Eco-Hydrology of Dynamic Wetlands in an Australian Agricultural Landscape: a Whole of System Approach for Understanding Climate Change Impacts

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Abstract

Increasing rates of water extraction and regulation of hydrologic processes, coupled with destruction of natural vegetation, pollution and climate change, are jeopardizing the future persistence of wetlands and the ecological and socio-economic functions they support. Globally, it is estimated that 50% of wetlands have been lost since the 1900's, with agricultural changes being the main cause. In some agricultural areas of Australia, losses as high as 98% have occurred. Wetlands remaining in agricultural landscapes suffer degradation and their resilience and ability to continue functioning under hydrologic and land use changes resulting from climate change may be significantly inhibited. However, information on floodplain wetlands is sparse and knowledge of how ecological functioning and resilience may change under future land use intensification and climate change is lacking in many landscapes. These knowledge gaps pose significant problems for the future sustainable management of biodiversity and agricultural activities which rely on the important services supplied by wetland ecosystems. This research evaluates the impact that hydrology and land use has on the perennial vegetation associated with wetlands in an agricultural landscape, the Condamine Catchment of south-east Queensland, Australia. A geographical information system (GIS) was used to measure hydrological and land use variables and a bayesian modeling averaging approach was used to generate generalised linear models for vegetation response variables. Connectivity with the river and hydrological variability had consistently significant positive relationships with vegetation cover and abundance. Land use practices such as, irrigated agriculture and grazing had consistently significant negative impacts. Consequently, to understand how climate change will impact on the eco-hydrological functioning of wetlands, both hydrological and land use changes need to be considered. Results from this research will now be used to investigate how resilient these systems will be to different potential scenarios of climate change.

Keywords: wetlands, vegetation, hydrology, land use, climate change

Introduction

Floodplain wetlands and their perennial fringing vegetation provide significant biodiversity and ecosystem services in agricultural systems. In Australia and elsewhere, many inland wetlands are temporary due to the region's climatic variability (Roshier et al., 2001). Accordingly, significant changes to climate may have serious effects for these systems. Wetlands in agricultural landscapes are generally poorly understood, with management often based on models of perennial hydrological connectivity that fail to consider dynamic and unpredictable hydrological regimes.

Globally, wetland loss and degradation has occurred as a result of agricultural expansion and intensification in many parts of the world. For example, in the Balkans large areas of wetlands have been drained to support the spread of intensive agriculture (Skoulikidis, 2009). Similarly, in agricultural landscapes of Australia, there has been up to 98% loss of wetlands (Jensen, 2002).

Wetland loses in agricultural landscapes have been driven by land use and coinciding hydrological changes, which have together lead to clearing of vegetation, increased pressure from grazing and alterations to wetland hydrology through extraction and alteration of hydrological pathways. In production landscapes, the extraction and alteration of water resources for cropping, coupled with damage to vegetation and soil structure caused by grazing, has the potential to greatly reduce the resilience of wetland systems. A reduction in resilience may inhibit the ability of wetlands to persist and continue functioning in the face of climate change. This is likely to have consequences for both biodiversity and the future sustainability of agricultural systems which are dependent on the ecosystem services provided by wetland systems and there associated fringing vegetation

The timing, frequency and duration of hydrologic inputs and outputs affect the movement of nutrients to and from wetlands (Gabriel et al., 2008), triggering the release of nutrients from soils, grasses and accumulated tree debris (Junk et al., 1989; Reid and Brooks, 2000). These nutrient pulses in turn support the growth and reproduction of vegetation which shape the structure and function of wetlands. This vegetation then provides organic material and food sources for aquatic invertebrates and habitat for birds and helps maintain soil structure (Boulton and Lloyd, 1991; Briggs et al., 1997; Brauman et al., 2007). Consequently, changes to wetland hydrology, either as a result of human activities or as a result of future climatic changes, are likely to have serious implications for biodiversity, both at the local wetland scale and across the landscape.

