Physical modelling of the combined effect of vegetation and wood on river morphology

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Abstract

The research reported in this paper employs flume experiments to investigate the potential effects of living vegetation and large wood on river morphology, specifically aiming to explore how different wood input and vegetation scenarios impact channel patterns and dynamics. We used a mobile bed laboratory flume, divided into three parallel channels (1.7 m wide, 10 m long) filled with uniform sand to reproduce braided networks subject to a series of cycles of flooding, wood input, and vegetation growth. Temporal evolution of river configuration (in terms of the braiding index), vegetation establishment and erosion, and wood deposition amount and pattern was recorded in a series of vertical images. The experiments reproduced many forms and processes that have been observed in the field, from scattered logs in unvegetated, dynamic braided channels, to large wood jams associated with river bars and bends in vegetated, stable, single thread rivers. Results showed that the inclusion of vegetation in the experiments changes wood dynamics, in terms of both the quantity that is stored and the depositional patterns that develop. Vegetated banks increased channel stability, reducing lateral erosion and the number of active channels. This promoted the formation of stable wood jams, where logs accumulated continuously at the same locations during subsequent floods, reinforcing their effect on river morphology. The feasibility of studying these processes in a controlled environment opens new possibilities for disentangling the complex linkages in the biogeomorphological evolution of the fluvial system and thus for promoting improved scientific understanding.

Keywords: *wood and vegetation dynamics*; wood deposition; river morphology; physical modelling

1. Introduction

The importance of vegetation and wood for river morphology has been recognized only quite recently (for reviews see Gurnell, 2013, 2014). Initially, this recognition developed from field observations, but over the last two decades vegetation has increasingly been incorporated into numerical models (Camporeale et al., 2013, Ruiz Villanueva et al., 2014) and some physical modelling has also started to investigate how wood and plants interact with fluvial processes. However, in previous physical modelling studies the influence of large wood and riparian vegetation have been studied separately, whereas in this paper, we focus on physical modelling incorporating both living vegetation and wood.

Traditionally, physical modelling has been used largely to investigate interactions between water and sediment, reproducing forms and processes in an effective way (Paola et al., 2009). Where vegetation has been incorporated, the focus has been largely on aquatic vegetation and, particularly, on the ways in which it affects the flow field (e.g., Folkard, 2009; Nikora, 2010; Nepf, 2012) and associated sediment dynamics. Riparian vegetation has also been incorporated into flume experiments, for example, illustrating how it is a crucial ingredient for reproducing single thread / meandering rivers (Gran and Paola, 2001; Tal and Paola, 2007, 2010; Braudrick et al., 2009; van Dijk et al., 2013).

Inclusion of biotic (i.e. living) elements in physical models is challenging, not only because the experimental set-up has to support vegetation growth and survival, but more crucially because it poses scaling problems (Thomas et al., 2014). However, if the experiments are used to investigate processes rather than to reproduce field prototypes, fast growing plant species such as alfalfa (*Medicago sativa*) provide the possibility of exploring a range of influences of above-ground and below-ground vegetation biomass on river processes and morphology (Clarke, 2014). For example, vegetation impacts can be investigated at both fine scales, such as the contribution of root reinforcement to bank cohesion, and at coarser scales, such as the retention of sediment by vegetation to build islands (e.g. Gran and Paola, 2001; Perona et al., 2012).

Large (dead) wood has also been studied in the laboratory, mostly to investigate its effect on the flow field and to assess the conditions under which wood can be mobilized and transported (Braudrick et al., 1997; Braudrick and Grant, 2001; Bocchiola et al., 2006; Welber et al., 2013). The interaction between wood and bridges during floods has also been investigated (Schmocker and Weitbrecht, 2013). Only recently, laboratory experiments have been used to investigate the interaction between large wood and river morphology, relating bed forms and sediment dynamics with wood dispersal (Welber et al., 2013; Bertoldi et al., 2014).

Despite the fact that living vegetation and dead wood are closely related in nature (Moulin and Piégay, 2004; Gurnell et al., 2005; Collins et al., 2012), to date no experiments have been conducted to investigate their joint influence on river morphology. In this paper, we demonstrate that flume experiments can be an effective tool for investigating the variables controlling the morphological evolution of rivers bordered by riparian woodland and thus affected by the occurrence of large wood deposits. The experiments also allowed us to explore the coupled role of riparian vegetation and large wood on river channel forms and dynamics, particularly on the landforms created by their interaction.

2. Methods

The following experiments were conducted within the “Total Environmental Simulator” facility, located at the University of Hull, UK.

2.1. Experimental set up and network development

Three 1.7 m wide, 10 m long flumes were built within the Total Environmental Simulator. Each had an initial slope of 1.3% and was filled with well-sorted sand (median grain size 0.73 mm). Water and sediment inputs to the flumes were set to 1.26 l/s and 1.9 g/s, respectively, to simulate high flow conditions. Flow and sediment inputs were provided using submerged pumps and automatic sediment feeders.

Prior to the experiments, the flumes were run under steady high flow conditions for 21 hours to obtain freely developed, steady-state braided networks (for further details see Bertoldi et al., 2014). Experiments were then run, first to explore the dispersal and retention of wood through the flumes under different wood supply rates in the absence of any vegetation cover, and then to explore wood dispersal and retention when vegetation was present.

2.2. Experiments without vegetation

A first set of experiments was conducted where wood was fed into the steady-state braided networks of the three unvegetated flumes to simulate the delivery of uprooted trees and very large logs to a „large‟ braided river (i.e. a „small‟ log length relative to the width of the anabranches, Gurnell et al., 2002).

Large wood was simulated using cylindrical wooden dowels (hereafter called logs), some with and some without attached cross-shaped „root wads‟. The length of the logs was 8 cm, to represent „large‟ river conditions, as defined above. The diameter of the logs was 3 mm, so that the length to diameter ratio was representative of data collected on the gravel-bed, braided Tagliamento River, northeastern Italy (Bertoldi et al., 2013). Log diameter was comparable to flow depth in many parts of the channel network. As a result, logs moved mostly by floating in the main anabranches and by rolling or sliding in the shallow areas on top of sediment bars. Sediment diameter was scaled to the median grain size of the same river. The logs were made of birch wood with a wet density of 0.67 kg/dm^3, which closely matches density values reported by Thévenet et al. (1998) for riparian species along the Drôme river, France, where the riparian woodland composition is typical of southern European rivers, including the Tagliamento. The logs were colour-coded to facilitate counting. High flow conditions were maintained over 18 hours as groups of logs were added to each flume at regular time intervals at a point immediately downstream of the flume inlet to sustain a „Low“, „Medum“ and „High“ wood input regime to flumes 1, 2 and 3, respectively (Table 1). Cohorts of logs were fed into each flume every 15 minutes. Individual logs within the same cohort were released at approximately 3 second intervals to ensure uncongested transport conditions, as defined by Braudrick et al. (1997). These inputs achieved a total input rate of 60, 120 and 180 logs per hour in the first 6 hours and 40, 80, 120 logs per hour in the remaining 12 hours of the experiment to flumes 1, 2 and 3, respectively (Table 1, for further information see Bertoldi et al., 2014).

<insert Table 1 near here>

Following the above experiments, the flumes were prepared for the experiments with vegetation by manually removing all logs from each flume and then running high flow conditions for one hour to remove any imprint of the logs on the flume bed.

2.3. Experiments with vegetation

To explore interactions among wood and vegetation, the three flumes were prepared by broad-seeding them with alfalfa seeds at a density of 35 g/m^2 during low flow conditions (0.2 l/s). The flumes were then maintained under low flow conditions for four days while the seeds germinated and established. During this time, some hydrochorous reworking and dispersal of seeds was achieved through the channel network by the low flows. The low flow discharge was not sufficient to transport sediment, and no sediment was input to the flumes. Alfalfa seedlings had the twofold role of stabilizing the sediments by root reinforcement, and interacting with flow and transported logs, reproducing the effect of flexible riparian vegetation in the forms of shrubs and young deciduous trees, as it is typical of the Tagliamento River. Following the vegetation establishment period, the three flumes were subjected to three different wood input regimes through four cycles of high flows interspersed with four days of vegetation regeneration under low flows. During these cycles no wood was input to flume 1, while flumes 2 and 3 were subject to „Low‟ and „High‟ wood input regimes (Table 1), i.e. 60 and 180 logs per hour during the first two hours and thereafter 40 and 120 logs per hour, respectively.

