Author/s:
Stout, JC;Rutherfurd, ID;Grove, J;Webb, AJ;Kitchingman, A;Tonkin, Z;Lyon, J

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Stout Justin, Collin (Orcid ID: 0000-0001-5540-4000)
Rutherfurd Ian, D (Orcid ID: 0000-0001-6229-7223)
Webb J. Angus (Orcid ID: 0000-0003-0857-7878)
Tonkin Zeb (Orcid ID: 0000-0001-9299-6404)
Lyon Jarod (Orcid ID: 0000-0002-8762-4128)

Passive recovery of wood loads in rivers

J. C. Stout[1,2], I. D. Rutherfurd[2], J. Grove[2], A. J. Webb[3], A. Kitchingman[4], Z. Tonkin[4], and J. Lyon[4]

[1]Australian Rivers Institute, Griffith University, Nathan, Australia

[2]School of Geography, University of Melbourne, Melbourne, Australia

[3]Department of Infrastructure Engineering, University of Melbourne, Melbourne Australia

[4]Department of Environment Land Water and Planning, Arthur Rylah Institute for Environmental Research, Heidelberg, Australia

Corresponding author: Justin Stout (j.stout@griffith.edu.au)

Key Points:

- Desnagged rivers can recover a natural wood load, but will take centuries rather than decades to passively return to pre-snagging loads.
- Recovery time is a function of wood removal rates from the reach, while the volume of wood is a function of input/removal rates to the reach.
- Desnagged rivers will typically go through five stages of recovery, with the final one depending on the storage of large key logs in the bed.

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Abstract

A growing worldwide body of literature is demonstrating the geomorphic and ecological roles played by wood in rivers. After more than a century of removing wood from rivers in many parts of the world, researchers and managers are now interested in returning the load of wood back to a more natural condition. The mechanical placement of wood in rivers is expensive, and so it is useful to know how long it will take for in-stream wood loads to passively recover a target load by recruitment from riparian forests. Of fundamental interest to managers and researchers alike are the questions: 1) can a river passively recover to a pre-removal load of wood, and 2) if so, how long will recovery take? We address these questions using the example of the anabranching King River, Northeast Victoria, Australia which was desnagged twice; once in 1957 and again in 1980. We predict a recovery time of 255 ±23 years using a complete census of recovering wood loads to develop and parameterize a mass balance delivery model run in a Monte Carlo simulation. Our results indicate that with a healthy supply of riparian vegetation and minimal interference from managers, rivers are likely to passively recover natural wood loads at least two and a half centuries after desnagging. Using the data and methods described in this paper we develop a theory of recovery, conceptually describing the recovery process as a sequence of five stages that can be used to monitor and track wood loads through time.

1 Introduction

Dead trees (also known as large in-stream wood and large woody debris) have long been recognized as an important driver of geomorphic processes in river channels and floodplains [*Beechie et al.* 2000, *Eaton et al.* 2012, *Gippel et al.* 1996a, *Gurnell et al.* 2000, *Gurnell et al.* 2002, *Montgomery et al.* 2003, *Nakamura and Swanson* 1993, *Piegay and Gurnell* 1997, *Wohl et al.* 2012]. Desnagging, or the removal of large in-stream wood, has been a major part of lowland river management and engineering practices over the past century [*Erskine and Webb* 2003, *Montgomery et al.* 2003]. Large lowland rivers were generally desnagged to improve navigation and water conveyance, while smaller lowland rivers were desnagged to reduce perceived flood risk and protect infrastructure from floating debris [*Strom* 1962, *Wohl* 2014]. Now, after nearly a century of desnagging rivers, managers and researchers are interested in restoring and returning the load of wood back to more natural conditions. This can be done both passively and actively by stopping the artificial removal of wood from the channel, and allowing wood to once again accumulate in the river.

Active restoration techniques involve mechanically placing and anchoring individual logs or engineered log jams (ELJs) on the river bed and banks [*Brooks et al.* 2006]. This is coupled with riparian planting projects, with this vegetation eventually providing a source of wood for future recruitment to the river [*Bernhardt et al.* 2005, *Lester and Boulton* 2008, *Lester et al.* 2007]. Given that the mechanical placement of wood in rivers is expensive, waterway managers are increasingly interested in how long it could take rivers to passively recover their target or natural wood load.

Earlier work on recruitment rates of wood into rivers has largely focused on North American rivers where wood loads were depleted by logging of the riparian area, or by splash damning and log floating [*Beechie et al.* 2000, *Hyatt et al.* 2004, *Roni et al.* 2014, *Wohl* 2014]. The general predicted time to recovery (i.e. natural wood loads) is in the order of multiple decades to centuries [*Bragg* 2000, *Erskine and Webb* 2003, *Fryirs et al.* 2012], and is largely driven by the rate of riparian forest regrowth (i.e. stand age) and the rates of input and subsequent decomposition of wood in the channel [*Gregory et al.* 2003, *Meleason et al.* 2007]. In some instances where the removal of wood has altered the state of the river channel, or where riparian and floodplain habitats have been denuded of woody vegetation, the recovery of natural wood loads is improbable over any time scale [*Wohl* 2014]. The questions of whether a river can passively recover a pre-disturbance load of wood, and if so, how long it will take, are of fundamental interest to stream managers and researchers alike. Importantly, it is not just the wood load that is of interest, but how long it takes to recover the spatial distribution of wood in the channel. To answer these questions, we must first understand the delivery and removal processes of wood into the river, and how those processes drive spatial and temporal variation in the load of wood distributed within the channel. We answer these questions through a case-study on the King River in SE Australia. We build on previous ideas and methods by utilizing a full census of wood loads to assess the variability and spatial distribution of wood loads along the channel to represent delivery and removal mechanisms as a stochastic process, and thereby derive real measurements of wood load recovery rates over decadal scales.

Here we use a wood budget model to estimate how long it will take for our study river (King River) to recover its wood load. The King River is a natural laboratory by which we can assess the accumulation rate of wood over time. The dominant tree species (*Eucalyptus camaldulensis*) is a dense hardwood (green density of approx. 1.12 g cm^{-1} [*White* 1998]). This results in minimal transport and loss of wood from the reach over time. The bank erosion rates on the river tend to be low (tens of centimetres per hundred years [*Schumm et al.* 1996]). Additionally, the trees along the study reach are approximately as tall as the channel is wide which further reduces the ability of the river to transport and rearrange wood [*Stout et al.* 2016]. A combination of all these factors results in the King River likely being an endmember in the pathway of recovery of wood loads. We report on results from a complete census of wood in the King River, which was desnagged in 1957 and select reaches desnagged again in 1980. The wood census results were used to empirically develop probability distributions for wood accumulation rates. From the accumulation rates, estimates of delivery and removal rates were used to drive a mass balance wood delivery model to predict the time needed for a dynamic steady state wood load to accumulate within the channel. Recovery of the wood load was modelled using a Monte Carlo simulation of a wood delivery model. The delivery model provides estimates of the time required to reach steady state loads, and these were compared against predicted natural wood loads for the sampled reaches [*Kitchingman et al.* 2015]. We use the theory presented in *Stout et al.* [2016] to predict the likely spatial distribution of wood in the river, and compare the current distributions of each reach to track the recovery of the spatial distribution of wood in the channel. Finally, we present a conceptual model of in-stream wood recovery for lowland Australian rivers and discuss how the conceptual model might apply to rivers elsewhere.

2 Background and Methods

2.1 Theoretical Background

2.1.1A mass balance of large in-stream wood

The majority of research into in-stream wood does not differentiate between delivery and removal processes, but focuses on the overall load of stored wood in the reach [*Benda et al.* 2003]. The volume of stored wood is representative of the balance between the accumulation and depletion rates within a reach of river. Quantifying the delivery and removal processes and rates provides a spatial understanding of which processes are dominant in a particular reach, and are driving contemporary wood loads. Accumulation and process rates can be extrapolated to predict future wood loads [*Benda et al.* 2003, *Benda and Sias* 2003]. The recruitment, removal, and storage of wood over time can be assessed in terms of a mass balance or wood budget [*Benda et al.* 2003, *Martin and Benda* 2001]. The load or stored volume of wood in a reach is simply the sum of the changes in storage through time (Equation 1):

$$S_c = \sum_{i=1}^{n} \Delta S_i \qquad (1)$$

Where, S_c is the load of wood, measured as a volume over a length of river (L^3 L^{-1}), ΔS_i is the change in storage in the reach (L^3L^{-1}) per time step (*i*), which is typically on an annual time step. The change in storage is essentially the relationship between inputs and outputs through time and can be expressed as,

$$\Delta S_i = I_i - O_i \qquad (2)$$

Where I_i is the volume of wood delivered to the channel per linear length of the channel (L^3 L^{-1}), and O_i is the volume of wood removed per linear length of the channel (L^3 L^{-1}). The input volume of wood to the river channel can be expressed as the sum of volumes delivered to the channel in each section of the study reach (Equation 3)

$$I_i = \frac{V_{be}+V_m+V_e+V_{Qin}+V_f+V_{df}}{L} \qquad (3)$$

Where V_{be} is the volume delivered through bank erosion, V_m is the volume delivered through tree or stand mortality, V_e is the volume delivered through the exhumation of buried logs or log jams, V_{Qin} is the volume of wood delivered via transport into the reach, V_f is the volume delivered due to stand-killing fires, and V_{df} is the volume of wood delivered through mass movements or debris flows. *L* is the length of each section that the volume of wood is measured

The removal of wood (O_i) (Equation 4)from each section of the study reach is a function of the volume of wood decayed from the section (D_v), the volume of wood transported out of the section (V_{Qout}), and the volume of wood lost or transported onto the floodplain (V_l).

$$O_i = \frac{D_v + V_{Qout} + V_l}{L} \quad (4)$$

The volume of decayed wood (D_i) for each time step can be modelled as an exponential decay function (Equation 5) [*Garrett et al.* 2008].

$$D_i = Sc_{i-1} - (Sc_{i-1}e^{-kt}) \quad (5)$$

Where Sc_{i-1} is the stored load of wood in the channel from the previous time step (*i*), *k* is the decay constant of wood, and *t* is the length of time from the previous time step (typically on an annual time step).

In wood delivery models, often the balance between the volumes of wood transported in and out of a reach is assumed to be in balance (i.e. $V_{Qin} - V_{Qout} = 0$) [*Benda et al.* 2003]. For the purpose of the model described here, we assume that the volume of wood accumulated each year (V_Q) can be estimated as the difference between V_{Qin} and V_{Qout} and can be characterized as a normal distribution with a mean of zero, and some variance around the mean (Equation 6). This will result in the accumulation of wood due to transport is positive some years and negative other years.

$$V_Q = V_{Qin} - V_{Qout} \sim N(0, \delta^2) \quad (6)$$

It should be noted that the assumption that $V_{Qin} = V_{Qout}$ is likely not valid over long (10's of kilometres), as the channel width and catchment area increases. However, for the reaches modelled here, catchment area and channel width do not change markedly and so the assumption is valid.

