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DEOXYGENATION POTENTIAL OF THE RICHMOND RIVER ESTUARY FLOODPLAIN, NORTHERN NSW, AUSTRALIA

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ABSTRACT

Periodic deoxygenation events (DO < 1 mg/L) occur in the Richmond River Estuary on the east coast of Australia following flooding and these events may be accompanied by total fish mortality. This study describes the deoxygenation potential of different types of floodplain vegetation in the lower Richmond River catchment and provides a catchment scale estimate of the relative contribution of floodplain vegetation decomposition to deoxygenation of floodwaters. Of the major vegetation types on the floodplain slashed pasture was initially (first 5 to 7 h) the most oxygen demanding vegetation type after inundation (268 $\pm$ mg $O_2\,m^{-2}\,h^{-1}$), followed by dropped tea tree cuttings (195 $\pm$ 18 mg $O_2\,m^{-2}\,h^{-1}$) and harvested cane trash (110 $\pm$ 8 mg $O_2\,m^{-2}\,h^{-1}$). However, 10 h after inundation the oxygen consumption rates of slashed pasture (105 $\pm$ 5 mg $O_2\,m^{-2}\,h^{-1}$) and tea tree cuttings (59 $\pm$ 7 mg $O_2\,m^{-2}\,h^{-1}$) had decreased to a rate less than the harvested cane trash (110 $\pm$ 8 mg $O_2\,m^{-2}\,h^{-1}$). The oxygen demands of the different floodplain vegetation types when inundated were highly correlated with their nitrogen content ($r^2 = 0.77$) and molar C:N ratio ($r^2 = 0.82$) reflecting the dependence of oxygen demand of vegetation types on their labile carbon content. The floodplain of the lower Richmond River (as flooded in February 2001) has the potential to deoxygenate about 12.5×10^3 mL of saturated freshwater at 25°C per day which is sufficient to completely deoxygenate floodwater stored on the floodplain with 3 to 4 days. In addition, oxidation of Fe^{2+} mobilized during the decomposition of floodplain vegetation via iron reduction and discharged from groundwater and surface runoff in acid sulfate soil environments could account for about 10% of the deoxygenation of floodwater stored on the floodplain. Management options to reduce floodplain deoxygenation include removing cuttings from slashed pasture and transporting off-site, reducing slashed pasture windrow loads by using comb-type mowers, returning areas of the floodplain to wetlands to allow the establishment of inundation tolerant vegetation and retaining deoxygenated floodwaters in low lying areas of the floodplain to allow oxygen consumption process to be completed before releasing this water back to the estuary. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: deoxygenation; floodplain vegetation; fill kills; acid sulphate soils; modified drainage

INTRODUCTION

It has long been known that decomposing vegetation consumes oxygen due to microbial respiration and chemical oxidation (e.g. Witkamp, 1966). When rewetted, plant material leaks soluble, easily decomposed substances that stimulate respiration of soil microbes responsible for decomposition of organic material (Nykvist, 1963). Within the upper soil horizons the oxygen demand is usually controlled by the activity of these organic matter decomposers. These microbes need moisture to survive and soil desiccation can severely reduce their numbers (Qiu and McComb, 1995).

Around the boundary between oxic and anoxic conditions within the soil, chemical oxidation of reduced chemical species takes place. Such species include methane, ammonia, nitrite, ferrous iron and manganous manganese (Stumm, 1992). For a partially wetted soil the anoxic boundary will usually reside in the subsoil layers. Upon wetting, surface organic matter will create an oxygen demand due to the leakage of soluble material. Any chemical oxygen demand will exist below the surface around the oxic/anoxic boundary. As the soil becomes saturated this boundary will move towards the surface as soil oxygen is consumed, producing anoxia within the soil

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profile (Megonigal *et al.*, 1993). With water standing on the soil surface and ongoing oxygen demand by organic decomposers within the water, the anoxic boundary can rise into the water body itself. Oxygen diffuses much slower in water than in air and the oxygen consumption can outstrip the rate of diffusion.

Because floodplain vegetation and soils are only periodically inundated they have a high potential to deoxygenate floodwaters. Despite the potential of floodplains to deoxygenate floodwaters few studies have examined the importance of floodplains and floodplain modification to the deoxygenation of floodwaters. Two upland and one lower river studies have looked at the export of oxygen consuming material off the floodplain (Hamilton *et al.*, 1997; Johnston *et al.*, 2003; Valett *et al.*, 2005). Lower river floodplains (tidal river or river estuary) are commonly used for intensive agricultural production and many have been comprehensively modified to increase the productive area through the construction of drains and levees. Drainage alterations can change the return period of floodplain inundation (Valett *et al.*, 2005), the dominant vegetation (Pressey and Middleton, 1982), the type of organic matter that accumulates (Kang and Stanley, 2005), and results in a greater area of desiccated soils, all which can enhance the deoxygenation potential of the floodplain. Lower river floodplains also commonly contain acid sulphate soil landscapes (e.g. Johnston *et al.*, 2003). However, there have been no *in-situ* measurements of the oxygen demand of lower river floodplains or catchment scale estimates of the potential for lower river floodplains to deoxygenate receding floodwaters. As such, it is unknown which parts of the lower river floodplain have the greatest deoxygenation potential and therefore it is unknown how best to manage lower river floodplains to improve water quality in receding floods.

