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Effects of vegetation distribution on experimental river channel dynamics

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[1] Strong feedbacks exist between channel dynamics, floodplain development, and riparian vegetation. Earlier experimental studies showed how uniformly distributed riparian vegetation causes a shift from a braided to a single-thread river because riparian vegetation stabilizes the banks and focuses discharge off the floodplains into channels. These experiments tested anemochorously distributed vegetation, i.e., by wind, whereas many riparian species in nature are also distributed hydrochorously, i.e., by flowing water. The objective of this study is to test experimentally what the different effects are of hydrochorously and anemochorously distributed vegetation on channel pattern and dynamics. The experiments were carried out in a flume of 3 m wide and 10 m long. We compared experiments with the two forms of vegetation distribution methods to control experiments without vegetation. To independently quantify bank retreat rate as a function of seed density and vegetation age, we used a small bank erosion test. In agreement with other work, the uniformly distributed vegetation decreased bank retreat, often stabilized banks and tightened meander bends. Vegetation seeds distributed by the flow during floods settled at lower elevations compared to the uniformly distributed vegetation. Inner bend vegetation stabilized a part of the point bar and hydraulic resistance of the vegetated bar forced water into the channel and over the floodplain. As a result, sediment was deposited upstream of vegetation patches. We conclude that seeds distributed by the flow during floods lead to island braiding: a patchy multithread river with stable vegetated bars, whereas vegetation uniformly distributed on the floodplain of a single-thread meandering river increases sinuosity and decreases bend wavelength. This implies that the combination of discharge variations and vegetation settling behavior has a large effect on the morphology and dynamics of rivers. The experimental approach opens up a wide range of possibilities to explore hydro-bio-geomorphological interactions with a high degree of control.

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1. Introduction

[2] The interaction between river morphodynamics and riparian vegetation development plays an important role on geomorphological processes and distinctive river patterns [e.g., *Kirkby*, 1995; *Gurnell et al.*, 2012; *Camporeale et al.*, 2013]. Here riparian vegetation is defined as the biotic community near the river banks, which is sustained by, and interacts with the flow [after *Hughes*, 1997]. Earlier experiments [*Gran and Paola*, 2001; *Braudrick et al.*, 2009; *Tal and Paola*, 2010] and numerical simulations [*Murray and Paola*, 2003; *Perucca et al.*, 2007] show that riparian vegetation has an important role in the development of a river. Riparian vegetation stabilizes the banks and reduces the number of active channels when uniformly distributed on the floodplain [*Gran and Paola*, 2001; *Murray and Paola*, 2003; *Tal and Paola*, 2010]. In such conditions vegetation has an important role in formation of a meandering river [e.g., *Bennett et al.*, 2002; *Braudrick et al.*, 2009]. However, these experiments and simulations all assume that vegetation settles wherever the conditions permit, which represents anemochorously distributed vegetation, i.e., by wind, whereas many riparian species in nature are distributed hydrochorously, i.e., by flowing water. In natural conditions, most of the time it may be rather a combination of both dispersion modalities, e.g., for *Populus* and *Salix* spp., but to unravel combined effects and possible interactions it first must be investigated what the effects of either one or the other distribution style is in isolation. Here we report on the comparison of river pattern experiments with uniformly distributed seeds and with seeds that are distributed by the flow. Control experiments are used to describe river pattern and dynamics without vegetation and a small bank erosion test is used to quantify the effect of vegetation density and age on bank erosion rates.