In the first two cycles, the high flows and wood input (0 – 2 h rate, Table 1) were run for two hours, and this was followed by reseeding by broad-casting at 35 g/m^2 across the entire flume surface. A period of four days of vegetation recovery under low flows followed. In the third cycle, the high flows and wood input (2 - 16 h rate) were run for four hours, no reseeding followed, but vegetation regeneration occurred under low flows over four days. In the fourth cycle, the high flows and wood input (2 - 16 h rate) were run for eight hours and then the experiments were terminated. Overall, these cycles simulated a trend of decreased seeding and an increase in the length of high flows and wood inputs.

2.4. Data collection

Logs exiting the flume were collected and counted after each input, and bedload output volume was measured every hour. A series of vertical images covering the entire length of the three flumes was acquired every hour using a reflex camera mounted on a 1.5 m high overhead gantry (resolution 2 pixels/mm).

Pictures were georeferenced and processed to produce wood storage and vegetation maps and to estimate the reach-averaged braiding index following Egozi and Ashmore (2008) (see Figure 1).

<insert Fig. 1 near here>

Isolated logs and wood jams (comprising at least two logs of wood touching each other) were manually mapped on the images by recording site coordinates and the number of stored logs with and without roots. In addition, the number of logs joining or leaving each wood storage site was evaluated by comparing pairs of subsequent pictures. Vegetated areas were mapped using a combination of automated image classification and manual digitising. As a first step, vegetation maps representing the initial conditions at the beginning of each of the four cycles were built using a supervised classification routine within GRASS version 6.4.2 to minimise operator bias in the definition of vegetated/unvegetated areas. A maximum-likelihood algorithm was used to assign image pixels to one of three coverage categories (dry bare surfaces, water, vegetated surfaces). Changes in vegetation cover due to erosion at high flow were manually mapped by comparing sequences of images.

3. Results

3.1. Vegetation development and erosion

Vegetation quickly established within the flumes at the end of each of the high flow cycles, as illustrated by the photographs of flume 1 (no wood supplied, Figure 1). Despite the cessation of reseeding and the increase in the duration of high flow periods from 2 h to 4 h and 8 h in flow cycles 3 and 4, respectively, a high vegetation cover was retained during these final two cycles.

The periods of high flow induced partial erosion of the vegetated area (Fig. 2). The proportion of the vegetated area eroded during each cycle decreased from one cycle to the next, despite the fact that the duration of the period of high flows increased. This reflects the developing above ground and (presumably) below ground biomass which probably provided additional resistance against erosion. After the first cycle, the low wood input regime showed the highest relative erosion of vegetated patches, and the high wood input regime showed the lowest erosion of vegetated patches in cycles 3 and 4. However, the proportion of the vegetated area that was eroded in all of the flumes became very small after the first cycle (where rates varied around 10%), falling to less than 1% in cycle 2 and around 0.1% in cycles 3 and 4.

<insert Fig. 2 near here>

3.2. Complexity of the channel network

The evolution of the channel pattern within the flume during the imposed high flows is shown in Figure 3. This figure illustrates that during the first experiments, where there was no vegetation in the flume (15 to 42 hours flow time, with 18 hours of wood input commencing at flow time 23h), there was little change in the braiding index and little difference among the flumes that were subject to low (flume 1), medium (flume 2) and high (flume 3) wood input regimes. As these experiments with and without wood have already been investigated in detail (Bertoldi et al., 2014), results from the medium wood input regime experiment, which was only run in the unvegetated case (Table 1), are not presented here. However, results from the low and high wood input regimes are illustrated for comparison with the vegetated runs.

<insert Fig. 3 near here>

From Figure 3, it appears that wood alone had little impact on channel network complexity. However, following the introduction of vegetation, there was a sharp reduction in braiding intensity in all flumes through the first two cycles of high flows, after which a lower braiding index was maintained. The flume with no wood supply showed a higher network complexity than the two flumes that received wood input. Indeed, the simultaneous presence of wood and vegetation caused a shift towards an almost single-thread morphology (braiding index = 1). However, two very large jams, which formed at the upstream end of central bars under the high wood input regime, caused flow diversion that helped to maintain a reach-averaged braiding index close to 2.

3.3. Wood retention and delivery

Wood retention (i.e. storage in the flume) and delivery (i.e. output from the flume) can be compared under low and high wood input regimes in association with unvegetated and vegetated conditions, by comparing observations in flumes 1 and 3 without vegetation and flumes 2 and 3 with vegetation (i.e. low and high wood input regimes with and without vegetation). The hourly amount of wood exiting the flume is notably higher for the high wood input regime in comparison with the low wood input regime when no vegetation is present (Figure 4A). However, there is little difference in wood output from the vegetated flume runs, with the output from the high wood input regime being drastically reduced when vegetation is present.

When the accumulated wood output from each flume is subtracted from the accumulated wood input, the trend of increasing wood storage within the flumes during the experiments is clearly evident (Fig. 4B). Without vegetation, wood storage increased steadily during the first 6 hours of the experiment under the high wood input regime, and then stabilized around a value of approximately 800 logs (about 75 logs/m²). After 14 hours, wood storage increased again to reach 950 logs (87 logs/m²) at 18 hours. Much slower wood accumulation was observed for the low wood input regime, where stored wood continued to increase throughout the simulation, although, as for the „high" input regime, there was a slight decrease after 6h, which corresponds to the time when the wood input rate was reduced (Table 1). The final density of stored logs (about 39 logs/m²) was approximately half of that observed with the high wood input regime, despite the fact that the wood input rate was only one third of that under the high wood input regime.

<insert Fig. 4 near here>

With vegetation, the flume that was subject to the high wood input regime continued to accumulate wood throughout the experiments, reaching a final spatial density of about 130 logs/m². In contrast, wood storage in the vegetated channel subject to the low wood input regime increased for the first 9 hours, and then remained fairly constant, achieving a value of about 23 logs/m^2 by the end of the experiments, which is lower than in the unvegetated case. Although the unvegetated runs showed a slight response to the lowered wood supply after 6 hours, there was no detectable response to the lowered wood supply after the first two hours in the vegetated runs.

Overall, there was little difference in the outcomes of the unvegetated and vegetated experiments with a low wood input, but with a high wood input, there was much higher wood retention and lower wood output in the vegetated than the unvegetated experiment.

3.4. Wood jam size

The location and size of wood jams that developed during the experiments displayed very different patterns in response to the different treatments. The changing proportion of logs retained in jams of different size under the four different experimental treatments (i.e. low and high wood input regime, with and without vegetation) is illustrated in Figure 5. Broad trends of increasing wood jam size can be seen across the graphs from A to D as wood input rate increased and vegetation was incorporated into the experiments. Overall, the proportion of wood stored as single, isolated logs decreased over time in all simulations.

<insert Fig. 5 near here>

Under a low wood input regime (Figs. 5A and 5C), the initial percentage of isolated logs (after one hour of high flows) was greater than 65%. In the unvegetated experiment, this declined gradually and steadily over the first 6 to 8 hours and then stabilised at around 45% (Fig. 5A). In the vegetated channel, the proportion of isolated logs declined more rapidly over the first 8 hours and then stabilised at around 30%.

Under a high wood input regime (Figs. 5B and 5D), a much smaller proportion of wood was retained as isolated logs after the first hour, and a sharper contrast existed between the unvegetated and vegetated experiments. In the unvegetated channel, isolated logs represented approximately 50% of the total logs at the end of the first hour, whereas in the vegetated channel isolated logs accounted for only 30%. After 16 hours, isolated logs comprised only 25% and 10% of the total logs retained in the unvegetated and vegetated channels, respectively.