Following a 1 in 10 year return period flood in February 2001, 50 km of the Richmond River Estuary, northern NSW, Australia was closed to commercial and recreational fishing due to the complete deoxygenation of the water column (DO $< 1\ \mathrm{mg\,L^{-1}}$) and associated total fish mortality. Similar deoxygenation events in the estuary, albeit not as severe, have been recorded for the last 50 years (Eyre, 1997). One of the factors implicated in the deoxygenation of floodwaters during the February 2001 event was vegetation decomposition on the lower river floodplain (Slavich, 2001). This study describes the deoxygenation potential of different types of floodplain vegetation in the lower Richmond River catchment and provides a catchment scale estimate of the relative contribution of lower river floodplain vegetation decomposition to deoxygenation of the February 2001 floodwaters.

METHODS

Study area

The Richmond River catchment has an area of 6860 km^2 and the mouth of the Richmond discharges into the Tasman Sea at Ballina, on the east coast of Australia. Half the catchment normally receives from 800–1300 mm of rain annually with at least 10 days of rain over 25 mm. The north-eastern quarter of the catchment receives on average 1500 mm. Runoff for the whole catchment is about 23% of rainfall (EPA, 1996) but for the Wilsons River catchment (joining the Richmond at Coraki) the runoff can be as much as 46% of rainfall. The lower Richmond floodplain, defined as the catchment below the tidal limit in the Richmond River, has an area of about 1070 km^2 (15% of the whole catchment). Hundreds of drains of various sizes, from roadside table drains 0.5 to 1 m deep to main drains up to 5 m deep and up to 25 m wide, dissect the lower floodplain (Atkinson *et al.*, 2000). Large areas of acid sulphate soils including Tuckean Swamp, Rock Mouth Creek and Bundgawalbyn/ Sandy Creek have developed in protected estuarine embayments and behind barrier systems during the formation of the middle section of the lower Richmond River Holocene floodplain (Figure 1). For further details of the estuary and catchment see McKee and Eyre, (2000).

Water quality

Dissolved oxygen concentrations ($\pm 0.1\ \mathrm{mg\,L^{-1}}$) were measured *in situ* at 30 sites (Figure 1) using a TPS 90 FLMV field lab (TPS Pty Ltd, Springwood, Brisbane Australia). Sites 1, 7 and 25 were in the main arm of the Richmond River and the remaining sites were in floodplain drains (Figure 1). Before each sample run a two point calibration was carried out using a zero oxygen solution (sodium sulphide) and air saturated water of known temperature. Measurements were made on two occasions (9th and 18th March) following the 6th March, 2004 flood