Due to the difficulty in measuring actual input and removal rates, the above delivery and removal rates of wood to the channel can be treated as probability distributions. For the purpose of our study, we use a combination of field measured accumulation rates to populate the delivery variables for the dominant delivery processes, and make assumptions based on literature and field observations regarding the removal process. Assumptions and probability distribution fitting process are discussed in the Methods section below.

2.1.2 Defining natural wood loads and recovery

Most often the load of wood in a river refers to the volume of wood per unit length or area of the river (i.e. m^3/100 m or m^3/ha). In undisturbed catchments, the stored load of wood in the channel is referred to as the natural load. There is often an assumption made that, given long enough, the load of wood will reach some long term steady state of accession and depletion [*Bragg* 2000, *Bragg and Kershner* 2004, *Eaton et al.* 2012]. In this study, when we define a natural load of wood, we assume that the load of wood over a reach of river approaches such a dynamic steady state. However, because the total load of wood relies on the stochastic processes of bank erosion, fires, landslides, tree mortality, and transport within the channel [*Benda et al.* 2002, *Martin and Benda* 2001], a natural load of wood should not only be characterized by the average load, but also by some description of the spatial and temporal variability of wood distribution [*Stout et al.* 2016]. For example, while two rivers might have the same average load of wood, the load in one river, is characterized by a few large log jams, whereas the load in the other river is distributed nearly uniformly in the bed of the river. The spatial distribution of wood is therefore characterized by the ability of the river to move and transport wood within a reach. The ability to predict this distribution is beneficial for restoration projects attempting to mimic a reference or natural load of wood. As a restored reach of river approaches both the natural load of wood, and the natural spatial distribution of wood, only then might the river be considered recovered.

2.2 Methods

2.2.1 Study Area

The King River is a natural experiment in the effects of passive recovery. Desnagging occurred twice in the past, but the majority of land holders have since fenced the river off from cattle access, and thus the river is beginning to recover. The study area (Figure 1) is a 3.3 km section of the King River – a north flowing tributary of the Murray River, with its headwaters in the Great Dividing Range of Victoria, Australia. At the study reach, it has a catchment area of approximately 1356 km^2. The planform of the channel in the study section is classified as anabranching [*Schumm et al.* 1996], with an average channel slope of 0.002. Although the river is classified as anabranching, the majority of flow, even during high flows, is routed through a single channel. Therefore, for the purposes of this study, we solely focus on the main channel, treating it as a single threaded meandering river with cohesive banks. The river has steep banks associated with cohesive sediments, an average channel depth of three meters and average bankfull width of 23 meters [*DEPI* 2013]. Flow regulation in the catchment is minimal, with only a small (13.5 x 10^6 m^3 capacity) reservoir in the upper reaches of the catchment. No major tributaries enter the river within the study site.

We surveyed wood over three desnagged sub-reaches of the total study site. Reaches 1 (1.1 km long) and 3 (1.2 km long) were desnagged in 1957 [*DWRV* 1989], while reach 2 (1.1 km long) was desnagged once in 1957 and again in 1980 [*DWRV* 1989]. The data collected describe two periods of passive recovery: t = 34 years (reach 2), and t = 57 years (reaches 1 and 3). There has been little modification to the channel except for the placement of less than 100 m of rock revetment to stabilise stream banks near a bridge crossing. There is continuous riparian forest along both banks, dominated by river red gums (*Eucalyptus camaldulensis*) along all three reaches (1-200 m riparian forest width, average of 25 m wide).

2.2.2 Measurement of wood loads

During the summer low flow period of 2014, a full census of all large wood within the bankfull channel was undertaken. Large wood was defined as that greater than 0.1 m in diameter and 1.0 m in length [*Gippel et al.* 1996a, *Gippel et al.* 1996b]. Where wood was underwater, we probed the pools in a gridded pattern, to feel for submerged or buried pieces of wood. For each piece of wood, we measured ten variables (Table 1) that describe its position within the channel, the state of decay, and amount of transport of wood in the channel (i.e. log jam membership).

The loading of wood in each of the thirty-three 100 meter long sections (m^3/100 m) was calculated from the census data along each of the three study reaches, assuming each piece of wood was cylindrical. The reaches were subdivided into 100 meter long sections, and then the load from each section was then fit to a Weibull distribution using MATLAB, where the scale (central tendency) and shape (spatial distribution) parameters were estimated [*Stout et al.* 2016].

2.2.3 Modelling passive recovery time

To model the delivery of wood over time and the time to recover a natural load, input variables, delivery process (Equation 3), and removal process (Equation 4) were parameterized for use in the model by empirically fitting probability distributions to the data representing each of the delivery and removal processes. Each probability distribution was randomly sampled for each time step of the model (one year time steps). The selected accumulation and depletion values were used to calculate the change in storage for each time step (Equation 2). This process was iteratively performed for each years of the 500 year model. The model was run in a Monte Carlo simulation which was scripted in Python – running a thousand iterations of the delivery model. This was done to predict the behaviour of the average wood load through time for the entire 3.3 km long reach. Figure 2 provides a graphical depiction of the model.

Using the measured wood census, delivery classes of the surveyed wood (bank erosion, mortality, exhumation, or unknown) were assigned based on physical assessments of the wood in the river bed (as described in Table 1). Logs in the channel were assumed to have been delivered via bank erosion if there was a root wad present. Logs were assumed to have been delivered via mortality if the tree was ramped up the bank onto the floodplain, or if it appeared to have been a broken branch from limb drop. Logs were only classified as having been exhumed if the piece was eroding out of a cut bank, meaning that it was buried in the floodplain and was currently being exhumed to become part of the contemporary wood load. Logs that were racked as part of a log jam were classified post survey as likely delivered to the section as transported wood. Using the maximum size of log racked in log jams (excluding key members) as an indicator for potential to transport, pieces of wood that were classified as an unknown delivery mechanism, and that were smaller than the maximum transported log, were also classified as being transported wood. The remaining pieces of wood that were still classified as having an unknown delivery mechanism were later added to one of the three dominant delivery mechanisms in accordance with the relative proportion of those mechanisms. The accumulation rate for each delivery mechanism in each 100m section was estimated by dividing the volume of wood by the time since desnagging. This allowed us to use the variability of the accumulation rates in each section to empirically fit probability distributions to the data for further modelling of the behavior of the average wood load along the entire reach.

Probability distributions for wood transport rates could not be constructed from field data as there is only a single wood census. Two assumptions were made in order to model the transport of wood. First, we assumed that the loss of wood to the floodplain owing to overbank transport from the channel (Equation 4) has been negligible, as there is no evidence of wood being floated onto the floodplain in the reach. Second, we assumed that the volume of wood transported into the reach is equaled by wood transported out of the reach (Equation 6) over long periods of time. In the model, wood transport into the reach (V_{Qin}) was estimated by randomly drawing a value from the distribution of transported wood accumulation values (Figure 2). Transport out of the reach (V_{Qout}) was estimated by again randomly drawing a value from the distribution of transported accumulation values. The difference between V_{Qin} and V_{Qout} resulted in the accumulation of wood due to transport randomly fluctuating between positive and negative values from year to year (Equation 7).

$$V_{Q_i} = V_{In_i} - V_{Out_i} \qquad (7)$$

Where V_{Qi} is the volume of wood accumulated due to transport for each time step. V_{Ini} is the volume of wood delivered, and V_{Outi} is the volume removed. We can test if this method of modeling transport is consistent with our second assumption by randomly drawing transport input and outputs over the runtime of the model, and creating a histogram of wood accumulation rates (V_{Qi}) over the runtime of the model. If the resulting histogram can be described using a normal distribution with a mean near zero, then the second assumption is upheld.

Information regarding the decay constant of wood in rivers, or the breakdown rate of wood in rivers is generally focused on the breakdown or decay of sticks and twigs [*Díez et al.* 2002, *Elosegi et al.* 2007]. Reported values of breakdown or decay rates vary largely due to the type of wood [*Díez et al.* 2002], and the environment [*Andersen et al.* 2016]. Decay models (e.g. Equation 5), tend to use a best fit decay constant (k) for the loss of wood over time [*Hyatt and Naiman* 2001]. For this paper we were unable to determine an empirical decay or breakdown rate of the wood in the river. To circumvent this, we treated the decay constant (*k*) in Equation 5 as a normal distribution, truncated at zero, based on decay constants reported in the literature. The decay constant (*k*) was selected from data reported in *Hyatt and Naiman* [2001], which indicates that data collected from the Queets river (mean width of 165 m) had a decay constant around 0.03. Other papers utilize depletion rates (our decay constant) with a range of 0.016-0.011 in rivers that are 20-30 m wide [*Murphy and Koski* 1989]. As the King River has a mean width of 23 m, and *Eucalyptus camaldulensis* trees tend to be more resistant to decay than trees used in these earlier studies [*White* 1998] we selected a mean decay constant (k) which is at the lower end of these studies: 0.012.

Variations in the rate of accumulation of wood from the dominant delivery processes will obviously affect the rate of wood accumulation and load in the channel. Additionally it is likely that the decay and transport of wood are important variables that slight variations in the rates may result in the model being highly sensitive and drastically alter the rate of wood accumulation in a river. After the initial run of the delivery model, a sensitivity test was performed by individually varying each of the input and removal values (Figure 2) by ±20%. This was done to determine if a slight change in anyone of the variable resulted in a drastic change both in the average load of wood (m^3/100m) or in the time for the load of wood to approach a steady state. A more severe sensitivity test (Table S1) was run on the model to test the basic behaviour of input and removal processes in driving the time to recovery and the load of wood. Briefly, the input and removal variables were varied by three orders of magnitude. All possible combinations of input and removal rates were evaluated to determine the major driving parameter(s) for both the amount of time required for the wood load to reach a steady state, and the load of stored wood when the model reached a steady state.

The delivery model was run to simulate three different scenarios that equate to common riparian management strategies. The first scenario assumes that the riparian source of wood remained constant (i.e. no change in spacing and size of trees), and river channel processes remain constant over the 500 years. This scenario was used to investigate the potential recovery time of the reaches assuming the riparian zone is stable and unchanging. The second simulation assumes that 100 years after desnagging, all the banks along the river reach have been artificially stabilized (i.e. no bank erosion), and the only delivery of wood is from mortality of trees. This is to simulate reaches that have been artificially stabilized (e.g. revetted) and to test the importance of bank erosion as a delivery mechanism. The third scenario assumes that 100 years after desnagging, all trees along the bank have fallen and there are no more trees in the riparian source area. It is common in this region for streams to be separated from crops or pasture by a single row of mature trees along the stream bank, with little recruitment of young trees [DEPI 2013].