Large wood jams (> 10 logs) were rare in the unvegetated, low wood input regime experiment (Fig. 5A), as they accounted for < 10% of the total logs retained after 16 hours. However, in the unvegetated, high wood input regime (Fig. 5B), vegetated, low wood input regime (Fig. 5C), and vegetated, high wood input regime (Fig. 5D) experiments, the percentages of wood retained in large jams was 35%, 35% and 80%, respectively. In particular, in the vegetated, high wood input regime experiment, 60% of wood was stored within large wood jams after only the first 3 hours of high flows.

Intermediate sized jams (2 to 9 logs) remained quite well represented in the unvegetated channels throughout the experiments, with approximately 45% and 40% of logs retained in intermediate sized jams in the low and high wood input regime experiments, respectively, after 16 hours. However, intermediated sized wood jams were far less common in the vegetated channels, accounting for less than 30% and 15% of the logs stored in the low and high wood input regime experiments, respectively, after 16 hours.

In the vegetated, low wood input regime experiment (Fig. 5C), there was a relatively high retention of isolated logs, which can be explained by the following process. Individual logs were deposited widely within the braided channel network during the first cycle, when vegetation was quite sparse (as observed in the top image of Figure 1). However, with vegetation development and a rapid transition from a multi-thread to an almost single thread channel, many of these single logs became stranded on the vegetated floodplain, where they remained isolated from flows that could remobilise them and transfer them into wood jams.

3.5. Wood mobility

Wood mobility was quantified by analysing both the flume-integrated remobilisation of formerly deposited logs and the deposition of newly introduced logs.

Wood remobilisation was computed as the number of logs removed from the flume in each time interval (i.e. between t=k and t=k+1) divided by the total number of logs retained in the flume at the beginning of the time interval (i.e. at t=k). Hourly changes in remobilisation through the experiments with and without vegetation and under high and low wood input regimes are presented in Figure 6. This figure illustrates that in all cases, wood remobilisation decreased with time. In the absence of vegetation, remobilisation was relatively high regardless of the wood supply regime, ranging between 40% and 60% in the first 6 hours, and between 25% and 45% thereafter.

<insert Fig. 6 & 7 near here>

Remobilisation in the presence of vegetation was much lower than when vegetation was absent. Under the vegetated, low wood input regime, wood remobilisation of almost 60% took place in the first hour of the experiment, but then rapidly declined to below 10% within the first 4 hours, and then remained at that level with the exception of the period between 8 and 10 hours. This short period of higher mobilisation was probably linked to local erosion processes (described below and Figure 7). Remobilisation was extremely low throughout the experiment in the vegetated, high wood input regime case, where it never exceeded 20% and dropped below 5% after the first 2 hours.

By tracking the movement of individual logs through the experiments, it is possible to reconstruct how wood jams develop, are modified and disappear. In Figure 7, newly deposited logs observed at each time step are attributed to three categories: i) wood joining existing wood depositional sites; ii) logs becoming trapped by vegetation; and iii) wood deposited on unvegetated bars. Figure 7A illustrates deposition of new logs in the vegetated, low wood input regime case and Figure 7B illustrates the vegetated, high wood input regime case.

In both wood input regimes, few logs were deposited on bare sediment (black shading in Figure 7), although under the low wood input regime (Fig. 7A), the proportion was quite high during the first two hours, which was during the first cycle when vegetation cover was relatively sparse in the flumes (Fig. 1, top image).

Addition of new logs to existing wood jams was an important process (white shading in Figure 7) after the first 3-5 hours under the high and low wood input regimes. Thereafter, the proportion of new wood trapped by existing jams fluctuated between 30 and 70% under the low wood input regime, and exceeded 70% (after 4 hr) - 90% (after 11 hr) with the high wood input regime. Deposition of new wood on pre-existing jams in the unvegetated experiments is superimposed as a heavy black line on Figures 7A and B, for the low wood input and high wood input cases, respectively. Without vegetation, new wood additions to jams were far less frequent than in the case of vegetated tests, regardless of the wood input regime. Indeed, more than 90% of new wood deposited as individual logs or newly-formed jams on bare sediment in the low wood input case, and between 60% and 95% in the high wood input case.

Retention of newly deposited logs by vegetation (grey shading in Figure 7) varied markedly with wood supply rate. Under the vegetated, low wood input regime, vegetation retained new logs at a relatively constant rate of between 20% and 40%. Under the vegetated, high wood input regime, around 70% of logs were retained by vegetation in the first 3 hours of the experiment, but then decreased rapidly (to less than 5% after 9 hours).

Many of the fluctuations through time displayed in Figure 7 can be explained by local-scale phenomena. For example, in the vegetated channel subjected to the high wood input regime, a peak in wood deposition on unvegetated bars at 10 hr corresponded to the deposition of 10 logs at the apex of a rapidly growing mid-channel bar. In the vegetated flume run with low wood input, an island that had been acting as a major wood retention site was eroded (commencing at 9 hours), resulting in a reduction of deposition of new wood on existing wood jam sites (Fig. 7A) and a peak in wood remobilisation (Fig. 6).

3.6. Wood jam types and landforms

In the vegetated experiments, the channel planform gradually adjusted from a multi-thread to a single-thread pattern through the four cycles, particularly in those flumes where wood was added (Fig. 3). As this transition occurred, different wood jam types were observed. In the early stages, while a generally bar-braided pattern was maintained, wood was widely distributed across bar surfaces, producing some distinctive patterns similar to those observed on bar-braided reaches of the Tagliamento River (Fig. 8). Furthermore, wood tended to form rather small jams, except where larger bar-apex jams developed at bifurcations. However, as vegetation developed, not only did the bar apex jams develop into distinct landforms, but a wider variety of types of jam developed involving larger numbers of logs (i.e. $\geq$ 10, Fig. 9), often retaining sediment and inducing local scour. These different landforms are discussed in more detail below.

<insert Fig. 8 & 9 near here>

4. Discussion

4.1. Interactions between riparian vegetation, wood and river characteristics at the reach scale.

The flume experiments analysed in this paper have allowed us to observe the dynamics of several important processes that are difficult to monitor in the field, by which riparian vegetation, both alone and in combination with wood, influences the morphology of „large‟ rivers (i.e. those where the length of wood elements is shorter than the width of the active channel(s)). Our preliminary results reveal changes in wood dynamics in relation to different wood input regimes and vegetation densities that are relevant to the possible occurrence of specific thresholds, above which wood transport and deposition patterns may drastically change. These preliminary observations need further investigation in the field and through modelling. In particular, these experimental runs considered a simplified wood input process, with a regular supply from upstream, whereas innatural systems wood recruitment may be highly variable in space (i.e. from upstream areas as well as from areas within the reach) and quite concentrated in time (i.e. sudden massive inputs from landslides or large bank failures). Moreover, our experiments represented living and dead plants as two different elements (alfalfa seedlings and wood dowels, respectively), where erosion of vegetated patches does not increase large wood input.

The experiments confirmed that vegetation can confer considerable stability to river banks, significantly reducing bank erosion, as is illustrated by Figure 2 (e.g. van Dijk et al., 2013). Of course, it is essential to qualify this statement in relation to the experiments that were conducted, in which a single species was introduced to represent woody vegetation, and a single high flow was used to disturb it. Nevertheless, field observations and analyses have shown the importance of vegetation for stabilising river banks (e.g. Abernethy and Rutherfurd, 2000, Pollen Bankhead and Simon, 2010), particularly where the bank height is not greater than the predominant rooting depth. Even in incised gravel bed rivers, where bank undercutting is not significantly reduced by tree root systems, vegetation still exerts a strong morphological control within the channel by stabilizing sediment bars (Comiti et al., 2011).