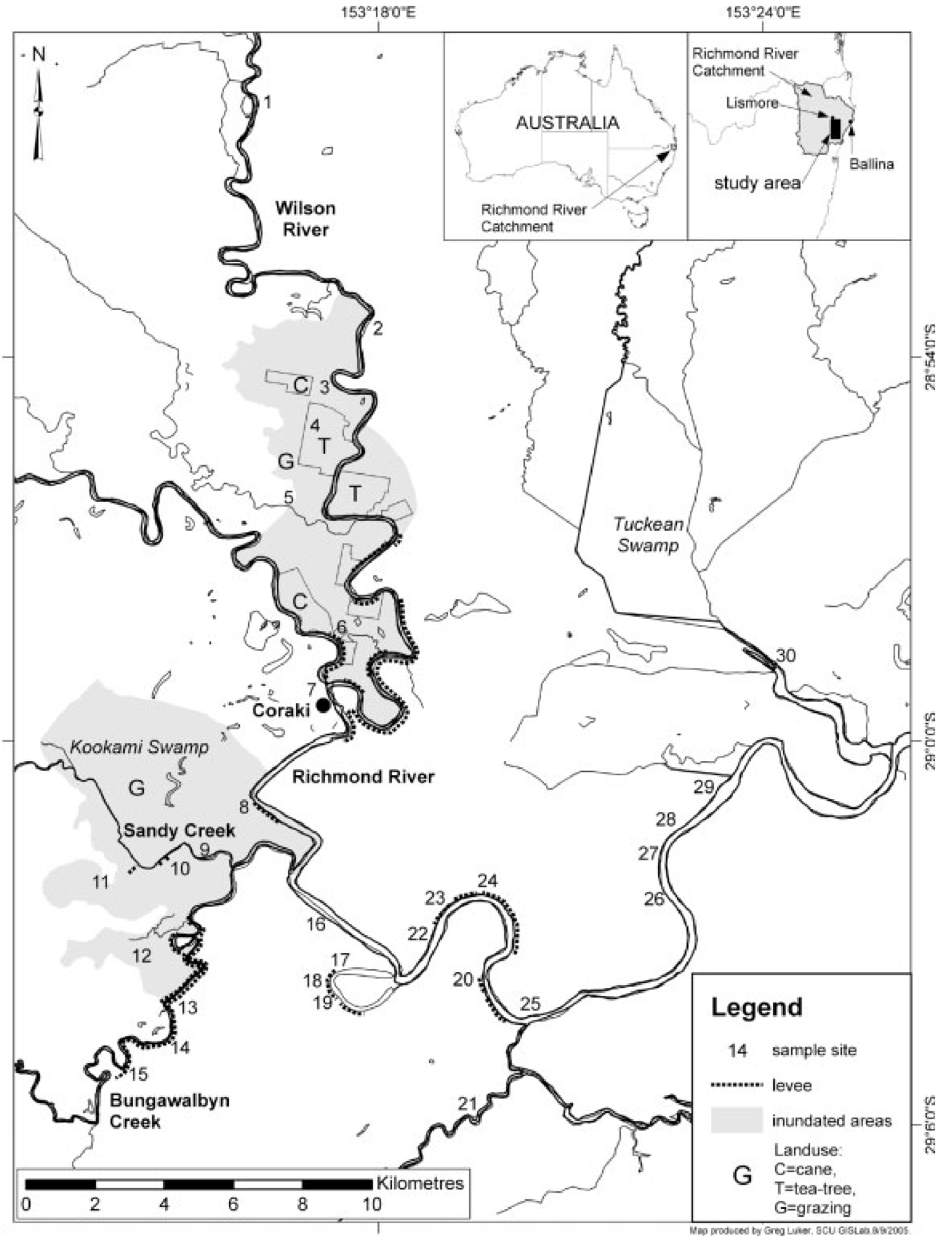

Figure 1. Location of the sampling sites, position of levees and areas of different land use inundated by the February 2001 flood in the lower Richmond River catchment

event to monitoring oxygen concentrations in water coming off various parts of the floodplain. Sampling runs commenced about 9 am from the Wilsons River (Site 1) and continued down catchment, concluding at the Tuckean Swamp Barrage (Site 30) at about 2:30 pm.

Laboratory experiments—Oxygen consumption by vegetation

Vegetative materials including straw, grasses, cane, leaves, rushes and bark were collected from various parts of the floodplain during the 2002–2003 summer. All materials were in an air-dried state due to lack of rain during several previous months. Cut grasses were collected from windrows formed during pasture slashing. Five grams of dry vegetative matter was added to 1 litre of milli-Q water in beakers within a water bath to maintain a constant temperature. Plastic netting (gutter leaf shield) was used to keep plant materials submerged. Dissolved oxygen, conductivity and temperature were measured hourly using a TPS 90 FLMV field lab. For one grass incubation a small amount of $AgNO_3$ (1 mg) was added to the water to suspend bacterial activity. All incubations were run in triplicate at 20°C. The grass incubations were also run at 3 different temperatures. A sub sample of all vegetative material was dried (70°C, 24 h) and ground (Cyclone Sampling Mill—Udy Corporation) and analysed for carbon and nitrogen content (LECO CNS).

Field experiments—Oxygen consumption by vegetation

Plastic stormwater pipe (300 mm diameter) was cut into 450 mm long sections with one end being ground to a sharp edge. For penetration of drier clay soils this cutting edge was enhanced by the addition of a metal strip projecting 50 mm below the plastic edge. Pipe sections were driven 50–100 mm into floodplain soils supporting vegetation of three different land uses; slashed pasture, dropped tea tree cuttings and harvested cane. The harvested cane and tea tree incubations included some mixed forbes and couch grass that grows between the individual tea tree plants and cane stalks. Pipe sections were filled to at least 300 mm depth with water from an adjacent river or drain source. A field lab (TPS 90 FLMV) was used to record dissolved oxygen (DO) within the pipes at hourly intervals. Experiments were run in summer in triplicate over ten hours. Oxygen consumption rates were calculated by linear regression of the concentration data as a function of incubation time, core water volume and surface area. Because the oxygen versus time curves were non-linear (see Figure 6), different rates were calculated for the initial and final parts of the incubation.

Land use classification

Orthophoto and aerial photograph mosaics and ground truthing were used to identify the main land uses on the floodplain downstream of Lismore (lower Wilsons River floodplain) and the Bungawalbyn floodplain west of Coraki as well as the floodplain between Coraki and Woodburn. Areas cultivated for sugarcane and tea tree were identified and the balance was classified as grazing land. Small areas of soybean production were grouped with cane because in most cases soybean cropping was on previously fallow cane land. Areas of each land use were calculated from topographic maps; Woodburn 9539–1 N 1:25.000 (CMA, 1987), and Wardell 9540-2-S (CMA, 1986).

Hydrology

Gauged flow data for the Casino (Station: 203004), Leycester (Station: 203010) and Wilsons (Station: 203014) was supplied by the Department of Natural Resources. Discharge from the ungauged parts of the catchment was estimated by correcting gauged flow by an area coefficient to account for the ungauged areas and adjusting for different runoff coefficients of the sub-catchments (Hossain, 1998).

RESULTS

Rainfall and dissolved oxygen

The largest rainfall event during the study period occurred on 6th March 2004 and caused minor flooding (1 in 2 year return period) in Wilsons River (Figure 2). This rainfall event resulted in depressed dissolved oxygen concentrations (<20% saturation) in drains on the larger areas of the lower Richmond River floodplain (Figure 3). Recovery to pre-event dissolved oxygen concentrations was slow with many drains on the floodplain remaining less than 40% saturated for more than one month (data not shown). Dissolved oxygen concentrations were also slightly depressed at Site 1, which is upstream of the lower floodplain (Figure 3). There was a decrease in dissolved oxygen from about 80% saturation to about 40% saturation moving downstream (i.e. from Sites 1 to 7 to 25; Figure 1) in the main arm of the lower Richmond River and estuary). Dissolved oxygen concentrations in the main arm took about 2 months to recover to pre-event dissolved oxygen concentrations (data not shown).