Climate change projection for eastern inland Australia predicts that by 2030 there will be a 9% reduction in annual run-off (CSIRO, 2008). Additionally, projections estimate that climate change will most likely cause changes to land use practices, with irrigated agriculture being replaced by dryland agriculture in some areas as a result of less water being available (Hafi et al, 2009). The effects of climatic change is already noticeable in many ecological communities and are likely to intensify and affect an even wider range of species in the coming decades (Walther et al., 2002; Hughes, 2003; Winn et al., 2006; Hennessy et al., 2007). The consequences of climate changes for wetlands sensitive to alterations in hydrology could significantly compromise the current biodiversity and eco-services provided by wetlands in production landscapes.

To understand the future persistence of wetlands in agricultural landscapes there needs to be an understanding of the relationships between hydrology, land use and the wetland biota. The maintenance of biodiversity is important for how ecosystems may adapt to future disturbances and changes, such as climate change. However, there is little empirical data on the condition and biodiversity on hydrologically dynamic floodplain wetlands. This research surveyed the current state of wetlands and fringing vegetation in the Condamine Catchment, south-east Queensland, to understand the relative impacts of hydrology and land use context on wetlands to help understand how they may be affected by future climatic changes.

Methodology applied

The perennial fringing vegetation of 34 wetlands that varied in hydrology and land use context was extensively surveyed. Transect level and overall wetland perimeter assessments were undertaken on the cover, health and density of fringing woody vegetation within each wetland. Assessments on perennial vegetation was undertaken in three 150 m^2 meter linear (5 x 30 m) transects subjectively located the perimeter of the wetland to sample the range of fringing vegetation variation within each wetland (Figure 1).

Each tree within the transect was assessed and placed into one of 6 different size classes (Table, 1). Additionally, assessments on the total woody vegetation in different height classes surrounding the perimeter of the wetland were also undertaken. In the overall assessments the total vegetation cover and cover of vegetation at <10m, 10-30m and >30m was also recorded. The final set of vegetation variables modeled in this study is given in Table 1.

Table 1

Modeled vegetation variables

^Wetland perimeter vegetation cover variables	*All trees combined density counts	*Common species density counts
Perimeter total live woody vegetation	All seedling density	Acacia seedling density
Perimeter woody vegetation over 30 m	All sapling density	Acacia sapling density
Perimeter woody vegetation 10 – 30 m	All 10_20 cm density	Acacia 10_20cm density
Perimeter woody vegetation under 10m	All 20_50cm density	Acacia 20_50cm density
	All 50_75cm density	Acacia 50_75cm density
	All over 75cm	Acacia over 75cm density
	All live tree density	Total Acacia density (predominantly *Acacia stenophylla*)
		Red gum (*Eucalyptus camaldulensis*) seedling density
		Red gum (*Eucalyptus camaldulensis*) sapling density
		Red gum (*Eucalyptus camaldulensis*) 10 -20cm density
		Red gum (*Eucalyptus camaldulensis*) 20 – 50cm density
		Red gum (*Eucalyptus camaldulensis*) 50-75cm density
		Red gum (*Eucalyptus camaldulensis*) over 75cm density
		Total red gum (*Eucalyptus camaldulensis*) density

*groups for tree density are for tree diameter at breast height (dbh) in centimetres (cm)
^ groups for perimeter vegetation cover variables based on tree height in metres (m)

Hydrological metrics relevant to wetland ecological functioning were derived from different sources for each wetland. The percentage of time inundated, the longest consecutive wet and dry spells (in years) and the number of wet and dry cycles the wetland went through on an annual basis was derived from metadata from the Queensland dams and water bodies 2005 dataset (Queensland Environmental Protection Agency, 2005). For wetlands hydrological variables relating to catchment area and the wetlands connectivity to the riverine network were also measured using a GIS.

Land use and spatial variables were assessed for each wetland, by calculating the proportion (as a percentage) of vegetation, and land use practices in different selected categories in a 1km buffer around each wetland using Arc View 9.2 (Environmental Systems Research Institute, 2006). Within a 1 km buffer around each wetland, the percentage of intense agriculture, for example piggeries or cattle feedlots, dryland and irrigated agriculture was determined using a GIS. On site measurements of grazing intensity were also undertaken by counting the number of cow patties within each transect and wetland area was taken from the Queensland Environmental Protection Agency wetland mapping dataset (Queensland Environmental Protection Agency, 2008). The suite of explanatory variables used for modelling is listed in Table 2.