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[3] Multiple interactions between a dynamic river and riparian vegetation are present that influence the establishment of riparian vegetation. The establishment of riparian vegetation is determined by both biotic processes, i.e., seed dispersal, recruitment and vegetation growth, and abiotic factors, i.e., sediment types and substrate, and hydrologic processes such as uprooting by floods, drought, and burial [*Gurnell and Petts*, 2002]. These processes control sediment dynamics and lead to successive vegetation development along the channel [*Corenblit et al*., 2007]. In general, the duration and level of inundation, i.e., hydroperiod, control the spatial expansion of vegetation along a river reach [*Bertoldi et al*., 2011], affect the riparian vegetation patterns [*Osterkamp and Hupp*, 2010], and determine the dynamics of vegetation dispersal [*Edwards et al*., 1999]. The effect of floods on vegetation can be divided into hydrological effects, including mechanical damage, saturation of the soil, transport of seeds, and inundation influencing biochemical processes [e.g., *Blom and Voesenek*, 1996], and geomorphological impacts through erosion and deposition of sediment, where floodplain elevation determines the type of riparian vegetation that establishes [e.g., *Bendix and Hupp*, 2000]. Permeability of the substrate affects the settling of vegetation, e.g., fine sediment may retain moisture longer after the flood peak which extends the recruitment box where vegetation settlement may take place [*Perucca et al*., 2007]. Overall, the development of the riparian vegetation patch depends on; (1) resetting for pioneer species by the destruction of older vegetation, (2) dispersal of propagules, (3) germination of new plants in sediment deposited during floods, and (4) the absence of destructive floods which allows germination and vegetation growth [*Bendix and Hupp*, 2000; *Clarke*, 2002].

[4] In prior vegetation experiments, the natural distribution and establishment of riparian vegetation was ignored, as alfalfa (*Medicago sativa*) was manually and uniformly seeded on the floodplain as anemochorously distributed vegetation [*Gran and Paola*, 2001; *Braudrick et al*., 2009; *Tal and Paola*, 2010; *Perona et al*., 2012]. Yet hydrochory is an important process in colonization of riparian vegetation along the river [*Van Splunder et al*., 1995; *Nilsson et al*., 2010]. For example, experimental studies showed that seed deposition depends on hydraulic processes influenced by small-scale morphological characteristics [*Merritt and Wohl*, 2002; *Chambert and James*, 2009]. The dependency of vegetation on soil suitability, water availability, and river regime can create distinctive patterns in natural situations, and also reflect the combined disturbances thereof [*Bertoldi et al*., 2011]. River floodplains are often characterized by massive germination of propagules after floods in the spring. This results in the establishment of young riparian forest, while floods later erode the river banks and carry vegetation away [*Van Splunder et al*., 1995]. In this study, we isolate the variable of vegetation distribution, while other factors, e.g., settling rules for vegetation and flow regime, are considered to be constant.

[5] The ultimate bar and river pattern is determined by the channel width-depth ratio, which is controlled by the bank strength [see *Kleinhans*, 2010, for review]. Vegetation on the floodplain and banks, in turn, affects hydrological processes. Riparian vegetation increases hydraulic resistance [e.g., *Baptist*, 2003; *Gurnell and Petts*, 2006; *Bennett et al*., 2008], increases bank strength due to root systems [e.g., *Thorne*, 1990; *Pollen and Simon*, 2005; *Eaton*, 2006], decreases the effective flow shear stresses [e.g., *Abernethy and Rutherford*, 2001] and increases bar sedimentation [e.g., *Gurnell et al*., 2001]. For example, the growth of vegetation leads to sediment trapping, i.e., growing by vertical accretion [*Gurnell and Petts*, 2002; *Baptist*, 2003; *Braudrick et al*., 2009; *Bertoldi et al*., 2011]. In a positive feedback loop, higher elevations provide a better environment, i.e., the frequency of floods and scouring reduces, so that former bare gravel bars become the new floodplain surface [e.g., *Corenblit et al*., 2007; *Gurnell et al*., 2012].

[6] During a number of prior flume studies vegetation (Alfalfa) was introduced to stabilize the banks and decrease the number of channels. Stronger banks resulted in a lower width-depth ratio, which is important in sustaining a meandering river [*Braudrick et al*., 2009]. Weaker banks led to channel widening, so that midchannel bars could develop. Alfalfa seeded on a braided experimental river stabilized the banks and led to local bend migration, forming a pattern best characterized as wandering [*Gran and Paola*, 2001; *Tal and Paola*, 2010]. *Bennett et al*. [2002] showed that adding vegetation alternately in flow direction of a straight channel promoted meandering, due to formation of alternate bars at the vegetation locations and bank erosion at the opposite side of the channel. Furthermore, *Perona et al*. [2012] showed that riparian vegetation is not a passive element in the river but, instead, it interacts with the flow, for instance through vegetated bar islands that divert the flow.

