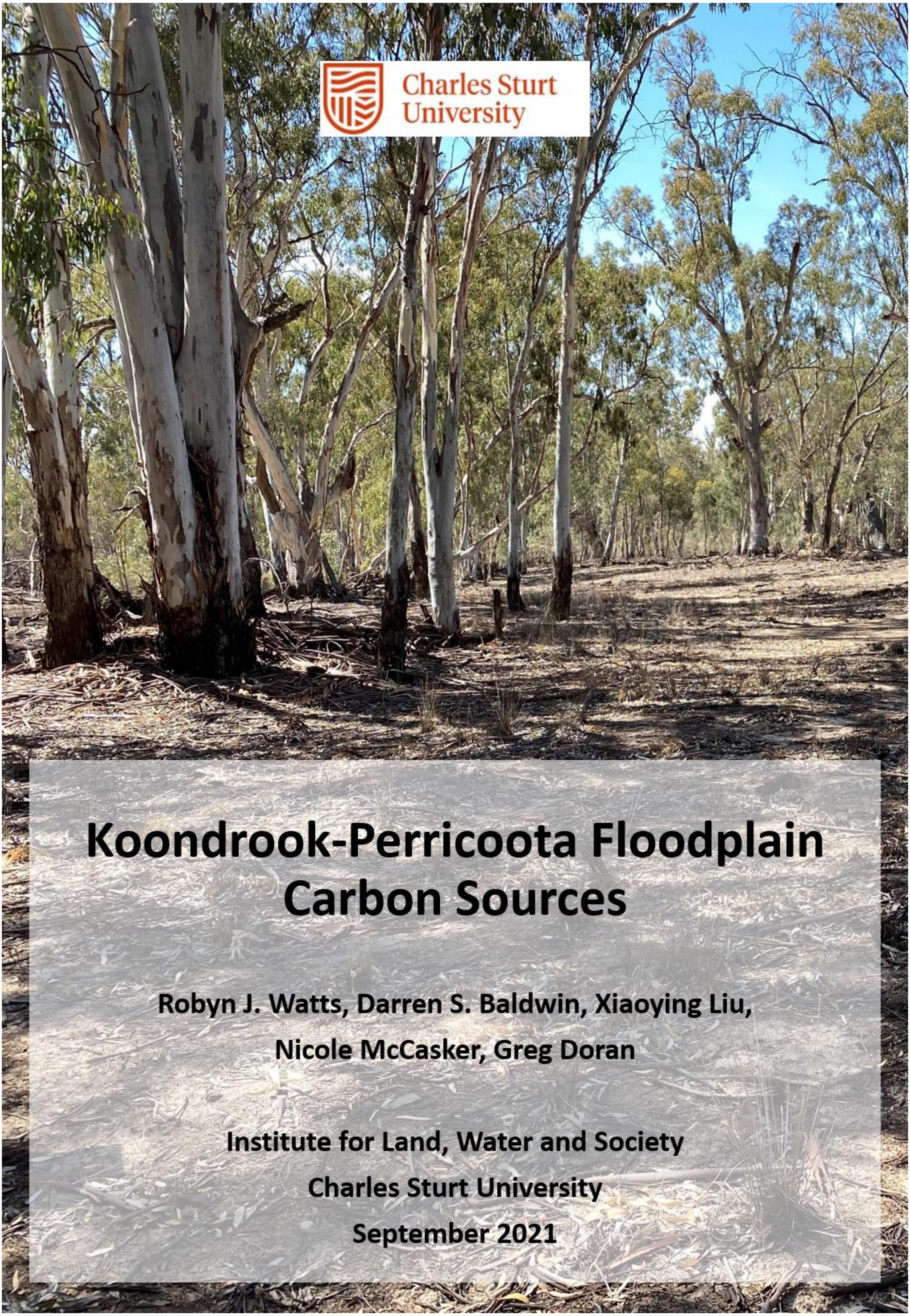

Charles Sturt University

Koondrook-Perricoota Floodplain Carbon Sources

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Institute for Land, Water and Society
Charles Sturt University

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Executive Summary

Background

Funded by The Living Murray (TLM) program, Forestry Corporation of NSW are seeking to inform water management at Koondrook-Perricoota (KP) Forest in southern NSW by reporting on floodplain carbon sources and hypoxic blackwater risk.

This project aims to improve understanding of the sources of carbon exported during flooding in KP Forest and the mode of decomposition of that carbon. The objectives were to:

1. Compare the organic litter loads and carbon sources across KP Forest
2. Quantify carbon leachate from litter relative to load, litter type, water temperature, inundation duration, and inundation frequency, and
3. Estimate the relative hypoxic blackwater risk from varying locations across KP Forest.

This project was undertaken by Charles Sturt University in collaboration with Rivers and Wetlands environmental consultancy in partnership with the Forestry Corporation of NSW.

The results from this project will inform future water management by quantifying carbon leachate potential across the floodplain and formulating hypoxic blackwater risk mitigation strategies. The results can be used to inform the timing, frequency and duration of future environmental watering actions.

Estimate of litter loads

Sampling was stratified throughout KP forest using its history of inundation to select sites with a range of flood inundation frequencies. Litter loads were sampled at 80 sites from each of three inundations zones: the 500 ML/day zone is low lying and inundated more regularly than other zones, and ground vegetation dominated by old man sneeze weed; 2000 ML/day zone has ground vegetation dominated by old man sneeze weed and Juncus *sp*; the >3000 ML/day zone is higher on the floodplain, is flushed only in large events, and had ground cover dominated by dead Paterson's curse. Two small areas of the forest that have been recently burnt were also surveyed.

Two methods were used to assess litter loads: A rapid assessment technique was undertaken at each of the 80 sites in the three inundation zones. Direct assessments of loads were undertaken at every fifth site in each inundation zone. There was a significant higher litter load in the >3000 ML/day zone, compared to the other two zones, and there was no difference in load between the 500 and 2000 ML/day inundation zones. There was a positive linear correlation between estimated litter volume and measured litter mass and a relationship was derived specifically for Koondrook -Perricoota Forest at the time of sampling. While there was variability between sites, there was no statistical difference in the ratios of bark, leaves and grasses and herbs among the flood inundation zones.

The mean litter loads were similar in the burnt and unburnt sites in the 500 ML/day inundation zone that has been inundated since the fire. In contrast, there was a lower mean litter load in the burnt sites in the 2000 ML/day and >3000 ML/day inundation zones that have not been inundated since they were burnt. These results should be interpreted with caution because there were considerably lower sample sizes in the burnt areas than the unburnt areas and the spatial the coverage of the burnt sites is small relative to the unburnt part of the forest.

Release and decomposition of DOC

A laboratory experiment was undertaken to quantify the rate of carbon leachate from a range of different carbon sources from parts of KP forest that have different history of inundation. In light of the field observations that there were different litter types and different vegetation types in the three inundation zones, the carbon sources were divided into six categories: 1) leaf litter 1 dominated by old man weed/river red gum leaves; 2) leaf litter 2 dominated by Paterson's curse /red gum leaves/blackbox leaves; 3) vegetation 1 dominated by old man weed; 4) vegetation 2 dominated by Paterson's curse/saltbush; 5) bark+twigs, and 6) bare soil.

The experiment treatments consisted of: a) six carbon sources; b) with and without sodium azide (NaN_3) to estimate rates of release and uptake by microbial activity; and c) an experimental temperature setup at 20 °C representing the common temperature occurring during summer period.

There was a high degree of variability calculated rates of release of dissolved organic carbon (DOC) from the various components of the litter. This is understandable given the heterogenous nature of the material. The maximum DOC released from the six litter components ranged from 0.38 mg/g for soil, 16.2 mg/g for bark+twigs, 29.5 mg/g for Vegetation 2, 40.1 mg/g for litter 1, 59.9 mg/g for vegetation 2, and 67.0 mg/g for litter 2. These values were slightly lower than those reported in Whitworth and Baldwin (2016), where values ranged from approximately 65 mg/g to over 100 mg/g for red gum litter.

There were substantial differences between the amount of DOC released from Vegetation 1 (from the 500 and 2000 ML/day zones) and Vegetation 2 (from the > 3000 ML/day zone). Similarly, there were large differences between Litter 1 (from the 500 and 2000 ML/day zones) and Litter 2 (from the > 3000 ML/day zone). Therefore, the values of m (the maximum amount of material released) for litter and grasses + herbs used in Blackwater Risk Assessment Tool (BRAT; Whitworth and Baldwin, 2016) scenarios depended on the size of the floods. For floods <3000 ML/day the values of m for litter and grasses + herbs used were 36.8 and 57.4 mg/g respectively. For floods >3000 mg/L day the values used are the average of m values of Vegetation 1 and Vegetation 2 (42.6 mg/g) and, Litter 1 and Litter 2 (47.6 g/mg).

Previous studies have evaluated DOC release from only red gum leaves and grass, however our survey showed that parts of the forest that have been recently flooded are dominated by old man weed, and areas that haven't been flooded for some time are dominated by Patterson's curse/saltbush. This is the first time that the carbon leachate from different sources of vegetation from different zones in KP Forest have been evaluated. From these results we can conclude that it is important to include estimates of leachate from different sources of carbon in different parts of the forest that will be inundated.

Estimating hypoxic blackwater risk

The Blackwater Risk Assessment Tool (BRAT; Whitworth and Baldwin, 2016) was used to estimate relative hypoxic blackwater risk for 50 flood scenarios.

Forty-seven single scenario runs were tested:

- 10 Traditional Flow scenarios (30 GL total volume, 30-120 days duration of inflows, no outflows)
- 6 spring flush scenarios (120 GL total volume, 30-60 days duration of inflows)

- 3 long and low scenarios (120 GL total volume, 120 days duration of inflows)
- 6 short pulse scenarios (180 GL total volume, 30-60 days duration of inflows)
- 10 Alternative downstream flow option event (ADFO) scenarios (600 GL total volume and 100 days duration of inflows) that involve using the maximum discharge rate during managed releases to Barbers Creek and Thule Creek to reduce the duration of the recession phase of a managed event.
- 6 large overbank scenarios (1000 GL total volume, 50 days duration of inflows)
- 6 major overbank scenarios (1800 GL total volume, 75 days duration of inflows)

Three hybrid scenarios (sequenced events) were also evaluated (winter managed event/summer overbank event, winter managed /spring managed event, winter managed/spring overbank event). Nine runs of the BRAT model were conducted for each scenario, and the results for each scenario were classified into five classes of risk of hypoxia: low, moderate, moderate to high, high, very high.

The outcomes of the single scenario models were variable. In general, flows that commenced later, and/or had lower inflows or shorter duration (30 days) had higher risk of hypoxia. Scenarios that commenced earlier (in winter or early spring), and/or had longer duration (60 days) or higher inflows had lower risk of hypoxia:

- Six of the 10 Traditional Flow (TF) scenarios (no outflows from the forest) that had 60 days inflow resulted in high or very high risk of hypoxia. Whereas the TF scenarios 7 to 10 that had 120 days inflow duration had low risk of hypoxia.
- Five of the six spring flush scenarios (120 GL total volume, 30-60 days duration of inflows) resulted in moderate to very high risk of hypoxia. The exception was spring flush scenario 4 that commenced earlier (July) and had 60 days duration.
- The long low scenario 1 commencing in July had low hypoxia risk, however, the long low scenarios with the same conditions but commencing in September or November had low to moderate hypoxia risk.
- The short pulse scenarios (180 GL total volume, 30-60 days duration of inflows) had variable risk, ranging from low/moderate, high or very high. The exception was the short pulse 4 scenario commencing in July that had a duration of 60 days.
- All of the Alternative Downstream Flow Option (ADFO) scenarios (600 GL total volume and 100 days duration of inflows) had low risk of hypoxia.
- Only one of the large overbank scenarios (1000 GL total volume, 50 days duration of inflows) had any risk of hypoxia. This scenario (Large overbank 6) commenced in November and had a low to moderate risk of hypoxia.
- None of the major overbank scenarios (1800 GL total volume, 75 days duration of inflows) were evaluated to have any risk of hypoxia.

All the hybrid model runs indicate that there would be a low to moderate risk of hypoxia during the initial winter flooding and a low risk of hypoxia in the subsequent spring or summer event. However, for the three hybrid runs and for the over bank floods in the single flood scenarios, these results are based the assumption that DO concentrations in the inflows are high and DOC concentrations are low. In reality, when there has been overbank flows upstream, DO concentrations in the inflows will be lowered and DOC concentrations would be elevated. The modelling clearly shows that water quality leaving KP Forest during overbank events will be strongly influenced by the water quality entering the forest.

Recommendations

Litter loads and carbon leachate

This study has demonstrated that different types of vegetation and litter in the different inundation zones in KP Forest may result in different litter loads and rates of release of DOC.

Recommendation 1: Future modelling of blackwater risk should consider the litter loads and carbon leachate of the different types of leaf litter and vegetation from different inundation zones within Koondrook-Perricoota Forest.

Risk of hypoxia

Results from running BRAT on 50 inundation scenarios suggest that inundation of the floodplain during the warmer months (late-spring to early autumn) and/or inundation regimes that have low inflows (30 GL) and/or shorter duration (30 days) inflows substantially increases the likelihood of hypoxic water leaving the forest in outflows.

Recommendation 2: To avoid the risks of hypoxic blackwater outflows and poor ecological outcomes downstream of KP Forest, it is important to optimise the magnitude and timing of flows through KP Forest and avoid scenarios where water stands for long periods of time. This is especially important during the warm months when carbon leaching can increase and have a detrimental effect on dissolved oxygen concentrations. Inundation scenarios that have higher inflows (120 GL or more), commence earlier, and/or have longer duration (60 -120 days) of transit time of water flowing through the forest, lower the risk of hypoxia.

Source water

The quality of the water leaving the forest during over-bank floods is highly influenced by the quality of the water entering the forest from upstream.

Recommendation 3: The water quality entering the forest from upstream sources should be monitored and taken into consideration when considering the downstream water quality impacts of the delivery of environmental water to Koondrook-Perricoota Forest.

Impact of fire on litter loads and water quality

Mean litter loads were similar in burnt and unburnt sites in the 500 ML/day inundation zone. However, there was a lower mean litter load in the burnt sites in the 2000 ML/day and >3000 ML/day inundation zones than in the unburnt sites that had not been inundated since they were burnt. These results suggest that managed burns could be used as a management tool to reduce litter loads prior to flooding to the forest. However, these results should be interpreted with caution due to low sample size and small area of burnt sites.

Recommendation 4: The impact of controlled burns or cultural burns on litter load needs to be further examined through experimental trials. These trials must examine the potential risks on water quality from toxins that leach from ash following inundation.

Other factors influencing litter load

There is a lack of knowledge on the effects of wetting/drying cycles and flooding on leaf shedding in river red gums.

Recommendation 5: A study be undertaken to improve knowledge about the impacts of wetting/drying, droughts and inundation on the volume and timing of leaf fall and litter loads.

1. Introduction

1.1 Purpose and project objectives

Koondrook-Perricoota State Forest is located on the mid-Murray floodplain between the townships of Barham in the west and Moama in the east. This Living Murray (TLM) Icon Site is approximately 32,000 ha and comprises a number of habitat types including: river red gum (*Eucalyptus camaldulensis*) forest and woodland, black box *(E. largiflorens*) and western grey box (*E. microcarpa*) woodlands.

Funded by The Living Murray (TLM) program, Forestry Corporation of NSW are seeking to inform water management at Koondrook-Perricoota Forest by reporting on floodplain carbon sources and hypoxic blackwater risk.

This project aims to improve our understanding of the sources of carbon exported during flooding and the mode of decomposition of that carbon. The spatial variation in bulk carbon loading and sources were examined with respect to flooding history in Koondrook-Perricoota Forest. The project also explored the origin of bioavailable carbon in floodplain leachate, and aspects of bioavailability and subsequent decomposition. The objectives of this project were to:

1) Compare the organic litter loads and carbon sources across Koondrook-Perricoota Forest
2) Quantify carbon leachate from litter relative to load, litter type, water temperature, inundation duration, and inundation frequency, and
3) Estimate the relative hypoxic blackwater risk from varying locations across Koondrook-Perricoota Forest.

The results from this project will inform future water management by quantifying carbon leachate potential across the floodplain and formulating hypoxic blackwater risk mitigation strategies. The results can be used to inform the timing, frequency and duration of environmental watering actions.

This project was undertaken as by Charles Sturt University in collaboration with Rivers and Wetlands environmental consultancy, in partnership with the Forestry Corporation of NSW.