Table 2

Hydrology and land use variables used in modeling

Hydrology variables	Land use variables
Wet dry cycle frequency	Catchment area
Inundation frequency	Grazing
Longest wet period	Dryland agriculture
Longest dry period	Irrigated and dryland agriculture
Stream flow connectivity	Intense agriculture
	Wetland area
	Vegetation cover at 1km

Figure 1
A representation of the vegetation sampling procedure. Detailed vegetation assessments were undertaken in linear quadrats at three locations around each wetland and more general assessments around the whole perimeter of the wetland. Photograph: Google Earth™

Analysis

The vegetation surveyed at each wetland was modelled hydrology and land use variables using a Bayesian model averaging approach, which was used to develop generalised linear models (GLMs) (Raftery et al., 2006) to multiple linear regression in the R statistical package (R Development Core Team, 2006). This approach allows multiple models to be considered and the parameter estimates to be averaged across a set of useful models Parameter estimates are then averaged across models in the confidence set and the probability of each variable being included in the best model calculated.The output then gives the probability of each variable being included in the best model and of all models gives the 'best' model based on the Bayesian information criteria (BIC) This value basically measures the efficiency of the parameterized model in terms of predicting the data, so it prevents over fitting and favors the most parsimonious model. The more negative the BIC value the parsimonious that model performs relative to the other models tested for the variable(s) being modeled (Raftery et al., 2006).

Case study description

The study area is located in the Condamine Catchment, which is situated at the headwaters of the Murray-Darling Basin in south-east Queensland. The Condamine Catchment is an agriculturally dominated landscape in south-east Queensland, Australia (Figure 1). The catchment covers an area of approximately 29,150 km^2 and is characterised by a highly variable sub-tropical climate. Precipitation falls throughout the catchment in a spatially and temporally variable manner and as result, droughts and floods characterise the area (Thoms and Parsons, 2003). Average annual precipitation for the area varies from 549 mm in the north to 689mm in the south (Bureau of Meteorology, 2009).

Since the mid 1800's, the catchment has lost most of its native vegetation and undergone major hydrologic alterations to support agricultural development (Fensham and Fairfax, 1997; Thoms and Parsons, 2003). Land use and coinciding hydrological changes were initiated by grazing in the 1840's and then more significantly by cropping since the early 1900's to the present time (Biggs and Carey, 2006). During the 1960's, the construction of public water storages allowed the development and expansion of irrigation throughout the region, which has further altered hydrologic processes (Thoms and Parsons, 2003). Today, the region is one of the most agricultural productive areas in Australia. The most intensive areas of production are on the fertile floodplain alluvial soils (Biggs and Carey, 2006). On the floodplains irrigated agriculture dominates in several areas and provides substantial economic benefits. For example, in 2006-07 irrigated farms generated just under $4000 AUD per ha (Hooper and Ashton, 2009).