As a consequence of bank and bar reinforcement, riparian vegetation colonisation and establishment influences river planform. In our experiments, there was a reduction in the braiding index when vegetation was introduced, as illustrated by Figure 3. This change in planform complexity has been illustrated by previous experimental work simulating rivers with perennial flow and riparian vegetation (e.g. Braudrick et al., 2009, Tal and Paola, 2007, 2010). In our experiments, wood alone appears to induce little change in braided channel complexity (see also Bertoldi et al., 2014), but when introduced in the presence of riparian vegetation, it leads to a further reduction in the number of active channels, ultimately transforming the braided channel into a wandering or single thread planform. Such a combined wood-vegetation effect has, to our knowledge, not been described before. Where a wandering planform is maintained in the presence of wood, it appears that wood jams retained against riparian vegetation can help a channel bifurcation to persist and remain active. Although this process has not been explicitly reported in the literature, the impact of wood on channel dynamics including the development of side channels through avulsions and the maintenance of anastomosing channel patterns and channel switching, have been reported (e.g. Collins and Montgomery, 2002, O‟Connor et al., 2003)

One of the key mechanisms that allows wood to influence channel form and dynamics in the presence of riparian vegetation is increased wood retention (in comparison with the unvegetated situation, Figure 4). Increased wood retention / storage results from a number of processes, including the drifting of wood into the floodplain, where it is retained, particularly when riparian vegetation is open and sparse (Wohl et al., 2011), and the incorporation of wood pieces into increasingly large jams as riparian vegetation becomes denser and more mature and also as wood supply increases (Fig. 5) (Wohl and Beckman, 2014). In our experiments, approximately 0%, 10%, 25% and 80% of wood pieces were retained in jams containing > 10 logs in the unvegetated, low wood input regime; unvegetated high wood input regime; vegetated, low wood input regime; and vegetated, high wood input regime, respectively. Thus, once retained, wood remobilisation is very low where riparian vegetation is well-developed (Fig. 6) and retention tends to be achieved mainly by the development of increasingly large accumulations of wood rather than by the retention of isolated wood pieces (Fig. 7). This potential for unmanaged rivers bordered by riparian woodland to retain large quantities of wood has been widely observed in the field (e.g. Piégay et al., 1999; Gurnell et al., 2000; Wyzga et al., 2005; Lassettre et al., 2008).

Overall, our results have illustrated for the first time through an experimental approach, how riparian vegetation and wood interact to have an enormous influence on river channel morphology and features. They also illustrate how the magnitude of that influence increases with the development of the riparian „forest‟ and the quantity of wood supplied to the river (Wohl, 2013; Surian et al., 2015).

4.2. Wood jam types and landforms

Most of the wood jams observed in the flumes are very similar to wood jams and associated landforms observed in the field (for a recent review see Gurnell, 2013).

On bar-braided reaches of the Tagliamento River, for example, large inputs of wood from bank erosion of the floodplain and islands have been observed to form distinctive patterns on bars located immediately downstream (Bertoldi et al., 2013), that closely resemble the patterns observed in the flumes in the early stages of vegetation development (Figure 8). Individual or small jams of uprooted trees are deposited across the bar surfaces. Where particularly large trees or jams of several trees occur towards the upstream end of a bar, they are often effective in trapping additional logs to produce bar apex jams, similar to those described by Abbe and Montgomery (2003).

In island-braided channels, wood tends to accumulate around island margins, especially at their upstream end, and wood plugs develop at the upstream end of avulsion or distributary channels that cross islands or enter the riparian forest from the braid plain (Gurnell et al., 2001, 2005). In wandering and single thread sinuous rivers, wood interacts with the channel margins and wooded floodplain in more complex ways (Gurnell et al., 2002; Abbe and Montgomery, 2003; Dufour et al., 2005; Lassettre et al., 2008; Moulin et al., 2011; Collins et al., 2012).

Of particular relevance in the present context is the wood jam classification proposed by Abbe and Montgomery (2003) as a result of their observations on the Queets River, USA. They proposed three broad groups of jams, i.e. „in situ" (key log has not moved down channel); „combination" (key log has not moved down channel but there is additional racked wood that has moved); „transport" (key log has moved some distance downstream).

Given the design of the present experiments, which aimed to simulate the conditions of a „large" river, we would only expect to observe jams of the last type. Abbe and Montgomery described six jam types within the transport group: „debris flow / flood" are chaotic jams that have been catastrophically emplaced; „bench" are jams along the channel margin behind which sediment and wood accumulate to form a bench; „bar apex" are often associated with the development of an island or bar; „meander" are typically buttressed and racked along the outside of meander bends; „raft" are very large jams capable of plugging large channels; „unstable" are jams of racked logs on bar tops or banks. Most of these jam types appear to have formed during the experiments (Fig. 9). Although described as an „in situ" type, by Abbe and Montgomery, a log traversing the small channel in Figure 9 B could be interpreted as an incipient „log step‟. The other „transport‟ types in Figure 9 are a „bar apex‟ jam (D), a „meander‟ jam (E), a „debris flood‟ jam within the margins of the „riparian forest‟ (F), and „bench jams‟ (A and C – sediment is already accumulating behind some of the logs in A). In addition, although not included in the Abbe and Montgomery classification, wood can be observed blocking a chute channel (G).

5. Conclusions

Our experiments have reproduced many forms and processes that have been observed in the field. They have confirmed the important joint impact of riparian woodland and large wood on river channel form and dynamics, illustrating their aggregate effects on the morphology of river reaches and also the range of landforms that are constructed locally. In nature, wood is produced by standing trees, and both drive a „large wood cycle‟ (Collins et al., 2012) that may extend over centuries and is easily broken. In systems where deposited wood can sprout to form new trees, the cycle is tighter and quicker, extending over multiple decades rather than centuries, and thus is able to recover more quickly (e.g. Zanoni et al., 2008). Nevertheless, the crucial contributions of wood and trees to river ecosystems need to be recognised, and their joint conservation needs to be incorporated where possible into river management. The experimental results presented in this paper provide confidence that many vegetation and wood related processes and features are common across a wide range of environments, and are not just associated with specific, localised conditions.

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List of Figures

Fig. 1. Vegetation distribution in flume 1 (no wood) at the end of each of the four high flow cycles illustrated in chronological order from top to bottom. (Flow time 44, 46, 50, 58 hours, respectively).

Fig. 2. The proportion of the vegetated area eroded within the three flumes during each of the four cycles.

Fig. 3. Changes in the reach-averaged braiding index during high flows through the sequence of experiments (the dashed vertical line marks the commencement of the wood experiments, the solid vertical grey line marks the commencement of the vegetation experiments at the first cycle (which includes the one hour high flow preparation of the flumes prior to commencement of log introduction for 2 hours), followed by three thin grey lines marking the ends of the second, third and fourth high flow cycles under vegetated conditions).

Fig. 4. Wood retention and delivery from the flume during 18 hours of high flows under low and high wood input regimes and with no vegetation and a vegetation cover present. A. The number of logs output from the flume each hour. B. The number of logs retained within the flume at the end of each hour.

Fig. 5. The proportion of logs stored in jams of different size under A. unvegetated, low wood input regime; B. unvegetated, high wood input regime; C. vegetated, low wood input regime; D. vegetated, high wood input regime.

Fig. 6. Log remobilisation under the presence and absence of vegetation and low and high wood input regimes (wood remobilisation is computed as the ratio of the number of logs delivered from the flume during each hour as a proportion of the number of logs stored within the flume at the beginning of each hour).

Fig. 7. The proportion of new logs deposited within vegetated flumes on bare sediment (dark grey), vegetation (light grey), and previously deposited logs (white) under A. a low wood input regime and B. a high wood input regime. The heavy black line refers to new logs deposited on previously deposited wood in unvegetated flumes under the same wood input regime.

Fig. 8. Comparisons between flume-scale and field-scale wood deposition patterns: braided morphology.

Fig. 9. Comparisons between flume-scale and field-scale wood deposition patterns: single-thread / wandering morphology.

Table 1. Wood input regimes applied to the three flumes.