1.2 Background

The hydrological connection between river channel and floodplains promotes the transportation of carbon and nutrients, influencing in the functioning of the entire system (Harris et al. 2016). Export of dissolved organic carbon (DOC) from floodplains during inundation events provides vital support to riverine food webs and is an important energy subsidy for lowland rivers (Junk et al. 1989; McGuiness and Arthur 2011). However, in some instances water returning from floodplains to river channels containing elevated concentrations of DOC could cause riverine hypoxic blackwater events occurring, potentially resulting in adverse effects on the ecological conditions of the receiving water.

The frequency and timing of inundation of the floodplains of lowland rivers in south-eastern Australia can vary significantly (Baldwin and Mitchell 2000). Extensive areas of floodplains in the southern Murray-Darling Basin (MDB) in south-eastern Australia were flooded in summer of 2010-2011 following a decade long drought. More than 2000 km of river channel was affected by hypoxic blackwater for up to six months and the large-scale hypoxic blackwater pulse caused catastrophic effects on the aquatic ecosystem leading to substantial mortality of aquatic organisms including fish and crustaceans. In late 2016, there was another widespread flood in the southern MDB and extensive areas of the floodplain were inundated that had not been flooded for more than 20 years (Bureau of Meteorology 2017). These unregulated flows inundated the floodplains including Koondrook-Perricoota Forest, Barmah-Millewa Forest, as well as agricultural lands (Watts et al. 2017b) and hypoxic blackwater events occurred in association with the floods.

Extensive overbank natural flooding in Koondrook-Perricoota Forest in 2010 and 2016 resulted in export and decomposition of carbon from the floodplain and subsequent death of aquatic organisms downstream due to hypoxia. This was due to microorganisms consuming the DOC and using up oxygen in the water column. The oxygen consumption by microbial activity is often faster than the oxygen can be replenished from the atmosphere (Howitt et al. 2007; King et al. 2012; Whitworth and Baldwin 2016). Therefore, the occurrence of blackwater is often accompanied by quite low levels of dissolved oxygen in the water column, leading to hypoxia.

Large quantities of DOC can be released from red-gum leaf litter on the floodplains under inundation (O'Connell et al. 2000; Whitworth et al. 2012; McInerney et al. 2017). Indeed, inundation of different floodplain areas (including forests, croplands, and pasturelands) during summer can be a major source of DOC and nutrients and a major contributor to dissolved oxygen depletion (Liu et al. 2019). A clearer understanding of the sources of bioavailable carbon and the decomposition processes will assist water managers to optimise the benefits of flood return water from the floodplain while minimising the environmental risk of downstream hypoxia. In addition, models for the prediction of hypoxic blackwater from lowland river-floodplain inundation can also play a significant role to inform water managers regarding the environmental risk.

It is expected that in the near future water managers will have the capacity to deliver environmental water to the Koondrook-Perricoota floodplain to meet environmental objectives. Research has highlighted the potential benefits to primary production from carbon exports, as well as the complexity of the processes that lead to hypoxia. Returning flood waters are predicted to have both positive and negative impacts on downstream ecosystems. A clearer understanding of the sources of bioavailable carbon and the decomposition process will assist water managers to optimise the benefits of flood return water from the floodplain while minimising the risk of downstream hypoxia.

In order to achieve the project objectives, field observation and sample collection were conducted throughout Koondrook-Perricoota Forest to evaluate carbon loads and sources. A laboratory experiment was undertaken to quantify carbon leachates from different carbon sources of the forest. The Blackwater Risk Assessment Tool (BRAT; Whitworth and Baldwin 2016) was used estimate relative hypoxic blackwater risk from varying locations across Koondrook-Perricoota Forest and the outputs for flood scenarios were produced to enable different management option to be assessed. Recommendations provided based on the models can be used to inform the timing, frequency and duration of inundation.

1.3. Koondrook-Perricoota Forest

Koondrook Perricoota (KP) Forest in southern New South Wales (NSW) (Figure 1) is an internationally significant forest consists of an extensive forest of river red gums and woodland. It is listed as a Ramsar wetlands of international importance, is an icon site under The Living Murray program and is part of the NSW Central Murray Forests. The Koondrook-Perricoota Forest Report card for 2019-20 states that the wetlands across the site are still in overall poor condition and well below target levels for wetland health (MDBA 2020).

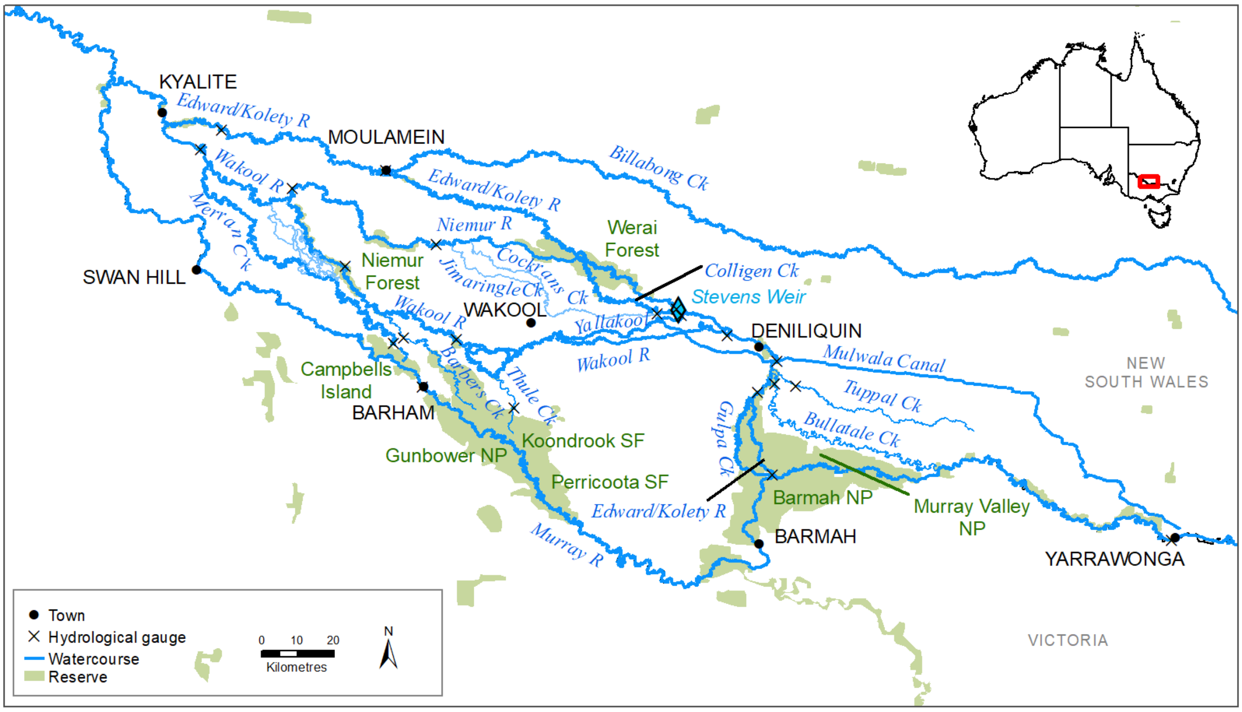

Figure 1: *Map showing location of Koondrook-Perricoota Forest in the mid-Murray region of NSW.*

1.4. Hypoxic Blackwater and the Blackwater Risk Assessment Tool (BRAT)

Blackwater events are a natural part of the ecology of lowland river systems. During a flood, carbon components are leached from, dead and dying vegetation, leaf litter on the floodplain and from the soil. This carbon is an important energy source for the functioning of river systems, and the reduction in flood extent has been linked to a decrease in productivity in rivers in the Murray-Darling Basin (Boulton and Lloyd 1992; Brookes et al. 2009; Kirby et al. 2013). The amount of carbon leached will depend on a number of factors such as the type and age of the litter and dead vegetation, the amount of material on the floodplain, the area of inundation, whether or not the material has been flooded and, the temperature (Figure 2).

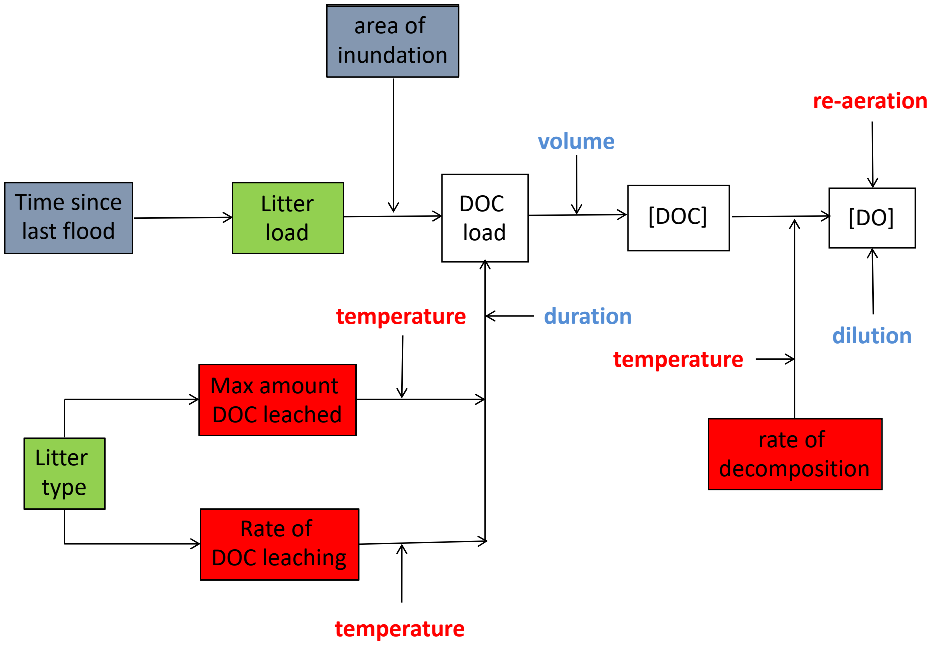

Figure 2: *Framework on which the Blackwater Risk Assessment Tool is based (Source: Whitworth and Baldwin, 2016)*

Blackwater events markedly change water quality. Microbes can use a proportion of the carbon leached from the leaf litter for metabolism. During this process they consume oxygen in the water column. If the rate of consumption of oxygen is faster than it can be replenished from the atmosphere, the dissolved oxygen (DO) concentration in the water column will be begin to fall - potentially reaching levels too low to support aquatic life - this is known as hypoxic blackwater. Large hypoxic blackwater events have occurred in the southern Murray-Darling Basin most recently in 2012 (MDBA 2011; Whitworth et al. 2012) and in 2016 (Watts et al. 2017a).

The Blackwater Risk Assessment Tool (BRAT; Whitworth and Baldwin, 2016) was developed to help inform managers about the likelihood of a hypoxic blackwater event occurring following floodplain inundation. BRAT is a process-based model which predicts DO and dissolved organic carbon (DOC) concentration on a forested floodplain during a flood event. A dilution module in BRAT also allows prediction of DO and DOC concentrations in receiving waters downstream of the floodplain.

The model has three components (Figure 2)[1]:

- A simple description of the flood hydrograph. Inputs include total volume of floodwater, period of inflows, transit time across the flood plain, maximum area inundated and, maximum outflow.
- A description of the type and load of carbon sources on the floodplain and,
- Algorithms to describe the rates of carbon release and decomposition on the floodplain and the subsequent impact on dissolved oxygen concentrations.

The first component is determined in a large part by the characteristics of a particular floodplain and, except for flow volumes and timing, that are generally fixed. The amount of carbon on the floodplain can be estimated from the time since last flood (Howitt et al. 2007)

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[1] A reprint of the paper describing the model in greater detail is available on request; the model itself can be downloaded from www.riversandwetlands.com.au

but is best determined empirically. Section 2 of this report describes an empirical study to determine the standing stock of litter and dead grasses and herbs on the KP floodplain in January 2021. These data were used as inputs to the BRAT model. BRAT has default values for the rates of carbon release and decomposition for key litter components necessary for the computation of DO. Section 3 of this reports explores the validity of those default values for key carbon sources found in KP Forest.

2. Estimate of litter loads in Koondrook-Perricoota Forest

The type and load of carbon sources on the floodplain are key components of the BRAT model (Figure 2). The amount of carbon leached will depend on several factors such as the type and age of the litter and dead vegetation and the amount of material on the floodplain. In this part of the project the organic litter loads and carbon sources were surveyed in different parts of KP Forest that have different history of inundation. Based on our previous experience in undertaking these surveys, many replicates are needed to assess loads in different parts of the floodplain due to the high spatial variability in the forest.

2.1. Methods

2.1.1 Study area

Sampling throughout KP Forest was stratified using its history of inundation to select sites with a range of flood inundation frequencies. Flood inundation maps of KP Forest were available for a range of different inundation scenarios:

- KP mapped area of inundation for a managed event in 2019 that had approximate inflows of 500 ML/day, duration of approximately 60 days
- KP inundation model 1: 500 ML/day for 60 days from inlet channel (e-water infrastructure)
- KP inundation model 2: 1000 ML/day for 28 days from Swan Lagoon (natural inflow point)
- KP inundation model 3: 2000 ML/day for 28 days from Swan Lagoon (natural inflow point)
- KP inundation model 4: 3000 ML/day for 28 days from Swan Lagoon (natural inflow point)

Figure 3 shows the area inundated under the managed 500 ML/day inflow event in 2019, 2000 ML/day floodplain inundation model, and 3000 ML/day floodplain inundation model. It is evident that the different inundation zones are not in clearly defined bands in separate parts of KP Forest, but are intermixed throughout the forest, reflecting the complex floodplain morphology and many low-lying flood runners that intersect this forest.

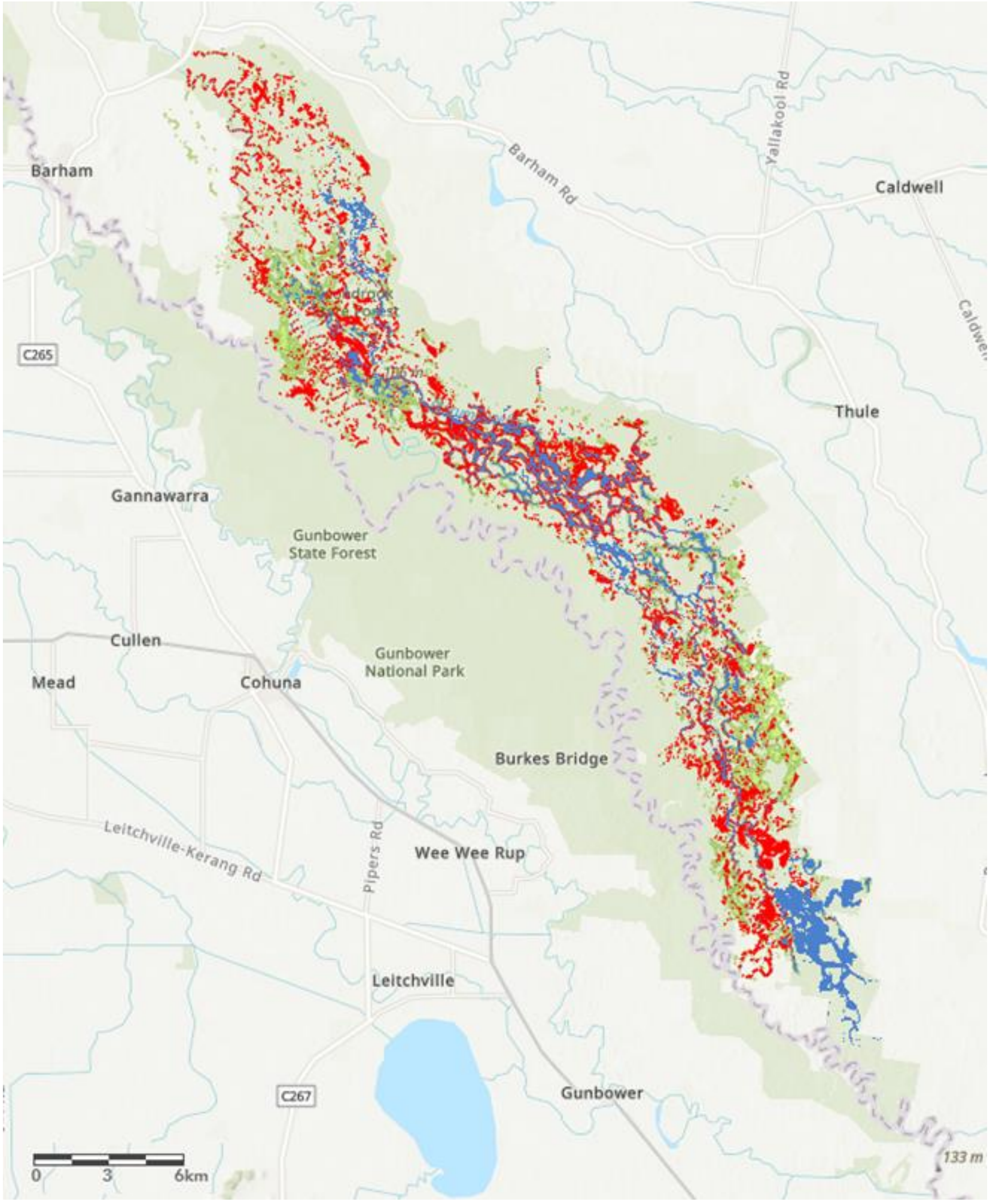

***Figure 3:** Flood inundation map showing the extent of inundation extent under the managed 500 ML/day inflow event in 2019 (blue), 2000 ML/day floodplain inundation model (red), and 3000 ML/day floodplain inundation model (green).*

Three flood inundation zones were selected to be surveyed in this study to ensure we surveyed across the widest range of inundation scenarios. The three zones were the 500 ML/day zone that is low lying and inundated more regularly than other zones, 2000 ML/day inundation zone, and to the >3000 ML/day zone that is higher on the floodplain and is only flushed in large events that are greater than the 3000 ML/day inundation model.