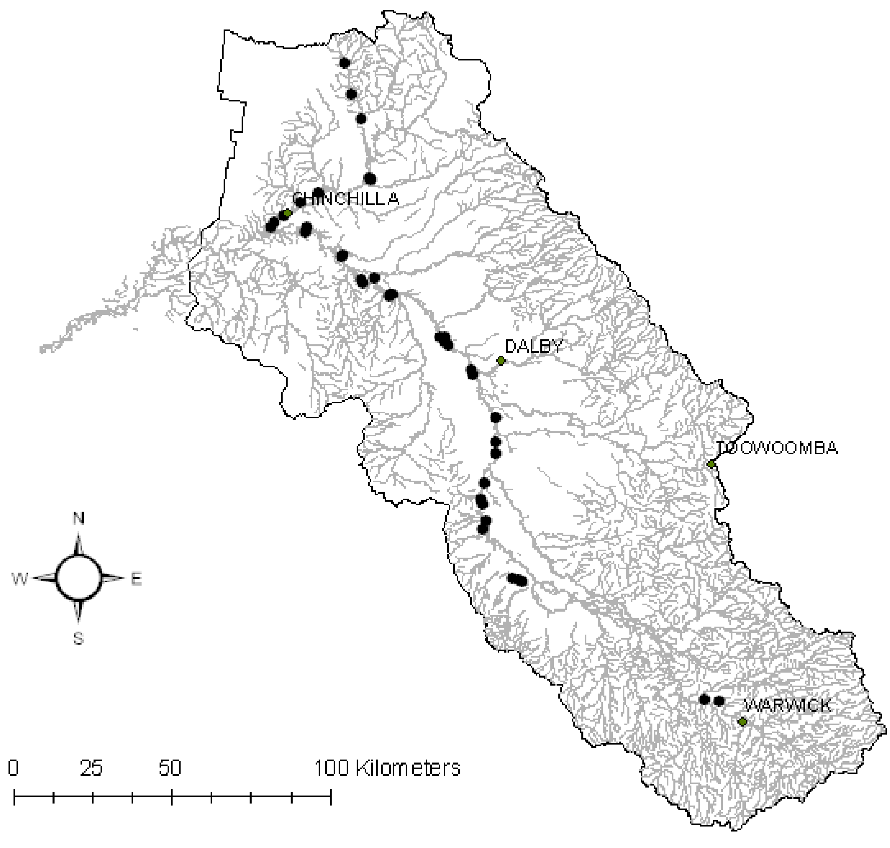

Figure 2
The Condamine Catchment of southeast Queensland, Australia. The location of the 34 study sites and the riverine network throughout the catchment are shown.

Results obtained

The results of the GLMs from the BMA procedure indicate that the number of wet dry cycles and stream connectivity had a consistently positive relationship with many of the vegetation response variables modelled (Table 1). Both these explanatory variables also had a consistently high likelihood of being in the best model. Figure 4 shows the relationship between the number of wet dry cycles and the total amount of woody fringing vegetation around the perimeter of the wetland.

In contrast, many of the land use explanatory variables, such as irrigated agriculture and grazing intensity had a negative relationship with the vegetation (Table 1). Figure 4 shows the relationship between irrigated agriculture and live tree density. All significant models, with the exception of Total Acacia species density and Acacia 10_20cm density, included both land use and hydrological explanatory variables. Aside from land use related variables, the area of the wetland also had a negative influence on the amount of woody fringing vegetation cover under 10 metres in height (Table 1).

There were also several models for which no suitable explanatory variables were selected. For overall seedling density, Acacia species seedling density and the density of trees over 75cm and some other vegetation variables there were no suitable models were selected by the Bayesian modelling averaging procedure (Table 1).

Table 1
Results of BMA modelling procedure for selected vegetation variables measured. Values in parenthesis represent the probability as a percentage that the variable is not zero given the data.

Response variable	Significant explanatory variables	BIC	R^2
Perimeter total live woody vegetation	irrigated agriculture^ (100) wet dry cycles# (94.2) stream connectivity# (93.3) vegetation cover_1km# (71.9)	-14.56	0.570***
Perimeter woody vegetation over 30 m	wet dry cycles# (59.2) vegetation cover_1km# (42.2) irrigated agriculture# (73.9)	-2.36	0.317*
Perimeter woody vegetation under 10 – 30 m	inundation frequency# (77.1) wet dry cycles# (99.2) wetland area^ (76.6)	-13.29	0.505**
Perimeter woody vegetation under 10m	stream connectivity# (98.6) vegetation cover_1km# (88.9) wetland area^ (84.6) inundation frequency^ (80.3) intense agriculture_1km^ (52.4)	-8.47	0.536**
All 20_50cm dbh density	inundation frequency^ (39.2) wet dry cycles# (64.8) stream connectivity# (94.3) grazing_site scale^ (91.9) irrigated agriculture^ (70.9)	-5.448	0.493**
All 10_20 cm dbh density	Inundation frequency^ (40.2) wet dry cycles# (68.7) stream connectivity# (82.3) grazing_site scale^ (68.4) irrigated agriculture^ (53.0)	-2.867	0.453**
All sapling density	stream connectivity# (90.9) vegetation cover_1km# (96.6)	-5.88	0.316*