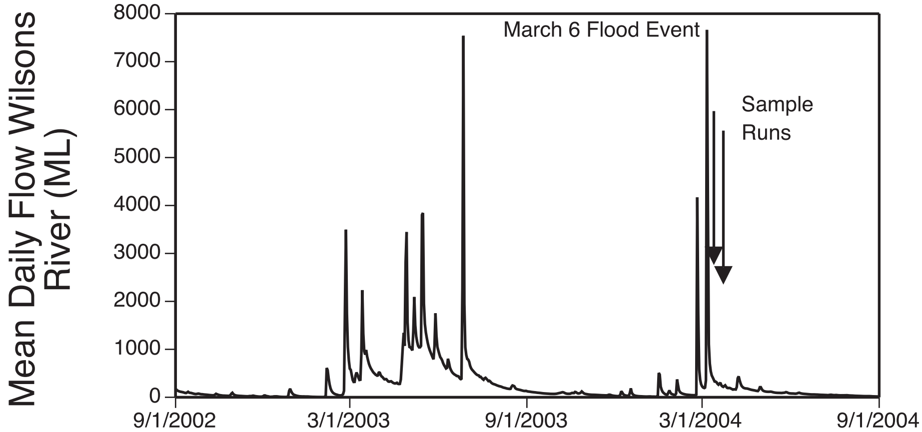

Figure 2. Discharge in the Wilsons River and Richmond River during the study period

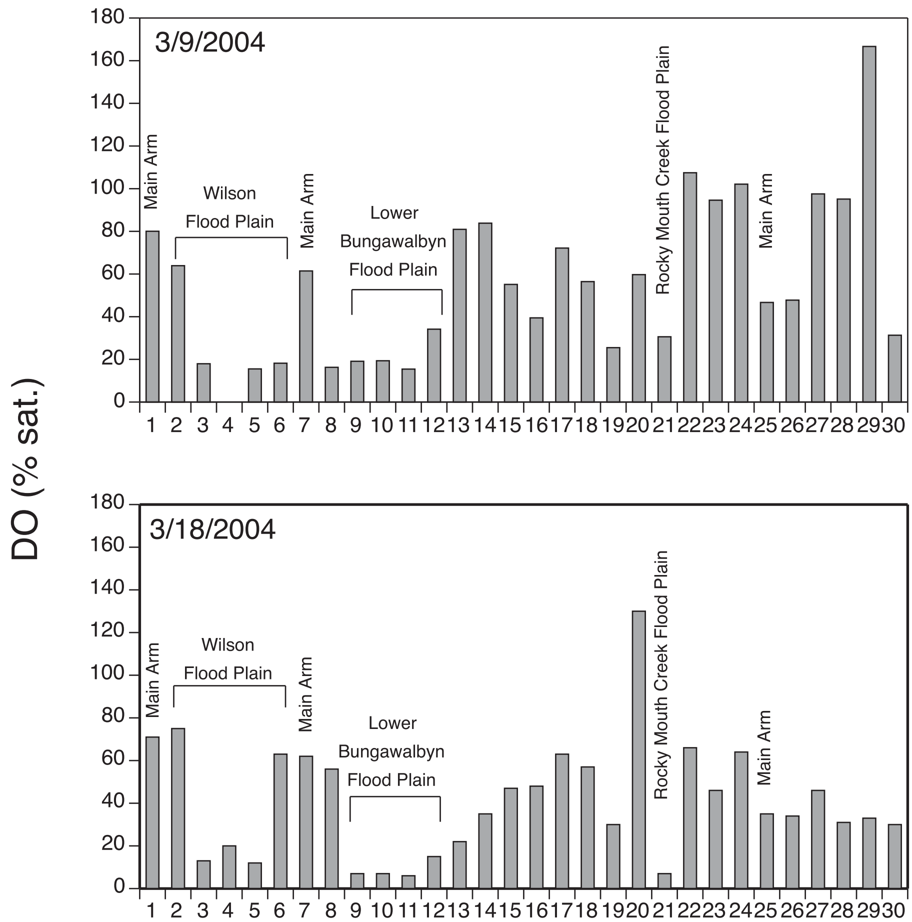

Figure 3. Dissolved oxygen concentrations (% saturation) in the lower Richmond River catchment following the 6th March 2004 flood event

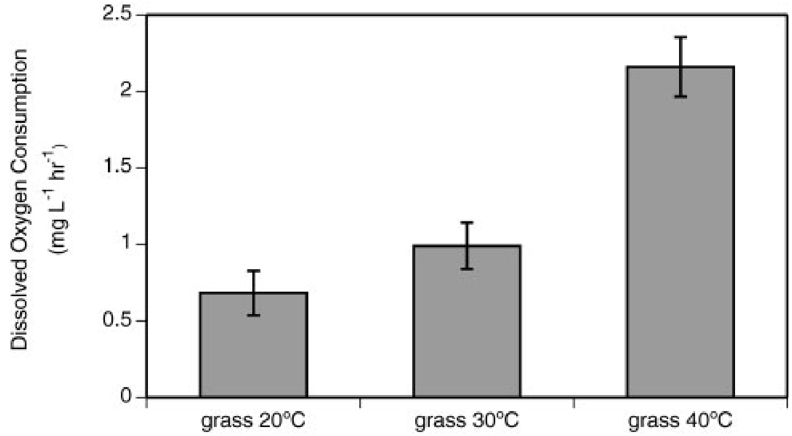

Figure 4. Mean (±SE, $n=3$) dissolved oxygen consumption rates by inundation of dry grass cuttings at three temperatures