1) **500 ML/day inundation zone** was previously inundated in 2016 and during a managed flow in 2019. This zone is the low-lying part of the forest that is inundated more regularly than other zones, and it includes many channels and flood runners. During the field survey sites in this zone typically had a ground cover of partly green old man sneeze weed (*Centipeda cunninghamii*) (Figure 4). The leaf litter at these sites was dominated by dead old man sneezeweed leaves and red gum leaves.

Figure 4: *Sites within the 500 ML/day inundation zone that were dominated by old man sneezeweed (Centipeda cunninghamii).*

2) **2000 ML/day inundation zone** was last inundated in the large unregulated flood in late 2016. Sites in this zone typically had sparse vegetation cover of dead old man sneezeweed and some Juncus *sp*. The litter was made up of dead old man sneezeweed leaves and red gum leaves, similar to that in the 500ML/day zone.

3) **>3000 ML/day inundation zone** is high on the floodplain and was not inundated in 2020. Sites in this zone are outside the mapped flooded areas shown in Figure 5. This zone includes areas of red gum and black box. Sites in the red gum areas typically had a thick cover of dead Paterson's curse (*Echium plantagineum*) and sometimes paper daisies. The leaf litter was dominated by thick layer of dead Patterson's curse leaves with some red gum leaves (Figure 5, left). This zone also included areas of black box forest, particularly in the southern half of KP Forest. The dominant ground cover at these sites was saltbush (*Enchylaena tomentosa* and *Einadia nutans*), and the litter at these sites was black box leaves (Figure 5, right).

Figure 5: *Sites within the >3000 ML/day inundation zone. Left – sites in river red gum forest with dead Paterson's curse (Echium plantagineum). Right – sites within black box woodland.*

Two small areas of the forest that have been recently burnt were also included in the field surveys to provide insight as to the outcomes of reinstating cultural burning by the Traditional Owners of KP, which would potentially have the additional benefit of mitigating blackwater risk. These areas were:

- Burnt area in the north west of KP Forest west of Fence Trail and north of Waterhole Trail (Figure 6) experienced a fire in February 2020 and has not been inundated since the fire. Part of this burnt area is in the 2000 ML/day inundation zone, and part is in the >3000 ML/day inundation zone.

- Burnt area north of Marywood Road at the southern end of the forest experienced a fire in February 2019 and was inundated by the managed event in August 2019. Based on sentinel images, the inundation was confined to the creek lines which are well defined in this area. The low-lying part of this burnt area is in the 500 ML/day inundation zone, and part is in the >3000 ML/day inundation zone.

Figure 6: *Burnt area in the north west of KP Forest west of Fence Trail and north of Waterhole Trail.*

2.1.2 Field litter load assessment in unburnt areas of KP Forest

Prior to undertaking the field surveys, approximately 100 sites in each of the three flood inundation zones were selected and loaded onto an ARCGIS map and downloaded for offline use on the ArcGIS Collector app that enables fieldworkers to use maps on mobile devices even in areas with no internet service. The criteria for site selection was that sites had to be less than 500 m from a forest road and the sites within each flood inundation zone had to be randomly distributed throughout the whole forest. When undertaking field surveys these sites were located using the ArcGIS Collector App. However, if a site showed signs of having been recently logged or disturbed by vehicles, the site was not included in the surveys and we moved on to the next site. Having randomly selected sites in each inundation zone, afforded some redundancy as we only needed to have 80 sites that were suitable for the surveys.

A total of 80 sites in each of the three flood inundation zones (500 ML/day, 2000 ML/day, >300 ML/day inundation zones) were surveyed throughout the unburnt areas of the forest (total 240 sites) (Figure 7). The surveys were undertaken from 18 to 22 January 2021. Eighty sites were surveyed in each of the inundation zones to ensure we could get a good estimate of litter loads due to the high spatial variability of litter across the forest.

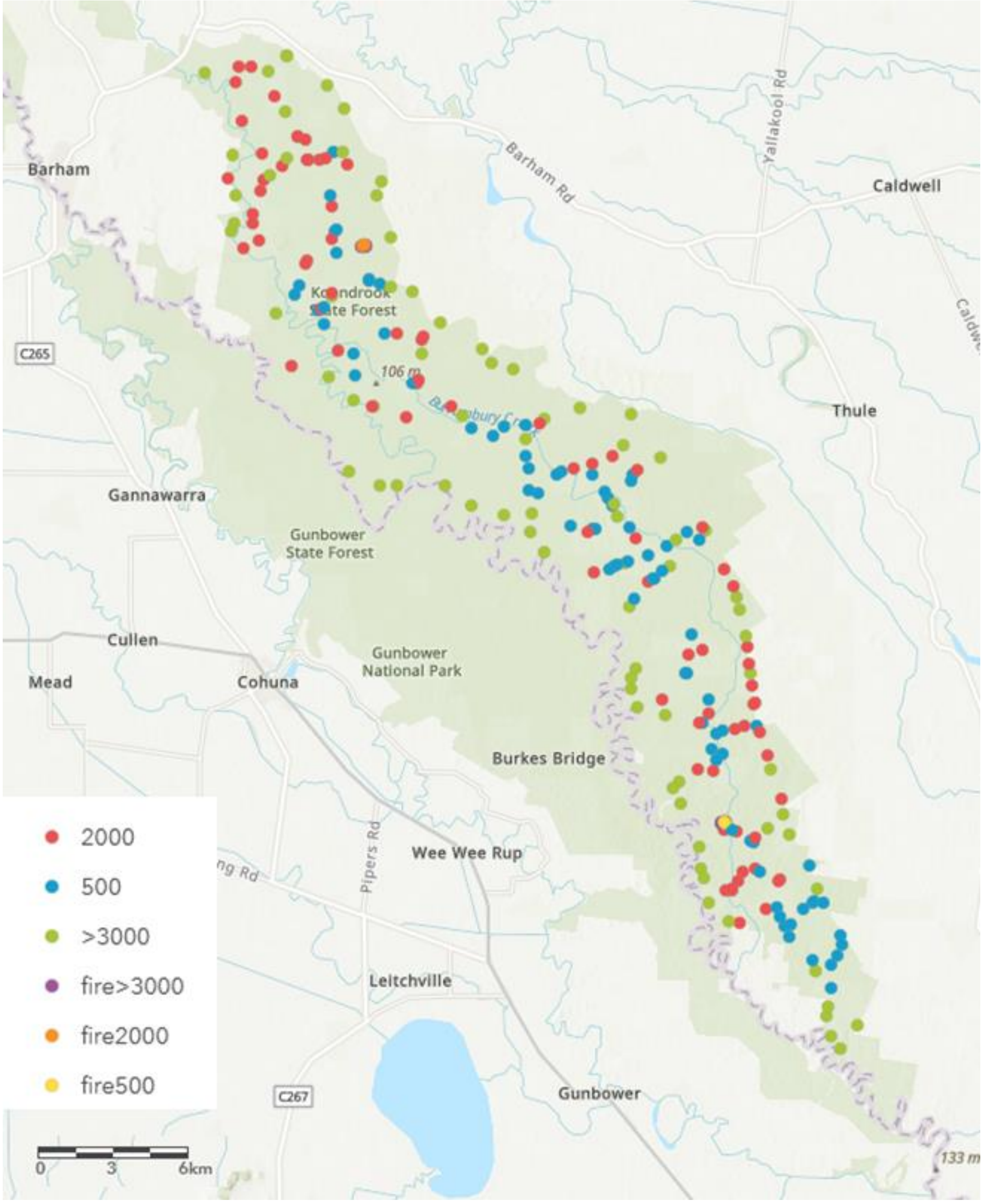

***Figure 7:** Location of 80 sites in each of the three flood inundation zones; 500 ML/day (blue), 2000 ML/day (red), >3000 ML/day inundation zones(in the forest outside the mapped inundation zones). The burnt site in the north west of KP Forest near Fence Trail is shown with orange symbol. In the second burnt area near Marywood Road is shown with a yellow symbol.*

Two methods were used to assess litter loads:

1. A rapid assessment technique was undertaken at each of the 80 sites in the three inundation zones. This rapid assessment method was specifically developed for the Blackwater Risk Assessment Tool (BRAT) (Whitworth and Baldwin, 2016). The rapid assessment technique allowed for a large number of sites to be surveyed in a single day, which reduced uncertainty in the litter load estimate. To undertake this rapid estimate 5 measures of litter depth were recorded from within a 5 x 5 m quadrat.
2. Direct assessments of loads were undertaken at every fifth site in each inundation zone (total of 16 sites per inundation zone). The direct assessments of litter loads were used to validate the rapid assessment technique. At each survey site, a 1 m × 1 m quadrat was randomly placed on the ground (Figure 8) and the percentage of area occupied by bare ground, litter and vegetation was recorded. The above-ground carbon sources were collected and samples were stored in labelled paper bags. Once back in the laboratory, the samples were separated into leaf litter, alive and dead plants, and bark/twigs and then weighed separately. A soil sample was also collected at each of these sites for use in the experiment on release and decomposition of DOC (see Section 3). Soil samples were collected to a depth of 5 cm from the areas within a 10-m radius with the same quadrats as centres and stored in zip-lock plastic bags.

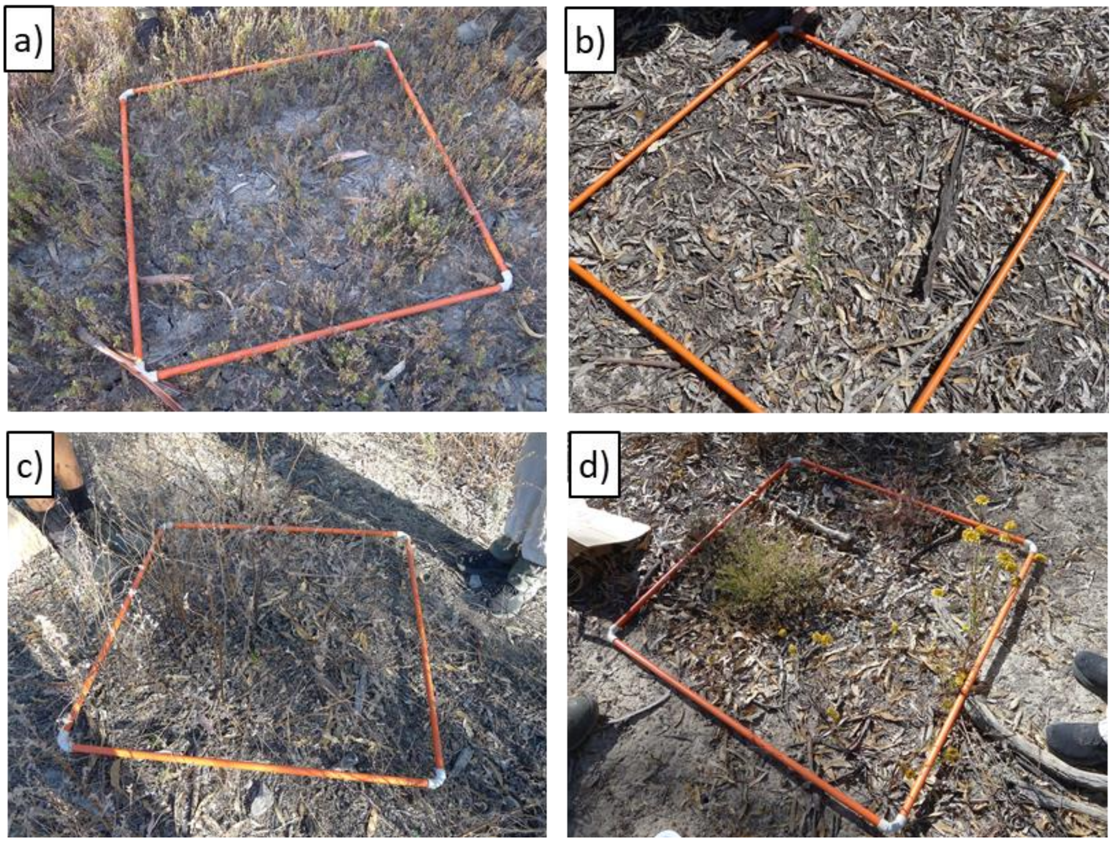

Figure 8: *Quadrat (1m x 1m) used for surveying litter loads.*
a) Drying old man sneeze weed in 500 ML/day inundation zone,
b) Red gum leaf litter in 2000 ML/day inundation zone,
c) Dead Paterson's curse in red gum forested part of >3000 ML/day inundation zone,
d) Salt bush and paper daisies in black box forested part of the >3000 ML/day inundation zone.

2.1.3 Field litter load assessment in burnt areas of KP Forest

Rapid estimates of litter load were also undertaken in the two burnt areas (Figure 9), using the method outlined in section 2.1.2. In the north west of KP Forest near Fence Trail we estimated litter load at 6 sites in >3000 M/day inundation zone and 6 sites in the 2000 ML/day inundation zone. In the second burnt area north of Marywood Road we estimated litter load at 6 sites in the 500 ML/day inundation zone and 6 sites in the >3000 ML/day inundation zone.

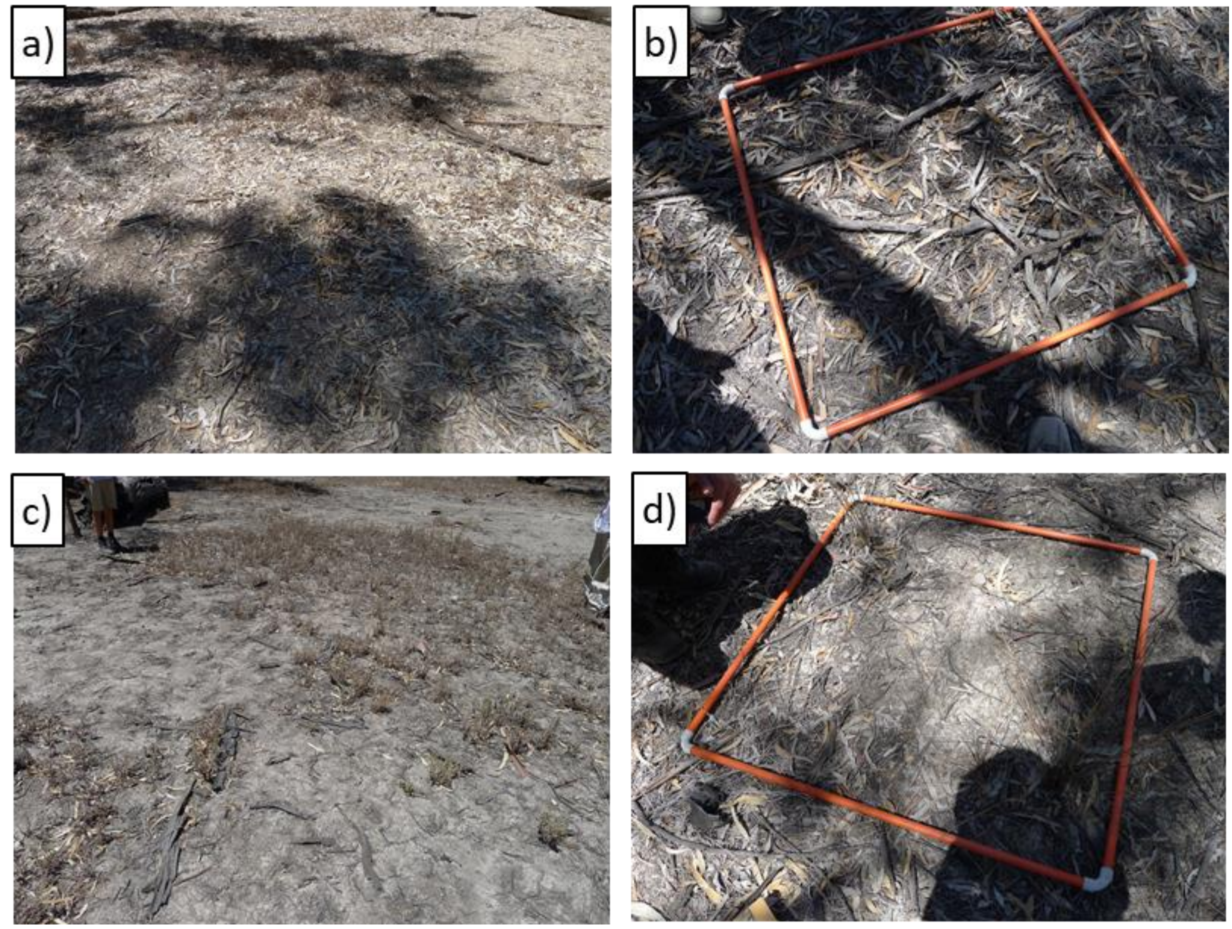

Figure 9: *Quadrats (1m x 1m) used for surveying litter loads:*
a) Burnt area in the 2000 ML/day inundation zone in near Fence Trail,
b) Burnt area in the 3000 ML/day inundation zone near Fence Trail,
c) Burn area in the 500 ML/day inundation zone near Marywood Road,
d) Burn area in the 3000 ML/day inundation zone near Marywood Road.