Total live tree density	wet dry cycles# (100) stream connectivity# (98.8) grazing_site scale^ (94.5) irrigated agriculture_1km^ (92.4) inundation frequency^ (81.9)	-11.81	0.579***
All 50_75cm dbh density	catchment area^ (92.9) wet dry cycles# (93.2) stream variability# (98.3)	-7.24	0.408**
Red gum (*Eucalyptus camaldulensis*) sapling density	vegetation cover# (100) stream connectivity# (88.9)	-8.16	0.361**
Total Red gum (*Eucalyptus camaldulensis*) density	grazing_site scale^ (91) wet dry cycles# (84.4) intense agriculture_1km^ (75.7)	-4.01	0.349*
Total Acacia species density (predominantly *Acacia stenophylla*)	wet dry cycles# (97.8) stream connectivity# (63.3)	-5.51	0.309*
Acacia 20_50cm density	wet dry cycles# (91.3)	-4.01	0.199
Acacia 10_20cm density	wet dry cycles# (100.0) stream connectivity# (60.1)	-6.76	0.334*
Red gum (*Eucalyptus camaldulensis*) over 75cm dbh density	catchment area# (76.8) stream connectivity^ (70.7) intense agriculture_1km^ (50.6)	-1.10	0.291*
Red gum (*Eucalyptus camaldulensis*) 50-75cm dbh density	catchment area^ (42.7) wet dry cycles# (61.8) stream variability# (77.4)	-1.71	0.303*
Red gum (*Eucalyptus camaldulensis*) 20 – 50cm density	stream connectivity# (82.5) grazing_site scale^ (71.8) irrigated agriculture^ (48.4)	-1.97	0.309*
Red gum (*Eucalyptus camaldulensis*) 10 -20cm density	wet dry cycles (2000-2005)# (41.0) stream connectivity# (73.6) vegetation cover_1km# (62.8) grazing site_scale^ (77.2)	-1.71	0.372**
Red gum (*Eucalyptus camaldulensis*) seedling density	No significant variables or models	0.00	0.00
Acacia seedling density	No significant variables or models	0.00	0.00
Acacia sapling density	No significant variables or models	0.00	0.00
Acacia 50_75cm density	No significant variables or models	0.00	0.00
Acacia over 75cm dbh density	No significant variables or models	0.00	0.00
All seedling density	No significant variables or models	0.00	0.00
All over 75cm dbh	No significant variables or models	0.00	0.00

p≤0.0001***; p≤0.001**, p≤0.01*
^variables that have a negative relationship with the data
#variables that have a positive relationship with the data

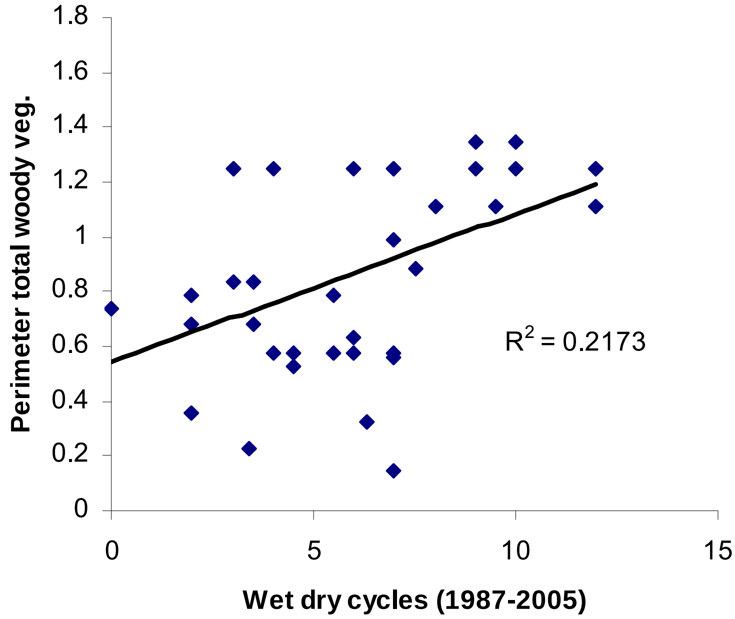

Figure 3
Relationship between the frequency of wet dry cycles and the total amount of live woody vegetation around the wetland

