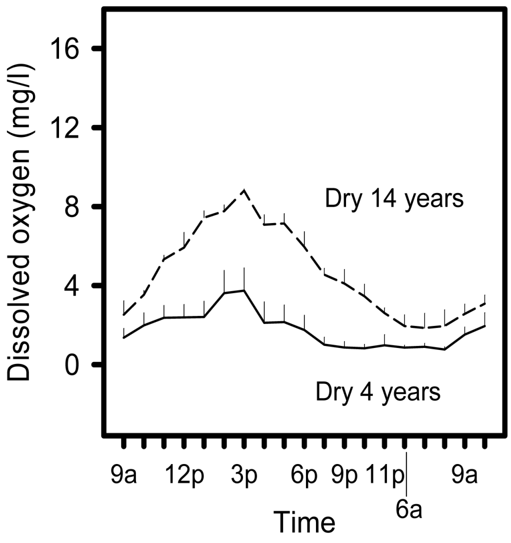

Figure 3. Dissolved oxygen (mg/L) levels for the 25 hours prior to 28 days after inundation in the laboratory. Sediments were last flooded 14 (dashed line) and 4 (solid line) years earlier. Data are means of three patches in each flood history and error bars are standard errors.

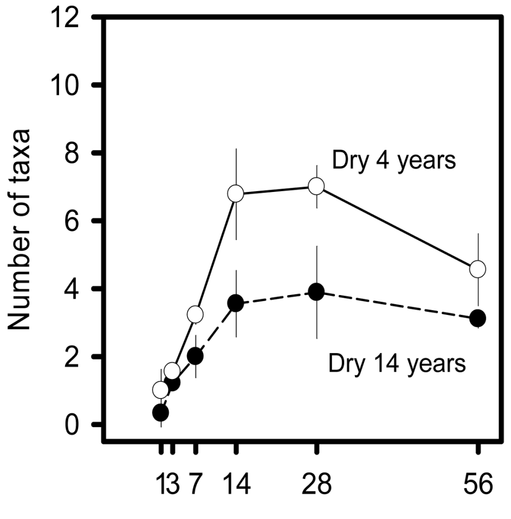

Figure 4. Number of microinvertebrate taxa that emerged from floodplain sediments from days1 to 56 after inundation in the laboratory. Sediments were last flooded 14 (dashed line, solid circle) and 4 (solid line, empty circle) years earlier. Data are means of three patches in each flood history and error bars are standard errors.

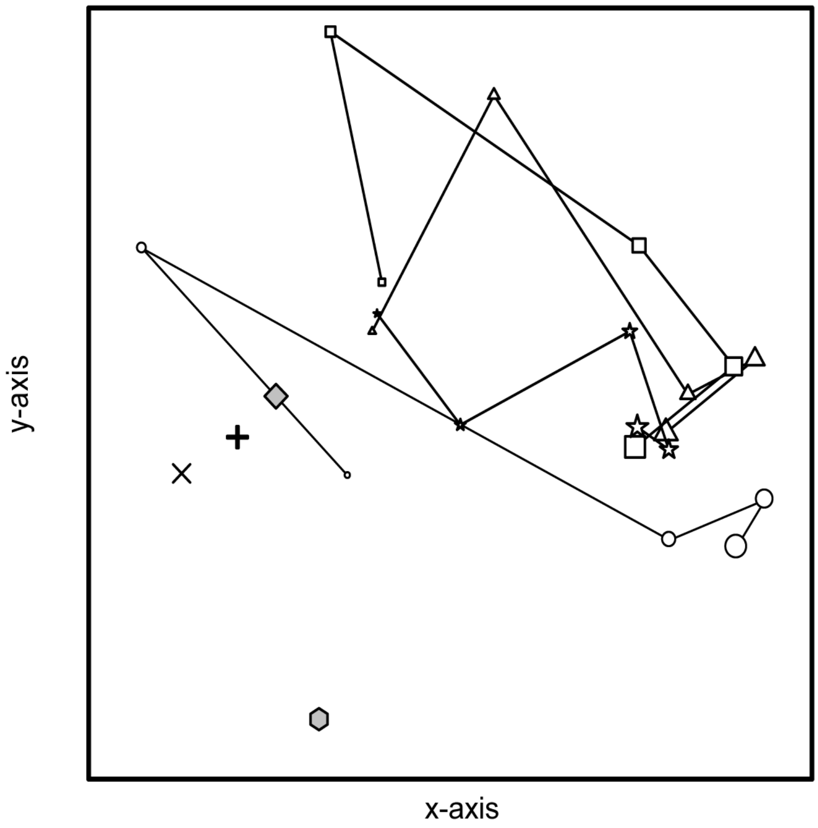

Figure 5. An MDS plot of macroinvertebrates from sweepnet samples in creek and floodplain habitats in the Macquarie Marshes during spring 2005 and spring 2006 . Note single sample times from floodplain and temporary creek habitats. Increasing symbol size denotes later sample times. Creeks are: □ = Macquarie, △ = Bulgeraga, ☆ =Monkeygar, ○ = Bora, ◆ = Gum Cowal, ⬢ = Ginket. Floodplains are: + = Bora floodplain, × = Gum Cowal floodplain.

of structurally significant species and functionally significant processes [49] may enhance wetland restoration.