2.2. Results and discussion

2.2.1. How much Litter is on the flood plain?

There are two ways to estimate the litter on a floodplain:

- Gravimetrically: by harvesting and weighing all the litter in a given area. The advantages of this method are that it is much more precise than, the alternate method, and, you can separate the litter into its various components. The disadvantage is that it is labour intensive, and therefore it is difficult to take enough samples to ensure that you have sufficient power to determine the actual load of litter across the floodplain.
- Estimating litter volume and then converting the volume to a weight: In this method the percent coverage of leaves in an arbitrary area coupled with the depth of the litter is used to estimate the volume of litter, and the volume is converted to mass using a pre-determined relationships. While this approach is less precise than the gravimetric method, it has the advantage that it is relatively rapid, so many more sites can be sampled in a given timeframe.

Both approaches were used in the current study. The advantage of doing both is that the gravimetric samples can be used to calibrate the relationship between litter volume and litter mass, without having to rely on pre-determined empirical relationships.

Litter mass and litter volume were determined at 48 sites - 16 in each of the three inundation zones. There was a positive linear correlation between estimated litter volume and measured litter mass (r = 0.66). Forcing a regression line through the origin (Figure 10) we can derive a relationship between litter mass and litter volume specifically for Koondrook -Perricoota Forest at the time of sampling:

Litter mass (g/m2) = litter volume (m3/m2) x 156366.

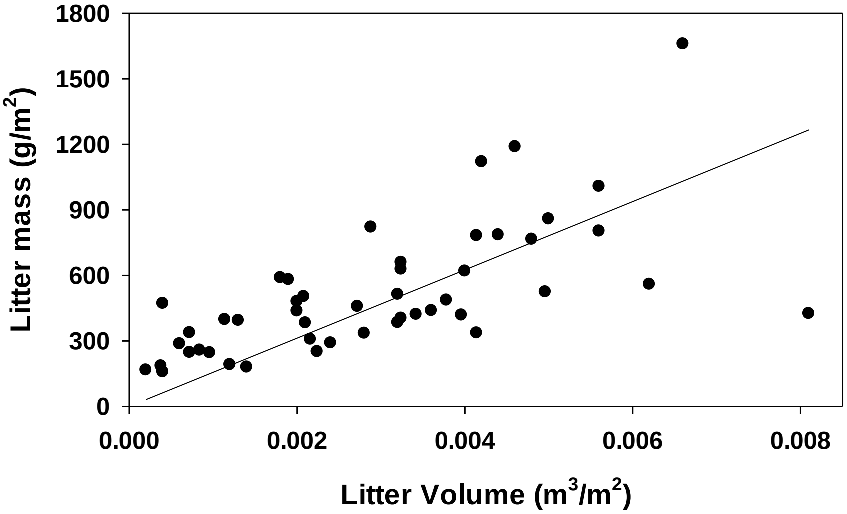

Figure 10: *Relationship between litter volume (m^3/m^2) and litter mas (g/m^2) based on samples from 48 sites in Koondrook-Perricoota Forest; 16 sites surveyed in each of the three inundation zones.*

Litter volume was calculated at 240 sites on the floodplain (80 in each of the three inundation zones). Using this relationship, we can calculate the litter mass at these sites and from that estimate a mean and upper and lower estimates of that mean that can be used in BRAT. Using litter volumes, we estimate that the average mass of litter on the floodplain was 487 g/m^2, and with 95% confidence, the actual mean is between 447 and 527g/m^2 based on 240 samples. If we only used the measured estimates of litter we get very similar results (mean = 514 g/m^2; 95% CI 428 to 600 g/m^2; n = 48).

2.2.2 How variable is the litter distribution on the floodplain?

Either using the measure litter loads, or estimates of litter loads, there is substantial variability in litter mass on the flood plain going from near zero to approaching 1700 g/m^2 (Figure).

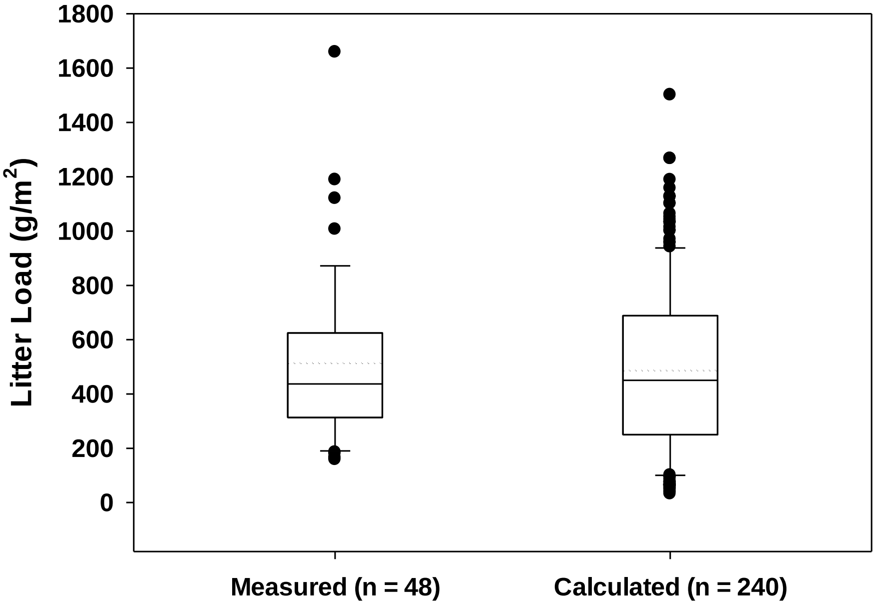

Figure 11: *Box and whisker plots of measured and calculated litter loading on Koondrook-Perricoota floodplain. The box outlines the 25th and 75th percentiles, and the bars on the whiskers are the 10th and 90th percentiles. The solid line inside the box is the median, and the dotted line is the mean. Points outside the 10th and 90th percentiles are plotted as individual points.*

There is also substantial variability in litter loading both within and between each of the three inundation zones (Figure). Based on the measured litter loads there was 383 ± 88 g/m^2 (mean ± 95% CI) in the 500 ML/day inundation zone; 625 ± 224 g/m^2 in the 2000 ML/day inundation zone and 535 ± 107 g/m^2 in the >3000 ML/day inundation zone. When calculated loads are included the values are 350 ± 63 g/m^2, 440 ± 66 g/m^2 and 562 ± 70 g/m^2 respectively. There was a significant difference (one-way ANOVA; $p < 0.001$) in the calculated loads in the >3000 ML/day inundation zone, compared to the other two zones, but there was no difference between the 500 and 2000 ML/day inundation zones.

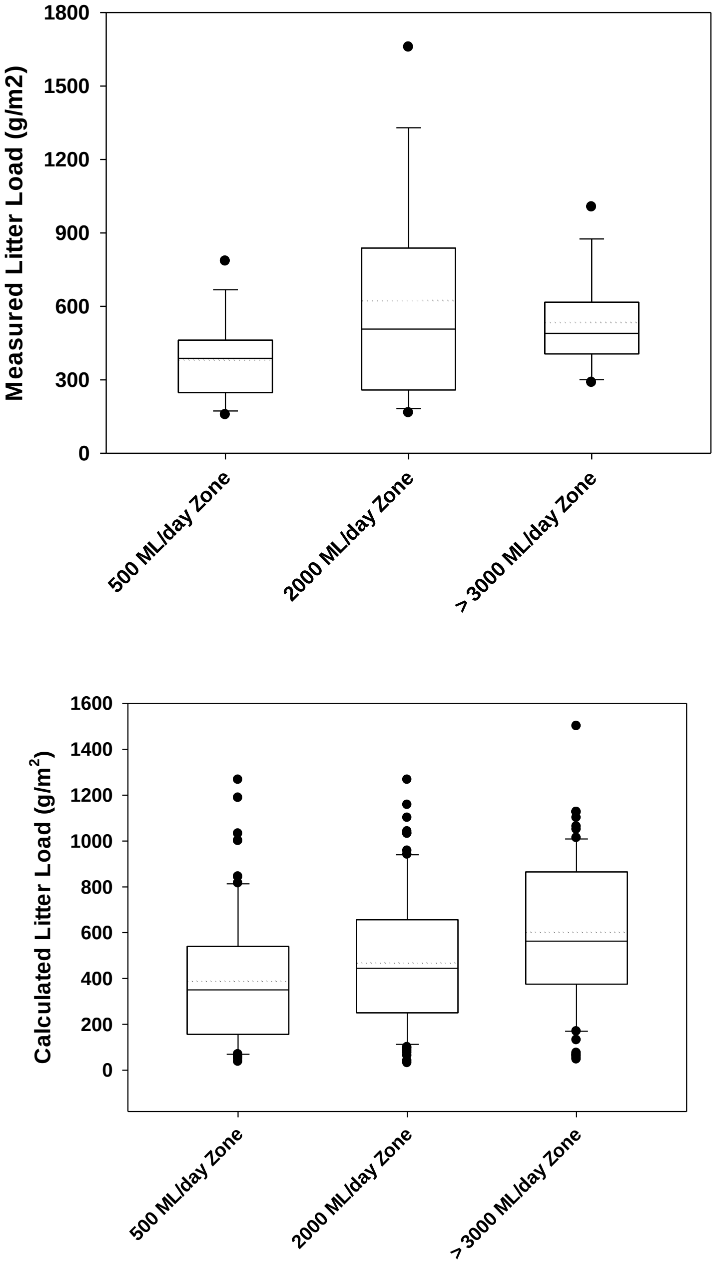

Figure 12: *Box and Whisker plots of measured (top panel) and calculated (bottom panel) litter loadings in the three inundation zones sampled in Koondrook-Perricoota Forest.*

Litter loads in burnt and unburnt areas within each of the three inundation zones are presented in Figure 13. Visual interpretation suggests the mean litter loads were similar in the burnt and unburnt sites in the 500 ML/day inundation zone that was inundated since the fire. In contrast, there was a lower mean litter load in the burnt sites in both the 2000 ML/day and >3000 ML/day zones that have not been inundated since they were burnt.

This figure should be interpreted with some caution: there were considerably lower sample sizes in the burnt areas than the unburnt areas. There were 80 sites in each of the unburnt inundation zones, 6 sites in the burnt 500 ML/day inundation zone, 6 sites in the burnt 2000

ML/day inundation zone and 16 sites in the burnt 3000 ML/day inundation zone. In addition, the spatial the coverage of the burnt sites is very small relative to the unburnt part of the forest. There are also potential negative impacts of burning that aren't reflected in this simple measure of load reduction. For example, burning may not be the best option because the leachate from ash can contains toxins such as cyanide.

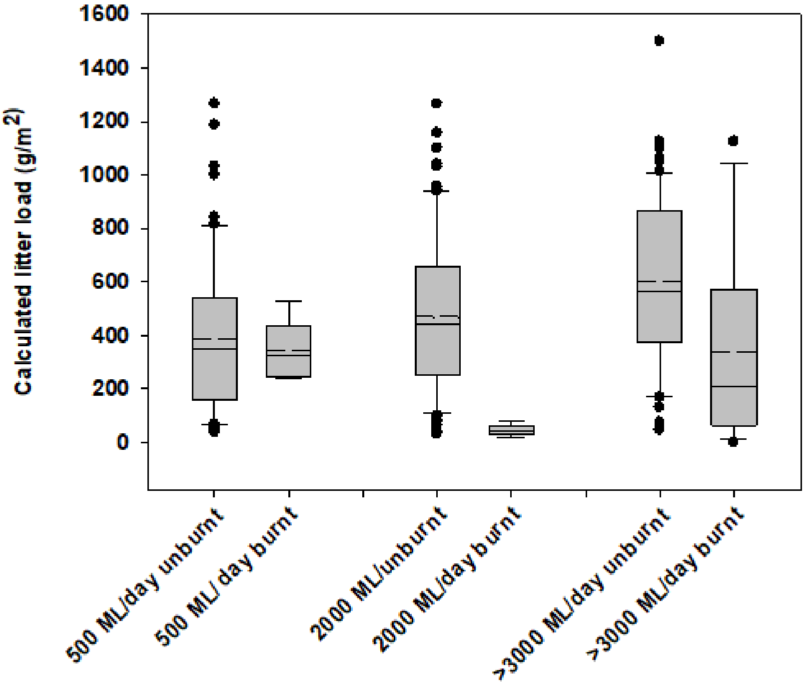

Figure 13: *Box and Whisker plots of calculated litter loadings in unburnt and burnt plots in three inundation zones sampled in Koondrook-Perricoota Forest.*

2.2.3 How variable is the relative contribution of the components of litter across the floodplain?

Figure 14 shows the ratios of bark, leaves and grasses and herbs in the three inundation zones. Again, the distributions were variable, both within and between flood zones. The sites were all dominated by bark + twigs, with similar amounts of leaves and grasses + herbs. While there was variability between sites, the difference was not statistically significant (p >0.05; one-way ANOVA).

Qualitatively, the make-up of the litter was different between the zones. The predominant tree leaf-material across all sites were red gum leaves, but in the >3000 ML/day zone there was also some *Eucalyptus largiflorens* (black box). The dominant grass + herbs in the 500 ML/day and 2000 ML/day zones was *Centipeda cunninghamii* (old man sneeze weed) while it was *Echium plantagineum* (Patterson's curse) and *Enchylaena tomentosa* and *Einadia nutans* (salt bush) in the >3000 ML/day zone.

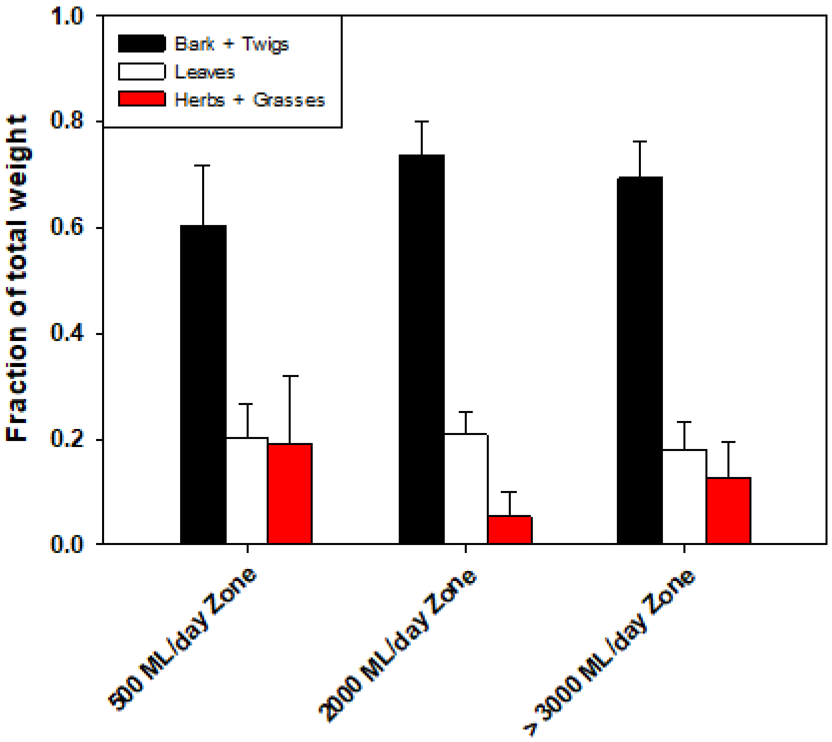

Figure 14: *Relative ratio of bark + twigs, leaf material and grasses + herbs in the three inundation zones in Koondrook-Perricoota Forest.*

2.3 Using the observed litter distribution to inform BRAT modelling

2.3.1 Litter loads

Because of the high spatial variability of litter distribution across a floodplain, typically when undertaking BRAT runs, for each flooding scenario three different litter loads are used in individual runs - the calculated mean litter load, and both the lower and upper value for the 95% confidence interval. Because there was a statistically significant difference in litter loading across the three inundation zones, it would be prudent to change the litter loadings used depending on which zones are flooded during each scenario. So, for scenarios that only inundate the 500 ML/day zone, the mean and upper and lower 95% confidence intervals determined for the 500 ML/day zone are used (Table 1). For flood scenarios that flood both the 500 ML/day and 2000 ML/day zones, the values used are the mean and 95% confidence intervals of those two zones combined. For flood scenarios which inundate the >3000 ML/day zone, the average and 95% confidence intervals across the whole flood plain are used (see Figure 11).