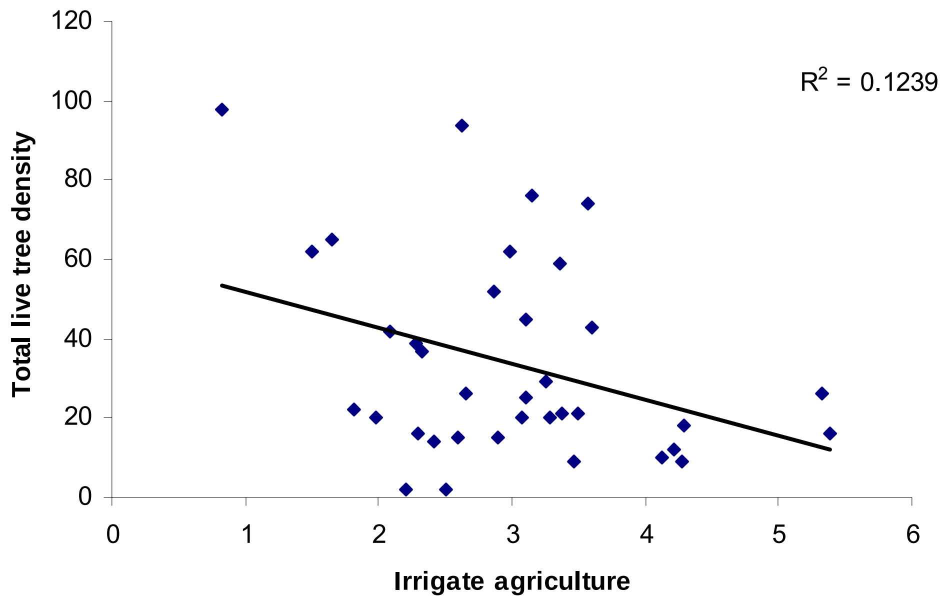

Figure 4
Relationship between total live tree density and the proportion of irrigated agriculture surrounding the wetland

Discussion

Both hydrological and land use explanatory variables were important factors explaining the variation for many of the vegetation response variables modelled. Stream connectivity, wet dry cycling and canopy cover at 1km had a consistently positive relationship with the vegetation while, irrigated agriculture, intense agriculture, wetland area and grazing intensity had a consistently negative relationship (Table 1).

A positive relationship between the wet dry cycles and vegetation is to be expected, given the naturally dynamic nature of these systems. The life cycle and reproductive strategies of the vegetation in temporary wetland systems are dependent on the timing, frequency and duration of wet dry cycles (refs). An increase in either the length of time the wetland is wet or dry can therefore have detrimental effects.

There is growing research showing that the diversity, composition, condition and recruitment of wetland fringing vegetation are intrinsically linked to the water regime of a wetland (Toner and Keddy, 1997; Leck and Brock, 2000; Pettit and Froend, 2001; Warwick and Brock, 2003; Siebentritt et al., 2004; Capon and Brock, 2006). In the New England Tablelands of New South Wales, Brock et al., (1999) argue that wetlands are reliant on the dynamic and fluctuating water regimes to maintain habitat diversity. Similarly, in the Great Lakes of Michigan, Wilcox and Nichols (2008) found that alterations between wet and dry periods were an important condition for generating diversity in the plant community. Consequently, alterations in the timing, duration, frequency, extent and variability of water regime can have potentially long term effects on community species richness and composition (Brock, 2003).

Changes in the frequency of inundation or frequency of dry periods can have impacts on the biophysical nature of wetland systems. In wetlands of the river Murray River in south-east Australia, Francis (2005) found that permanent inundation (decrease in wet dry cycles) reduced periods of peak nutrient availability and phytoplankton productivity associated with flood pulse events that occur after dry periods. The end result is lower levels of nutrients and less phytoplankton productivity in wetlands that are more permanently inundated (Francis and Sheldon, 2002). In addition, in Australia, the seed banks of temporary wetlands germinate in response to wet/dry cycles and not to seasonal changes (Leck and Brock, 2000).

While this study did not directly consider species diversity and composition, our results are consistent with the patterns observed in other studies examining potential drivers of species diversity within wetland communities. Wet dry cycling is thus not only an important factor for maintaining species diversity in these wetland communities, but also for maintenance and persistence of the more permanent fringing perennial vegetation.