	Flume 1*		**Flume 2**		**Flume 3**		**Flume 2**		**Flume 3**	
VEGETATION	**Experiments without vegetation**						**Experiments with vegetation**			
WOOD INPUT REGIME	**Low**		**Medium**		**High**		**Low**		**High**	
	hours 0 ÷ 6	hours 6 ÷ 18	hours 0 ÷ 6	hours 6 ÷ 18	hours 6 ÷ 18	hours 6 ÷ 18	hours 0 ÷ 2	hours 2 ÷ 16	hours 0 ÷ 2	hours 2 ÷ 16
Wood input rate [logs/hour]	60	40	120	80	180	120	60	40	180	120
Input frequency [cohorts/hour]	6	4	6	4	6	4	6	4	6	4
Cohort size [logs]	10	10	20	20	30	30	10	10	30	30
Logs with roots [% of total wood input]	60%	40%	60%	40%	60%	40%	40%	40%	40%	40%

* no wood was input to flume 1 during the experiments with vegetation

Figure 1

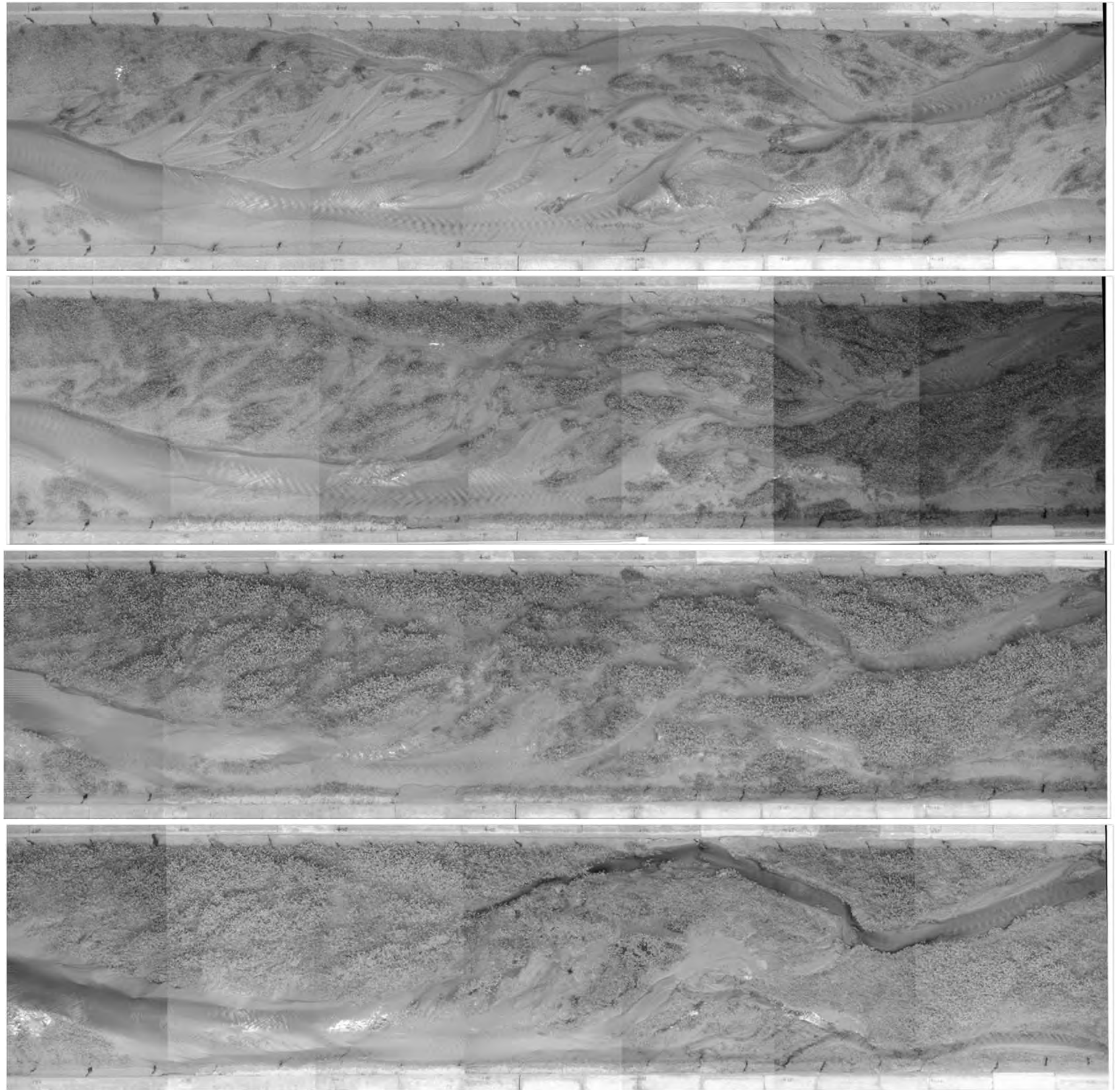
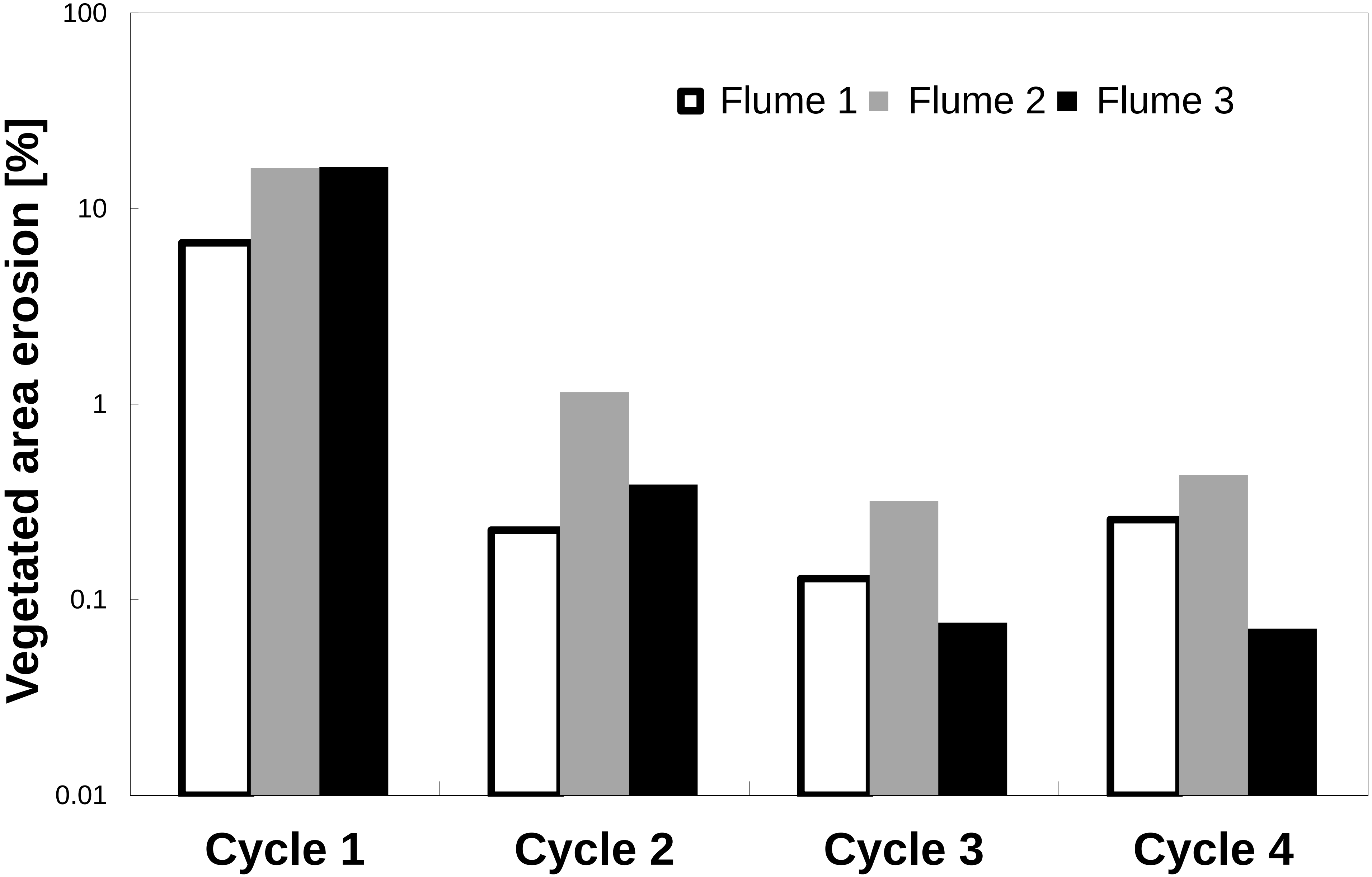