Table 1: *Litter loadings used in BRAT runs under different flow scenarios.*

Flood	Lower 95% CI (g/m^2)	Mean (g/m^2)	Upper 95% CI (g/m^2)
<500 ML/day	287	350	413
500 - 3000 ML/day	348	394	440
> 3000 ML/day	447	487	527

2.3.2 Litter Ratios

There was no significant difference in the litter ratio between the three zones studied, so it was valid to use a single set of ratios across all flood scenarios. The default litter ratios used in BRAT for "non-grassy" forested floodplains are bark + twigs: leaves: grass + herbs[2] of 0.7 : 0.2 : 0.1 are very similar to that observed in Koondrook-Perricoota Forest (0.68 : 0.2 : 0.12). Therefore, given the error around the means (see Figure 14) the default ratios were used in all BRAT runs.

3. Release and Decomposition of DOC

The maximum amount of DOC leached and the rate of DOC leaching are key components of the BRAT model (Figure 1) and the amount of DOC leached will depend on litter type. In previous studies, leaching experiments have focussed on DOC from river red-gum tree litter, twigs, bark and grass (e.g. Hladyz et al. 2011; Baldwin et al. 2013). However, as described in section 2, during the field surveys we found that there was different litter types and dominant groundcover vegetation in the three inundation zones in KP Forest. Old man sneeze weed and red gum leaves were the dominant litter type in low-lying parts of the forest (500 ML/day and 2000 ML/day inundation zones), whereas the >3000 ML/day inundation zone was dominated by Paterson's curse litter, red gum leaves, black box leaves and saltbush. Thus, it is important to model the release and decomposition of DOC to flooding for different litter types in different parts of KP Forest.

In this part of the project a laboratory experiment was undertaken to quantify the rate of carbon leachate from a range of different carbon sources from parts of KP Forest that have different history of inundation.

3.1. Methods

3.1.1. Experimental Methods

A carbon leaching experiment was undertaken in a temperature-controlled room at National Life Sciences Hub (NaLSH), Charles Sturt University (CSU), Wagga Wagga, New South Wales (NSW), Australia between 22 June and 23 July 2021 to quantify the rate of carbon leachate from different carbon sources of Koondrook-Perricoota Forest.

In light of field observations that there were different litter types and different vegetation types in the three inundation zones, the carbon sources collected from the forest were divided into six categories:
1) leaf litter 1 collected from 500 ML/day and 2000 ML/day inundation zones dominated by old man sneeze weed (*Centipeda cunninghamii*)/red gum (*Eucalyptus camaldulensis*) leaves
2) leaf litter 2 collected from >3000 ML/day inundation zone dominated by Paterson's curse (*Echium plantagineum*)/red gum leaves/black box (*Eucalyptus largiflorens*) leaves
3) vegetation 1 collected from 500 ML/day and 2000 ML/day inundation zones dominated by old man sneeze weed
4) vegetation 2 from >3000 ML/day inundation zone dominated by Paterson's curse/saltbush ((*Enchylaena tomentosa* and *Einadia nutans*)
5) bark/twigs collected from 500 ML/day, 2000 ML/day and >3000 ML/day inundation zones
6) bare soil collected from 500 ML/day, 2000 ML/day and >3000 ML/day inundation zones.

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[2] Although only referred to in BRAT as "grass" it is meant to encompass all ground covers.

The experiment treatments consisted of: a) six carbon sources; b) with and without sodium azide (NaN_3) to estimate rates of release and uptake by microbial activity; and c) an experimental temperature setup at 20 °C representing the common temperature occurring during summer period.

In the experiment, 1.5 g of leaf litter, 4.0 g of vegetation, 10.0 g of bark/twigs and 50.0 g of soil were loaded into 1-L glass fluted jars. 1 L of Murray River water was added into each jar and the river water was collected from near a boat ramp located at Noreuil Park, Albury, NSW, Australia (36°05'08.9"S 146°54'28.5"E). River water was added as the extractant to each jar, because it would include microbes, thus providing a more realistic representation of what would occur during flood conditions. The microbial activity in half of the samples was suppressed by adding NaN_3 to give a final concentration of 2.5 mM. Each leaching treatment had five replicates. In addition to these treatments, 1-L Murray River water without NaN_3 and 1-L Murray River water with NaN_3 as river water controls, and 1-L instrument grade water (ultrapure water) without NaN_3 and 1-L instrument grade water with NaN_3 as water quality control were added into fluted jars and placed the temperature-controlled room as well.

The temperature-controlled room set at 20 °C was started two days before the beginning of the leaching experiment to allow temperature equilibration, after which, the treatment jars and control jars were randomly aligned in two shelves (2 × 32 grid) (Figure 15). Therefore, sixty-four jars were placed in the temperature-controlled room. All jars were sealed and wrapped with aluminium foil and maintained at constant temperatures under no ambient light conditions. The oxygen concentration of floodwater flowing through the red gum forests is usually low as a result of microbial activity, consequently no attempt was made to keep the jars under oxic conditions (Glazebrook 1995).

Figure 15: *Sample jars setup at 20 °C in a constant temperature chamber at CSU, Wagga Wagga.*

To determine changes in leachate water sample over the course of the experiment, 10 ml of water from each jar was collected on Days 1, 2, 4, 8, 16 and 32 and analysed for dissolved organic carbon (DOC). These collected samples were stored in refrigerator at 4 °C for later analysis.

DOC analysis was performed at NaLSH Laboratories, CSU, Wagga Wagga, Australia. A sucrose stock solution (2000 mg C/L) was used as a calibration standard. Sample or standard (5 mL) was added to a microwave digestion tube (75 mL, Mars Xpress), followed by concentrated H_2SO_4 (1 mL). Potassium dichromate solution (0.3 mL, 0.4 M) was added, the tubes mixed and then capped. Tubes were heated to 135 ˚C over 10 mins and held for 2 hours. After cooling, the absorbance of each solution was measured at 600 nm using a 5 cm pathlength, low volume, quartz cuvette. The cuvette was rinsed with instrument grade water and the solution for analysis prior to refilling with the solution for analysis. Any sample over calibration range was analysed using 2 mL of sample and 3 mL of instrument grade water. The lower limit of quantitation was 3 mg/L organic carbon.

3.1.2. Data Analysis

Previous studies have shown that DOC leaching from litter can be modelled using the first order rate equation (e.g. O'Connell et al, 2000):

$$[DOC]_t = m \times (1 - e^{-kt})$$

where $[DOC]_t$ is the amount of DOC released (with units of mg/g dry weight), m is the maximum amount of material released from the litter, *t* is time and *k* is the first order rate equation. *k* and m are used in BRAT to determine DOC in flood waters at any given time. To fit the equation to the data, the average value of the blank (river water plus sodium azide) over the course of the experiment was subtracted from the measured DOC concentration from each sample. The concentration of DOC was then converted to concentration per unit weight by dividing the measured concentration, less the blank value, by the weight of material initially leached. The concentration at day zero was set to 0 mg/g and then all of the data (replicates and time) was fitted to the first order rate equation using the program Sigmaplot. Sigmaplot also calculates the standard error around the data, which was converted so 95% confidence intervals by multiplying by 1.96. The data from Day 2 was anomalously high and were removed from the fitting as were two replicates on Day 1 from the leaves treatment.

The mean rate of decomposition of each of the litter components was determined by first subtracting the mean of the concentration from DOC that did not have sodium azide added from the mean of the concentration that had azide added for each time step to determine the difference. Then, the difference was plotted against time to determine when the point of inflection was. This point indicates the point in time (t_{max}) where maximum DOC consumption has occurred (e.g. for Vegetation 1 t_{max} occurs at about 8 days, Figure 16:6). To determine the mean decomposition rate constant for each component of the litter, an iterative model was developed to determine the first order rate constant that would be needed to reduce the mean concentration of DOC for each component of the litter with the sodium azide treatment at time t_{max} to the mean concentration of DOC without azide (again at t_{max}) over the period of t_{max}. This is best explained with an example. Figure 17 shows the predicted uptake of dissolved organic carbon at three different values of *k* (0.09, 0.10 and 0.11 days^{-1}). A value of *k* of 0.10 days^{-1} best predicts the rate of decomposition so that by day t_{max} (=day 8) DOC levels had fallen from the mean amount of DOC in treatments with azide at day t_{max} to the concentration of treatments without.

To determine the potential error in the estimates of the decomposition rates a similar process was undertaken. Firstly the 95% confidence intervals around the mean were determined for the previously determined t_{max} for each of the components of the litter. The maximum rate was estimated by fitting a curve similar to Figure 17 except with the upper boundary equal to the upper 95% confidence interval for the amount of DOC with sodium azide added and the lower boundary set to the lower 95% confidence interval for the amount of DOC without sodium azide added (i.e. the maximum 95% CI bounds). Similarly, the lower limit was set with the upper boundary equal to the lower 95% confidence interval for the amount of DOC with sodium azide added, and the lower boundary set to the upper 95% confidence interval for the amount of DOC without sodium azide added (i.e. the minimum 95% CI bounds).

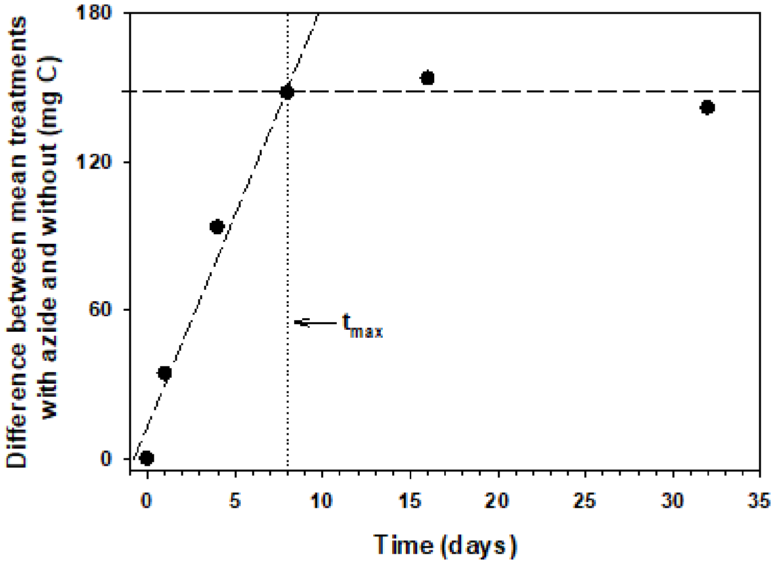

Figure 16: *Difference in the mean rates of decomposition between treatments with and without sodium azide.*

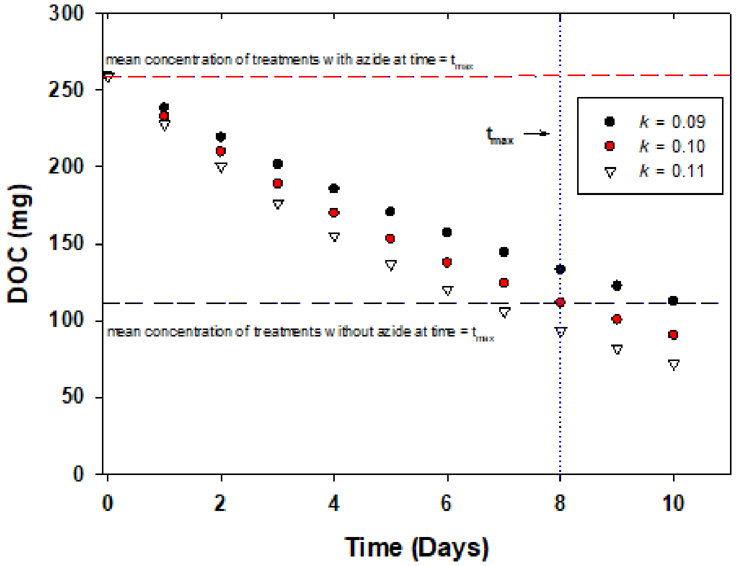

Figure 17: *Predicted uptake of dissolved organic carbon at three different values of* k *(0.09, 0.10 and 0.11 days^{-1}).*

3.2 Results and discussion

3.2.1 Rates of DOC released from each component of the litter

The calculated rates of release of DOC from the various components of the litter is presented in Table 2. There is high degree of variability in the data, as indicated by the relative low fit of the first order model to the data (relatively low r^2 values) and the wide range of the 95% CI intervals. This is understandable given the heterogeneous nature of the material. The value derived for both litter samples is similar to the default value in BRAT, which is understandable given that the major component of both the litter samples is red gum leaves.

Table 2: *Calculated rates of release of DOC from the various components of the litter in Koondrook-Perricoota Forest. Litter 1 is from 500 ML/day inundation zone, dominated by old man weed/redgum leaves; litter 2 is from >3000 ML/day inundation zone dominated by Paterson's curse/redgum leaves/blackbox leaves; Vegetation 1 was collected from 500 ML/day inundation zone and 2000 inundation zone dominated by old man weed; vegetation 2 was from >3000 ML/day inundation zone dominated by Paterson's curse/saltbush.*

Component	r^2	Lower 95% CI of k (days^{-1})	Mean value of k (days^{-1})	Upper 95% CI of k (days^{-1})	Default value in BRAT (days^{-1})
Litter 1	0.33	0.49	0.98	1.47	0.860
Litter 2	0.35	0.17	0.91	1.65	
Vegetation 1	0.80	1.03	2.21	3.39	0.380
Vegetation 2	0.68	0.76	1.54	2.32	
Bark + Twigs	0.55	0.30	0.32	0.34	0.173 (Bark) 0.078 (Twigs)
Soil	0.34	0.0	0.058	0.12	Not used

3.2.2. Maximum amount of DOC released from litter components

The maximum of material released from each litter component is presented in Table 3. Water colour of DOC samples with and without sodium azide collected at Day 32 was different (shown in Figure 18). The value for both of litter components is slightly lower than that used in BRAT, but as noted in Whitworth and Baldwin (2016), reported values range from about 65 mg/g to over 100 mg/g for redgum litter.

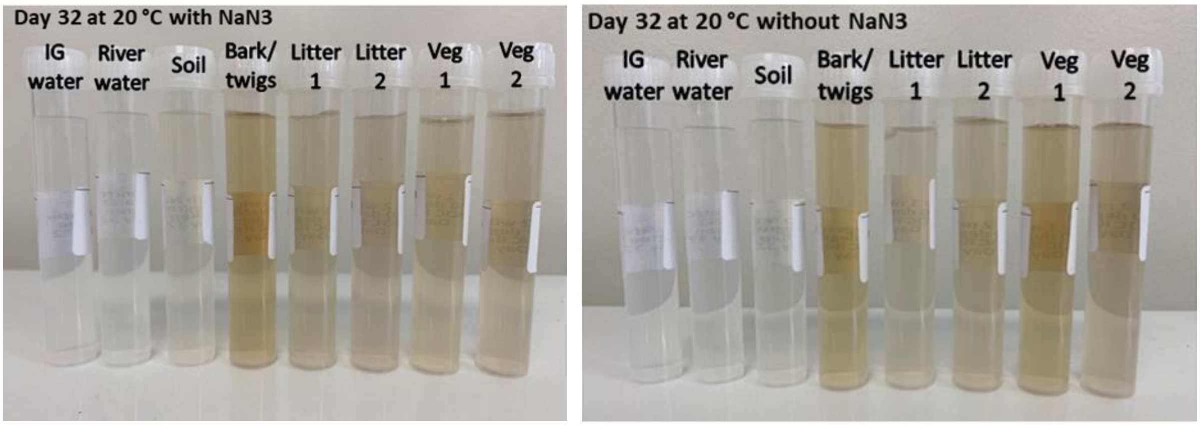

Figure 18: *Water colour of dissolved organic carbon samples with (left) and without (right) sodium azide collected at Day 32. From left to right: instrument grade water, Murray River water, bare soil, bark/twigs, leaf litter 1, leaf litter 2, vegetation1 and vegetation 2.*

Table 3: *Maximum of dissolved organic carbon released from each litter component.*

Component	r^2	Lower 95% CI of m (mg/g)	Mean value of m (mg/g)	Upper 95% CI of m (mg/g)	Default value in BRAT (mg/g)
Litter 1	0.33	33.5	36.8	40.1	80
Litter 2	0.35	49.8	58.4	67.0	
Vegetation 1	0.80	54.9	57.4	59.9	45
Vegetation 2	0.68	25.9	27.7	29.5	
Bark + Twigs	0.55	12.2	14.2	16.2	10 (Bark) 10 (Twigs)
Soil	0.34	0.10	0.24	0.38	Not used

3.2.3. Rates of decomposition of DOC released from the different litter components

The rates of decomposition of DOC leached from the various components of the litter is presented in Table 4. It was not possible to calculate a value for the decomposition rate for soils because it hadn't reached t_{max} by the end of the experiment. This isn't a significant issue. Soil is treated differently from other components in the BRAT model. Although it is likely that the soils will release some carbon on initial re-wetting, the amount is generally much less than the other components (e.g. O'Connell et al, 2000). Furthermore, the sediments are a major site of carbon decomposition - through microbial activity. Therefore in BRAT soil processes are represented as a net sink of oxygen through sediment oxygen demand - (see Whitworth and Baldwin 2016 for further details).

