

# Effects of vegetation on braided stream pattern and dynamics

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[1] Investigations using a 16 m by 2 m recirculating experimental flume model of an ephemeral braided river indicate that the presence of large and erosion-resistant plants within the channel (e.g., trees or shrubs) can have a significant impact on channel pattern and planform dynamics. Simulations show that these plants have two effects. First, they act as obstructions, in some cases forcing the flow to divide. This flow separation can allow the deposition of a small island immediately in the lee of the plant splitting the channel. The net result is a substantial increase in the number of channels and, correspondingly, the braid index. This is in direct contrast to previous studies, where increased levels of vegetation in perennial streams have decreased the braid index. Second, the plants stabilize braid bars and can form relatively stable islands in their lee, significantly reducing the longitudinal migration of islands typically associated with braided rivers.

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## 1. Introduction

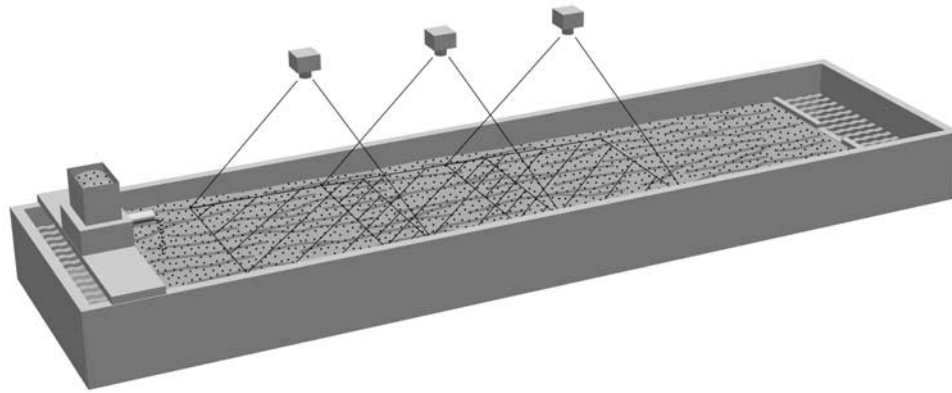
[2] Vegetation has a complex relationship with river dynamics and morphology. It can substantially alter flow velocities and direction, as well as change the cohesion and physical resistance of bank material. For example, *Thorne* [1990] identified several effects that vegetation can have on river bank erosion. It can (1) slow near bank velocities, reducing boundary shear stresses and thus erosion, (2) reduce soil erodibility, (3) increase bank strength though soil reinforcement and by improving bank drainage, and (4) lead to accretion at the base of the bank, especially on the inside of a meander. Altering these flow and bank properties can then affect channel pattern [Mackin, 1956; Nanson and Knighton, 1996; Millar, 2000]. For example, *Huisank et al.* [2002] describes how vegetation limits bank erosion and sediment supply in the Russian Usa catchment, which prevents it from becoming braided, thus maintaining a meandering/anabranching form. Riparian vegetation can also alter the width, depth and velocities of streams [Graf, 1978; Huang and Nanson, 1997]. *Hey and Thorne* [1986] demonstrated that the widths of channels with densely vegetated banks were approximately 50% narrower than similar but sparsely vegetated channels.

[3] However, while vegetation can exert considerable controls on channel behavior, the type and concentration of vegetation is in turn largely controlled by river dynamics. For example, vegetation may become buried by the deposition of a gravel bar or splay, or have difficulty becoming established in areas that are frequently submerged. *Hupp and Osterkamp* [1996] described how riparian vegetation is largely controlled by patterns of erosion and deposition along braided streams in the Great Plains area, and in channelized streams vegetation patterns were governed by cycles of degradation and aggradation. In a comprehensive

study, *Johnson* [2000] also demonstrated how river dynamics affects vegetation by monitoring tree and sapling distribution at 296 sites on the River Platte, Nebraska. He showed that tree recruitment was largely controlled by stream flows in June, whereas the mortality of seedlings was controlled by summer floods burying plants, and by ice flows disturbing the bed in winter.

[4] These studies have focused largely on perennial streams, whereas in ephemeral streams patterns of vegetation growth can be significantly different, as during dry periods where there is little or no flow, vegetation can grow anywhere across the channel belt. *Hupp and Osterkamp* [1996] observe that in semiarid regions, areas of riparian vegetation are closely related to patterns of water availability. Indeed, the channel bed and low points such as scour holes may become preferential locations for colonization as they lie closer to the water table. When water levels rise the survival of a plant then depends upon the flow strengths at its location, and how well established or resistant to flow the plant has become. Surviving plants may then in turn influence channel dynamics. For example, *Nakayama et al.* [2002] recorded a series of “obstacle marks” or small islands deposited in the lee of vegetation on the Burdekin River, Australia. These features ranged in size from small scour features around tufts of grass to substantial islands in the lee of trees that caused flow to separate. Some of these islands may then become ideal sites for fresh colonization adding strength to the island as well as causing it to grow. A similar process has been suggested as being responsible for the formation of anabranching channel patterns in central Australia [Tooth and Nanson, 2000]. However, much uncertainty surrounds precisely how such large vegetation interacts with flow, and what effect it may have on depositional features and channel planform.

[5] To assess the impact of vegetation on river channels under more controlled conditions, researchers have used laboratory based flume experiments. For example, *Bennett et al.* [2002] used plastic rods to simulate how vegetation



**Figure 1.** Schematic diagram of flume and camera configuration.

may promote a straight channel to meander. More recently, a series of experiments conducted at the St. Anthony Falls Laboratory, Minnesota, by *Gran and Paola* [2001] and *Tal et al.* [2004] have used live alfalfa shoots grown in the flume to simulate the effect of vegetation colonization on braided rivers. These novel experiments have shown that in perennial streams increased vegetation densities growing on unsubmerged bars or floodplains can stabilize banks, reduce lateral erosion, increase mean channel depths and significantly reduce the ratio of channels per cross section (the braid index (BI)). Importantly, studies of this kind begin to explore the effects of vegetation not only on linear bank erosion but also on two-dimensional channel pattern evolution.