Figure 2



Vegetated area erosion [%]
100
10
1
0.1
0.01
☐ Flume 1
▨ Flume 2
■ Flume 3
Cycle 1
Cycle 2
Cycle 3
Cycle 4

Figure 3

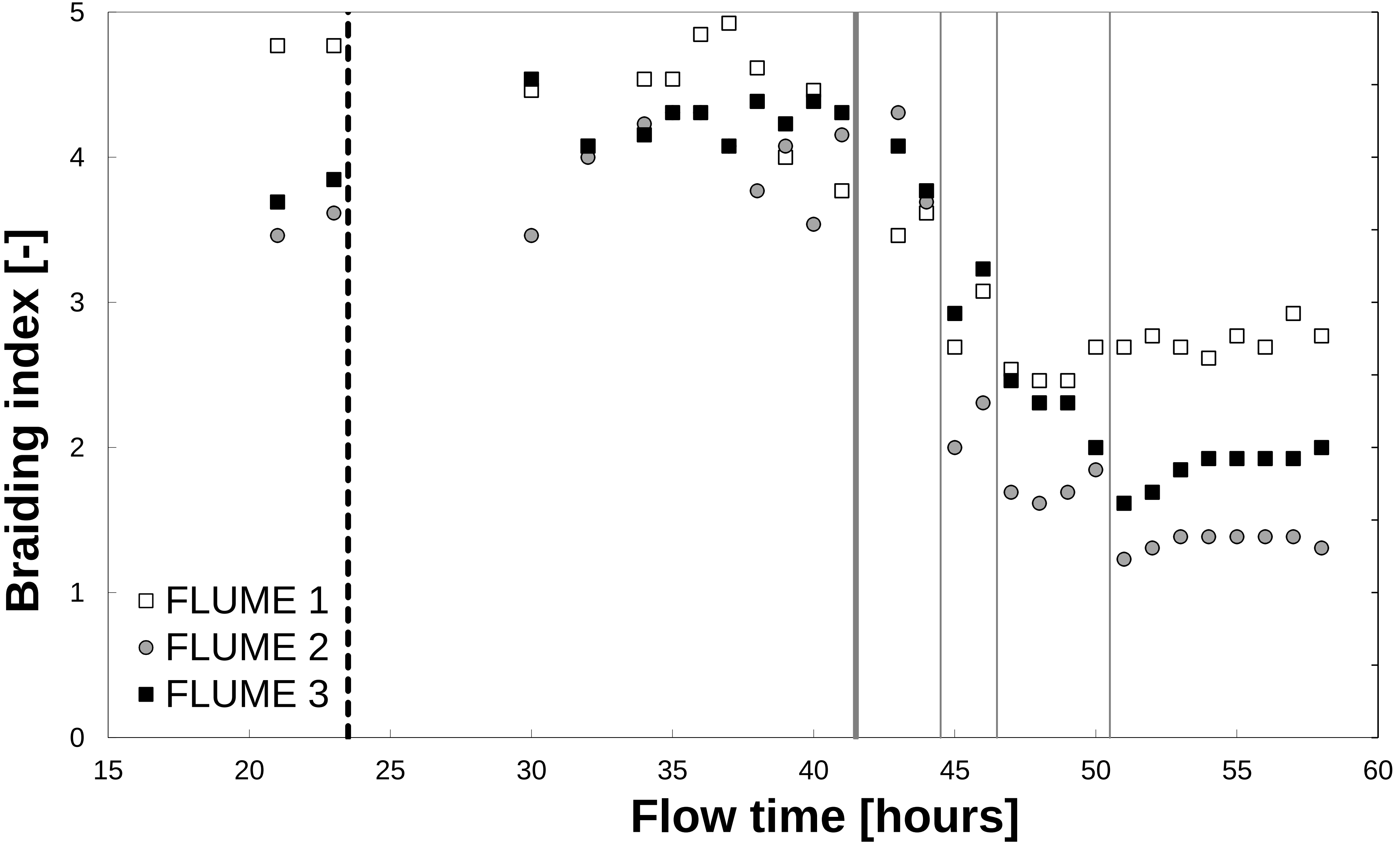

Braiding index [-]
0
1
2
3
4
5
Flow time [hours]
15
20
25
30
35
40
45
50
55
60
FLUME 1
FLUME 2
FLUME 3