Table 4: *Rates of decomposition of DOC leached from the various components of the litter. Litter 1 is from 500 ML/day inundation zone, dominated by old man weed/redgum leaves; litter 2 is from >3000 ML/day inundation zone dominated by Paterson's curse/redgum leaves/blackbox leaves; Vegetation 1 was collected from 500 ML/day inundation zone and 2000 inundation zone dominated by old man weed; vegetation 2 was from >3000 ML/day inundation zone dominated by Paterson's curse/saltbush.*

	t_{max} (days)	Rate of decomposition: lower 95% CI (days^{-1})	Mean rate of decomposition (days^{-1})	Rate of decomposition: upper 95% CI (days^{-1})
Litter 1	8	0.002	0.070	0.20
Litter 2	8	0.045	0.099	0.12
Vegetation 1	8	0.065	0.10	0.14
Vegetation 2	8	0.040	0.094	0.13
Bark + Twigs	32	0.020	0.040	0.052
Soil	Not reached	-	-	-

3.3. Populating BRAT with the results of the litter leaching and decomposition experiment

3.3.1 Setting values for the rate of release of DOC from litter (*k*)

BRAT is relatively insensitive to changes in the rate that DOC is released from the litter. This is because the rate of release is fairly rapid. For example, a trial run using the Spring Flush 1 scenario, the appropriate litter loading (Table 1) using all of the Default Values in BRAT, only changing the rate of DOC release for grasses + herbs gave a critical value of DO at the outfall of 4.66 mg/L when the rate from grasses + herbs was set to 3.30 days^{-1} (the upper 95% CI for Vegetation 1; Table 2) and 4.65 mg/L when it was set to 0.79 days^{-1} (the lower 95% CI for Vegetation 2; Table 2). Therefore, the values for *k* used in all BRAT runs, irrespective of flood volume are:

- Litter - 0.95 days^{-1}; the average of mean Litter 1 and Litter 2
- Grasses + herbs - 1.9 days^{-1} ; the average of mean Vegetation 1 and Vegetation 2
- Bark + Litter - 0.32 days^{-1} for both.

3.3.2 Setting values for the maximum amount of DOC from litter (*m*)

The difference between the Lower and Upper 95% CI for all of the litter components is not great - typically about ± 10% of the mean, which is less than the uncertainty inherent in a model like BRAT. Therefore, for each litter component, the mean value was used in BRAT runs. There were substantial differences between the amount of DOC released from Vegetation 1 (from the 500 and 2000 ML/day zones) and Vegetation 2 (from the > 3000 ML/day zone). Similarly, there were large differences between Litter 1 (from the 500 and 2000 ML/day zones) and Litter 2 (from the > 3000 ML/day zone). Therefore, the values of m for litter and grasses + herbs used in BRAT runs will depend on the size of the floods. For floods <3000 ML/day the values of m for litter and grasses + herbs used were 36.8 and 57.4 mg/g respectively. For floods >3000 mg/L day the values used are the average of m values of Vegetation 1 and Vegetation 2 (42.6 mg/g) and, Litter 1 and Litter 2 (47.6 g/mg).

3.3.3 Setting values for the rate of decomposition of DOC

BRAT only uses a single value for the decomposition of all DOC. The default value is 0.03 day^{-1}. The overall rate of decomposition can be calculated by weighting the value of a particular component of the litter by the proportion of that component on the floodplain. So, for floods of <3000 ML/day the rate can be calculated as:
(rate of decomposition for bark + twigs x proportion of bark + twigs in the litter) + (rate of decomposition for Vegetation 1 x proportion of grasses + herbs on the flood plain) + (rate of decomposition of Litter 1 x proportion of leaves on the floodplain) = (0.04 x 0.7) + (0.1 x 0.1) +(0.07 x 0.2) = 0.052 day^{-1}. A similar processes can be used for floods > 3000 ML/day (substituting the rated for Vegetation 1 and Litter 1 with the rates for Vegetation 2 and Litter 2, which gives an overall rate of 0.056 day^{-1}. Given how similar the values are, the average of the two (0.054 day^{-1}) was used for the initial run for each scenario.

There is a degree of uncertainty around the actual value of the decomposition rates for each component of the litter (see Table 4) so there is a risk that the model may predict that there won't be hypoxia when there actually may be (because the overall decomposition rate used in the modelling was too low) or vice versa. Therefore, for each run which predicted that there would not be hypoxia on the floodplain under a given scenario, the model was re-run with the highest possible decomposition rate based on the data in Table 4 (0.09 day^{-1}). If model still predicted that there would not be hypoxia on the floodplain, then there is additional confidence in the veracity of the result. Similarly, if a run predicted that there would be hypoxia on the floodplain, the model was re-run with the lowest possible decomposition rate based on the available data (0.018 day^{-1}).

4. Blackwater Risk Assessment Tool (BRAT) runs

The Blackwater Risk Assessment Tool (BRAT; Whitworth and Baldwin 2016) was used estimate relative hypoxic blackwater risk for 50 flood scenarios. The outputs for these flood scenarios enable different management options to be compared.

4.1. Methods

In this section we describe the flood scenarios that were evaluated using the Blackwater Risk Assessment Tool. Fifty scenarios were provided by Forestry Corporation for evaluation.

4.1.1. Single inundation scenarios

Forty-seven were single scenario runs were tested (Table 5):

- 10 traditional flow (TF) scenarios (no outflow)
- 6 spring flush scenarios
- 3 long and low scenarios
- 6 short pulse scenarios
- 10 Alternative Downstream Flow Option Event (ADFO) scenarios that involve using the maximum discharge rate during managed releases to Barbers Creek and Thule Creek to reduce the duration of the recession phase of a managed event (GHD, 2015).
- 6 large overbank scenarios
- 6 major overbank scenarios

Table 5: *Table listing the conditions of the 47 single inundation scenarios assessed by the Blackwater Risk Assessment Tool (BRAT).*

Scenario	Inflow start	Total volume (GL)	Inflows duration (days)	Outflow	Outflow max (ML/day)	Daily flow (ML/day)	Max inundated area (ha)	Transit times (days)
TF 1	1-Jul	30	30	No	0	0	4500	45
TF 2	1-Sep	30	30	No	0	0	4000	45
TF 3	1-Nov	30	30	No	0	0	3500	45
TF 4	1-Jul	30	60	No	0	0	4000	60
TF 5	1-Sep	30	60	No	0	0	3500	60
TF 6	1-Nov	30	60	No	0	0	3000	60
TF 7	1-Jul	30	120	No	0	0	1800	120
TF 8	1-Aug	30	120	No	0	0	1400	120
TF 9	1-Sep	30	120	No	0	0	1300	120
TF 10	1-Nov	30	120	No	0	0	1000	120

Spring flush 1	1-Jul	120	30	Yes	500	300	10000	23
Spring flush 2	1-Sep	120	30	Yes	500	300	9000	23
Spring flush 3	1-Nov	120	30	Yes	500	300	8000	23
Spring flush 4	1-Jul	120	60	Yes	500	300	8000	30
Spring flush 5	1-Sep	120	60	Yes	500	300	7000	30
Spring flush 6	1-Nov	120	60	Yes	500	300	6000	30
Long, low 1	1-Jul	120	120	Yes	500	300	6000	45
Long, low 2	1-Sep	120	120	Yes	500	300	5000	45
Long, low 3	1-Nov	120	120	Yes	500	300	4000	45
Short pulse 1	1-Jul	180	30	Yes	500	300	12000	20
Short pulse 2	1-Sep	180	30	Yes	500	300	11000	20
Short pulse 3	1-Nov	180	30	Yes	500	300	10000	20
Short pulse 4	1-Jul	180	60	Yes	500	300	10000	25
Short pulse 5	1-Sep	180	60	Yes	500	300	9000	25
Short pulse 6	1-Nov	180	60	Yes	500	300	8000	25
ADFO 1	1-Jun	600	100	Yes	1500	750	16000	45
ADFO 2	1-Jul	600	100	Yes	1500	750	16000	45
ADFO 3	1-Aug	600	100	Yes	1500	750	16000	45
ADFO 4	1-Sep	600	100	Yes	1500	750	16000	45
ADFO 5	1-Oct	600	100	Yes	1500	750	16000	45
ADFO 6	1-Jun	600	100	Yes	3000	1500	12000	28
ADFO 7	1-Jul	600	100	Yes	3000	1500	12000	28
ADFO 8	1-Aug	600	100	Yes	3000	1500	12000	28
ADFO 9	1-Sep	600	100	Yes	3000	1500	12000	28
ADFO 10	1-Oct	600	100	Yes	3000	1500	12000	28
Large overbank 1	1-Jun	1000	50	Yes	10000	5000	26000	15
Large overbank 2	1-Jul	1000	50	Yes	10000	5000	26000	15
Large overbank 3	1-Aug	1000	50	Yes	10000	5000	26000	15
Large overbank 4	1-Sep	1000	50	Yes	10000	5000	26000	15
Large overbank 5	1-Oct	1000	50	Yes	10000	5000	26000	15
Large overbank 6	1-Nov	1000	50	Yes	10000	5000	26000	15
Major overbank 1	1-Jun	1800	75	Yes	12000	6000	30000	12
Major overbank 2	1-Jul	1800	75	Yes	12000	6000	30000	12
Major overbank 3	1-Aug	1800	75	Yes	12000	6000	30000	12
Major overbank 4	1-Sep	1800	75	Yes	12000	6000	30000	12
Major overbank 5	1-Oct	1800	75	Yes	12000	6000	30000	12
Major overbank 6	1-Nov	1800	75	Yes	12000	6000	30000	12

Nine runs of the BRAT were conducted runs for each scenario listed in Table 5. These runs were the lower, mean and upper 95% confidence intervals for litter load times the lower, mean and upper 95% CI for decomposition rate. The runs were used to calculate the value of dissolved oxygen concentration (DO) at the outlet. The results for each scenario were classified into five classes of risk of hypoxia: low, moderate, moderate to high, high, very high. If all of the 9 runs had DO outlet results greater than 4 mg/L, the scenario was classified as low risk. If 6 or more of the 9 runs resulted in DO at the outlet less than 2mg/L the risk was classified as very high. The results were tabulated and colour coded: red >2mg/L, yellow 2 - 4 mg/L, no shading for low risk.

Unless otherwise stated the water temperature in the inflow water was set as “seasonal”, which varies with time of year based on a predetermined relationship (see Whitworth et al, 2016 for further details) ,dissolved oxygen concentration in the inflow water was set as “saturated’, and is based on the modelled water temperature, and dissolved organic carbon concentration was set at 2 mg/L, which is the long-term average concentration for this section of the Murray River.

4.1.2. Hybrid inundation scenarios

Three hybrid inundation scenarios were evaluated using the Blackwater Risk Assessment Tool (Table 6). These hybrid models test how effective early winter releases are for mitigating hypoxic blackwater from later spring or early summer managed or overbank events. These scenarios test the hypothesis that an early winter pulse will mobilise carbon from the floodplain but will not cause DO problems in the Wakool River owing to water low temperatures, leaving less carbon for bacteria to consume during subsequent events.

To calculate litter load for the hybrid scenarios the floodplain was divided into areas that were flooded by the proceeding winter managed event and those areas that weren’t. The litter load in the areas that were flooded was estimated by the time since last flood method, while the area that wasn't flooded used the measured values. The amount of litter across the whole floodplain was calculated by weighting the litter based on area. For Hybrid runs 2 and 3, for the second flood in the sequence, the amount of litter estimated to have accumulated on the flood plain since the last flood, was dependent on the date of the flood commencing. Therefore low, mean and upper confidence intervals do not apply to these scenarios. It is also assumed that dissolved organic carbon in the inflow water was similar to background levels in the Murray River (typically about 2 mg/L).

Table 6: *Table listing the conditions of the three hybrid inundation scenarios assessed by the Blackwater Risk Assessment Tool (BRAT).*

Scenario	Inflow start	Total volume (GL)	Inflows duration (days)	Outflow	Outflow max (ML/day), return to the Wakool R	Max Daily flow (ML/day)	Max inundated area (ha)	Transit times (days)
Hybrid scenario 1: Winter managed event, summer overbank								
Winter managed event	1-Jul	150	30 days @ 5000 ML/d	yes	3000 Total 70 GL	1000 Thule 2000 Barbers	10,000	50
Summer overbank	1 Feb	106	30 days	yes	4000 Total 40 GL	1000 Thule 2000 Barbers 1000 return channel	12,000	60
Hybrid scenario 2: Winter managed event, spring managed event								
Winter managed event	1-Jul	150	30 days @ 5000 ML/d	yes	3000 Total 70 GL	1000 Thule 2000 Barbers	10,000	50
Spring pulse managed event	1-Sep	90	30 days	yes	3000 Total 30 GL	1000 Thule 2000 Barbers	5000	50
Hybrid scenario 3: Winter managed event, spring overbank event								
Winter managed event	1-Jul	150	30 days 5000 ML/d	yes	3000 Total 70 GL	1000 Thule 2000 Barbers	10,000	50
Spring overbank event (mimics 2016 flood)	1-Sep	790	90 days	yes	20,000 Total 400 GL	20,000	18,000	120

4.2. Results and discussion

4.2.1 Single inundation scenario runs

- Six of the 10 Traditional Flow (TF) scenarios (no outflows from the forest) that had 60 days inflow resulted in high or very high risk of hypoxia (Table 7). Whereas TF scenarios 7 to 10 that had 120 days inflow duration had low risk of hypoxia.
- Five of the six spring flush scenarios (120 GL total volume, 30-60 days duration of inflows) resulted in moderate to very high risk of hypoxia. The exception was spring flush scenario 4 that commenced earlier (July) and had 60 days duration.
- The long low scenario 1 commencing in July had low hypoxia risk, however, the long low scenarios with the same conditions but commencing in September or November had low to moderate hypoxia risk.
- The short pulse scenarios (180 GL total volume, 30-60 days duration of inflows) had variable risk, ranging from low/moderate, high or very high. The exception was the short pulse 4 scenario commencing in July that had a duration of 60 days.
- All of the Alternative Downstream Flow Option Event (ADFO) scenarios (600 GL total volume and 100 days duration of inflows) had low risk of hypoxia.
- Only one of the large overbank scenarios (1000 GL total volume, 50 days duration of inflows) had any risk hypoxia. This scenario commenced in November and had a low to moderate risk of hypoxia.
- None of the major overbank scenarios (1800 GL total volume, 75 days duration of Finflows) were evaluated to have any risk of hypoxia.

In the case of both the overbank flows in the single runs, and overbank flows in the hybrid runs, the modelling was based on the assumption that dissolved oxygen concentration in the incoming water was saturated and, the dissolved organic concentration was low. In reality, if there is a significant overbank flood in KP Forest, then upstream floodplains would likely have been flooded, meaning the incoming flood water would be lower in DO and Higher in DOC than the values used in the modelling. This is discussed further in Section 4.2.2.

The effects of transit times on DO in outflows was interesting. It could be assumed that longer transit times (such as 120 days starting in September) would lead to lower DO as water is transiting during the warmer months. However, these results suggest that longer transit times can lead to higher DO in the outflows, because over the long period of time that the water flows through the forest all the DOC is leached and consumed, so the water quality improves.