Vegetation experiments

Inundation simulations of the various floodplain vegetation types showed that the rate of oxygen demand is temperature dependant (Figure 4) and that herbaceous materials have a higher demand than leaf litter or rushes (Figure 5). Sugar cane billets (spill from harvesting operations) had a surprisingly low oxygen demand considering the sugar content (Figure 5). The oxygen demand of floodplain vegetation types when inundated was highly correlated with its nitrogen content ($r^2 = 0.76$) and molar C:N ratio ($r^2 = 0.82$) (Table I). Addition of $AgNO_3$ to the grass resulted in almost complete suppression of oxygen demand.

Field experiments

Slashed pasture, dropped tea tree cuttings and harvested cane were the three major vegetation types in the lower Richmond River catchment. Each vegetation type showed a distinctly different oxygen consumption rate versus time relationship (Figure 6). The slashed pasture with abundant dry material rapidly consumed oxygen (268 ± 3 mg $O_2\,m^{-2}\,h^{-1}$) for the first 7 h than the oxygen consumption rate decreased to 105 ± 5 mg $O_2\,m^{-2}\,h^{-1}$. Dropped tea

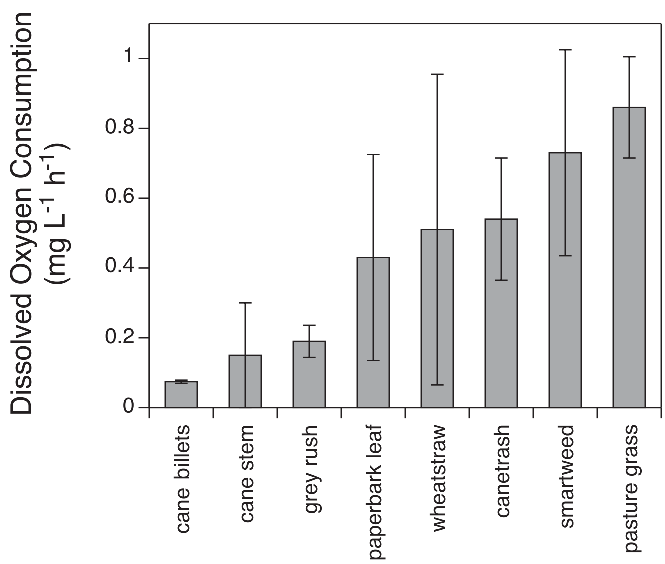

Figure 5. Mean (±SE, $n=3$) dissolved oxygen consumption rates by inundation of various dry vegetative materials at 20°C

Table I. Carbon and nitrogen content of vegetative matter used in assessing oxygen demand upon inundation

	Carbon (%)	Nitrogen (%)	Molar C:N ratio
Grey rush	50.0	0.17	374
Sugarcane stem	43.0	0.16	342
Wheatstraw	48.0	0.38	161
Canetrash (leaf)	46.0	0.45	130
Paperbark leaf	58.0	0.84	88
Cattle manure	33.0	1.62	26
Pasture grass (stooling)	46.0	1.63	36
Ti tree	53.0	1.66	41
Couch grass (turf)	40.0	1.92	27
Smartweed	49.0	2.16	29

tree cuttings also showed a higher initial oxygen consumption rate for the first 5 h (195 ± 18 mg $O_2\,m^{-2}\,h^{-1}$) and then the oxygen consumption rate decreased to 59 ± 7 mg $O_2\,m^{-2}\,h^{-1}$. The harvested cane trash had the lowest initial oxygen consumption rate (110 mg $O_2\,m^{-2}\,h^{-1}$), but this rate remained constant over the 10 h incubation and as such was the highest final oxygen consumption rate (110 ± 8 mg $O_2\,m^{-2}\,h^{-1}$). The initial oxygen consumption rates of all three vegetation types were significantly different from each other (Student T-Test; $p = 0.01$). The final oxygen consumption rates of the pasture and cane were not significantly different, but both were significantly different to the final tea tree oxygen consumption rate.

Areas of floodplain land use

Orthophoto and aerial photograph analysis and observations during flooding showed that about 10 km^2 of the lower Wilsons floodplain between Lismore and Woodburn that supports grazing would have been inundated by the February 2001 flood (Figure 1; Table II). About 7 km^2 of tea tree and 4 km^2 of sugarcane on the lower Wilsons River floodplain would also have been inundated by the February 2001 flood (Table II). Immediately west and southwest of Coraki is an area of the floodplain critical to river water oxygenation after flooding because the floodwaters, confined upstream by levees, flow backwards into Bungawalbyn and Sandy Creeks to spread out over mainly grazing land (10 km^2) established on former peatswamp (Table II).

DISCUSSION

Location of oxygen sags

Although the March 2004 flood was only a minor event, floodwaters in the Wilsons River (Site 1) were already slightly deoxygenated before they reached the lower floodplain most likely due to the upstream mobilization of fine organic material (Eyre and Twigg, 1997; Webster *et al.*, 1999). However, the major oxygen sags occurred in the middle reaches of the lower floodplain (Wilsons River, Bungawalbyn Creek and Rocky Mouth Creek floodplains). Depressed dissolved oxygen concentrations in the middle reaches of the lower floodplain were also noted following the large February 2001 flood (Slavich, 2001). This is upstream of other substantial sources of deoxygenation potential such as iron monosulphides in agricultural drains (i.e. Tuckean Swamp) (unpublished data). As such, the lower Richmond River floodplain appears to be a major source of floodwater deoxygenation.