The delivery model was run in yearly time steps for a total runtime of 500 years. The maximum, average, and minimum values of the load of wood for each time step were extracted. The modelled loads were then compared to the predicted natural load of wood for the study reach estimated by *Kitchingman et al.* [2015] (48 m^3/100 m) as a point of comparison. Briefly, *Kitchingman et al* [2015] mapped natural wood loads along 105 km of undisturbed rivers in Victoria Australia. The dataset was modelled using boosted regression trees against climactic, environmental, and geomorphic variables to predict natural wood loads in disturbed rivers. We do not use their predicted load as a value to calibrate our model, but as a point of comparison to compare outputs and results.

2.2.4 Predicting the spatial distribution of wood loads in the reach

To predict the natural spatial distribution for the King River, we followed the method of *Stout et al*. [2016]. Using the same sites and data reported in *Stout et al.* [2016], we fit a logarithmic model to the data to develop a predictive equation for the spatial distribution of wood that we might expect in the King River reach. The equation in *Stout et al.* [2016] requires (1) the total stream power of the mean annual flood, (2) the dry density of the dominant riparian tree type, (3) the length to width ratio of trees to the channel width, and (4) the sinuosity of the channel. The stream power of the mean annual flood was calculated from the flow gage located midway through the site (Gage ID: 403223), with the slope of the channel measured from the 1 meter resolution LiDAR available for the site. Sinuosity and channel width was also measured from the LiDAR. The average height of trees was measured from the first return layer derived from the LiDAR, and the dry density of the dominant riparian tree (*Eucalyptus calmundensis*) was obtained from forestry lookup charts [*DCNR* 1992].

Lastly, we estimated the shape parameter of the Weibull distribution for the natural load of wood on the King River. Using the predicted average load from the Monte Carlo simulation as a proxy for the scale parameter, we used the Weibull distribution parameters as our natural wood load for comparison to the recovering reaches on the King River. The wood load census data for each reach was fitted to a Weibull distribution using MATLAB, and compared against the predicted natural wood load and spatial distribution.

3 Results

3.1 Current wood loads and rates of delivery

A total of 1,229 pieces of wood were measured across the three reaches. The wood census shows a high variability of wood loads amongst the thirty-three 100 m sections in all three reaches, ranging from 2 m^3/100 m to 108 m^3/100 m (Figure 3A). Within each of the three reaches, the range of loads were again highly variable (Figure 3A), with all reaches again varying over two orders of magnitude. The comparison of the other metrics measured in the census (Table 1), indicates that while the measured loads of the reaches differ (Figure 3A), the physical configuration, the location within the channel, the decay class, and shape of the logs are relatively similar among reaches. Most logs are oriented roughly parallel to the flow (Figure 3A), and most logs (71 percent) in all reaches are cylindrical in shape (Figure 3B), located on the bed (74 %) of the channel (Figure 3C), 71 percent fall into the cylindrical decay class (Figure 3D). and lastly each reach has a similar proportion of the wood load in each of the seven stability classes (Figure 3E).

When the 100 m sections are lumped and analyzed together at the reach level (~ 1 km), a recovery pattern emerges. Reaches 1 and 3 (desnagged 57 years ago) have recovered an average load of 38 m^3/100 m, and Reach 3 (desnagged 34 years ago) has recovered a load of 26 m^3/100 m. These delivery rates can be more easily visualized as how often (in years) relatively small and relatively large trees are delivered to each 100 m reach of the river. Based on the average delivery rate of all delivery mechanisms to the King River, we would expect that a volume of wood equivalent to the same volume of one small tree (0.3 m diameter breast height (DBH) by 10 m tall) to be delivered every 4 to 5 years, per 100 meters; and the volume of wood equivalent to one large tree (0.8 DBH by 20 m tall) every 55 to 64 years, per 100 meters.

3.2 Distribution fits to model variables

Using the empirically calculated accumulation rates for each of the delivery mechanisms, distributions were empirically fit using MATLAB. Datasets were binned using the Friedman-Diaconis rule to determine bin size. Unless the distribution appeared normal, we fit a 2-parameter Weibull distribution. This is largely due to the idea that delivery processes can potentially be modelled using the Weibull distribution as the Weibull easily handles extreme value data sets well [*Stout et al.* 2016]. As a result, input variables of Bank Erosion, Mortality, Transport, and Exhumation were well described using a Weibull distribution (Figure 4). The balance between transported wood into and out of the reach (test second assumption, Equations 6 and 7) was well describe as a normal distribution (Figure 4) with a mean near zero ($\mu = -0.0009$, $\sigma = 0.013$). This normal distribution centered on zero is consistent with our model design, meaning that wood delivered to a reach via transport is equaled by wood lost via transport over long time frames. The decay constant (k) used for the model was assumed to have a normal distribution ($\mu = 0.012$, $\sigma = 0.01$). However, as it would be impossible to have negative decay constant (i.e. net positive gain from decay), the normal distribution was truncated at zero so as to only produce values greater than zero (Figure 4).

3.3 Delivery model results

By considering the range of possible values in a wood delivery and loss model, the Monte Carlo simulation predicts when the river would reach a steady state of wood input and output. We consider this to be the best description of a natural (or target) load, as the mean value has reached an average unchanging value. This steady state point is defined here as the point of inflection on the load curve, when the lower and upper 1st standard deviations become constant ($dS_c/dt <$

0.01). The modelled results suggest that this inflection point occurs at an average wood load of 46.7 m^3/100 m and that this load is reached after 255 ± 23 years (Figure 5A). It is interesting to note that the predicted natural load is very close to the natural load estimated from the measured data in *Kitchingman et al.* [2015] (48 m^3/100 m).

3.4 Modified wood source scenarios

The two additional scenarios show the importance of long-term management strategies on the load of wood over time (Figure 5b,c) By artificially stabilizing the river banks, the major delivery mechanism of bank erosion is removed, effectively disconnecting the river from the dominant source of wood (Figure 5b). In this scenario, the river is beginning to recover a load of wood, peaking at 41 m^3 /100m. However, once all of the banks are stabilized, the wood in the channel begins to decay, slowly depleting the load of wood. After 300 years the load has reached its background level of 20 m^3 /100m and is maintained by tree mortality. The second scenario (Figure 5c) considers delivery from a single stand of riparian trees along the banks. It shows that the load of wood, begins to recover (peaking at 42 m^3 /100 m) , but that once the immediate source of wood from the riparian forest is lost, average loads fall to half over the next 50 years and wood has disappeared from the channel altogether by 300 years after desnagging.

3.5 Sensitivity of the delivery model

Sensitivity of the model was analyzed by varying each of the input variables (Figure 4) by ±20%. Based on the sensitivity analysis, unsurprisingly, it appears that the variations in the dominant delivery process (bank erosion) and the dominant removal process (decay) have the largest effect on the overall load of wood once steady state is reached (Table 3). The removal of wood via decay, and loss/gain of wood due to transport in and out of each section appears to be the most important driver of the amount of time needed for a system to reach steady state. Lastly, the range (± time to steady state) is influenced by all of the variables. Although most of the variables have a large impact (>20%), note that none of the variation increases or decreases the range of recovery times more than an order of magnitude from the original model.

For brevity, we do not report the results of the more severe sensitivity analysis in detail, but use the results to discuss the dominant drivers (input vs output) on the amount of time need to recover and the final load in our stated model. The analysis (see Supplemental Information) clearly indicates that the time to recovery (i.e. a steady state wood load) is solely a function of the removal rate of wood from each section (Figure S1a), meaning that the input rate of wood to the channel is of minimal significance on the time required for a wood load to reach a steady state. However, the final load of wood once the reach approaches a steady state is a complicated combination of both the delivery rate of wood to the channel and the removal of wood (Figure S1b).

3.6 Spatial Distribution of wood in the channel

The Weibull distribution that describes the spatial distribution of the natural wood load in the reaches surveyed has a shape parameter of 2.2, and from the results of the Monte Carlo simulation, the scale parameter for the Weibull distribution is the modelled natural load of 46.7 m^3/100 m. Fitting Weibull distributions to the three study reaches, begins to describe the recovery sequence. Reach 2 (recovery time of 34 years) has a Weibull shape parameter of 1.8, whilst reaches 1 and 3 (recovery time of 57 years) have a shape parameter of 1.4 and 1.2 respectively (Figure 6a, b). The longer tails in the distributions of Reaches 1 and 3 represent sections that have infrequent high loads, observed in the field as log jams. Comparison of the fit distributions to the census data, suggests that sections which were entirely dominated by large to medium sized log jams, are generally represented by the 90th percentile of the distribution (Figure 6abc).

4 Discussion

4.1 Recovery of wood loads

Our results are consistent with previous studies that have measured or predicted wood delivery and removal rates on disturbed rivers, and we conclude that the recovery of a natural wood load takes centuries rather than decades [*Benda et al.* 2003, *Benda and Sias* 2003, *Bragg* 2000, *Eaton et al.* 2012, *Erskine and Webb* 2003, *Martin and Benda* 2001]. The recovery time frame is largely driven by the removal rate of wood from the reach, meaning the more slowly that wood is removed (through a combination of decay, breakage, and transport), the more time is needed to recover a natural load for that reach (Figure S1a). Furthermore it is likely that recovery is additionally based on the recruitment of old growth timber to act as key members in log jams [*McHenry et al.* 1998]. The final recovered volume of wood is a function of both the delivery and removal rates of wood into and out of the reach (Figure S1b). The closest example of using measured wood loads, and extrapolating wood loads through time to reach natural conditions, was presented by *Meleason et al.* [2007]. They predicted that the time to regrow riparian vegetation and then deliver a load of wood that reached a steady state was nearly 450 years; however their model assumed that it takes nearly 200 years to grow a riparian forest that will contribute trees large enough to remain in the channel. In our model, we already had a healthy riparian area delivering trees that were large enough to cause channel spanning jams and act as key members of log jams. Therefore, our prediction of 255 ±23 years for recovery is similar to this earlier study, and underpins the importance of delivery of large trees to act as key members in log jams, which are a major driver in the recovery of the spatial distribution of wood loads along a reach.