[6] Reviewing the studies described here, it is apparent that there are contrasting effects generated by the effect of different plant types on flow patterns, as well as how in turn the plants are affected by the flow, in these different environments. For example, in a perennial stream grasses may colonize a bar. Their small individual size may have limited effects on flow patterns, and as they are relatively shallow rooted they may be removed by the flow. However, they have a dense spatial coverage, stabilizing a large area. In contrast, in an ephemeral setting, the *Pandanus* palm has deep roots, a thick stem and is resistant to flow, but it only occupies and stabilizes a small area of a channel bed or bar. Furthermore, these plants are more significant hydraulic structures and may lead to flow divergence and deposition in their lee, as previously described. This raises important research questions as to how these differing processes may alter channel pattern and dynamics across a range of environments. To address these issues, this paper describes a series of flume experiments carried out at St. Anthony Falls Laboratory during the summer of 2003. Over 70 experiments were conducted examining the impact of coarse vegetation, at different densities, on braided channel pattern and dynamics, and these were compared to previous flume experiments [*Gran and Paola*, 2001; *Tal et al.*, 2004].

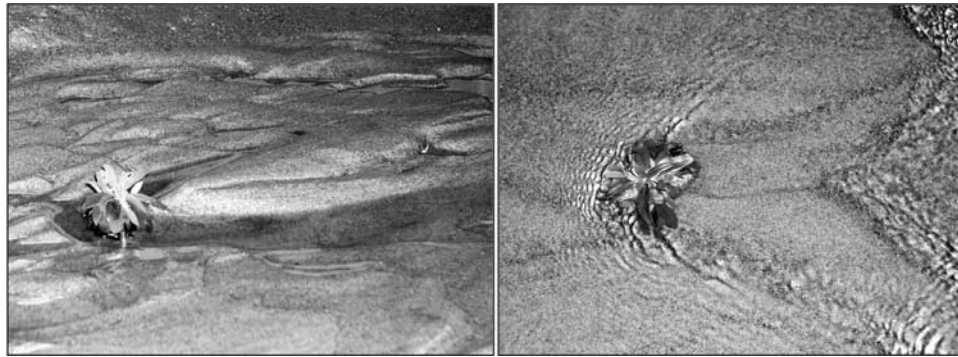
## 2. Methods

[7] The experiments were conducted in a 2 by 16 m water-recirculating flume (Figure 1). A sediment feeder was located where water was introduced at the top of the flume. Three digital cameras were positioned above the mid portion of the flume spaced 2.5 m apart, covering 7.5 m

of the channel and the full width (Figure 1). These were linked to a laptop computer and synchronized to take pictures simultaneously at prescribed intervals (typically 60 s). The channel bed slope was set to 0.015 and a mixed “lakeland” sand was used with a  $D_{50}$  of 0.36 mm. The grain size and gradient were determined, using the tilting bed flume facility at St Anthony Falls Laboratory, as the smallest grain size and lowest slope sufficient to prevent the formation of ripples. Froude numbers were measured for all series of runs, within individual channels, and varied from 0.38 to 0.98. Reynolds numbers were similarly calculated and ranged from 600 to 2400. This indicates that flow was both subcritical and turbulent, as would be expected in a natural braided river. Typical particle Reynolds numbers were calculated and ranged from 85 to 159. During the experiments, mean channel widths of 0.169 m and mean flow depths of 0.0049 m were measured and these compare favorably with similar models [*Gran and Paola*, 2001; *Ashworth et al.*, 2004]. Blue dye (Food and Drug Administration Blue number 1) was added to the water in order to differentiate between channels and bars on camera images. To simulate trees/shrubs, three different varieties of similar sized bedding plants were used, *Gomphrena*, *Impatiens* and *Petunias*. They were commonly available from local markets and varied in size from 5–10 cm tall with a single stem emerging from the root ball which rapidly divided into multiple stems. The root ball was approximately 5 cm in diameter and 5–8 cm deep. The plants were flexible and in strong flows could deform with the flow. They were similar in miniature form to low trees and shrubs typical of ephemeral streams, for example the *Pandanus* palm, the teatree (*Melaleuca glomerata*) and other shrubs (*Acacia* spp.). When planted, a small hole was made in the bed of the flume, the root ball inserted and gently packed down. The root ball contained the soil that the plant was grown in and as the sand was frequently wetted/saturated it tightly bedded down the plant. Therefore the plants not only simulated the hydraulic effects of the stem, but also of the subsurface root system if it were exposed by erosion. Over 70 individual runs were carried out and for ease of presentation are divided in to four series’ of runs.

### 2.1. Series 1

[8] These runs were designed to determine how varying plant densities affected the channel. This started with a leveled flume bed over which a discharge ( $Q_w$ ) of 3.6 l/s



**Figure 2.** (left) Oblique view of plant and the island formed in its lee with no flow. (right) Plan view with flow. In both pictures the plant is 5 cm in diameter, and flow was from left to right.

was run with a sediment feed rate ( $Q_s$ ) of 45 kg/hour. After an hour, when a “stable” planform had established (see sections 3 and 4 and Figure 4), the flume was stopped. Plants were then planted at random locations across the full width of the flume from 4–9 m from the flume head, at an initial density of 2 plants/m<sup>2</sup>. The flume was restarted and run for a further hour using the same water and sediment feed rates. Throughout the runs, photographs were taken at 60 s intervals. The flume was then leveled and the above sequence repeated a further four times increasing the plant densities from 2 to 4, 6, 8 and 10 plants per m<sup>2</sup> respectively. The  $Q_w$  of 3.6 l/s is intentionally high, and was chosen during trial runs as being sufficient to fill the width of the flume when initially leveled, as well as being deep enough to submerge the base of the plants. The sediment feed rate was also determined during these runs as being sufficient to maintain a stable long profile.