***Table 7:** Values of DO (mg/L) at the outlet for single scenario runs. The results are colour coded red for DO <2 mg/L, yellow for DO 2 - 4 mg/L. The number in brackets is the number of days the model predicted the DO was < 2mg/L. Estimated likelihood: If 6 or more of the 9 runs per scenario was less than 2 mg/L then the risk was scored as very high. If less than 6 of the 9 runs per scenario was less than 2 mg/L then the risk was scored as high. If 6 or more of the 9 runs per scenario was less than 4 mg/L then the risk was scored as moderate. If all of the runs were greater than 4 mg then the risk was scored as low.TF = Traditional Flow, ADFO = Alternative downstream flow option event. This involves using the maximum discharge rate during managed releases to Barbers Creek and Thule Creek to reduce the duration of the recession phase of a managed event (GHD, 2015).*

Scenario	Lower 95% CI Litter			Mean Litter			Upper 95% CI Litter			Risk of hypoxia
	Lower 95% CI Decomp	Mean Decomp Rate	95% CI Upper Decomp Rate	95% Lower CI Decomp	Mean Decomp Rate	95% CI Upper Decomp Rate	95% Lower CI Decomp	Mean Decomp Rate	95% CI Upper Decomp Rate	
TF 1	4.9	1.3 (23)	0.0 (21)	4.5	0.2 (30)	0.0 (24)	3.9	0.0 (36)	0.0 (27)	Very High
TF 2	2.9	0.0 (20)	0.0 (11)	2.3	0.0 (22)	0.0 (13)	1.3 (34)	0.0 (24)	0.0 (14)	Very High
TF 3	1.0 (18)	0.1 (12)	1.1 (4)	0.3 (23)	0.0 (13)	0.9 (5)	0.0 (28)	0.0 (14)	0.7 (6)	Very High
TF 4	5.6	3.3	0.9 (13)	5.0	2.8	0.0 (19)	4.3	2.4	0.0 (23)	High
TF 5	3.7	0.1 (13)	0.4 (8)	2.9	0.0 (16)	0.1 (10)	2.1	0.0 (19)	0.0 (11)	Very High
TF 6	2.2	0.3 (9)	1.0 (5)	1.3 (14)	0.1 (11)	0.7 (6)	0.5 (21)	0.0 (13)	0.4 (7)	Very High
TF 7	6.6	6.0	6.6	6.2	5.6	6.3	5.9	5.2	5.9	Low
TF 8	6.3	6.4	6.9	6.0	6.1	6.8	5.8	5.9	6.6	Low
TF 9	5.8	6.1	6.5	5.6	5.9	6.3	5.3	5.7	6.2	Low
TF 10	6.1	6.4	6.8	5.9	6.3	6.7	5.7	6.2	6.6	Low
Spring flush 1	6.1	3.9	1.4 (17)	5.9	3.3	0.8 (24)	5.6	2.8	0.0 (30)	High
Spring flush 2	4.6	0.5 (25)	0.0 (28)	4.3	0.0 (30)	0.0 (29)	4.0	0.0 (31)	0.0 (30)	Very High
Spring flush 3	2.8	0.0 (27)	0.0 (21)	2.5	0.0 (28)	0.0 (22)	2.1	0.0 (29)	0.0 (23)	Very High
Spring flush 4	7.1	6.3	5.0	7.0	5.8	4.5	6.8	5.4	4.0	Low
Spring flush 5	6.0	3.8	2.6	5.8	3.3	2.0	5.5	2.8	1.4 (15)	Mod
Spring flush 6	4.8	2.3	1.2 (20)	4.5	1.8 (8)	0.6 (25)	4.2	1.3 (17)	0.0 (27)	Very High
Long, low 1	7.7	6.2	5.5	7.0	5.9	5.1	6.8	5.6	4.7	Low
Long, low 2	6.0	4.6	3.8	5.8	4.3	3.4	5.7	3.9	3.0	Low to Mod
Long, low 3	5.5	3.8	2.8	5.4	3.5	2.4	5.2	3.3	2.0	Low to Mod
Short pulse 1	6.9	5.3	3.3	6.7	4.9	2.8	6.5	4.5	2.2	Low to Mod

Short pulse 2	5.6	2.3	0.2 (21)	5.3	1.8 (9)	0.0 (23)	5.1	1.3 (17)	0.0 (25)	High
Short pulse 3	3.9	0.0 (24)	0.0 (22)	3.5	0.0 (26)	0.0 (22)	3.2	0.0 (28)	0.0 (23)	Very High
Short pulse 4	7.2	6.2	4.9	7.1	5.9	4.5	7.0	5.6	4.1	Low
Short pulse 5	6.0	3.5	2.2	5.8	3.2	1.7 (8)	5.6	2.8	1.3 (15)	Mod to High
Short pulse 6	4.2	1.8 (8)	0.5 (26)	4.3	1.4 (16)	0.1 (31)	4.1	1.1 (20)	0.0 (32)	Very High
ADFO 1	7.8	8.1	7.8	7.7	8.1	7.6	7.7	8.1	7.5	Low
ADFO 2	7.6	7.3	6.8	7.6	7.2	6.6	7.5	7.0	6.4	Low
ADFO 3	7.2	6.2	5.5	7.1	6.0	5.3	7.0	5.8	5.1	Low
ADFO 4	6.5	5.1	4.4	6.4	4.9	4.2	6.3	4.7	3.9	Low
ADFO 5	5.9	4.3	3.5	5.8	4.1	3.3	5.7	3.9	3.0	Low
ADFO 6	7.9	8.1	8.1	7.9	8.1	8.1	7.9	8.1	8.1	Low
ADFO 7	7.8	7.9	7.6	7.7	7.8	7.4	7.7	7.7	7.3	Low
ADFO 8	7.5	6.7	6.5	7.4	6.8	6.4	7.4	6.7	6.2	Low
ADFO 9	6.9	6.0	5.5	6.9	5.9	5.3	6.8	5.7	5.2	Low
ADFO 10	6.4	5.3	4.7	6.3	5.2	4.6	6.3	5.0	4.4	Low
Large overbank 1	7.6	7.9	7.9	7.6	7.9	7.8	7.5	7.9	7.6	Low
Large overbank 2	7.7	7.9	7.7	7.7	7.9	7.5	7.7	7.9	7.3	Low
Large overbank 3	7.7	7.9	6.6	7.6	7.1	6.4	7.6	7.0	6.2	Low
Large overbank 4	7.3	6.1	5.3	7.2	5.9	5.0	7.1	5.7	4.8	Low
Large overbank 5	6.6	5.1	4.2	6.5	4.9	4.0	6.4	4.7	3.8	Low
Large overbank 6	5.9	4.2	3.3	5.8	4.0	3.1	5.7	3.7	2.8	Low to Mod
Major overbank 1	8.1	8.2	8.2	8.1	8.2	8.2	8.1	8.2	8.2	Low
Major overbank 2	8.0	8.2	8.2	8.0	8.2	8.2	8.0	8.2	8.2	Low
Major overbank 3	8.0	8.2	8.2	8.0	8.2	8.2	8.0	8.2	8.2	Low
Major overbank 4	7.9	7.8	7.6	7.9	7.8	7.6	7.9	7.8	7.6	Low
Major overbank 5	7.6	7.1	6.9	7.6	7.1	6.8	7.6	7.1	6.8	Low
Major overbank 6	7.3	6.6	6.3	7.3	6.6	6.3	7.3	6.6	6.3	Low

4.2.2 Hybrid inundation scenario runs

All the hybrid model runs indicate that, at best, there would be a low to moderate risk of hypoxia during the initial winter flooding and a low risk of hypoxia in the subsequent spring or summer event (Table 8). However, this is based on a number of assumptions.

All hybrid runs assumed that DO concentrations inflow is saturated and only contained a minimal amount of DOC. For both hybrid runs 1 and 3, the amount of DOC in the inflow during the second flood was probably not negligible. For these floods to occur, upstream floodplains, including Barmah-Millewa Forest, would have been flooded. Therefore, DO concentrations of the inflows would likely be depressed and DOC concentrations would have been elevated. This would have significant impacts on the water quality leaving Koondrook-Perricoota Forest.

Figure 19 shows the DO concentration at the outfall for Hybrid Run 1 with a January flood, with the litter levels and decomposition rate both set to the mean values, but the amount of DOC in the inflows varied. This shows that DO downstream of the forest is strongly impacted by the water quality in the inflows. Therefore, when considering water quality downstream of Koondrook-Perricoota Forest, the water quality entering the forest from upstream sources should be taken into consideration.

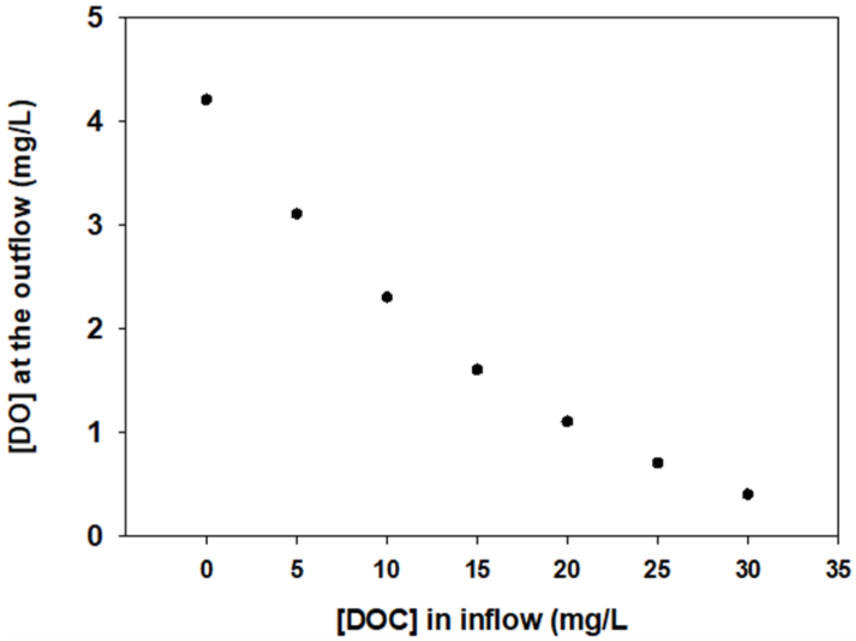

Figure 19: *DO concentration (mg/L) at the outfall for Hybrid Run 1 with a January flood, with the litter levels and decomposition rate both set to the mean values, but the amount of DOC in the inflows varied*

A second assumption, applicable to Hybrid Scenarios 2 and 3, is that litter loads are reset to zero following the previous flood. While it has been shown that experimentally, the amount of DOC that can be extracted from red gum litter that has previously been flooded is quite low (typically less than 10% of the total amount of DOC that could be extracted - Whitworth et al , 2013), it is possible that flooding induces new litter fall. While there is no evidence that this occurs for red gums, a study by Pook (1985) of leaf dynamics in spotted gum *Eucalyptus maculata* forests (now in the genus *Corymbia*) on the NSW coast and tablelands suggests that the effects of wetting/drying cycles may enhance leaf shedding. The study by Pook (1985) extended over a severe drought in 1979–1980, followed by drought-breaking rains in February 1981 and a period of above-average rainfall thereafter. This study found that eucalypt leaf fall for the 12 months July 1980–June 1981 (inclusive) was 3.7 tha^{-1}, 60% higher than the average leaf fall recorded during non-drought years. When examined by season, spring 1980 leaf fall was found to be about 3.5 times the average of other years, whereas summer 1980–81 leaf fall was unusually low, presumably because the bulk of readily abscised foliage had already been lost in spring. After the February rains, leaf fall increased again to a peak in autumn 1981, concurrent with a flush of new foliage. The autumn peak and a later peak in winter, were also coincident with heavy rains, suggesting that the physical effects of rain and/or wetting-drying cycles may have enhanced leaf shedding. It is proposed that a study be undertaken to determine if flooding induces increased litter fall in red gum forests.

It is also of note that the estimated DO was also impacted by the transit time used in the modelling (Figure 20) which varied between scenarios. Transit time is the time it takes from when the water first enters the forest to the time it first reaches the furthest downstream point on the forest. A transit time of 120 days seemed long. Re-running Hybrid model 3 a September flood and assuming the mean decomposition rate, shows a strong dependence of DO at the outfall and the transit time. If the water takes a long time to transit through the forest, it will first become hypoxic but will have enough time to become re-aerated before it exits the forest. The BRAT model includes a re-aeration component.

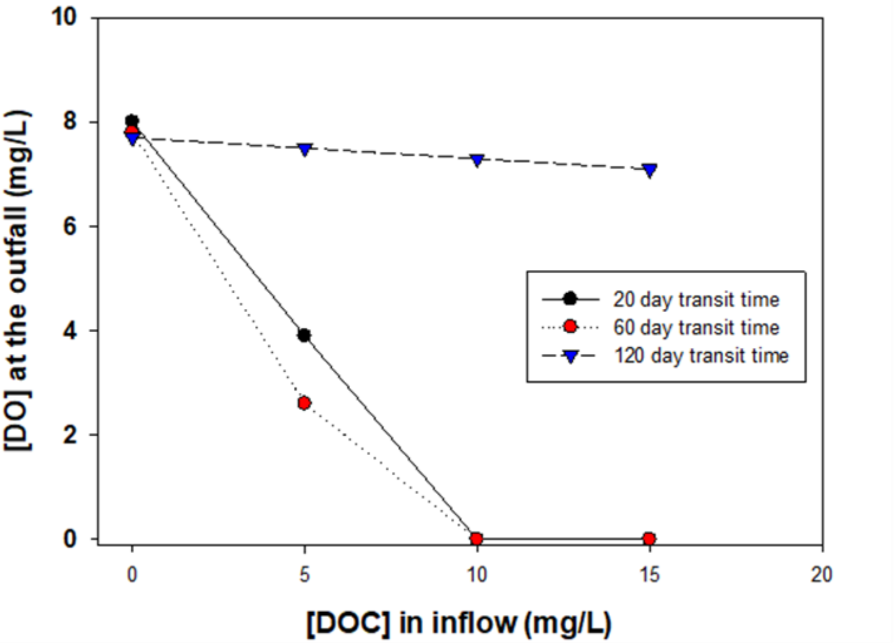

Figure 20: The impact of transit time on the *DO concentration (mg/L) at the outfall.*

Table 8: *Results of three hybrid inundation scenarios. WME= winter managed event, SOB = summer overbank, spME = spring managed event, spOB = spring overbank. The results are colour coded red for DO <2 mg/L, yellow for DO 2 - 4 mg/L. Estimated likelihood: If 6 or more of the 9 runs was less than 2 mg/L then the risk was scored as very high. If all of the runs were greater than 4 mg then the risk was scored as low. n/a = not applicable - there is no difference between lowest, mean or highest litter loading for these scenarios.*

Scenario		Lowest Estimated Litter			Mean Estimated Litter			Upper Estimated Litter Load			Risk of hypoxia
		Lower 95% CI Decomp	Mean Decomp Rate	95% CI Upper Decomp Rate	95% Lower CI Decomp	Mean Decomp Rate	95% CI Upper Decomp Rate	95% Lower CI Decomp	Mean Decomp Rate	95% CI Upper Decomp Rate	
Hybrid Run 1: Winter managed event, summer overbank											
WME	June	6.8	5.9	4.6	6.7	5.5	4.2	6.5	5.2	3.8	Low
	July	6.0	5.5	4.2	5.8	5.2	3.7	5.7	4.8	3.2	Low to Mod
	Aug	5.5	4.0	3.0	5.4	3.6	2.5	5.3	3.2	2.1	Low to Mod
SOB	Dec	3.9	3.8	4.4	3.9	3.7	4.4	3.8	3.7	4.4	Low to Mod
	Jan	3.8	3.8	4.6	3.7	3.7	4.6	3.6	3.5	4.5	Low to Mod
	Feb	4.8	5.1	6.3	4.7	5.1	6.3	4.6	5.0	6.3	Low
Hybrid Run 2: Winter managed event, spring managed event											
WME	June	6.8	5.9	4.6	6.7	5.5	4.2	6.5	5.2	3.8	Low to Mod
	July	6.0	5.5	4.2	5.8	5.2	3.7	5.7	4.8	3.2	Low to Mod
	Aug	5.5	4.0	3.0	5.4	3.6	2.5	5.3	3.2	2.1	Low to Mod
SpME	Sept	n/a	n/a	n/a	n/a	n/a	n/a	6.3	6.7	7.0	Low
	Oct	n/a	n/a	n/a	n/a	n/a	n/a	5.7	6.2	6.4	Low
	Nov	n/a	n/a	n/a	n/a	n/a	n/a	5.3	5.9	6.1	Low
Hybrid Run 3: Winter managed event, spring overbank event											
WME	June	6.8	5.9	4.6	6.7	5.5	4.2	6.5	5.2	3.8	Low to Mod
	July	6.0	5.5	4.2	5.8	5.2	3.7	5.7	4.8	3.2	Low to Mod
	Aug	5.5	4.0	3.0	5.4	3.6	2.5	5.3	3.2	2.1	Low to Mod
SpOB	Sept	n/a	n/a	n/a	n/a	n/a	n/a	7.0	7.5	7.7	Low
	Oct	n/a	n/a	n/a	n/a	n/a	n/a	6.9	7.3	7.5	Low
	Nov	n/a	n/a	n/a	n/a	n/a	n/a	7.0	7.5	7.6	Low

5. Summary of key findings

Objective 1. Compare the organic litter loads and carbon sources across Koondrook-Perricoota Forest

Litter loads in three inundation zones (500 ML/day inundation zone, 2000 ML/day floodplain inundation zone, and >3000 ML/day floodplain inundation zone) were assessed in this study. There was a significant higher litter load in the >3000 ML/day zone, compared to the other two zones, but there was no difference in load between the 500 and 2000 ML/day inundation zones. There was a positive linear correlation between estimated litter volume and measured litter mass. While there was variability between sites, there was no statistical difference in the ratios of bark, leaves and grasses and herbs among the flood inundation zones.