This study is the first study to predict possible ranges of recovery based on measured data from the field. The Monte Carlo simulation used in this study addresses the variability in the delivery mechanisms to the river, and tracks the mean behavior of the entire reach through time. It is important to note that the reference load predicted by our model for the King River (46.7 m^3/100 m) could be reached sooner in individual sections of the reach because of spatially variable wood loads around the mean. Therefore, natural wood loads and target recovery wood loads must be expressed as an average load over a long reach with some measure of variability in the load from section to section. Current loads of wood in the King River are spatially variable, which is to be expected for a river with natural delivery and removal processes occurring along the reaches. Although the loads among the 100 meter sections vary widely, these loads reflect the distribution of delivery and removal rates that are being driven by the processes of tree mortality, bank erosion , fluvial transport, decay and burial within each of the reaches.

4.2 Sensitivity and general applicability of the recovery model

The sensitivity of the model to the dominant delivery and removal processes provides a mechanism by which we can begin to think about the time to recovery of rivers globally. From our sensitivity tests, a variation of just ±20% shows that the model is sensitive to changes in most of the input variables. However, it should be noted that the decay constant (k) is the dominant driver of the time to steady state. This is due to the use of a simple exponential decay function in our model, which means that the approximate time to plateau scales with k. In rivers where the removal rate is high (high decay/ high export) but the delivery rate is slow we might expect that the wood load in the river could reach a dynamic steady state relatively fast. An example of this might be a large lowland river where the length to width ratio of the trees to the river (i.e. L^*) is smaller than one. An L^* may allow for higher transport rates, and if the river has cohesive banks, this might result in slow bank erosion rates and therefore slow delivery of wood from the river banks. In contrast, a river which has a slow removal rate will take a relatively longer time to reach a dynamic steady state where inputs are equal to outputs. Our sensitivity analysis shows that a combination of removal and delivery rates drives the average wood load in a river. Stochastic delivery processes like fire, debris flows, mass movements, avalanches, and extensive blow down events, will likely not have a major effect on the overall length of time needed for recovery. These events, however, will be a major driver in the overall average load and variation of the average load over time. Furthermore, stochasticity in the delivery processes may result in a wider spread in the time needed to reach a steady state load. From the sensitivity test of this model, we argue that the average load of wood in a reach is a balance between the dominant delivery and removal processes, and that the overall time to reach a steady state wood load is largely dependent on the rate of wood removal from that reach.

4.3 Conceptual model of recovery

The spatial distribution of wood is important for determining if a river has actually recovered. Log jams, channel spanning jams, and deflector jams, are important habitat for fish and other aquatic organisms [*Beechie and Sibley* 1997, *Nagayama and Nakamura* 2010]. If target or natural wood loads are described as a combination of both the average load of wood for a reach, and the spatial variability of loads across the reach, then we are able to begin tracking the recovery of wood loads through time. We propose a conceptual model of wood load recovery based on our field observations and the results of the delivery model (Figure 7). In the conceptual model, we provide a description of each recovery stage based on our modelled reaches. We also provide a small discussion as to how differences in the major delivery and removal processes and rates might result in a different spatial distribution or an alternate stable state of the wood loads. Variations in delivery and removal rates are likely to result in an infinite combination of stages and spatial distributions of wood. However, simple thought experiments around the delivery and removal of wood from each section can provide insight as to how each stage may differ based on the dominant processes at the site.

Stage 1: Immediately following desnagging, the wood load is at a minimum. This stage lasts until the next major delivery event (i.e. storm, flood, fire) that delivers a pulse of trees to the channel. We assume here that there is a healthy riparian area or at least some trees ready to be delivered to the channel.

This stage is likely not to be affected by any variation in delivery or removal processes. If there was buried wood in the bed of the river, or the floodplain, the increase in velocities in flow post-clearing of the river may exhume wood. This has been noted in desnagged streams [*Strom* 1962], and wood has been shown to be stored in the floodplain [*Collins et al.* 2012]. Additionally, if there is not a healthy riparian area, it is likely that the wood load will remain in a depleted state. Any delivered trees will likely be removed via transport.

Stage 2: Unless a major event such as fire or blow down event occurs, we assume that small to medium sized trees are delivered to the channel regularly. However, because the earlier desnagging will have increased flow velocities and scour of the bed and banks, these small trees are likely not large enough to form log jams and are instead flushed out of the reach.

A major delivery event such as a fire or blow down event, could produce a uniform distribution of wood along the reach. This would essentially create an alternate path to recovery. Starting with a uniform distribution of wood would likely impede the transport of smaller pieces. As the wood begins to decay and breakdown, transport will start to increase, likely forming small, tightly spaced jams. If the river is large, and the trees are easily transportable then large jams or rafts may form.

Stage 3: Eventually, enough time passes that large channel spanning trees begin to fall into the river (note that this took 50 to 60 years on the King River). These trees form key pieces for log jams. However, as there are few of these large trees, they tend to collect a large number of small trunks, producing large jams.

If the river is much wider than the trees are tall ($L^* << 1$), then rather than forming channel spanning jams, log jams may form on bars (i.e. point bars, mid-channel bars), or they may form on the edge of the channel. Initially, we would still expect these jams to be unusually large. If $L^* \approx 1$ and a large jam forms, it may trap all of the wood in transport forming a log raft, again resulting in an alternate state that persists through time.

Stage 4: As more key pieces are delivered, delivery of trees from bank erosion will slow due to an increase in hydraulic roughness (and therefore reduced scour) from the increasing wood load. However, there are still large gaps between large log jams. Trees are continually delivered, and due to the breakage and decay of wood in the river, smaller jams form between the larger jams. Over time the average wood load over the entire reach begins to reach a steady state of accession and depletion.

Transport bottlenecks, such as rock outcrops, or narrow sections of the river may result in a wood load dominated by large extensive log jams. In smaller rivers, debris flows and high transport events may result in sections of the river being devoid of wood with a few sections having much of the wood stored in large log jams.

Stage 5: The wood load is fully recovered when delivery and removal processes are balanced across the reach and the steady state average load is approached. Smaller log jams form and are relatively tightly spaced.

If large log jams have persisted from stages 3 or 4, we would expect to see sections of the river with relatively little wood with other sections punctuated by extremely high loads. The dominance of removal process (transport and decay) will largely determine the spatial distribution and the state of the wood load in stage 5. As shown in *Stout et al.* [2016] the spatial distribution of a wood load is a function the ability of the river to transport and rearrange wood.

While this conceptual model of wood recovery following desnagging is developed based on wood loads and an understanding of how wood moves in lowland Australian rivers, we believe its principles are generally applicable. Log jams are an important driver of the spatial distribution of wood within a channel and the overall load of wood stored within a reach [*Beckman and Wohl* 2014, *Eaton et al.* 2012]. The recovery of a natural load of wood is largely dependent on the formation of these log jams, and so the relative length of each stage in the conceptual model is dependent on the amount of time necessary to form large log jams. Furthermore, the recovery of dynamic steady state of wood in any river is highly dependent on a healthy riparian forest (i.e. a source of wood), and the rate at which wood is removed from the river.

4.4 Effects of management on recovery times

In most rivers, given a healthy riparian area, the most important factor in recovery is time. However, managers can also play an important role in either aiding or retarding the recovery of in-stream wood loads. The two alternate scenarios tested in the Monte Carlo simulation illustrate the importance of maintaining a sufficient source of wood to the stream. Often, in desnagged rivers, banks are revetted and stabilized in response to the increased stream power from the removal of wood [*Shields and Smith* 1992]. Figure 5b, illustrates that even if the river has a healthy riparian area, bank protection can disconnect the river from the dominant delivery mechanism of bank erosion and result in a depleted wood load, relative to the load that should actually be present. Additionally, Figure 5c illustrates that if revegetation projects are not implemented well enough in advance, eventually the source of in-stream wood will be lost as the channel migrates away. However, well planned placement of wood in rivers (re-snagging), with large key members, can compensate for the lack of source-wood while riparian revegetation is growing.

Restoration of rivers and streams must account for how human activities have altered the river [*Gregory* 2006, *Wohl* 2011, 2014]. This will allow managers to determine if the river can actually recover, or is only suitable for rehabilitation or remediation [*Rutherfurd et al.* 2004]. Often the removal of in-stream wood from rivers has resulted in the incision or widening of the channel due to the changed hydraulic conditions. This in turn, has delivered more trees to the stream [*Shields and Gippel* 1995], resulting in managers re-clearing the river within a few years [*Strom* 1962]. Vegetation has also been removed from riverbanks, effectively decreasing the supply of wood to the stream, further exacerbating the depletion of wood in the river [*Boyer et al.* 2003, *Shields et al.* 2003]. In sections of the river, bank stabilization projects would reduce or stop bank erosion effectively removing what can be the dominant delivery mechanism. In such rivers, the recovery of the river to a natural condition is highly unlikely without active intervention. However, in rivers where there is a healthy riparian source of wood, and there has been minimal change to the channel geometry, and hydrology of the catchment, passive restoration (no wood removal, fencing of cattle) should be adequate to allow the river to recover a natural load of wood.

5 Conclusions

Recovery of wood loads from desnagging needs to be described in terms of both the load of wood, but also the spatial distribution of wood along the reach. It is not financially feasible to artificially restore historical loads of large wood to streams, but our results show that in a lowland desnagged river, recovery of a natural wood load and distribution will take on average

255 ± 23 years, assuming a healthy riparian area. If managers are unwilling to wait this long, then active restoration practices should be governed by the dominant delivery mechanisms and the predicted natural spatial distribution of wood. If renewal and regeneration of riparian source areas are not maintained through fencing out of livestock and/or revegetation, then rivers face the risk of available source wood being depleted, and natural wood loads never being achieved. There thus remains an imperative to continue replanting river banks and fencing livestock from the riparian zone in reaches of rivers that are most vulnerable to, or may have already lost, the source of large wood. From our results we show that the dominant delivery mechanisms can be determined by a simple census over a small reach of the river. In order to determine dominant removal mechanisms however, (transport and decay), multiple censuses are needed. The methods used in this paper can be used to identify the delivery and removal processes, and probabilistically determine an appropriate recovery target load, an appropriate spatial distribution of wood, and a potential time to recovery. We show from our sensitivity analysis of the model that the balance between the delivery and removal rates of any given reach drives the overall stored load, while the time to achieve a steady state load is solely dependent on the removal rate. Due to the sensitivity of our model to removal rates, further research is needed on the decay and removal rates of wood in fluvial environments. A better understanding of the variability of decay and breakage rates of wood in fluvial environments will provide a stronger estimate of the long term recovery rates. Lastly, from our five stage conceptual model and field observations, the recovery of desnagged or cleared rivers is largely driven by the delivery of large trees to act as nucleation sites for log jams. The spatial distribution of wood loads along a reach, and the average wood load is dominated by the formation of log jams. Without the formation of log jams, the storage and geomorphic impact of wood within a recovering river is likely to be minimal until a log jam can finally form and persist.