[7] The objective of this study is to assess the impact of different forms of seed dispersal methods on the river morphology of a meandering river. Small systematic tests were conducted to identify the effect of vegetation on bank stabilization. We conducted experiments where plant seeds were either uniformly distributed on the floodplain, or where seeds were distributed by the flow during floods. Subsequently, we examined the effect of the different seed dispersal methods on (1) bank stabilization, (2) hydraulic resistance, (3) channel dynamics, and (4) the resultant vegetation pattern. In our earlier work, we showed that a fluvially formed cohesive floodplain with fines in specific areas also decreased bank erosion rates and led to larger meander bends [*Van Dijk et al*., 2013]. For such systems, *Gurnell* [2007] suggested that vegetation is established at the same location as fine sediments. The present paper complements the work of *Van Dijk et al*. [2013] by controlled investigating the effects of riparian vegetation on experimental river morphodynamics.

2. Experimental Setup, Methods, and Materials

[8] The experiments were set up to represent a gravel-bed river dominated by bed load transport. The design conditions were not based on direct scaling from a particular natural river but, instead, on a minimization of scaling issues, i.e., low sediment mobility and scour hole formation [*Van Dijk et al*., 2012]. Alfalfa (*Medicago sativa*) was used [as in *Gran and Paola*, 2001; *Braudrick et al*., 2009; *Tal and Paola*, 2010; *Perona et al*., 2012] to represent riparian vegetation. To assess the one-way effects of channel dynamics on vegetation establishment and vice versa whilst

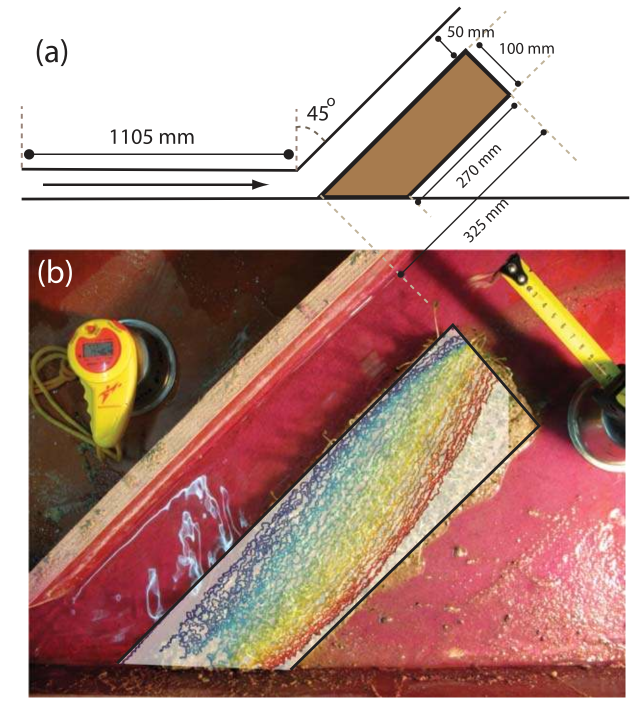

Figure 1. Setup of the bank erosion experiment to derive erosion rates. (a) Setup of the inlet channel and the experimental sediment block. (b) Initial image for vegetation experiment with colored lines as indication for bank line retreat derived from subsequent images.

excluding other factors, we performed several experiments. First, we quantified the effect of vegetation density and age on bank erosion rates at the same scale as in the river experiments in a small-scale bank erosion test setup to determine appropriate seeding densities. Second, we performed five stream table experiments (not shown) to determine appropriate seeding density, suitable seed supply rates and flood discharge. Here we show the results of two large experiments with entire river reaches where we varied the method of vegetation distribution: (1) uniformly distributed by hand on the floodplain, and (2) vegetation seeds distributed by the flow. These experiments are compared with three control experiments without vegetation but with conditions and sediments that bracket those in the vegetation experiments. These controls demonstrate the insensitivity of the morphodynamics to the discharge regime and the exact particle size distribution relative to the importance of vegetation distribution.

2.1. Bank Erosion Tests

[9] To obtain specific knowledge on riparian vegetation and bank stabilization in a scaled experiment, a bank erosion experiment was conducted [*Kleinhans et al*., 2010; *Van de Lageweg et al*., 2010; *Van Dijk et al*., 2013]. This experiment was inspired by the work of *Friedkin* [1945]. Additionally, tens of small-scale experiments of bank retreat were conducted (Figure 1). These tests were carried out to quantitatively assess the effect of different vegetation densities and growth duration on bank erosion rates and processes. Experiments were conducted in a flume with a duct of 50 mm wide and 1 m long on a slope of 0.01 m/m and a discharge of 400 L/h (0.1 L/s). At the end of the entrance, a sediment block of 20 mm thick with vegetation on top was placed. Here the water flow attacked the bank with an angle of 45°.