## 2.2. Series 2

[9] This sequence of runs was identical to series 1, except that a 50/50 mixture of fine (0.1 mm  $D_{50}$ ) and Lakeland (0.36 mm  $D_{50}$ ) sand was added. This series was designed to see whether the addition of cohesive sediment would influence pattern dynamics.

## 2.3. Series 3

[10] After series 2, the top 5 cm of sand was replaced, removing the fine sand mix. A series of runs was then carried out with identical flow durations, sediment and water discharges as series 1, except that the freshly leveled flume surface was then planted and run. After 1 hour the flume was stopped, the plants were removed, and the flume was run for a further hour. The surface was then leveled and replanted and the sequence was continued with increasing plant densities from 2, 4, 6, 8, and 10 plants per m<sup>2</sup>. This procedure was designed to firstly determine whether the initial conditions (planted or nonplanted) altered the flume behavior.

## 2.4. Series 4

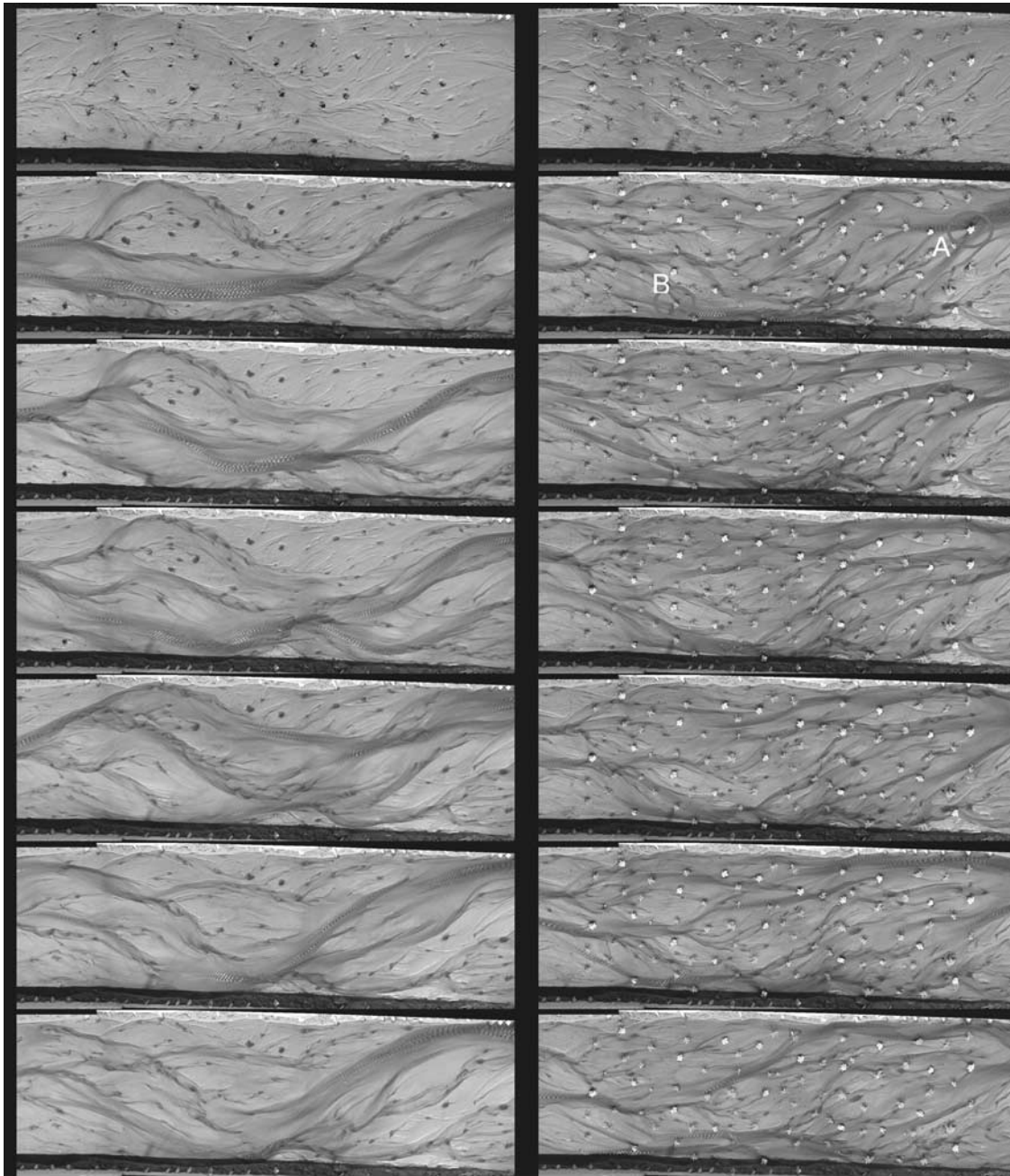
[11] This series of runs was carried out with a lower water discharge of 1.5 l/s in order to see whether lower-flow discharges would produce similar effects. Sediment feed rates were also dropped to 10 kg/hour which maintained an equilibrium long profile. The length of each run was extended to 4 hours giving approximately the same overall sediment throughput as series 1–3. In these runs the flume was run to a braided pattern (for 4 hours), then planted at

2 plants/m<sup>2</sup>, run for 4 hours and halted. Plants were then removed and run for a further 4 hours, then planted at 4 plants/m<sup>2</sup>. This plant/no-plant sequence was repeated up to a density of 12 plants/m<sup>2</sup>. As per series 1–3, photographs were taken every 4 min.