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Data and the script of the model used in this paper is available from Griffith Research Data Repository: https://www120.secure.griffith.edu.au/research/items/4195e1c7-1b8b-4e04-90ef-db10e3c64ed7/1/

References

Andersen, D., Stricker, C.A. and Nelson, S.M. (2016) Wood decay in desert riverine environments. Forest Ecol Manag 365, 83-95.

Beckman, N.D. and Wohl, E. (2014) Effects of forest stand age on the characteristics of logjams in mountainous forest streams. Earth Surface Processes and Landforms 39(11), 1421-1431.

Beechie, T.J., Pess, G., Kennard, P., Bilby, R.E. and Bolton, S. (2000) Modeling Recovery Rates and Pathways for Woody Debris Recruitment in Northwestern Washington Streams. N Am J Fish Manage 20(2), 436-452.

Beechie, T.J. and Sibley, T.H. (1997) Relationships between Channel Characteristics, Woody Debris, and Fish Habitat in Northwestern Washington Streams. T Am Fish Soc 126(2), 217-229.

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C. and Dunne, T. (2003) Wood recruitment processes and wood budgeting. Am Fish S S 37, 49-73.

Benda, L.E., Bigelow, P. and Worsley, T.M. (2002) Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, USA. Can J Forest Res 32(8), 1460-1477.

Benda, L.E. and Sias, J.C. (2003) A quantitative framework for evaluating the mass balance of in-stream organic debris. Forest Ecol Manag 172(1), 1-16.

Bernhardt, E.S., Palmer, M., Allan, J., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C. and Follstad-Shah, J. (2005) Synthesizing U. S. river restoration efforts. Science(Washington) 308(5722), 636-637.

Boyer, K.L., Berg, D.R. and Gregory, S.V. (2003) Am Fish S S. Gregory, S.V., Boyer, K.L. and Gurnell, A.M. (eds), pp. 407-420.

Bragg, D.C. (2000) Simulating catastrophic and indivdualistic large woody debris recruitment for a small riparian system. Ecology 81(5), 1383-1394.

Bragg, D.C. and Kershner, J.L. (2004) Sensitivity of a Riparian Large Woody Debris Recruitment Model to the Number of Contributing Banks and Tree Fall Pattern. West J Appl For 19(2), 117-122.

Brooks, A.P., Howell, T., Abbe, T.B. and Arthington, A.H. (2006) Confronting hysteresis: Wood based river rehabilitation in highly altered riverine landscapes of south-eastern Australia. Geomorphology 79(3-4), 395-422.

Collins, B.D., Montgomery, D.R., Fetherston, K.L. and Abbe, T.B. (2012) The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. Geomorphology 139, 460-470.

DCNR (1992) Forest Management Planners' Manual. Department of Conservation & Natural Resources, Melbourne.

DEPI (2013) Index of Stream Condition: The Third Benchmark of Victorian River Condition. Industries, D.o.E.a.P. (ed).

Díez, J., Elosegi, A., Chauvet, E. and Pozo, J. (2002) Breakdown of wood in the Agüera stream. Freshwater Biol 47(11), 2205-2215.

DWRV (1989) Water Victoria: An Environmental Handbook, VGPO, Melbourne, Victoria, Australia.

Eaton, B.C., Hassan, M.A. and Davidson, S.L. (2012) Modeling wood dynamics, jam formation, and sediment storage in a gravel-bed stream. Journal of Geophysical Research. Earth Surface 117.

Elosegi, A., Diez, J. and Pozo, J. (2007) Contribution of dead wood to the carbon flux in forested streams. Earth Surface Processes and Landforms 32(8), 1219-1228.

Erskine, W.D. and Webb, A.A. (2003) Desnagging to resnagging: New directions in river rehabilitation in southeastern Australia. River Research and Applications 19(3), 233-249.

Fryirs, K., Brierley, G.J. and Erskine, W.D. (2012) Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. Earth Surface Processes and Landforms 37(7), 763-773.

Garrett, L.G., Oliver, G.R., Pearce, S.H. and Davis, M.R. (2008) Decomposition of Pinus radiata coarse woody debris in New Zealand. Forest Ecol Manag 255(11), 3839-3845.

Gippel, C.J., Finlayson, B.L. and ONeill, I.C. (1996a) Distribution and hydraulic significance of large woody debris in a lowland Australian river. Hydrobiologia 318(3), 179-194.

Gippel, C.J., ONeill, I.C., Finlayson, B.L. and Schnatz, I. (1996b) Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. Regul River 12(2-3), 223-236.

Gregory, K. (2006) The human role in changing river channels. Geomorphology 79(3), 172-191.

Gregory, S.V., Meleason, M.A. and Sobota, D.J. (2003) Modeling the dynamics of wood in streams and rivers. Am Fish S S 37, 315-335.

Gurnell, A.M., Petts, G.E., Harris, N., Ward, J.V., Tockner, K., Edwards, P.J. and Kollmann, J. (2000) Large wood retention in river channels: The case of the Fiume Tagliamento, Italy. Earth Surface Processes and Landforms 25(3), 255-275.

Gurnell, A.M., PiÉGay, H., Swanson, F.J. and Gregory, S.V. (2002) Large wood and fluvial processes. Freshwater Biol 47(4), 601-619.

Hyatt, T.L. and Naiman, R.J. (2001) The residence time of large woody debris in the Queets River, Washington, USA. Ecol Appl 11(1), 191-202.

Hyatt, T.L., Waldo, T.Z. and Beechie, T.J. (2004) A watershed scale assessment of riparian forests, with implications for restoration. Restor Ecol 12(2), 175-183.

Kitchingman, A., Tonkin, Z., Ayres, R.M., Lyon, J., Stout, J.C., Rutherfurd, I.D. and Wilson, P. (2015) Predicting natural instream woody-habitat loads across large river networks. Mar Freshwater Res, -.

Lester, R. and Boulton, A. (2008) Rehabilitating Agricultural Streams in Australia with Wood: A Review. Environ Manage 42(2), 310-326.

Lester, R.E., Wright, W. and Jones-Lennon, M. (2007) Does adding wood to agricultural streams enhance biodiversity? An experimental approach. Mar Freshwater Res 58(8), 687-698.

Martin, D.J. and Benda, L.E. (2001) Patterns of instream wood recruitment and transport at the watershed scale. T Am Fish Soc 130(5), 940-958.

McHenry, M.L., Shott, E., Conrad, R.H. and Grette, G.B. (1998) Changes in the quantity and characteristics of large woody debris in streams of the Olympic Peninsula, Washington, USA (1982-1993). Can J Fish Aquat Sci 55(6), 1395-1407.

Meleason, M.A., Davies-Colley, R.J. and Hall, G.M.J. (2007) Characterizing the variability of wood in streams: simulation modelling compared with multiple-reach surveys. Earth Surface Processes and Landforms 32(8), 1164-1173.

Montgomery, D.R., Collins, B.D., Buffington, J.M. and Abbe, T.B. (2003) Geomorphic effects of wood in rivers. Am Fish S S 37, 21-47.

Murphy, M.L. and Koski, K.V. (1989) Input and Depletion of Woody Debris in Alaska Streams and Implications for Streamside Management. N Am J Fish Manage 9(4), 427-436.

Nagayama, S. and Nakamura, F. (2010) Fish habitat rehabilitation using wood in the world. Landscape and Ecological Engineering 6(2), 289-305.

Nakamura, F. and Swanson, F.J. (1993) Effects of Coarse Woody Debris on Morphology and Sediment Storage of a Mountain Stream System in Western Oregon. Earth Surface Processes and Landforms 18(1), 43-61.

Piegay, H. and Gurnell, A.M. (1997) Large woody debris and river geomorphological pattern: Examples from SE France and S England. Geomorphology 19(1-2), 99-116.

Roni, P., Beechie, T., Pess, G. and Hanson, K. (2014) Wood placement in river restoration: fact, fiction, and future direction. Can J Fish Aquat Sci 72(3), 466-478.

Rutherfurd, I.D., Ladson, A.R. and Stewardson, M.J. (2004) Evaluating stream rehabilitation projects: reasons not to, and approaches if you have to. Australian Journal of Water Resources 8(1), 57-68.

Schumm, S.A., Erskine, W.D. and Tilleard, J.W. (1996) Morphology, hydrology, and evolution of the anastomosing ovens and King Rivers, Victoria, Australia. Geol Soc Am Bull 108(10), 1212-1224.

Shields, F.D., Cooper, C.M., Knight, S.S. and Moore, M.T. (2003) Stream corridor restoration research: a long and winding road. Ecol Eng 20(5), 441-454.

Shields, F.D. and Gippel, C.J. (1995) Prediction of Effects of Woody Debris Removal on Flow Resistance. J Hydraul Eng-Asce 121(4), 341-354.

Shields, F.D. and Smith, R.H. (1992) Effects of Large Woody Debris Removal on Physical Characteristics of a Sand-Bed River. Aquat Conserv 2(2), 145-163.

Stout, J.C., Rutherfurd, I., Grove, J., Webb, J.A., Kitchingman, A. and Tonkin, Z. (2016) Using the Weibull distribution to improve the description of riverine wood loads. Earth Surface Processes and Landforms.

Strom, H.G. (1962) River improvement and drainage in Australia and New Zealand, A.C. Brooks, Government Printer, Melbourne.

White, K. (1998) Stability of instream large woody debris, The University of Melbourne.

Wohl, E. (2011) What should these rivers look like? Historical range of variability and human impacts in the Colorado Front Range, USA. Earth Surface Processes and Landforms 36(10), 1378-1390.

Wohl, E. (2014) A legacy of absence: Wood removal in US rivers. Progress in Physical Geography 38(5), 637-663.

Wohl, E., Bolton, S., Cadol, D., Comiti, F., Goode, J.R. and Mao, L. (2012) A two end-member model of wood dynamics in headwater neotropical rivers. J Hydrol 462, 67-76.