Additional to wet dry cycles, connectivity to the stream network in the landscape was also a consistently positive factor for the fringing perennial vegetation of these wetland systems. Connectivity between the river and its floodplain drives the functioning of floodplain ecosystems, by facilitating the exchange of organic matter and inorganic nutrients (Amoros and Bornette, 2002). As such, connectivity is critically important for the vegetation of floodplain wetlands. Hydrological connectivity has been shown to be an important factor for the ecological communities of wetlands. In floodplain habitats of Germany, seedling density, species richness and composition of vegetation was related to the degree of connectivity with the river, with the number of seedlings and species richness increasing with connectivity (Leyer, 2006).

However, hydrology was not the only factor that was consistently important in explaining the variability in the perennial vegetation response variables. Land use practices, especially the amount of irrigated agriculture were also consistently important in many models and often had a negative influence. Gerakis and Kalburtji (1998) argue that irrigated agriculture is the most decisive activity affecting important wetland sites in Greece, stating that it negatively influences all values and functions of these wetland systems. In eastern Ontario, Canada, Houlahan et al., (2006) found that the intensity of adjacent land use and amount of forest cover significantly influenced wetland plant species richness. Houlahan et al., (2006) observed that the amount of forest cover in the landscape was positively related to wetland native plant species richness and also argued that forest cover correlations with soil and nutrient levels may have also contributed to this relationship. In Australia, there has been little research on the affect of habitat modification and the associated land use change on wetlands (Jenkins et al., 2005), let alone its effect on wetland systems that have a variable hydrologic regime. However, the results of this study suggest that, as has been observed in other parts of the world, more intensive land use practices, such as irrigated agriculture have a detrimental effect on the vegetation of the wetlands surveyed.

At local scales, agricultural activities through grazing also seemed to affect certain components of the wetland vegetation surveyed. Throughout many production landscapes in Australia, grazing is one of the key disturbances on fringing wetland vegetation. However, despite many floodplain habitats being grazed, there have been relatively few studies on the impacts of grazing on wetlands (Jenkins et al., 2005). Grazing reduces plant biomass and reduces growth and reproduction (Brock, 2003). In agricultural landscapes, grazing is of particular concern for wetlands as domestic stock and feral grazing herds often congregate around water sources (Jansen and Robertson, 2001). However, Robertson and Rowling (2000) have demonstrated that livestock grazing has had substantial impacts on riparian vegetation of the Murrumbidgee River, southern New South Wales. Robertson and Rowling (2000) found that in sites where stock access was restricted, the abundance of seedlings and saplings of the dominant *Eucalyptus* species was up to three orders of magnitude higher relative to sites with stock present. The results of this study support these concerns, as grazing was a significant negative factor in models for total live tree density and total red gum density.

In the future climate change is likely to drastically change hydrological processes and land use practices. The woody fringing vegetation of wetlands is an important component of wetland systems and supports various important ecological functions (Reid and Brooks, 2000). However, in many agricultural landscapes modification of hydrology and additional stresses from land use intensification is degrading the values and services provided by wetlands and their vegetation. If the values and services of remaining wetlands in agricultural landscapes are to be maintained or improved it is therefore critical that how they interact with hydrology and landscape processes is understood.

Conclusions

In all but two of the significant models obtained through Bayesian model averaging across 34 wetlands, both hydrological and land use variables together explained variation in perennial fringing vegetation response variables. This research indicates that both hydrology and land use need to be considered as important drivers of processes contributing to the resilience of wetlands in agricultural landscapes. Together, regulation of water flows, in this case a reduction in wet-dry cycling and reduced connectivity (either through physical alteration or a reduction in stream flows) and intensity of land use practices, such as grazing and irrigated agriculture, can have significant effects on the ecology of wetlands. These findings are significant to understand how important biotic components, such as the fringing vegetation of wetlands, may change in the future under predicted climate change. Climate change may further exacerbate these changes caused by these anthropogenic activities, by further altering hydrologic processes in production landscapes. However, climatic changes are also likely to cause changes to land use practices in the region. Consequently, to gain a more holistic understanding of how wetland systems will be affected by climate change, models that incorporate both hydrology and land use practices need to be considered.

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