Figure 4

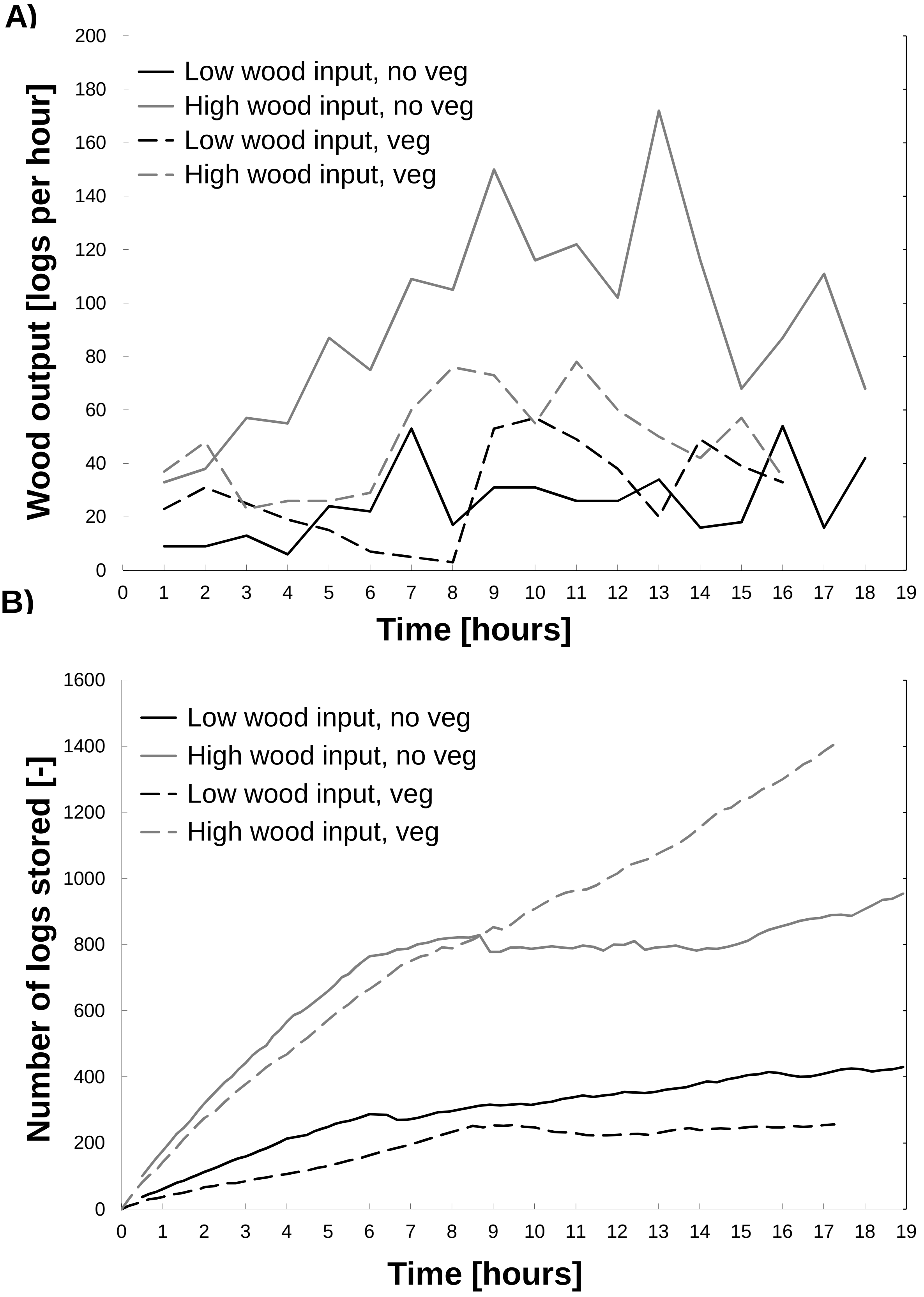

A)
Wood output [logs per hour]
0
20
40
60
80
100
120
140
160
180
200
Low wood input, no veg
High wood input, no veg
Low wood input, veg
High wood input, veg
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Time [hours]
B)
Number of logs stored [-]
0
200
400
600
800
1000
1200
1400
1600
Low wood input, no veg
High wood input, no veg
Low wood input, veg
High wood input, veg
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Time [hours]

Figure 5

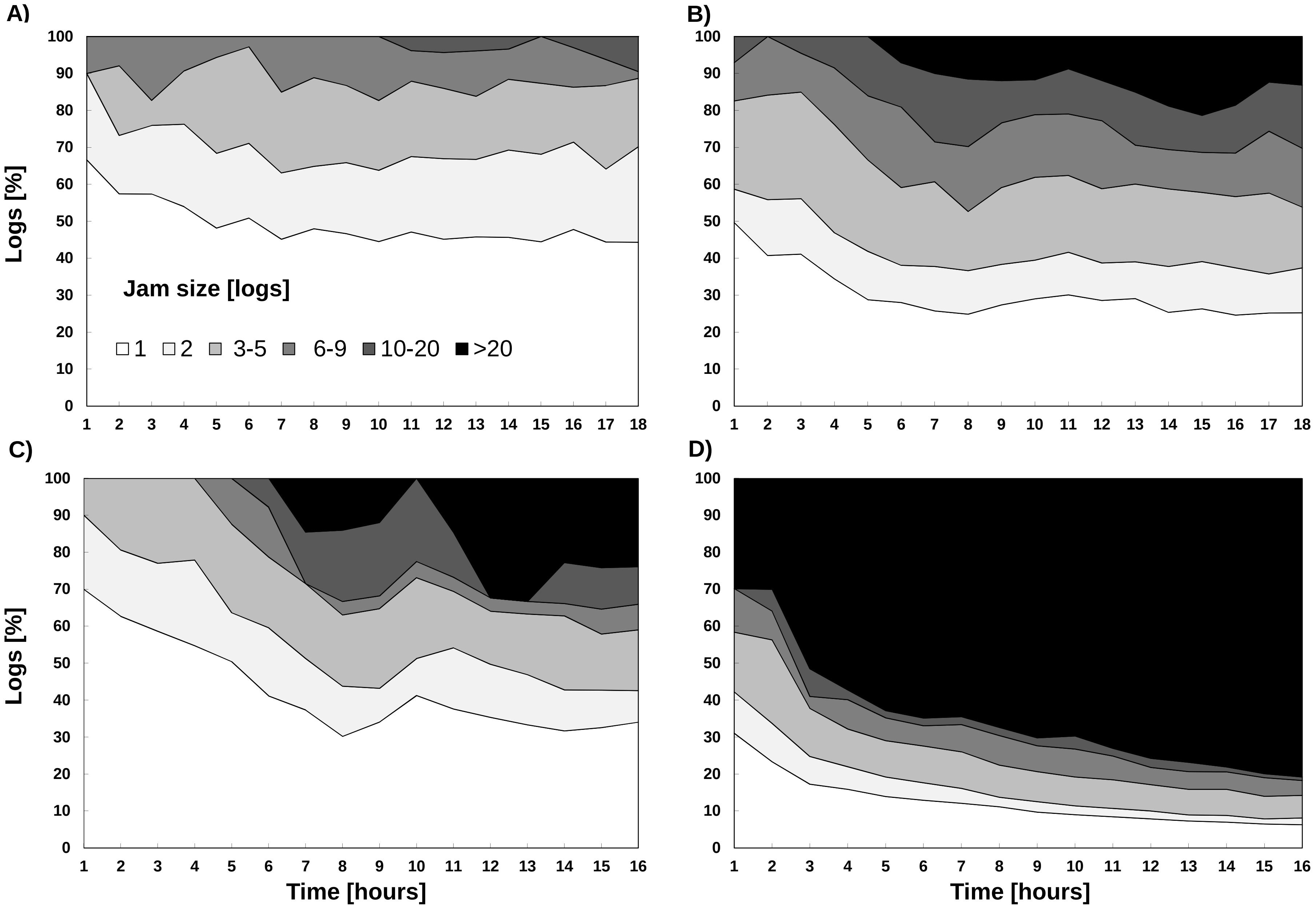
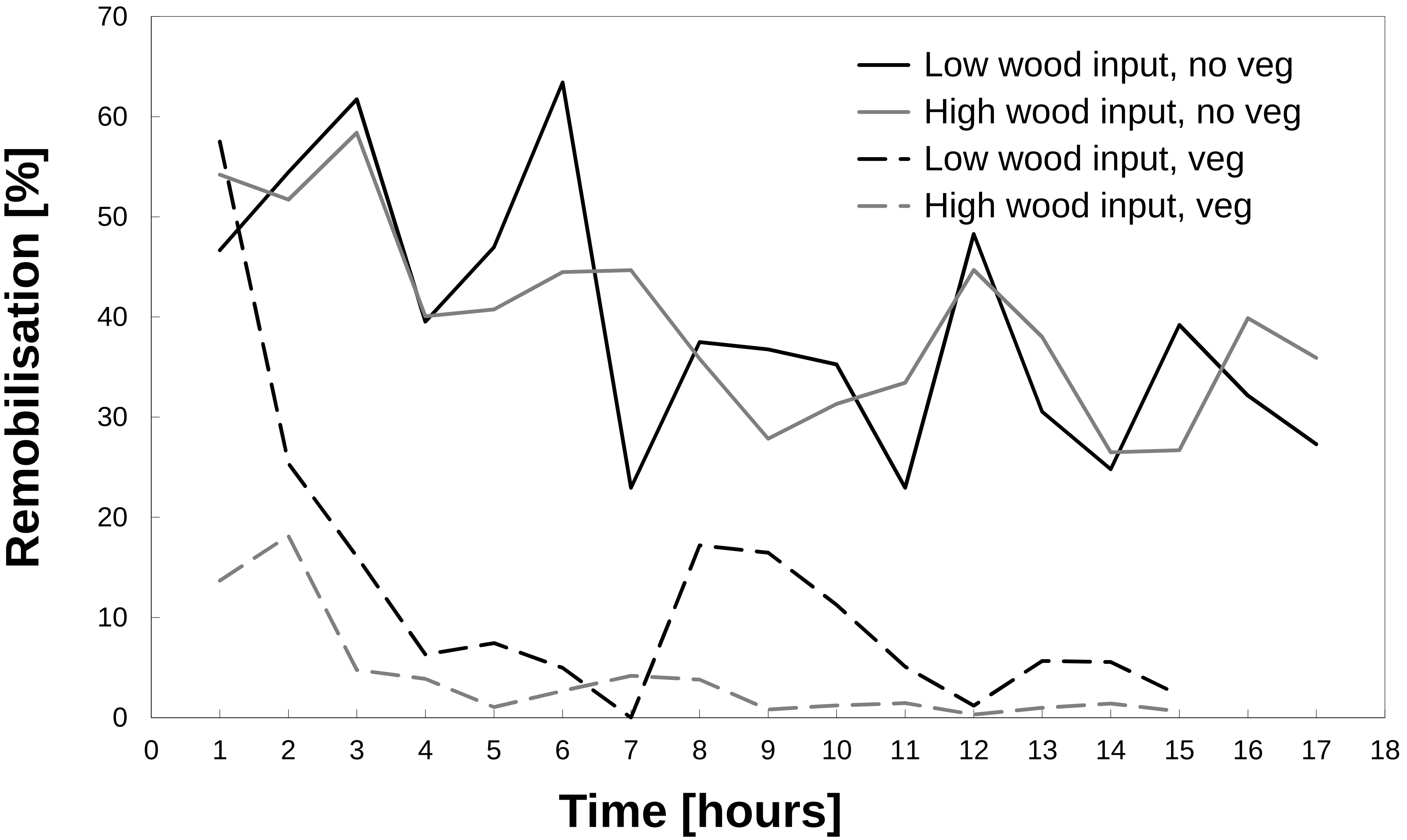