Floodplain vegetation decomposition

The *in-situ* mesocosm inundation experiments showed that slashed pasture was the most oxygen demanding vegetation type. Despite including mixed forbs and couch grass the tea tree droppings and harvested sugar cane were significantly less demanding than the slashed pasture. The perennial couch is prostrate and hence does not grow as tall as many of the pasture grasses. In addition, its leaves are small and short and it propagates by stolons. Similarly in the Clarence River floodplain (the next major catchment south of the Richmond) grasses have been

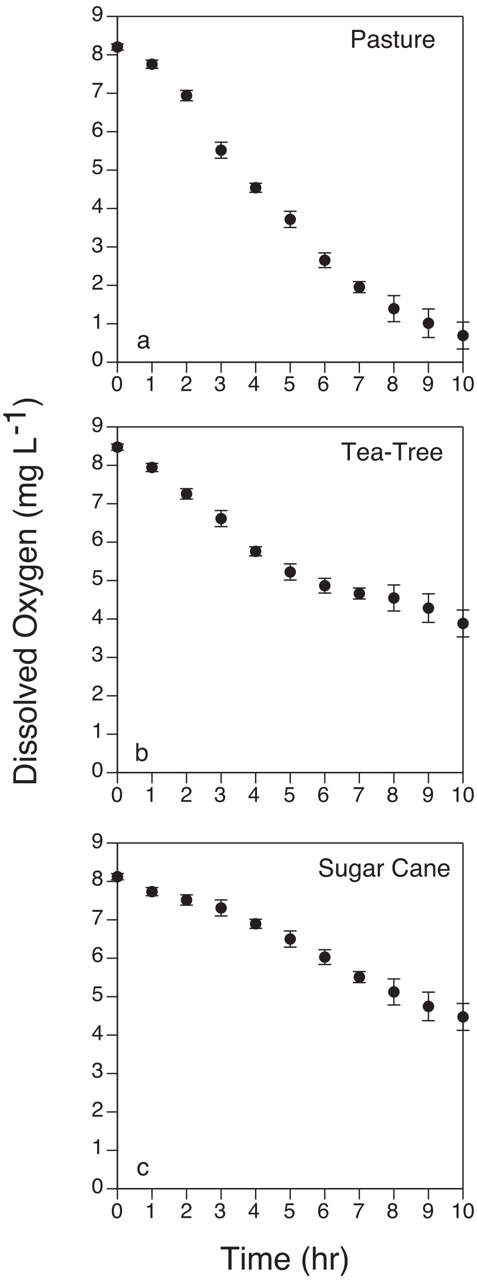

Figure 6. Mean ($\pm$SE, $n = 3$) oxygen concentrations as a function of time in the *in situ* incubation experiments on three different land uses in the lower Richmond River catchment; (a) pasture, (b) tea tree and (c) sugarcane

shown to have more labile carbon (water soluble content) and consume more oxygen upon inundation than leaf litter (*Melaleuca quinquenervia*), with pasture grass (*Paspalum distichum*) more oxygen demanding than couch (*C. dactylon*) (Johnston *et al.*, 2005). *P. distichum* was one of several species identified in the tall mixed pasture tested in the Wilsons and Richmond River floodplains.

The high oxygen consumption of slashed pasture is consistent with its low molar C:N ratio and high nitrogen content which reflects a more labile carbon content. The positive linear relationship between nitrogen content and decomposition rates of plant material is well established and reflects the importance of labile carbon and nitrogen

Table II. Potential deoxygenation of different land uses (vegetation types) on the lower Richmond River floodplain

Floodplain	Land use	Inundation area (km^2)	Initial oxygen consumption rate ($mg\ O_2\ m^{-2}\ h^{-1}$)	Final oxygen consumption rate ($mg\ O_2\ m^{-2}\ h^{-1}$)	1 Day deoxygenation potential (ML)[1]	7 Day deoxygenation potential (ML)[1]
Wilsons	Grazing	10	267 ± 3	105 ± 5	4 568	31 973
	Tea tree	7	195 ± 18	59 ± 7	2 072	14 504
	Sugarcane	4	110 ± 8	110 ± 8	1 320	9 240
Bungawalbyn	Grazing	10	267 ± 3	105 ± 5	4 568	31 973

[1]Saturated freshwater at 25°C.

for microbial decomposers (Enriquez *et al.*, 1993). Upon wetting the plant material leaks dissolved organic carbon (DOC) and dissolved organic nitrogen (DON), which stimulates bacterial activity (Nykvist, 1963); the higher the labile carbon content the greater the release of DOC and DON. The almost complete suppression of oxygen demand after the addition of silver ions indicates that the oxygen demand was mostly due to bacterially mediated processes. Carbon decomposition will initially proceed via aerobic oxidation and will then proceed to iron and sulphate reduction as the soil conditions become anaerobic and finally as methanogenesis as all electron acceptors except carbon dioxide become depleted. Iron and sulphate reduction and methanogenesis may produce soluble Fe^{2+}, H_2S and CH_4 which can deplete oxygen in receiving waters if transported and oxidized off-site, although H_2S would most likely be bound with Fe in the soil to form FeS and Fe_2S (van Breemen, 1993; Johnston *et al.*, 2003).