Tables:

Table 1. Metrics measured or classified during in-stream wood census

Measurement	Units	Description
1. Length	m	Measured from base of trunk (where root wad begins) along the longest branch until the branch is less than 10 cm
2. Diameter	m	Measured at 1.3 meters above root wad (if not possible, measured 0.25 cm from largest end of log)
3. Orientation	Degrees	Measured relative to the flow direction (0 degree = root wad is pointing upstream, 180 degree = root wad is pointing downstream
4. Shape	Class	Classes are C (cylindrical), B (< 3 branches), MB (> 3 branches)
5. Decay Class	Class	Numeric classification: 1- fresh tree, 2- no leaves, 3- only major limbs remain, 4- no bark remains on log, 5- cylindrical, 6- rotten/hollow log.
6. Delivery Class	Class	Visually assessed: BE- bank erosion (presence of root wad), M- mortality, including limb drop, C- cut log (anthropogenic delivery), E- exhumed from bed/banks, NI- no idea (unable to determine delivery mechanism)
7. Channel Position	Class	Position within channel: 1- bed, 2- banks, 3- ramp from bed to banks(rootwad in channel), 4- ramp from top of bank to bed (rootwad on bank), 5- bridged (no contact with bed)
8. Jam membership	Y/N	Jams are classified as 3 or more logs/trees in contact. Recorded number, and if log was key member in jam
9. Stability Class	Class	Numeric classification: 1- Loose in channel, 2- Bridge from bank to bank, 3- collapsed bridge, 4- Ramp up the bank, 5- pinned by another log/tree, 6- buried on one end, 6- buried both ends or embedded.
10. GPS location	m	Recorded the easting/northing coordinates for most downstream location of wood piece

Table 2: Variables measured from the King River used to predict the shape parameter that describes the spatial distribution of the recovered wood load.

Variable	**Value measured or calculated**
Sinuosity	Measured sinuosity is 2.21
Dry Density of *Eucalyptus camaldulensis*	Dry density of trees is 0.915
Stream power of mean annual flood	$\Omega = \rho g Q S$ where ρ is the density of water, g is gravity constant, Q is the mean annual flood (127 m^3 s^{-1}), and floodplain slope (S) is 0.002. Calculated stream power is 2495 w m^{-2}

Ratio of length of trees to width of the river	Average width of King River is 23m and average height of trees along the reach is 20m tall. *L** is 0.87

Table 3: Sensitivity of the model to individual variables was tested by varying the input variable by ±20 percent. Output from each variation were compared against the original output (Figure 5a). Values are show in this table as *italicized* text below each output. Specifically the average wood load (m^3/100m), the average time (years) for the model to reach a steady state, and the length of the steady state range (years) were recorded and compared to determine the percent increase or decrease in the output values.

	Average wood load *46.7m³/100m*		**Time to steady state** *255 years*		**Time range to steady state** *± 23 years*	
Variable	**+20%**	**-20%**	**+20%**	**-20%**	**+20%**	**-20%**
BE	53.1 *(14%)*	41.1 *(-12%)*	267 *(5%)*	243 *(-5%)*	43 *(87%)*	31 *(35%)*
M	46.4 *(-1%)*	43.2 *(-8%)*	253 *(-1%)*	243 *(-5%)*	25 *(9%)*	19 *(-17%)*
E	37.0 *(-21%)*	36.1 *(-23%)*	254 *(-0.4%)*	235 *(-8%)*	34 *(48%)*	27 *(17%)*
Q	46.7 *(0%)*	46.9 *(0.4%)*	250 *(-2%)*	265 *(4%)*	11 *(-52%)*	41 *(78%)*
D	39.8 *(-15%)*	58.4 *(-25%)*	219 *(-14%)*	325 *(27%)*	28 *(22%)*	27 *(17%)*

Figure captions:

Figure 1. Location of study reaches on the King River, northeast Victoria

Figure 2: For each time step of the model, random values are drawn from each of the delivery process distributions (bank erosion, mortality, exhumation, and transport). Wood delivered from bank erosion, mortality and exhumation are added to the load of wood delivered for the time step. The volume of wood delivered via transport is either stored, partially stored or passed through the section dependent on the drawn values of input and output of transported wood. The load of wood from the previous year is used to determine the volume of wood lost to decay. The summation of losses and gains, result in the volume of wood delivered to the channel for each time step. The model was run for 500 years, and for 1000 iterations. The runs in the model output graph are examples of three individual iterations of the model over the 500 year runtime

Figure 3. Results from the census of wood in the King River. Plot (a) illustrates the load (m3/100 m) of each section in the three previously-desnagged reaches for each survey reach, and the rose plots depicting the orientation of the root wad to the flow, where 0 degrees represents the root wad pointing upstream. Plots b, c, d, and e, are the total number of pieces of wood within each of the different morphological descriptors of the pieces of wood. Note that each reach has a similar proportion of logs in each of the different classes for the morphology descriptors.

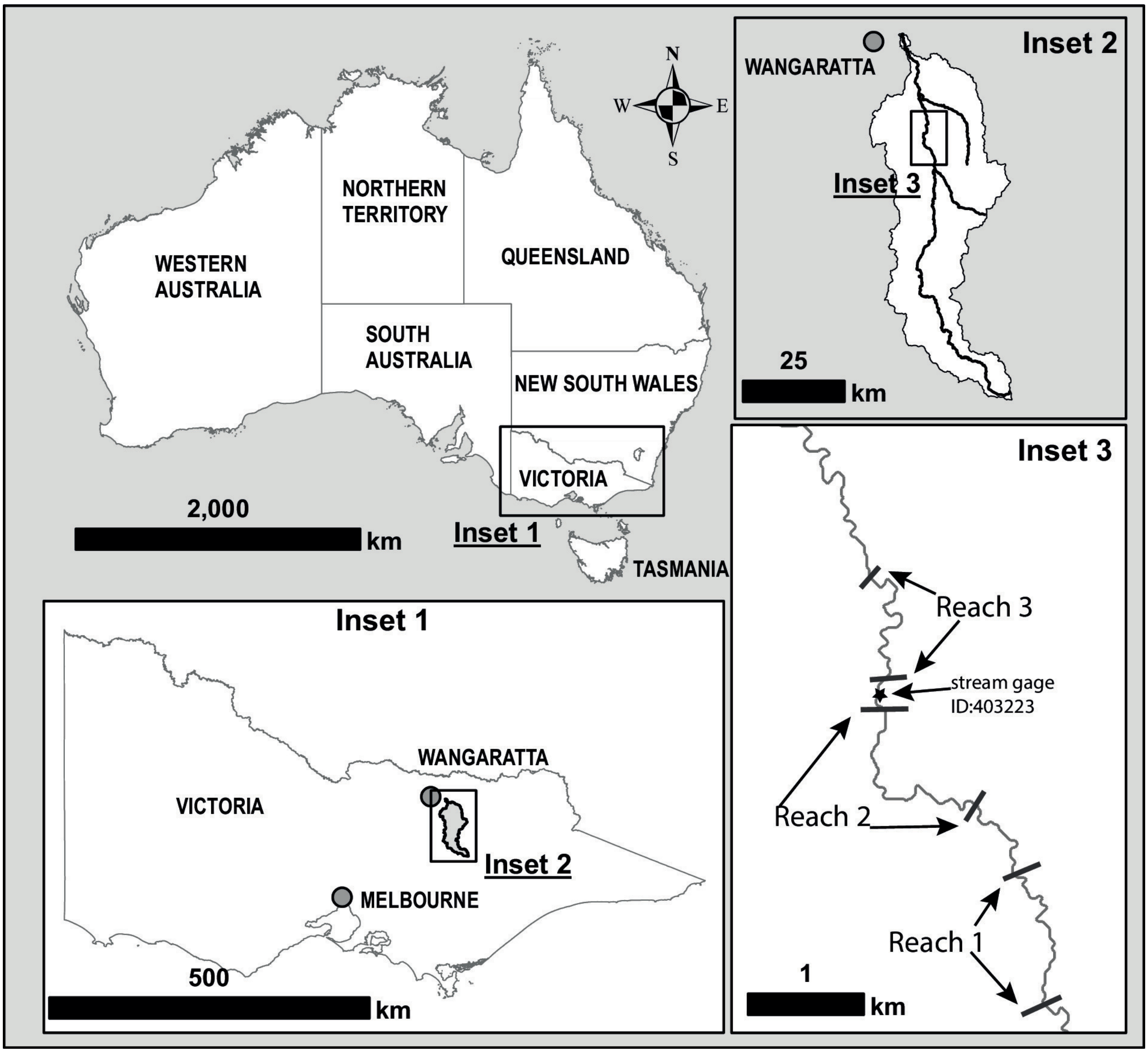
Figure 4. Results of empirically fitted distributions on derived accumulation rates for all three study reaches. Variables, bank erosion, mortality, exhumation and transport were well described using a 2-parameter Weibull distribution. The assumption of wood transport into the reach and out of the reach is upheld as the resulting distribution of transported wood values have a normal distribution with a mean near zero ($\mu = -0.0009$, $\sigma = 0.013$) Decay was modelled as a truncated normal distribution with a mean of 0.012 and a sigma of 0.01 based on values from the literature [*Díez et al.* 2002, *Murphy and Koski* 1989].

Figure 5: Results of the Monte Carlo simulation of the wood delivery model showing the average wood load through time. Graph a) Assuming the riparian area remains in the current

healthy state, the delivery model predicts that the average wood load will reach a 'steady state' at 255 ±23 years. Points A and C are the points in time when the upper and lower bounds of the first standard deviation of the distribution of average wood loads becomes stable, and point B is the point when the mean of the wood load becomes stable (46.7 m^3/100m). Graph b) Assumes that bank stabilization causes the loss of the dominant delivery mechanism of bank erosion, resulting in a depleted average load of wood. Graph c) assumes that after 100 years all of the trees along the riparian area have been delivered and that there is no longer recruitment of riparian vegetation along the reach.

Figure 6: Predicted Weibull probability distribution functions fit to the wood data. A comparison of panel a to panel b show that in the reaches (reaches 1 and 3) that have recovered for 57 years there are larger log jams than in reach 2 which has only been recovering for 34 years. We would expect smaller log jams with less frequency to be found in reach 2. Panel c illustrates the relationship of data from *Stout et al.* [2016], and the predicted spatial distribution of wood loads in the recovered reach.

Figure 7. Conceptual model of the recovery of wood loads in a desnagged river. The model illustrates the importance of spatial arrangements in wood during the recovery process. Initial delivery rates may be rapid, but a lack of key log jam pieces allows logs to be removed from the site during floods. As log jams form along the reach, initially very large log jams are present with large distances between jams. As key pieces are delivered between the large log jams, smaller jams form and effectively shift the reach into a steady state of accession and depletion. Note that the y-axis is the frequency of the load of wood in each section (in this case every 100m) across the reach.