## 3. Results

[12] For all four series of runs the plants caused flow to diverge and allowed a small island to form in their lee, as detailed in Figure 2. The islands varied in size from 0.05 to 0.5m in length and up to 0.05m in height above the local channel bed. Figure 3 illustrates how this affected the channel pattern over the whole of the flume, with a sequence of 14 images from series 4 running with a bare, nonplanted surface through to the introduction of 8 plants per m<sup>2</sup>. Readers are encouraged to view a series of digital video clips of channel development which can be viewed from on the Web at <http://www.coulthard.org.uk> and provide a more detailed view of how these sequences develop over time. Figure 3 (right) shows how the addition of plants after Figure 3 (left) dramatically alters the planform configuration of the experimental braided channel. The marked points labeled A and B show how plants located in the thalweg of the nonplanted channel split flow and allow the development of an island in the lee of the plant. The channel splits into two and these channels persist throughout the duration of the run. This and similar activity around other plants rapidly and significantly increases the number of channels and thus the BI of the channel after planting. In order to quantify these changes, braid indices for each run was determined using the method of *Richards* [1982], whereby the BI equals the ratio of total active channel length divided by the valley length. To determine this, the stream center lines of the active channels (where flow depth was greater than 0.002 m) were digitized from the digital photographs of the center section, the lengths totaled and divided by the length of the reach. In series 1–3 the BI was calculated from the image taken after 45 min of flume operation. Figure 4 shows how the BI for four nonplanted runs (from series 1 and 2) initially rises then drops, stabilizing after 30 min. Likewise, for the planted runs the BI rises and stabilizes after 30 min, indicating that 45 min is a representative time at which to assess the BI. In the low-flow runs (series 4) the image was taken after 3.5 hours of flume operation. Figure 5 shows the braid indexes for series 1–3 demonstrating how increasing the number of plants



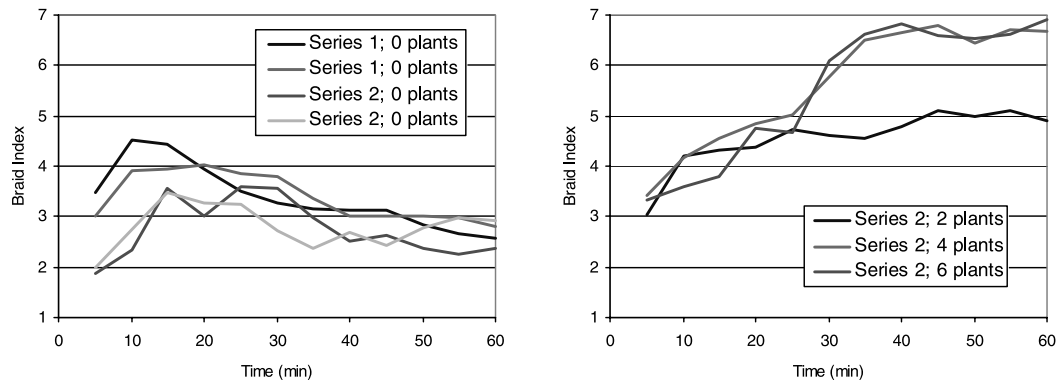


**Figure 3.** Images taken from consecutive low-flow runs ((left) 0 plants and (right) 8 plants/m<sup>2</sup>). These images show a 7 m stretch of the flume, 3 m from the top, with the planted section from 4 to 9 m. The images are a montage of three digital still pictures. The images are taken at 40 min. intervals and run sequentially from top to bottom, left to right. “Holes” in the bed at the top of Figure 3 (left) are where plants have been removed from the previous run. Flow is from right to left. See color version of this figure at back of this issue.

within the channel considerably increases the number of channels in a reach. The mean BI for non vegetated runs is substantially less than that for vegetated runs except for the lower vegetation densities. Figure 6 shows how the low-flow simulation (series 4) responded similarly.

[13] A further impact of the plants was to change the stability of the braid islands. An existing island with a plant near its head or an island that formed in the lee of a plant appeared stable, with the plant “pinning” the island. Furthermore, plants located at the edge of an island appeared to

slow lateral erosion. This was considerably different from nonplanted runs where islands and bars migrated laterally and downstream as typical of braided rivers [e.g., *Ashworth et al.*, 2000]. This is apparent in Figure 3, where the bare run shows lateral channel movement as well as the downstream migration of a bar feature at the top of the flume. In contrast, the planted runs also show changes, but these appear far less than the bare channel. This is easier to visualize using the video clips available at <http://www.coulthard.org.uk>. In order to quantify these changes,