Effects of levees and floodgates

Much of the lower Richmond River catchment has artificial levee banks built close to the stream bank. Levees are particularly extensive in the Coraki and Bungawalbyn Creek areas. For the Wilsons floodplain the levees ranged from 7 to 8 m AHD and as the river is tidal most of the levees would only be breached for a flood of about 8.5 m AHD at Lismore. East of Coraki there is a long stretch of levee known as the Tuckurimba levee that has blocked a floodway to the east. During the March 2004 flood event the flood peak travelled upstream in Bungawalbyn Creek then upstream in Sandy Creek, spreading over pasture in the Kookami swamp, a drained wetland. Water standing on the paddocks was low in oxygen ($3.34\ mg \cdot L^{-1}$) and relatively warm (25°C) (unpublished data). Without levees, much of the floodwater would have left the main stream upstream of Bungawalbyn Creek to spread over the floodplain and collect in wetland areas. However, because every former wetland area has been provided with a drain the water would not be retained for long enough to ensure the dominance of vegetation tolerant of waterlogging. The vegetation that does prevail (particularly pasture) rapidly consumes oxygen once inundated.

Floodplain drains are commonly provided with floodgates; structures allowing egress of drain waters but preventing the ingress of river waters to the drain. In combination with augmented riverside levees these structures ensure that the inter-flood interval for much of the floodplain is greatly increased, from around a 1 in 2 year return to around a 1 in 10 year return. Valett *et al.* (2005) used experimental flooding of disconnected floodplain (isolated by levees) to show that flooding produced prolonged anoxia. In contrast, connected floodplains maintained 3–8 $mg\ L^{-1}$ O_2 for the entirety of a natural flood. Kang and Stanley (2005) found that soil microbial activity was higher inside of levees than outside on the Wisconson River Floodplain and suggested this may be due to the differences in substrate quality as a result of vegetation differences. Baldwin and Mitchell (2000) suggested that drying of soils would increase the rate of mineralization of carbon, however the efficiency of substrate utilization is greatest with alternating oxic–anoxic conditions.

Floodgates have the effect of lowering the water table where the river is tidal by preventing the water at high tide from entering the drain (tidal pumping). Because much of the soil is drier the floodplain can support vegetation intolerant of waterlogging, which consequently decomposes faster and demands more oxygen after inundation. The term wetland does not imply frequent inundation; only that their soils periodically experience conditions of near saturation and usually have a surficial horizon with high organic matter content (histic epipedons–Megonigal *et al.*, 1993). Wetlands support vegetation tolerant of waterlogging. Whereas organic decomposition on the floodplain results in deoxygenation of floodwaters, it is the altered drainage of the floodplain that returns deoxygenated floodwaters to the main stream without time to reoxygenate (Johnston *et al.*, 2003).

Deoxygenation budget

The deoxygenation potential of the floodplain was estimated by multiplying the measured oxygen consumption rates of the different vegetation types (Figure 6) by the estimated areas of inundation during the February 2001 flood (Figure 1; Table II). The rates used for the 1 and 7 day extrapolations were calculated using the initial rate for the period over which it occurred, and then the final rate for the remainder of the period. These extrapolated rates may still be high however, because the *in situ* incubations were only carried out over 10 h and the oxygen consumptions rates may decrease over longer time periods as labile organic matter is consumed. Grazing land has the largest potential to deoxygenation floodwaters with equal amounts in the Wilsons and Bungawalban floodplains. Areas of tea tree have the second largest potential to deoxygenate floodwaters with areas of sugarcane having the smallest deoxygenation potential. The floodplain of the lower Richmond River (as flooded in February 2001) has the potential to deoxygenate about 88×10^3 ML of saturated freshwater at 25°C (i.e. 8 mg O_2 L^{-1}) over a 7 day period which is about 7% of the 7 day February 2001 flood flow (1.3×10^6 ML). However, the total flood flow is probably not that relevant as much of this water is rapidly discharged directly to the ocean without contacting the floodplain (Eyre and Twigg, 1997). In addition, severely deoxygenated water only started discharging to the estuary several days after the flood peak, once the water level in the main estuary began to drop and the floodplain began to drain (Slavich, 2001). Major fish kills in the Richmond River Estuary occurred following the discharge of this water from the floodplain (Slavich, 2001). Hamilton *et al.* (1997) also found the lowest oxygen concentrations occurred in the Paraguay River when waters contacted the floodplain. If it is assumed that floodplain was covered with an average depth of 1 m of water during the February 2001 flood (i.e. 31×10^3 ML) the floodplain has the potential to completely deoxygenate this water within 3 to 4 days, which is consistent with the observed discharge of completely deoxygenated water several days after the flood peak (Slavich, 2001). The Richmond River Estuary has an approximate mean water level volume of 54×10^3 mL (McKee and Eyre, 2000), which is similar to the volume of deoxygenated water on the floodplain during larger floods.