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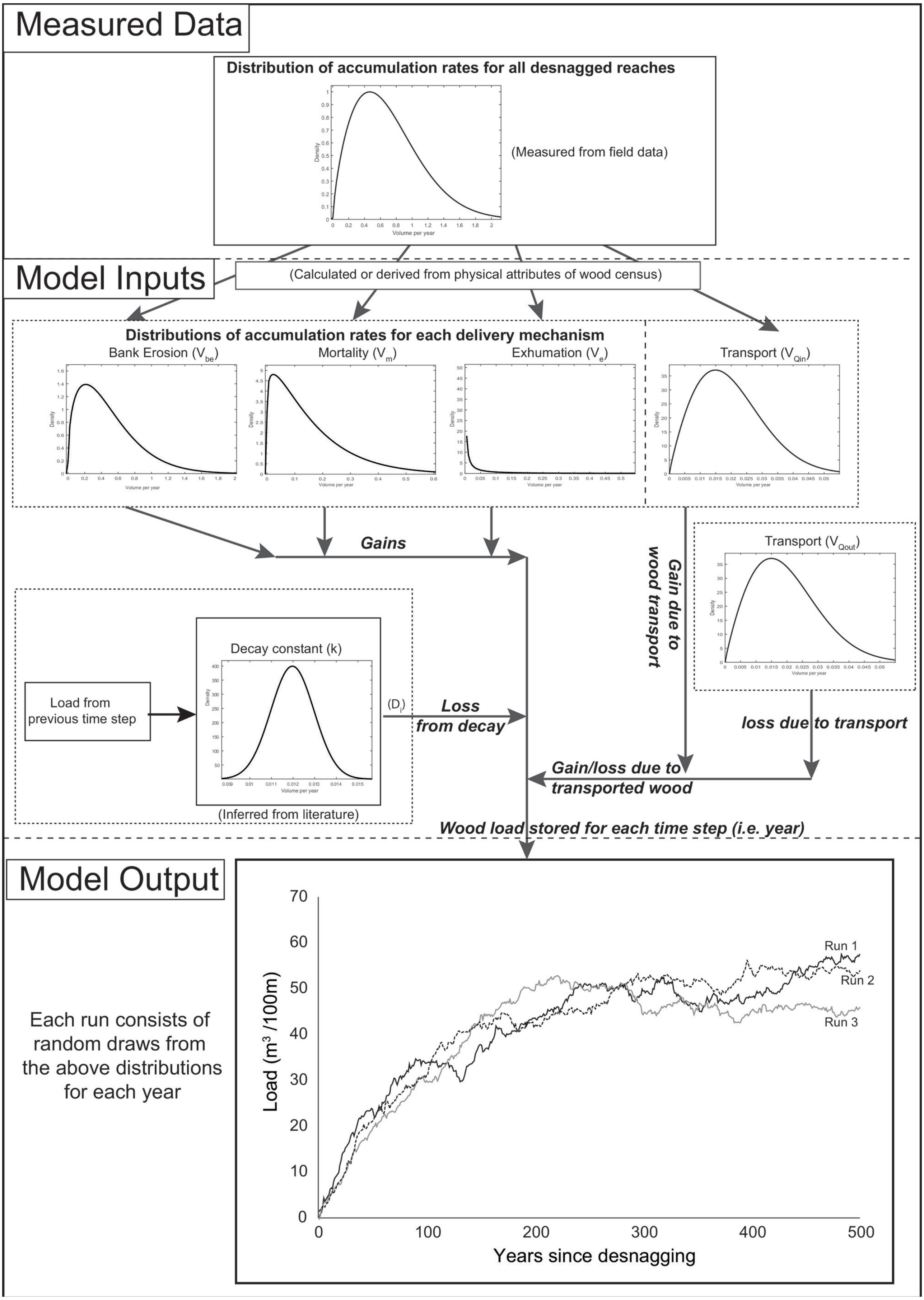

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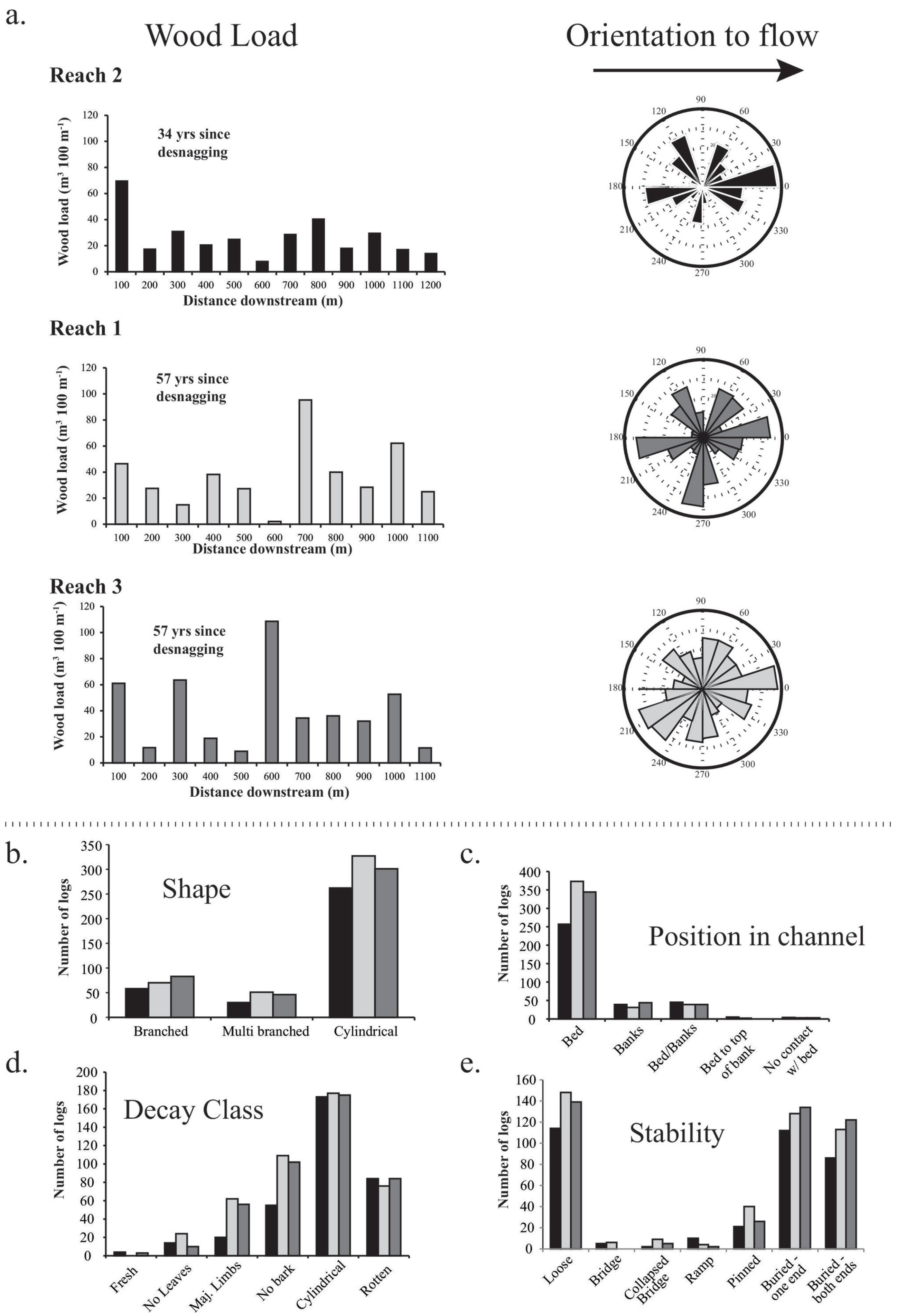

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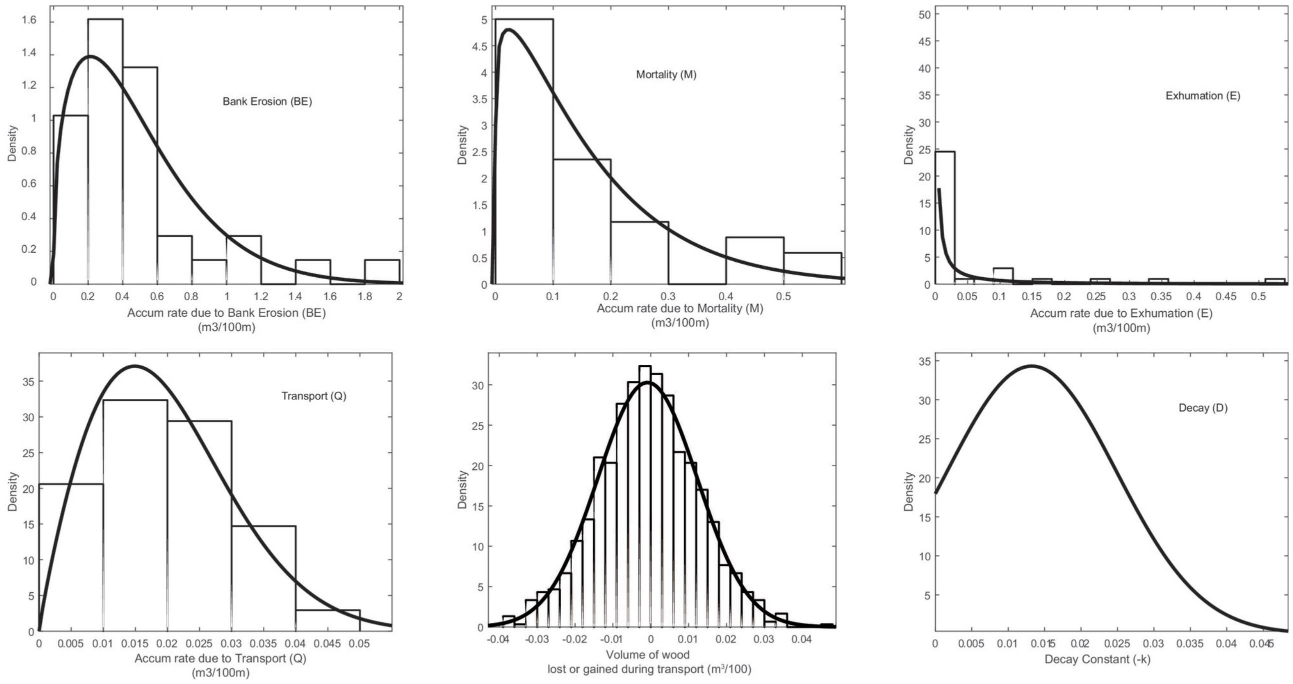