**Figure 4.** Braid index changes over time for (left) nonplanted and (right) planted runs.

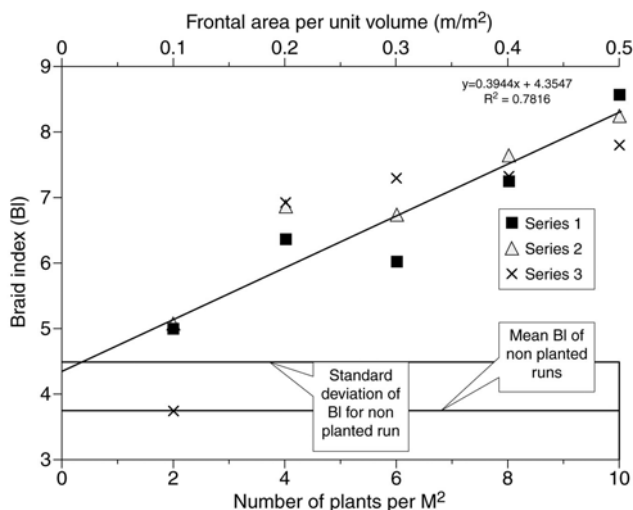
image analysis techniques were used to determine the changes in channel position between consecutive digital photographs. A program called “Image Math” developed by Michael Kelberer at St. Anthony Falls Laboratory allowed the user to identify key color features from the images, in this instance the channel was easily identifiable due to the blue dye added to the water. The program would then pick out these features (here with a hue value of 80–210), compare them to similar color features in consecutive images and calculate the number of pixels that were lost, gained or unchanged. Figure 7 illustrates output from the program where the shading corresponds to areas lost, gained or unchanged. Here the silhouette of plants not selected are identified with arrows. One problem encountered with this technique was that for series 1–3 the flume was leveled either before or after each planted run. This meant that after leveling, there was considerable channel movement and sediment reworking as the channel adjusted and incised into the newly leveled surface, giving disproportionately high movement readings. Thus we could not realistically compare movement between planted to nonplanted runs for

series 1–3. Therefore movement analysis concentrated on series 4 where the only disturbance between runs was the addition and removal of plants (see above). Often little change was recorded between individual photographs (4 min interval) so differences between images at 30 min intervals were recorded and are presented in Figure 8. One further difficulty with this technique is that the introduction of plants divides the flow, increasing the number of channels, in turn raising the number of channel edges. Therefore doubling the braid index also doubles the potential areas for image analysis to show change. To compensate for this, we divided the mean number of pixels moved per run by the braid index, and this is presented in Figure 9. This shows a clear negative relationship between the pixels moved and plant density. As shown in Figure 8, even when not normalized by the BI, there is a similar reduction, indicating the stabilizing effect produced by increasing plant density.

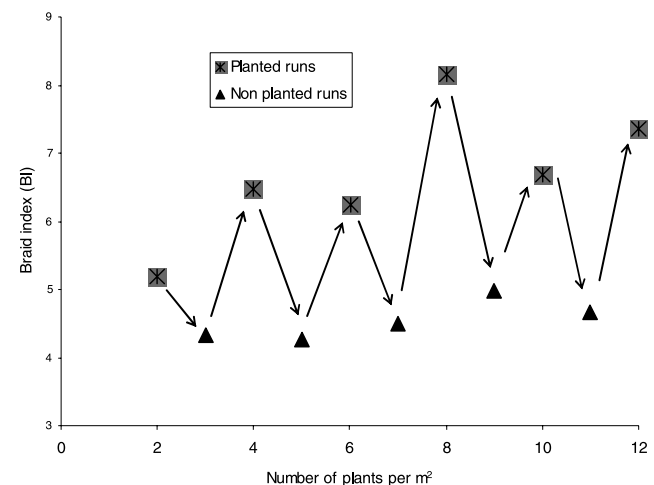
## 4. Discussion

### 4.1. Braid Index Changes

[14] These experiments show a marked increase in BI with increasing plant density (Figure 5). This contrasts with *Gran and Paola's* [2001] study (Figure 10), where there is a decrease in BI with plant density. Whereas initially appearing contradictory, both results are complementary. In their experiments, *Gran and Paola* [2001] simulated a perennial braided stream typical of temperate climates, where vege-



**Figure 5.** Braid index against number of plants per  $m^2$  for series 1–3. Here the frontal area per unit volume is also plotted. For this calculation it was assumed that the plants were never fully submerged, had an average width of 5 cm, and can therefore be described by a cylinder 5 cm in diameter.



**Figure 6.** BI from the low-discharge simulation (series 4).



**Figure 7.** Output from the Image Math program which shows areas of no change (black) and areas which have been gained (light gray) and lost (dark gray).

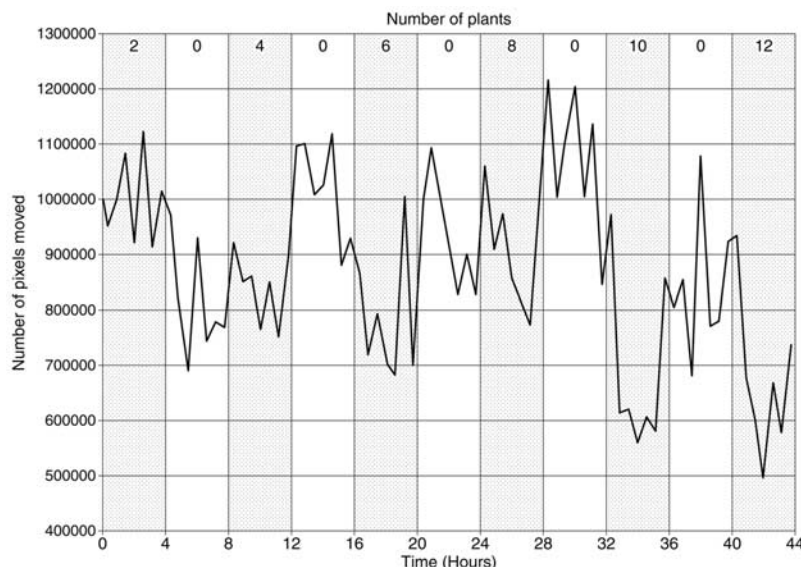
tation grows where there is little or no flow. As vegetation densities increased the channel was forced to occupy smaller channels, decreasing the BI. More recent experiments again using alfalfa (Tal, personal communication, 2004) show that increasing plant densities by reseeding the floodplain causes vegetated areas to encroach toward the channels, thus reducing the BI. In that case, Gran and Paola's and Tal's work in perennial streams channel position determines where vegetation can or cannot grow. By contrast, these experiments are more representative of ephemeral streams found in arid/semiarid areas where vegetation is less widespread due to lower rainfall. Here deep rooted vegetation (e.g., trees and shrubs) can grow within the ephemerally flowing channel and, as these experiments have illustrated, increase the BI by disrupting channel flows and encouraging bar development. Thus vegetation determines channel position.