Fe^{2+}, CH_4 and H_2S may also be mobilized during the decomposition of floodplain vegetation and may contribute to deoxygenation in the receiving waters (Hamilton *et al.*, 1997; Johnston *et al.*, 2005). FeS formed in the upper soil profile, and subsequently remobilized by floodwaters, may also contribute to deoxygenation. It addition, Fe^{2+} may also be discharged from groundwater and surface runoff in acid sulfate soil environments (Ferguson and Eyre, 1999). No measurements of CH_4 and H_2S have been undertaken in the lower Richmond River catchment, but Fe^{2+} concentrations in agricultural drains and the estuary have been well documented following floods (Ferguson and Eyre, 1999). When this Fe^{2+} is oxidized it would consume 1 mol of oxygen for every mol of Fe^{2+} oxidized (Stumm, 1992). pH is a critical determinant of the concentrations of Fe^{2+} in solution. The potential contribution of Fe^{2+} oxidation to deoxygenation during the February 2001 flood was estimated by multiplying the discharge of water from the Tuckean-Broadwater, Rocky Mouth Creek and Bora-Codrington Drain by the expected Fe^{2+} concentration in the discharge water. The Tuckean-Broadwater, Rocky Mouth Creek and Bora-Codrington Drain were chosen as they all have been shown to discharge low pH water following floods (see Ferguson and Eyre, 1995) and as such would have the highest concentrations of Fe^{2+}. The Fe^{2+} concentration was estimated by applying pH/Fe^{2+} relationships established for the lower Richmond River catchment (Ferguson and Eyre, 1999) to the pH at these sites measured during similar flooding in 1995 (Ferguson and Eyre, 1995). These calculations suggest that the oxidation of Fe^{2+} may have accounted for about 10% of the deoxygenation of water stored on the lower Richmond River floodplain during the February 2001 flood.

Major factors influencing the deoxygenation potential of the floodplain include the temperature and antecedent conditions such as floodplain dryness. A higher temperature combines the effects of lower oxygen concentrations in the water and faster microbial processes on the floodplain, and hence more rapid oxygen consumption (see Figure 4). A very dry floodplain would probably have a greater standing stock of undecomposed plant matter as microbial processes are retarded under dry conditions (Qiu *et al.*, 2005). This is consistent with the complete deoxygenation of the Richmond River Estuary following the February 2001 flood as the flood occurred in summer following an extended period of drought.

MITIGATING OXYGEN DEPLETION ON THE FLOODPLAIN

Slashed pasture with substantial windrows of cuttings was found to be the most oxygen demanding land use, suggesting removal of the cuttings would reduce the potential oxygen demand. Some slashed pasture in the lower Richmond River catchment is baled and sold off site (Michael Wood. Pers. Comm. 2005). However, costs, including fuel, labour and depletion of nutrients and deleterious effects on soil structure due to organic matter depletion may mitigate against this strategy being implemented on a larger scale. Slashing of pastures enhances nutrient cycling and would be regarded as good soil management practice (Peter Slavich. Pers. Comm. 2005). Alternatively, during favourable weather excess growth could be collected and stored as silage and subsequently fed to stock on site, which would not be as great a drain on nutrients or organic matter, due to manure input back to the paddocks. However, the manure also has an oxygen demand similar to the pasture (unpublished data) and therefore may contribute some oxygen demand. Consideration as to sugar content controls the time of silage making and for grasses must be prior to seed setting.

There were two major controls apparent on the deoxygenation of the Richmond floodwaters, artificial drainage and type of vegetation cover. Whereas artificial drainage patterns are largely static, the type of vegetation cover is largely determined by economic factors and there are opportunities for management alterations. Traditionally sugarcane leaves were burnt before harvest of the cane and are presently separated during harvest and collected for sale as mulch or stockpiled for burning at the sugar mill, producing electricity. Similarly the leaf and stem waste after extraction of tea tree oil is sold as mulch for urban landscaping. Additionally, grazing animals (sheep) are used as part of an integrated weed control program in tea tree plantantions to graze weeds. For both crops a considerable proportion of the carbon content and hence potential oxygen demand of the vegetation is removed from the floodplain.

In contrast, browsing cattle do not reduce the carbon load evenly and summer pasture growth exceeds consumption with the production of unpalatable seed heads on many pasture species, necessitating pasture maintenance. This maintenance usually involves cutting back the grasses and forbs (many being weeds). The tallest swathes occur on road verges due to lack of browsing, often within roadside drainage. Slashing of the summer growth produces large windrows of dead material, which sits on top of new growth and only slowly decomposes unless inundated. Among the options for reducing the windrow load were proposals to use comb type mowers rather than flail type slashers, producing smaller sections of stem and leaf that could fall through to the ground surface and commence decomposition with any available soil moisture. Some land managers chose to plough the sward into the soil but this precluded much browsing until pasture was re-established.

Artificial levee banks and floodgates increase the return period of floodplain inudation thereby demanding more oxygen when innundated and drains promote the rapid return of deoxygenated floodwaters to the estuary. Returning areas of the floodplain to wetlands and decreasing the return interval of floodplain innudation would allow more inundation tolerant vegetation to become established.The question remains as to how this could be achieved. For example it could be a voluntary scheme that targets critical areas for purchase with a combination of Federal, State and Local government funding (Michael Woods. Pers. Com. 2005). In addition, if deoxygenated floodwaters could be retained in lowlying areas of the floodplain until oxygen consumption processes were complete and then slowly released back to the estuary the recieving environment would be better able to assimilate this water. However, this would require a review of flood control structures and thier operation on the floodplain (Peter Slavich. Pers. Comm. 2005).

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