A)
B)
C)
D)
Logs [%]
Logs [%]
Jam size [logs]
1
2
3-5
6-9
10-20
>20
Time [hours]
Time [hours]
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 6



Remobilisation [%]
Time [hours]
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Low wood input, no veg
High wood input, no veg
Low wood input, veg
High wood input, veg

Figure 7

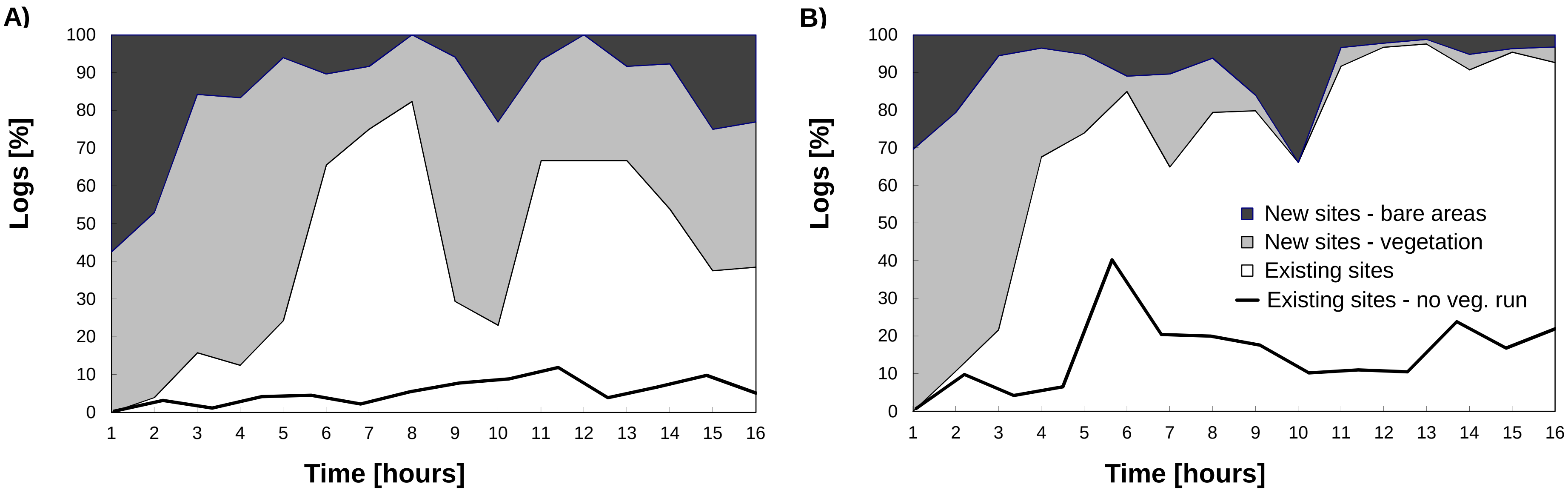

A)
B)
Logs [%]
Time [hours]
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
■ New sites - bare areas
▨ New sites - vegetation
□ Existing sites
— Existing sites - no veg. run

Figure 8

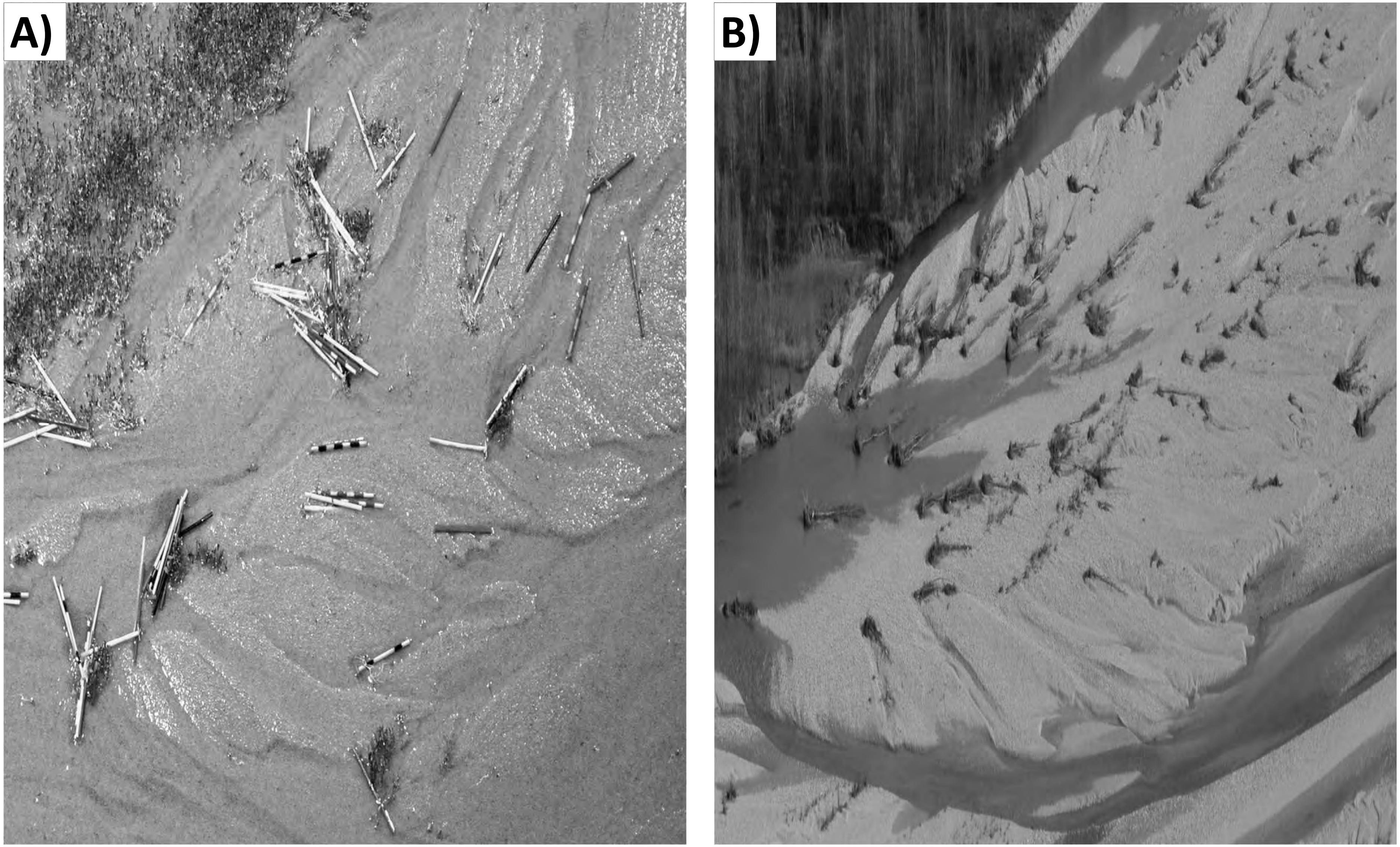


Figure 9