[10] Bank erosion rates were measured from time lapse photography of the sediment block, which was illuminated from the side. The progressive retreat of the bankline of the sediment block was obtained by image processing. The bankline was used to calculate sediment area, and as thickness was known, sediment block volume. Data was then reduced to half-life times to characterize bank erosion rates for different vegetation densities (0.5, 1.0, 2.2, and 4.4 stems/cm^2) and growth duration (2, 4, 6, or 8 days). Half-life time is defined as the time it takes to reduce the volume of the experimental sediment block to half the initial volume. Each experiment was repeated at least twice.

2.2. Flume Setup and Experimental Procedure

2.2.1. Scaling Rules

[11] The experiments represented a gravel-bed river and were scaled by similarity of dimensionless variables for hydraulic conditions, sediment transport conditions, and morphological features. Key dimensionless variables are kept within a range of values to ensure process similarity with natural gravel-bed rivers. The flow had to be subcritical (Froude number, $Fr < 1$) and turbulent (Reynolds number, $Re > 2000$). For sediment transport conditions, bed load sediment should be mobile $\theta > \theta_{cr}$ (Shields mobility number). The optimum conditions were obtained from a large number of pilot experiments on a stream table [*Kleinhans et al*., 2010] and experience from our successful meandering experiments [*Van Dijk et al*., 2012, 2013; *Van de Lageweg et al*., 2013a].

2.2.2. Experimental Setup

[12] Channel planform experiments were conducted in a flume of 3 m wide and 10 m long. The initial bed had a gradient of 0.01 m/m and initially a straight channel of 150 mm wide and 10 mm deep was carved. A fixed weir downstream kept the base level at a constant level. The flume was filled with a 100 mm thick layer of poorly sorted sand and every new experiment started with a new batch of sand. The location of the mined sand differed, so that between experiments the grain-sizes could differ as well. Therefore, the sediment in the experiment with uniformly distributed vegetation (exp. I) was slightly coarser than the experiment with vegetation seeds distributed by the flow (exp. II, Table 1). To maintain a similar sediment mobility in the experiment with coarser sediment we increased the discharge, so that both experiments fitted to the scaling rules (Table 2). For the scaling rules we used the expected channel width and depth according to the hydraulic

Table 1. Experiment Number and Conditions

	D_{10}	D_{50}	D_{90}	Unit	Q_c	Q_h	Unit	T_h
Vegetation Experiments								
exp. I	0.30	0.71	2.00	mm	0.5		m/s	
exp. II	0.26	0.51	1.35	mm	0.3	0.5	m/s	1:16
Control Experiments								
exp. III	0.30	0.71	2.00	mm	0.6		m/s	
exp. IV	0.26	0.51	1.35	mm	0.3		m/s	
exp. V	0.26	0.51	1.35	mm	0.25	0.5	m/s	1:5

Table 2. Initial and Designed Conditions[a]

	Symbol	Scale Rule	Value	Value	Unit
			Exp. I and III	Exp. II, IV and V	
Initial					
Median grain size	D_{50}		0.71	0.51	mm
Valley slope	S_v		0.01	0.01	m/m
Expected					
Channel width	W		262	201	mm
Channel depth	h		12	9	mm
Froude number	Fr	<1	0.76	0.68	
Reynolds number	Re	>2	3.1	1.8	$\times 10^3$
Shields mobility number	θ	>0.04	0.102	0.108	
Shear velocity	u_*		0.034	0.03	m/s
Grain Reynolds number[b]	Re^*	>11.6	68	40	
Bar wavelength[c]	L_p		2.1	1.5	m
Bar mode[d]	m		2.3	2.6	
Braiding index[d]	Bi		1.6	1.8	

[a]Range in values indicates conditions for the initial channel width-depth and for hydraulic geometric channel [according to *Parker et al*., 2007].
[b]Keulegan with $k_s = D_{90}$.
[c]*Struiksma et al*. [1985, their equations (26) and (28)].
[d]*Crosato and Mosselman* [2009, their equation (19)].

geometry for a noncohesive gravel bed river [*Parker et al*., 2007]. Furthermore, we conducted three experiments without vegetation (Table 1) to be certain that differences in channel dynamics were the result of the difference in seed dispersal methods.