[15] In climates verging between temperate and arid the distinction between whether vegetation is controlling channel position (as here) or vice versa may be a small one. However, in reality it is highly likely that both processes are operating together, for example an island may be formed initially in the lee of a bush or tree, with the whole island then becoming colonized and strengthened with smaller vegetation, e.g., grass or scrub. There is an ideal opportunity to simulate this joint interaction in future flume experiments by combining the action of small plants (as carried out here) with growing alfalfa [Gran and Paola, 2001; Tal et al., 2004].

[16] When comparing the two experiments it should be appreciated that Gran and Paola's vegetation type is significantly different with a larger number of smaller stemmed plants. To aid such comparisons, on Figures 5 and 10, vegetation densities are also plotted as frontal area per unit volume. Here we can see that similar ranges (0.2 to 0.5 for this experiment and 0.1 to 0.9 for Gran and Paola [2001]) result in these strikingly different results. This suggests that it is the type and organization or grouping of vegetation that affects the braid index rather than the overall obstructive effect on the whole flow.

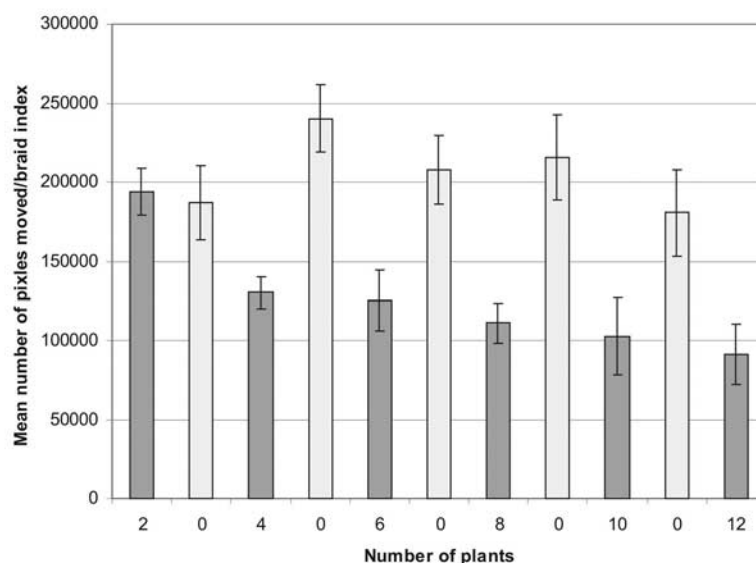
#### 4.2. Channel Pattern Dynamics

[17] Figures 8 and 9 demonstrate how channel migration (both lateral and downstream) is significantly altered by the addition of coarse vegetation, with rates of channel movement reduced from a maximum of 1,210,000 pixels to a minimum of 480,000 pixels per 30 min (30.9% and 12.3% of the flume surface, respectively). There is also a clear relationship between increased numbers of plants and a decrease in movement (Figure 9). Small numbers of plants (4 or less per  $m^2$ ) appear to have little impact on movement, despite altering the BI, which may be as plant densities are low enough to allow channels to pick their way around the plants. Above 10 plants per  $m^2$ , reductions in movement rate tail off and these experiments were not continued above 12 plants per  $m^2$  due to the large number of plants required. However, it is suggested that above a certain density,



**Figure 8.** Number of pixels moved per 30 min interval during series 4.





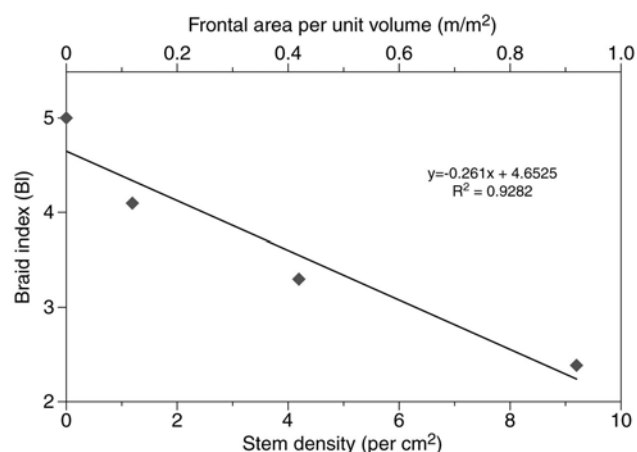
**Figure 9.** Number of pixels moved when divided by the braid index, normalizing for increased braid index. Standard deviation of mean/braid index is plotted as error bars. Dark bars correspond with planted runs, and light bars correspond to bare.

movement rates would stabilize as the channel is so densely planted, streams are forced to erode plants from their path. This effect was observed in an additional short run, where channels pushed through a 2 by 2m reach of the flume packed with 25 plants per  $m^2$ . *Gran and Paola* [2001] also showed that increasing vegetation densities decreased mobility rates, however, direct comparisons are difficult as *Gran and Paola* [2001] use a “topographic correlation coefficient” to describe reductions in movement rates. Despite both experiments having similar changes in frontal area per unit volume, reductions in movement rates are achieved here with comparatively fewer isolated “stands” of vegetation.