Water scarcity affects three critical sectors of society; social, economic and environmental with one in five people in developing countries lacking access to sufficient clean water and half the worlds wetlands disappearing in the last century as many rivers now fail to reach the sea [50]. By 2030 the global population is expected to reach 8.1 billion people, demanding a further 14 percent freshwater for agricultural production [51]. To raise awareness, the United Nations General Assembly has declared March 22 World Water Day and 2005-2014 the 'Decade of Action-Water for Life'. The water crisis and drying of our wetlands and rivers in Australia was identified in the Federal Government's 'Water for the Future' strategy in April 2008 [52]. In one of four key priorities over the next ten years, $3 billion will be spent 'Restoring the Balance' in the Murray Darling Basin by purchasing water for return to rivers and wetlands. The state governments of the Murray-Darling Basin (MDB) have committed $500M to the Living Murray Initiative and the NSW government is spending $105M buying back water entitlements from irrigators [53]. These programs that aim to return water to floodplain wetlands require scientific data for their implementation to be successful.

The flood pulse is recognised as the key event shaping biotic community structure and ecological processes in floodplain systems [3, 4]. In arid and tropical rivers, intermittent drying of floodplain, wetlands and channels is also critical [3, 12]. After drying, when temporary wetlands flood, microinvertebrates and insects colonise the turbid waters [6, 54], there is a pulse of nutrients [55], algal communities boom [56], waterbirds congregate in their thousands [5], fish populations proliferate [2, 11], and aquatic macrophytes germinate [57]. It is the cycle of wetting and drying that structures diverse habitat, aquatic communities and ecological processes in arid and tropical rivers [3, 4, 10-12, 58, 59]. The frequency and duration of wet versus dry periods influences the quantity and quality of organic inputs to floodplain wetlands [47, 60, 61].

However, when temporary wetlands remain inundated for too long due to river regulation, the densities of microinvertebrates, fish and waterbirds fall [62, 63]. Similarly, constant flows modify the critical function that flow variability plays in regulating biofilm production in floodplain rivers [64]. Conversely, extending the dry period for too long (more than 10 years) also leads to a decline in the numbers of microinvertebrates that emerge from dormant eggs [32]. It appears that dormant eggs have a finite lifespan and the egg bank is reduced during the dry period due to predation, burial, death and removal by wind [32]. Water extraction for water supply and irrigation have dramatically reduced the frequency of inundation for floodplain wetlands [58]. Wetlands that flooded naturally every one to two years are now dry for a decade, beyond the lifespan of many wildlife [13]. These changes also alter vegetation communities (eg. red gums, [65]) and modify deposition and break down rates of leaf litter on floodplains [47, 66]. Reserves of organic matter and carbon are also depleted during long dry periods as evidenced by this study. Subsequently, the length of the dry period is critical to the productivity and diversity of biota in these systems.

5. CONCLUSIONS

Conservation of floodplain wetlands and their dependent food webs should strive to maintain the carbon and biotic balance through appropriate water regime and land management practices. As floodplain wetlands continue to lose water to industry and urbanisation, the changes already apparent in the Macquarie Marshes, and many other wetlands, are expected to develop further. Here we have demonstrated that drying for periods up to 14 years, exceeding the natural range of variability, reduces organic matter content, total carbon and invertebrate diversity, impacting on heterotrophic production during times of flooding and upon the integrity of wetland food webs. Conversely, inundating channels with constant flows also produced different communities of macroinvertebrates than observed in temporary channel and floodplain habitats. Restoration is doomed when regulation and water extraction disrupts colonisation pathways of organisms (e.g. fish and invertebrates) [8, 32] such that waterbirds arrive, but the anticipated ‘boom’ in lower trophic organisms is inadequate. The concentration of carbon, organic matter and dissolved oxygen, density of microinvertebrates per litre, their diversity and also recruitment in fish, plants and waterbirds can all be key indicators of either the health or decline of floodplain wetlands. Heavily degraded wetlands are characterised by low numbers of animals and little or no recruitment. Post-flood responses can also be used to measure the success of rehabilitation measures such as environmental water allocations and guide the design of future environmental flow regimes based on knowledge of ecological thresholds.

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