[13] Experiments were conducted with a constant discharge except for the distribution of vegetation seeds on the floodplain which was done with a 15 min flood. *Van de Lageweg et al*. [2013b] showed that discharge variation had no measurable effect on channel cutting and migration compared to a constant discharge experiment, and showed that floods only affect floodplain deposition. The discharge for the uniformly distributed vegetation was $Q_c = 1800$ L/h (0.5 L/s) for 30 h and the discharge for the vegetation seeds distributed by the flow was $Q_c = 1080$ L/h (0.3 L/s) for 60 h (Figure 2a). The control experiments consisted of a constant discharge of $Q_c = 1800$ L/h (0.5 L/s) for the experiment with the slightly coarser sediment (exp. III), a constant discharge of $Q_c = 1080$ L/h (0.3 L/s) for the slightly finer sediment (exp. IV) and a variable discharge of $Q_l = 900$ L/h (0.25 L/s) and $Q_l = 1800$ L/h (0.3 L/s) in a ratio of 5:1 ($T_h = 1{:}5$) for the experiment with finer sediment (exp. V, last two mentioned experiments are also shown in *Van de Lageweg et al*. [2013b]). To keep the experiments dynamic we moved the inlet point transversally with a rate of 10 mm/h for all experiments to a maximum amplitude of 300 mm as in our earlier work [see also *Van Dijk et al*., 2012].

[14] To keep the sediment balance even, we monitored the detrended surface elevation and adjusted the sediment input when the mean elevation changed. The sediment feed was kept at a rate of 0.24 mL/h for experiments I and III with the coarser sediment. Sediment feed and discharge were kept constant in the control experiment (III), while in the experiment with vegetation (I) the sediment feed had to be reduced when the vegetation germinated and increased again when vegetation decreased due to mortality in the experiment with uniformly distributed vegetation (Figure 2b). The sediment supply was kept constant at a rate of 0.12 mL/h for experiments II, IV, and V.

2.2.3. Seeding Procedure

[15] Alfalfa was used to represent riparian vegetation. The seeds germinated in a few days. Vegetation seeds were added after the development of several bends in the experiments. The seeds were distributed by two methods, (1) uniformly on the floodplain or (2) adding vegetation seeds to the sediment and water feed. For the first seeding procedure, vegetation seeds were evenly sown with a density of

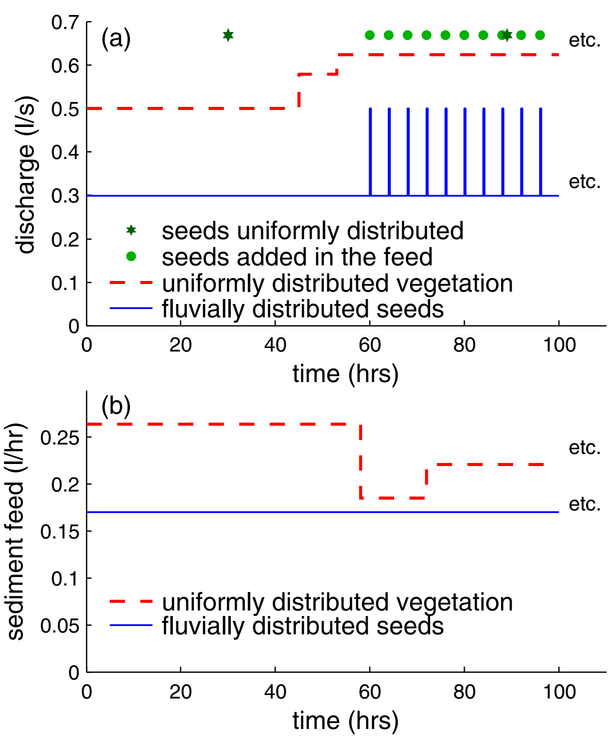

Figure 2. (a) Discharge regime and (b) sediment feed for the uniformly distributed vegetation (blue dashed-line) and the seeds distributed by flow (red solid-line) experiments. The star in Figure 1a indicates timing of addition of vegetation seeds in the experiments.