[18] While it is logical that trees may “pin” islands, restricting downstream migration, this does not explain the observed drop in lateral erosion. Indeed, the coarser isolated groups of vegetation used here cannot increase bank stability, and thus reduce lateral erosion, over the larger areas that the more evenly distributed alfalfa can [*Gran and Paola*, 2001; *Tal et al.*, 2004]. Furthermore, are reductions in channel movement local, caused by vegetation directly hindering erosion; or is the increase in the BI reducing average shear stresses, thus decreasing movement over the whole reach? Unfortunately, the spectral analysis technique used here to determine movement rates can at present neither discriminate between lateral and downstream movement, nor determine whether reductions in movement are local, linked to the presence of a plant, or operating over the entire area. One possible explanation, however, for the drop in channel movement rates may be provided by *Ashworth et al.* [2000]. They suggested that the deposition of a bar within a braided channel deflects flow to the bank, forcing lateral erosion. This starts a sequence whereby material from this lateral erosion forms a central bar which again diverts flow causing lateral erosion, and the process continues. In these experiments, by stopping or slowing the downstream migration of bars we may be thus

stopping or slowing lateral erosion, which suggests that the process identified by *Ashworth et al.* [2000] is a vital one in the formation of braided channels. It should also be noted that the spectral technique used here cannot differentiate between channel migration and changes caused by channel surface area shrinking (due to reduced local discharges or channels deepening and narrowing) or expanding (caused by increased local discharge or channels becoming shallower and wider).

[19] Figure 8 demonstrates that when plants are added to the flume, reductions in channel movement rates occur rapidly. For runs with 4, 6, 8, 10, and 12 plants (Figure 8),



**Figure 10.** Braid index related to stem density of alfalfa shoots after *Gran and Paola* [2001]. The frontal area per unit volume is also plotted. For this calculation it was assumed that the alfalfa plants were never fully submerged, had an average stem width of 1 mm [after *Gran and Paola*, 2001], and can therefore be described by a cylinder 1 mm in diameter.

**Table 1.** Details of Experimental Flume Setup From These Experiments (Series 1–4) and From Three Other Studies

	Study				
	Series 1–3	Series 4	<i>Gran and Paola</i> [2001]	<i>Stojic et al.</i> [1998]	<i>Ashmore</i> [1985]
Length, m	16	16	9	11.5	10
Width, m	2	2	2	2.9	2.3
Slope	0.015	0.015	0.014	0.012	0.01–0.015
Grain size $D_{50}$ , mm	0.36	0.36	0.5	0.7	0.7
Water input $Q_w$ , L/s	3.6	1.5	3.5	1.5	1.2–4.5

there is a sharp reduction in movement during the first 30 min of each run. Some increases toward the end of these runs may be due to movement rates being calculated from images taken as discharges were being lowered/stopped. Interestingly there is considerable variation in movement (up to 50%) during these runs, despite movement readings being calculated every 30 min. The BI also shows rapid temporal changes when plotted against time (Figure 4) with the BI stabilizing approximately 30 min after the plants were added. It is however important to note that changes in BI may not necessarily be directly linked to number of pixels gained or lost.

#### 4.3. Initial Conditions and Grain Size Effects

[20] The changes in initial conditions (series 1–3) were designed to answer the conundrum as to whether changes in the BI were influenced by the flume starting with a braided channel and then being planted, or a bare flume surface with vegetation. In other words, does vegetation growth and thus the BI relate to previously formed channels, or do the river channels develop around vegetation? This is an important issue considering differences in plant colonization patterns between perennial and ephemeral streams. Figure 5 shows no difference between series 1, 2, and 3, indicating that the initial conditions have little or no effect. This is reinforced by Figure 6 that shows how the BI adjusts rapidly following vegetation planting or removal. Again, this demonstrates the significant effect that sparse levels of coarse vegetation can have on determining channel behavior. Series 2 was run with a mixture of coarse and fine sediment to ascertain whether added cohesion from fine sediment would alter the BI or island formation. In these experiments this appeared to have no effect.

#### 4.4. Scaling

[21] These experiments were not designed to be a scale model of any real river system. They should therefore be viewed as exploratory or hypothesis testing experimental models. To test how coarse vegetation interacts with ephemeral braided rivers these experiments have been deliberately set up with slopes, grain sizes, water and sediment discharges that “promote” braiding, and have been shown to braid in previous experiments (see Table 1). As such, it could be inferred that this experiment is an analogue for comparable modeling studies shown in Table 1, but I would reiterate that these simulations are not based on any system.

[22] I do believe, however, that the impact that these plants have on the braided channel pattern and dynamics is not diminished by the “abstract” nature of the experiment. The underlying relationship between the plants and the

braiding pattern which we are simulating here appears very robust. This is reinforced by the similar results from a relatively large number of runs, which varied the plant numbers, grain size, initial conditions and discharges.

#### 4.5. Implications and Further Discussion

[23] For managing braided river environments these experiments show that the addition of trees or hydraulically similar structures could be used to stabilize the braided pattern. While these experiments are designed to show how vegetation growth in ephemeral channels can affect channel pattern and dynamics, these results should not be confined to ephemeral systems. If trees/shrubs have sufficient time to colonize parts of a braided system in a perennial environment, there is no reason why the channel behavior should not follow the same pattern as described by these experiments. Indeed, *Gurnell et al.* [2001] describe how similar islands can form in the lee of coarse woody debris deposited in the Fiume Tagliamento, Italy.

[24] The decrease in channel and bar movement caused by the introduction of the plants raises the question as to whether these streams are still braided? Are the features still bars or have they stabilized to become islands? Snapshots of the channel are indistinguishable from a braided system, but the dramatic drop in downstream and lateral movement suggests that it has been altered significantly from a “typical” braided system. *Gran and Paola* [2001] suggest that in their alfalfa based experiments that the channel stabilizes to that resembling a “wandering river.” However, in the experiments presented here, even when heavily planted there is still some channel movement, and the vegetation used in these experiments does not have the same “choking” capacity as the alfalfa. Therefore I would suggest that these experiments may have shifted the braided pattern toward the first stage of alluvial anabranch development, as suggested by *Tooth and Nanson* [2000].