500 ML/day Inundation zone:
- Inundated in 2019
- Low litter loads, not significantly different to the 2000 ML/day zone
- field observation of more bare ground than the other zones
- Ground vegetation dominated by old man sneeze weed

2000 ML/day Inundation zone:
- Low litter loads, not significantly different to the 500 ML/day zone
- Ground vegetation dominated by old man sneeze weed and Juncus *sp.*

>3000 ML/day Inundation zone:
- Significantly higher litter loads than the 500 and 2000 ML/day zones
- Sites in the red gum areas typically had a thick cover of dead Paterson's curse and sometimes paper daisies
- Sites in black box forest had saltbush ground vegetation

The mean litter loads were similar in the burnt and unburnt sites in the 500 ML/day inundation zone that has been inundated since the fire. In contrast, there was a lower mean litter load in the burnt sites in both the 2000 ML/day and >3000 ML/day zones that have not been inundated since they were burnt. These results should be interpreted with some caution because there were considerably lower sample sizes in the burnt areas than the unburnt areas and the spatial the coverage of the burnt sites is very small relative to the unburnt part of the forest.

Objective 2: Quantify carbon leachate from litter relative to load, litter type, water temperature, inundation duration, and inundation frequency

A laboratory experiment was undertaken to quantify the rate of carbon leachate from a range of different carbon sources from parts of KP forest that have different history of inundation. The different carbon sources collected from the forest were divided into six categories: 1) leaf litter 1 dominated by old man sneeze weed/river red gum leaves; 2) leaf litter 2 dominated by Paterson's curse /red gum leaves/black box leaves; 3) vegetation 1 dominated by old man sneeze weed; 4) vegetation 2 dominated by Paterson's curse/saltbush; 5) bark/twigs, and 6) bare soil.

The experiment treatments consisted of: a) six carbon sources; b) with and without sodium azide (NaN_3) to estimate rates of release and uptake by microbial activity; and c) an experimental temperature setup at 20 °C representing the common temperature occurring during summer period.

There was a high degree of variability calculated rates of release of DOC from the various components of the litter. This is understandable given the heterogeneous nature of the material. The maximum dissolved organic carbon released from the six litter components ranged from 0.38 mg/g for soil, 16.2 mg/g for bark+twigs, 29.5 mg/g for vegetation 2, 40.1 mg/g for litter 1, 59.9 mg/g for vegetation 2, and 67.0 mg/g for litter 2. These values were slightly lower than those reported in Whitworth and Baldwin (2016), where values ranged from approximately 65 mg/g to over 100 mg/g for redgum litter.

There were substantial differences between the amount of DOC released from Vegetation 1 (from the 500 and 2000 ML/day zones) and Vegetation 2 (from the > 3000 ML/day zone). Similarly, there were large differences between Litter 1 (from the 500 and 2000 ML/day zones) and Litter 2 (from the > 3000 ML/day zone). Therefore, the values of m for litter and grasses + herbs used in BRAT runs depended on the size of the floods. For floods <3000 ML/day the values of m for litter and grasses + herbs used were 36.8 and 57.4 mg/g respectively. For floods >3000 mg/L day the values used are the average of m values of Vegetation 1 and Vegetation 2 (42.6 mg/g) and, Litter 1 and Litter 2 (47.6 mg/g).

Previous studies have evaluated DOC release from red gum leaves and grass (e.g. O'Connell et al. 2000; Whitworth et al. 2012; McInerney et al. 2017) and shown that inundation of floodplain litter similarly leaches large quantities of dissolved organic carbon from leaf litter. This is the first time that the carbon leachate from different sources of vegetation from different zones in Koondrook-Perricoota Forest have been evaluated. From these results we can conclude that it is important to include estimates of leachate from different sources of carbon in different parts of the forest that will be inundated. As demonstrated in Liu et al. (2019), inundation of any vegetation during summer floods can be a major source of DOC and a major contributor to DO depletion.

Objective 3: Estimate the relative hypoxic blackwater risk from varying locations across Koondrook-Perricoota Forest.

Forty-seven single scenario runs were tested:

- 10 Traditional Flow (TF) scenarios (30 GL total volume, 30-120 days duration of inflows)
- 6 spring flush scenarios (120 GL total volume, 30-60 days duration of inflows)
- 3 long and low scenarios (120 GL total volume, 120 days duration of inflows)
- 6 short pulse scenarios (180 GL total volume, 30-60 days duration of inflows)
- 10 Alternative downstream flow option event (ADFO) scenarios (600 GL total volume and 100 days duration of inflows) that involve using the maximum discharge rate during managed releases to Barbers Creek and Thule Creek to reduce the duration of the recession phase of a managed event.
- 6 large overbank scenarios (1000 GL total volume, 50 days duration of inflows)
- 6 major overbank scenarios (1800 GL total volume, 75 days duration of inflows)

Three hybrid inundation scenarios (sequence of scenarios) were also evaluated using the tested using the Blackwater Risk Assessment Tool. These hybrid models test how effective early winter releases are for mitigating hypoxic blackwater from later spring or early summer managed or overbank events. The hybrid models were:

- Winter managed event, summer overbank
- Winter managed event, spring managed
- Winter managed event, large spring overbank event (mimicking 2016 flood event)

The outcomes of the single scenario models were variable (Table 9). In general, flows that commenced later, and/or had lower inflows or shorter duration (30 days) had higher risk of hypoxia. Scenarios that commenced earlier, and/or had longer duration (60-120 days) or higher inflows had lower risk of hypoxia:

- Six of the 10 Traditional Flow (TF) scenarios (no outflows from the forest) that had 30- or 60-days inflow resulted in high or very high risk of hypoxia. Whereas the TF scenarios with 120 days inflow duration had low risk of hypoxia.
- Five of the six spring flush scenarios (120 GL total volume, 30-60 days duration of inflows) resulted in moderate to very high risk of hypoxia. The exception was spring flush scenario 4 that commenced earlier and had 60 days duration (Table 9).
- The long low scenario commencing in July had low hypoxia risk, however, the same long low scenarios commencing in September or November had low to moderate hypoxia risk (Table 9).
- The short pulse scenarios (180 GL total volume, 30-60 days duration of inflows) had variable risk, ranging from low/moderate, high or very high. The exception was the short pulse 4 scenario commencing in July that had a duration of 60 days.
- All of the ADFO scenarios (600 GL total volume and 100 days duration of inflows) had low risk of hypoxia.
- Only one of the large overbank scenarios (1000 GL total volume, 50 days duration of inflows) had any risk hypoxia. This scenario (Large overbank 6) commenced in November and had a low to moderate risk of hypoxia.
- None of the major overbank scenarios (1800 GL total volume, 75 days duration of inflows) were evaluated to have any risk of hypoxia.

All the hybrid model runs indicate that, at best, there would be a low to moderate risk of hypoxia during the initial winter flooding and a low risk of hypoxia in the subsequent spring or summer event. However, for the three hybrid runs and for the over bank floods in the single flood scenarios, these results are based the assumption that DO concentrations in the inflows are high and DOC concentrations are low. In reality, where there have been overbank flows upstream, DO concentrations in the inflows will be lowered and DOC concentrations would be elevated. The modelling clearly shows that water quality leaving KP Forest during overbank events will be strongly influenced by the water quality entering the forest.

The effects of transit times on DO in outflows was interesting. It could be assumed that longer transit times (such as 120 days starting in September) would lead to lower DO as water is transiting during the warmer months. However, these results suggest that longer transit times can lead to higher DO in the outflows, because over the long period of time that the water flows through the forest all the DOC is leached and consumed, so the water quality improves.

Table 9: *Summary of results from the 47 single inundation scenarios assessed by the Blackwater Risk Assessment Tool (BRAT). TF = Traditional Flow, ADFO = Alternative downstream flow option. Estimated likelihood: If 6 or more of the 9 runs per scenario was less than 2 mg/L then the risk was scored as very high. If less than 6 of the 9 runs per scenario was less than 2 mg/L then the risk was scored as high. If 6 or more of the 9 runs per scenario was less than 4 mg/L then the risk was scored as moderate. If all of the runs were greater than 4 mg then the risk was scored as low.*

Scenario	Inflow start	Total volume (GL)	Inflows duration (days)	Out flow	Outflow max (ML/day)	Daily flow (ML/day)	Max inundated area (ha)	Transit times (days)	Risk of hypoxia
TF 1	1-Jul	30	30	No	0	0	4500	45	Very High
TF 2	1-Sep	30	30	No	0	0	4000	45	Very High
TF 3	1-Nov	30	30	No	0	0	3500	45	Very High
TF 4	1-Jul	30	60	No	0	0	4000	60	High
TF 5	1-Sep	30	60	No	0	0	3500	60	Very High
TF 6	1-Nov	30	60	No	0	0	3000	60	Very High
TF 7	1-Jul	30	120	No	0	0	1800	120	Low
TF 8	1-Aug	30	120	No	0	0	1400	120	Low
TF 9	1-Sep	30	120	No	0	0	1300	120	Low
TF 10	1-Nov	30	120	No	0	0	1000	120	Low
Spring flush 1	1-Jul	120	30	Yes	500	300	10000	23	High
Spring flush 2	1-Sep	120	30	Yes	500	300	9000	23	Very High
Spring flush 3	1-Nov	120	30	Yes	500	300	8000	23	Very High
Spring flush 4	1-Jul	120	60	Yes	500	300	8000	30	Low
Spring flush 5	1-Sep	120	60	Yes	500	300	7000	30	Moderate
Spring flush 6	1-Nov	120	60	Yes	500	300	6000	30	Very High
Long, low 1	1-Jul	120	120	Yes	500	300	6000	45	Low
Long, low 2	1-Sep	120	120	Yes	500	300	5000	45	Low to Mod
Long, low 3	1-Nov	120	120	Yes	500	300	4000	45	Low to Mod
Short pulse 1	1-Jul	180	30	Yes	500	300	12000	20	Low to Mod
Short pulse 2	1-Sep	180	30	Yes	500	300	11000	20	High
Short pulse 3	1-Nov	180	30	Yes	500	300	10000	20	Very High
Short pulse 4	1-Jul	180	60	Yes	500	300	10000	25	Low
Short pulse 5	1-Sep	180	60	Yes	500	300	9000	25	Mod to High
Short pulse 6	1-Nov	180	60	Yes	500	300	8000	25	Very High
ADFO 1	1-Jun	600	100	Yes	1500	750	16000	45	Low
ADFO 2	1-Jul	600	100	Yes	1500	750	16000	45	Low
ADFO 3	1-Aug	600	100	Yes	1500	750	16000	45	Low
ADFO 4	1-Sep	600	100	Yes	1500	750	16000	45	Low
ADFO 5	1-Oct	600	100	Yes	1500	750	16000	45	Low
ADFO 6	1-Jun	600	100	Yes	3000	1500	12000	28	Low
ADFO 7	1-Jul	600	100	Yes	3000	1500	12000	28	Low
ADFO 8	1-Aug	600	100	Yes	3000	1500	12000	28	Low
ADFO 9	1-Sep	600	100	Yes	3000	1500	12000	28	Low
ADFO 10	1-Oct	600	100	Yes	3000	1500	12000	28	Low
Large overbank 1	1-Jun	1000	50	Yes	10000	5000	26000	15	Low
Large overbank 2	1-Jul	1000	50	Yes	10000	5000	26000	15	Low

Large overbank 3	1-Aug	1000	50	Yes	10000	5000	26000	15	Low
Large overbank 4	1-Sep	1000	50	Yes	10000	5000	26000	15	Low
Large overbank 5	1-Oct	1000	50	Yes	10000	5000	26000	15	Low
Large overbank 6	1-Nov	1000	50	Yes	10000	5000	26000	15	Low to Mod
Major overbank 1	1-Jun	1800	75	Yes	12000	6000	30000	12	Low
Major overbank 2	1-Jul	1800	75	Yes	12000	6000	30000	12	Low
Major overbank 3	1-Aug	1800	75	Yes	12000	6000	30000	12	Low
Major overbank 4	1-Sep	1800	75	Yes	12000	6000	30000	12	Low
Major overbank 5	1-Oct	1800	75	Yes	12000	6000	30000	12	Low
Major overbank 6	1-Nov	1800	75	Yes	12000	6000	30000	12	Low

6. Management recommendations

Litter loads and carbon leachate

This study has demonstrated that different types of vegetation and litter from the different inundation zones in Koondrook–Perricoota Forest may result in different litter loads and different rates of release of DOC.

Recommendation 1: Future modelling of blackwater risk should consider the litter loads and carbon leachate of the different types of leaf litter and vegetation from different inundation zones within Koondrook-Perricoota Forest.

Risk of hypoxia

Results from running the Blackwater Risk Assessment Tool on 50 inundation scenarios suggest that inundation of the floodplain during the warmer months (late-spring to early autumn) and/or inundation regimes that have lower inflows or shorter duration (30 days) substantially increases the likelihood of hypoxic water leaving the forest in outflows.

Recommendation 2: To avoid the risks of hypoxic blackwater outflows and poor ecological outcomes downstream of KP Forest, it is important to optimise the magnitude of flows through KP Forest and avoid scenarios where water stands (not flowing) for long periods of time. This is especially important during the warm months when carbon leaching can increase and have a detrimental effect on dissolved oxygen concentrations. Inundation scenarios that have higher inflows (120 GL or more), commence earlier, and/or have longer duration (60 -120 days) of transit time of water flowing through the forest, lower the risk of hypoxia

Source water

The quality of the water leaving the forest during over-bank floods is highly influenced by the quality of the water entering the forest from upstream. Unlike Barmah-Millewa Forest that receives source water that generally has low dissolved carbon, KP Forest can receive source water that has already travelled across floodplains and low-lying farmland. Thus, there is the need to monitor DO and DOC in the source water as part of the planning for the delivery of environmental water to KP Forest.

Recommendation 3: The water quality entering the forest from upstream sources should be monitored and taken into consideration when considering the downstream water quality impacts of the delivery of environmental water to Koondrook-Perricoota Forest.

Impact of fire on litter loads and water quality

Mean litter loads were similar in the burnt and unburnt sites in the 500 ML/day inundation zone. However there was a lower mean litter load in the burnt sites in both the 2000 ML/day and >3000 ML/day inundation zones that had not been inundated since they were burnt. These results suggest that managed burns could be used as a management tool to reduce litter loads prior to flooding to forest. However, these results should be interpreted with caution for two reasons: a) there were considerably lower number of samples undertaken in the burnt areas than the unburnt areas, and b) the spatial the coverage of the burnt sites was very small relative to the unburnt part of the forest. There are also potential negative impacts of fire that need to be considered, rather than just focussing on a simple measure of litter load reduction. For example, the leachate from ash can contain toxins such as cyanide and this risk should be explored further in experimental trials.

Recommendation 4: The impact of controlled burns on litter load needs to be further examined through experimental trials. These trials must examine the potential risks on water quality from toxins that leach from ash following inundation.

Other factors influencing litter load

There is a lack of knowledge on the effects of wetting/drying cycles and flooding on leaf shedding in river red gums. One previous study in spotted gum forests (Pook, 1985) suggested that there was higher than average leaf fall during non-drought years, and that leaf fall increased following heavy rainfall, concurrent with a flush of new foliage.

Recommendation 5: A study be undertaken to improve knowledge about the impacts of wetting/drying, droughts and inundation on litter loads in red gum forests.

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