1.5 seeds/cm^2 (comparable with *Tal and Paola* [2010]) on the floodplain of an existing meander planform that evolved over the first 30 h of the experiment. Seeds were distributed on the floodplain with bankful discharge running at $Q = 1500$ L/h (0.42 L/s) to remove seeds from the channel bed. Afterward, the vegetation was allowed to grow for 5 days before the experiment continued. To keep the bed wet and stimulate germination, water flowed through the channel with a discharge of 600 L/h (0.17 L/s) for 15 min, four times a day. The experiment continued with a constant discharge of $Q_c = 1800$ L/h (0.5 L/s). Due to vegetation the channel dynamics decreased and the discharge was increased to $Q_c = 2250$ L/h (0.63 L/s) after 46 h. The seeding procedure was repeated when the vegetation died after a flow period of 89 h (Figure 2a).

[16] Second, we tested how vegetation seeds distributed on the river planform by hydrochory, i.e., dispersal by flow. For the dispersal of the seeds we used a flood of $Q_{high} = 1800$ L/h (0.5 L/s) for 15 min each 4 h (Figure 2a). The flood led to distribution of the vegetation seeds on the floodplain. We added 30 g (5000) alfalfa seeds during each high flow until the end of the experiment. The density of alfalfa seeds was about 1280 kg/m^3 and the size about 1 mm. Seeds can float on the water due to a coat layer, but here seeds were mixed with water before adding to the flow. After each flood, we stopped the experiment for that day to limit reworking of vegetation seeds before germination. The light condition for the vegetation growth was the same in both experiments.

2.3. Data Collection

[17] Several measurement techniques were used to record morphology of the experimental rivers. The bed topography was measured by projecting a line-laser onto the bed normal to the mean downstream direction of the channels and photographing the line with a digital camera (0.2 mm vertical resolution) mounted at an oblique angle with a 2 mm interval in longitudinal direction. Vegetation distribution was identified by a high-resolution camera mounted on the automated gantry with a pixel resolution of 0.25 mm/pixel. We measured and photographed the bed each 4 h for experiment II and each 3 h for experiments IV and V. Experiments I and III were only paused to record interesting phenomena of channel migration and chute cutoffs, which varied between 1 h and 6 h. Two LED floodlights mounted on the gantry suppressed ambient lighting. The point cloud from the line-laser was gridded on a 4 mm grid by median filtering to produce Digital Elevation Models (DEMs). Vegetation was filtered out by using the 10th percentile instead of the median elevation data. The high-resolution camera was remotely controlled and captured 36 images per full coverage of the flume during dry and wet bed conditions.

2.4. Data Processing

[18] The high-resolution images were used to segment channels and vegetation in the experiments. The high-resolution camera with RGB-band gives values for green, red, and blue, which can be transformed to a L^* a^* b^* color space. Herein, L^* represents the luminosity (low = black and high = white), a^* is the position between red/magenta (high values) and green (low values), and b^* is the position between yellow (high values) and blue (low values). The a*-band was used to segment vegetation in the dry photographs, while the a*-band of the wet photographs was used to segment the channels.

[19] To segment vegetation we used the a*-band and the difference between high and low elevation percentiles derived from the laser camera points filtered into each map pixel ($Z_{90} - Z_{10}$). We used threshold-values to identify the vegetation; pixels where $Z_{90} - Z_{10}$ exceeded 3 mm and where the a*-band was lower than 127. A vegetation map was created by a combined classification, followed by a spatial filter. To that end, we dilated and eroded the map by filling in holes and eroding loose pixels. The water was dyed with a violet color to determine the channel position and water depth. The intensity of the redness (a^*) was related to a proxy water depth for each time step, as the violet color differed during the experiment. The relation between proxy water depth and redness intensity was found by relating the bed elevation on a cross section with the redness intensity at that cross section.

[20] The initial bed surface slope of the DEMs was subtracted to detrend the DEMs. The detrended elevation was expressed relative to the surface that remained unchanged. DEMs of difference (DoD) were calculated by subtracting DEM pairs. DoDs were thresholded by the vertical resolution (0.2 mm) of the laser line scanner. The images were matched to the gridded laser scan data.