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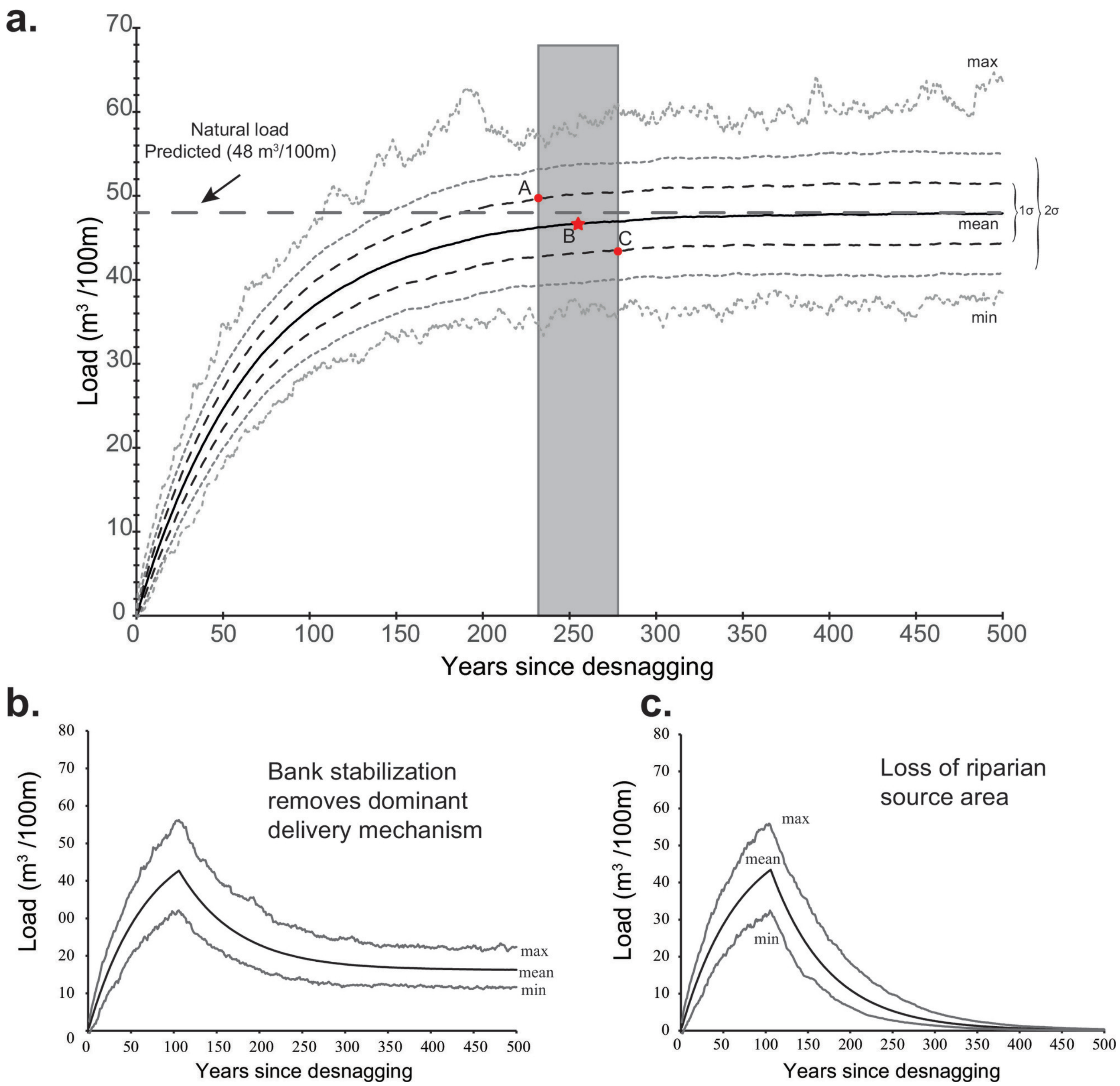

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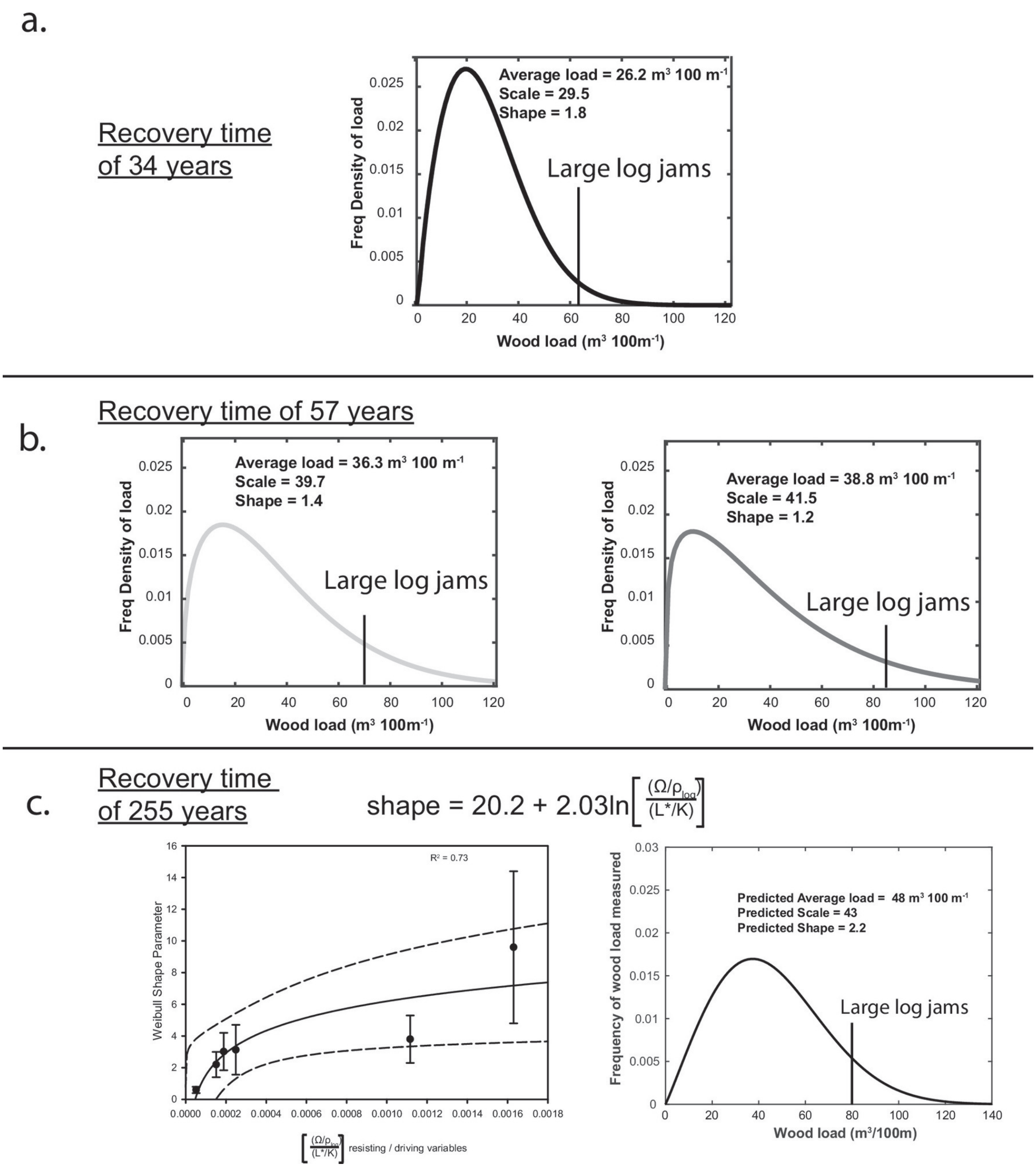

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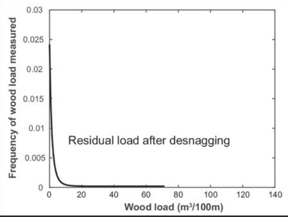
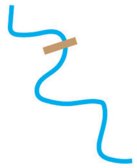
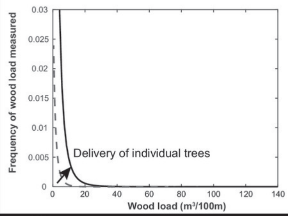
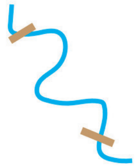
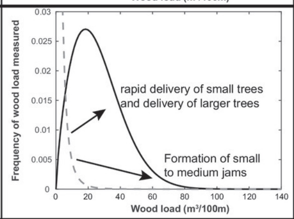
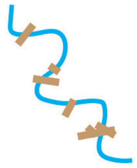
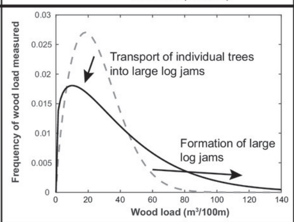
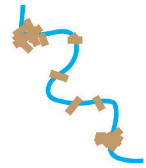
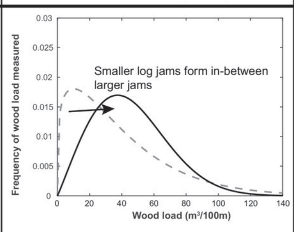
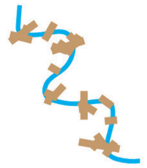
Changes in spatial distribution of wood load	Wood distribution	Description of stages	Variables which may change the spatial distribution
Stage 1 		**Stage 1** - Time zero - assume that all reaches have a zero load. Some sections may have exhumed wood or delivery from channel adjustment directly after desnagging	Incision of the river resulting in the exhumation of buried wood loads may increase the initial starting volume of wood within the reach
Stage 2 		**Stage 2** - Delivery of small to medium sized trees to river 5 to 10 years after desnagging.	Major delivery events (fire, landslides, avalanches, blow down) may produce a uniform load of wood across the reach. The uniform load of wood will retard the transport of wood through the reach until the load begins to decay and break apart.
Stage 3 		**Stage 3** - Rapid delivery of trees due to lack of roughness in the channel Some large trees are delivered and act as key pieces for the formation of log jams. This stage is potentially a "fools peak", as it may appear that the channel has fully recovered. This takes place 20 to 30 years after desnagging	Ratio of length of trees to the width of the river (L*) is a major driver on where log jams will begin to form. If L* is smaller than 1, log jams may form on the edges of the river or on bars. If the L* is close to one, and transport rates are high, very large log jams may form resulting in a log raft that results in an alternate state which may persist through time.
Stage 4 		**Stage 4** - Delivery slows as wood load reduces velocities and potentially protects banks from eroding. Large trees delivered serve as key pieces in log jams - trapping transported wood and forming large log jams. 50 to 70 years after desnagging	Transport bottlenecks due to the morphology of the river corridor may result in large extensive log jams. This may result in sections of the river with very little wood, while other sections have an extremely high load of wood. In smaller rivers, debris flows and high transport events may also result in a similar distribution of wood.
Stage 5 		**Stage 5** - Recovery. Smaller log jams form in between the larger jams. The spatial distribution (on average) has reached a stable state. This stage potentially takes the longest as the central tendency of the load across the entire reach slowly shifts to the right.	If large log jams (i.e. rafts) formed in either stages 3 or 4, it is likely that there will be sections with very little wood, and sections with very high loads of wood. The final spatial distribution in stage 5 is a balance between the delivery processes and the removal processes of the river.

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