#### 5. Conclusions

[25] These experiments show how relatively sparse levels of flow resistant vegetation can split flow and cause the deposition of islands in their lee. In turn, this can increase the braid index of a braided channel as well as reduce rates of downstream bar migration and lateral erosion. While identification of how such islands can form behind vegetation or woody debris is not new [see *Gurnell and Petts*, 2002, pp. 587–588; *Nakayama et al.*, 2002], this study is the first to quantify its effect on a braided stream and to illustrate how it alters the planform dynamics. As such these results have important implications for our understanding and management of braided rivers, as well as how vegetation interacts with flow and sediment erosion/deposition.

[26] **Acknowledgments.** This material is based upon work supported by the STC Program of the National Science Foundation under agreement number EAR-0120914. This project was funded as part of the NSF National Center for Earth Surface Dynamics (NCED) program. Stephen Tooth provided invaluable advice during project design and setting up the experimental runs. I wish to thank Jeff Marr, Luke Carlson, and the student technicians at St. Anthony Falls Laboratory, University of Minnesota, for their invaluable assistance in constructing and operating these experiments. I would also like to thank in particular Michal Tal and Chris Paola for their advice, assistance, encouragement and suggestions during the setup and operation of the experiments. This paper also benefited greatly from very detailed, perceptive, and objective comments from three anonymous referees.

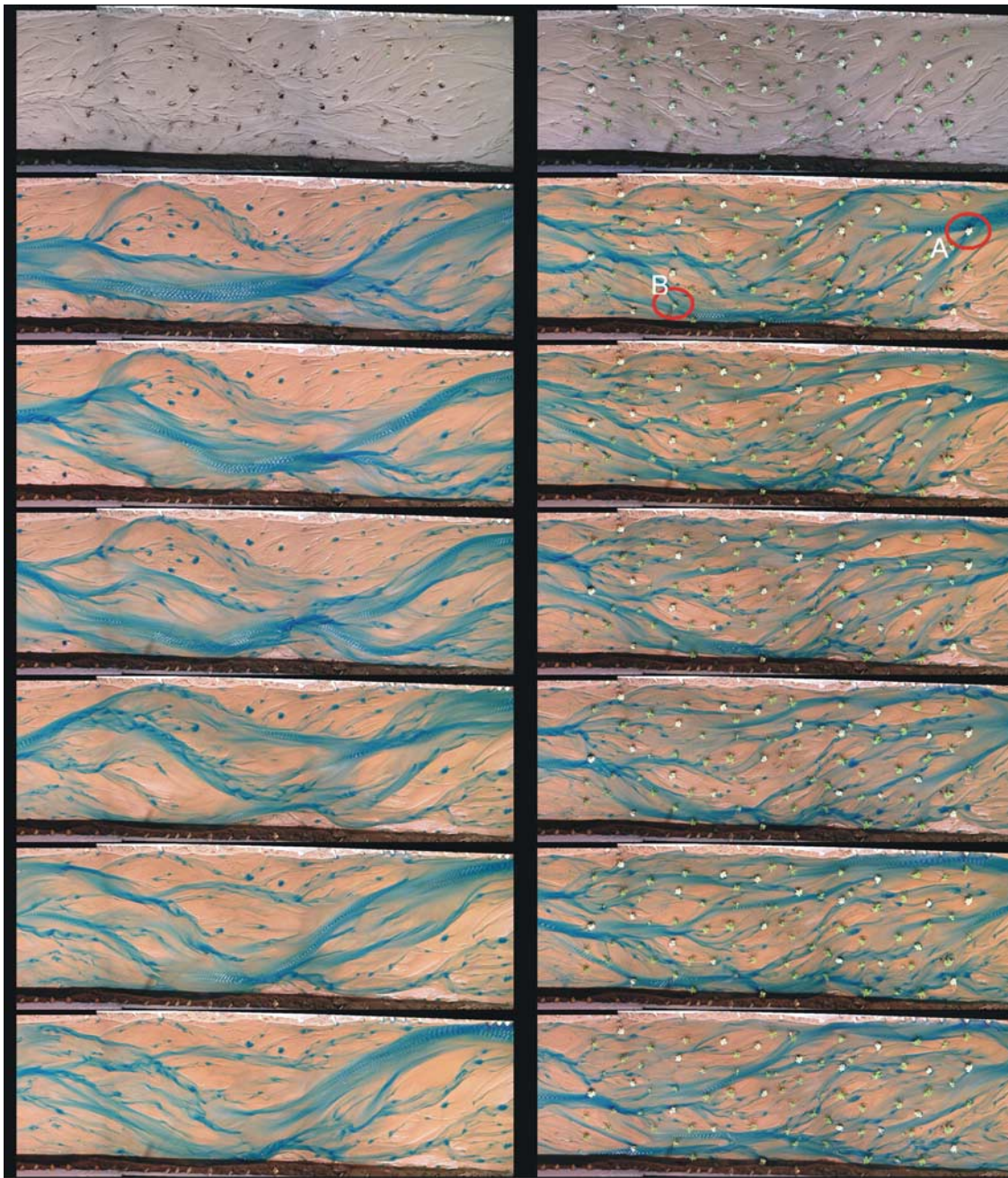


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**Figure 3.** Images taken from consecutive low-flow runs ((left) 0 plants and (right) 8 plants/m<sup>2</sup>). These images show a 7 m stretch of the flume, 3 m from the top, with the planted section from 4 to 9 m. The images are a montage of three digital still pictures. The images are taken at 40 min. intervals and run sequentially from top to bottom, left to right. “Holes” in the bed at the top of Figure 3 (left) are where plants have been removed from the previous run. Flow is from right to left.