2.5. Data Reduction

[21] To describe the evolution of the experimental river we calculated, the sinuosity, the braiding intensity, the channel belt area, the distribution of the surface elevation, and the morphological changes for every time step. The intensity of braiding was quantified by the braiding index (*BI*), by counting the number of parallel channels. Following *Bertoldi et al*. [2009], the *ABI* was calculated as the average number of channels which had net morphological change (e.g., erosion or deposition) observed on the DoD maps at six fixed cross sections. The morphological change was given as the summation of the eroded and deposited sediment from the DoDs. The frequency distribution of the detrended surface elevation was used to check whether the experiments did not aggrade or degrade, and to test if the experiment with vegetation developed deeper channels and higher floodplains than the experiment without vegetation.

[22] Furthermore, we looked at the transverse bed slope ($\frac{\partial z}{\partial n}$, where n is the transverse coordinate in a curvilinear coordinate system) in relation to the bend radii (R/h, bend radius normalized by water depth). R was calculated following *Fagherazzi et al*. [2004]. The transverse bed slope was compared between experiments and a transverse bed slope predictor [*Struiksma et al*., 1985, adapted by *Talmon et al*., 1995]. Transverse bed slope was measured on the DEMs in profiles perpendicular to the channel at the bend apex, where the bend apex was determined from the radius of curvature.

3. Results

3.1. Bank Stabilization Test

[23] Vegetation on the banks led to bank stabilization and reduced channel migration rates. Small-scale bank

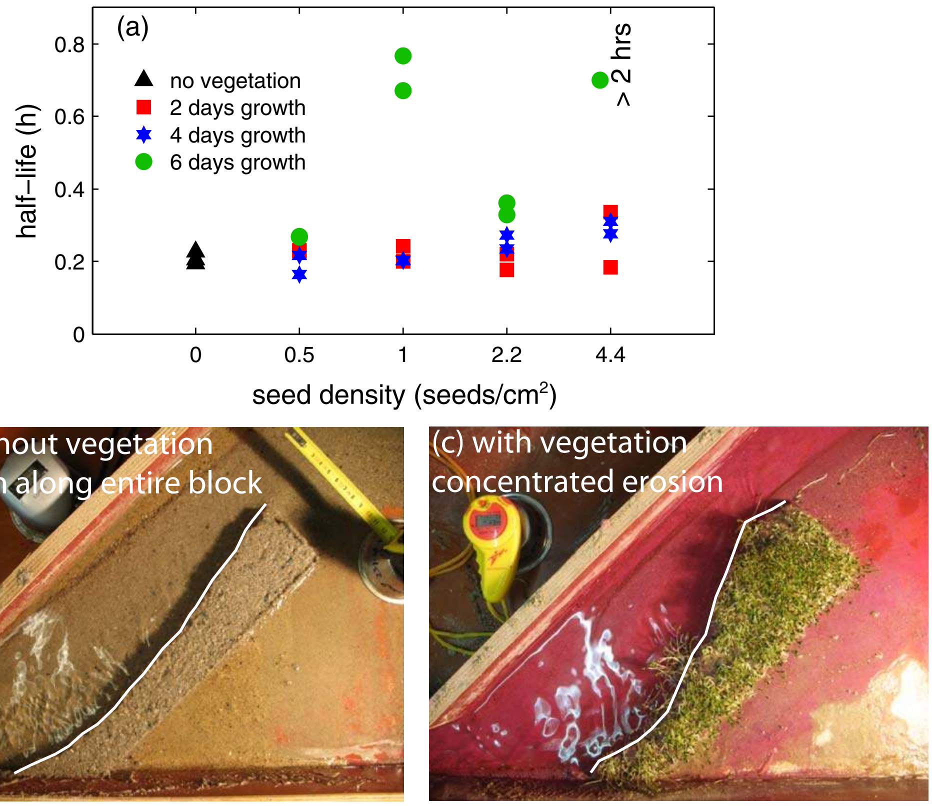

Figure 3. Effect of vegetation on bank erosion rates. (a) Half-life time scales of several vegetation densities and growth duration in the Friedkin bank erosion tests. (b) Image of a sediment block with the current bank line for an experiment without vegetation. (c) Image of a sediment block for an experiment with a vegetation density of 2.2 seeds/cm^2 and a growth period of 6 days.

erosion rate tests showed that the half-life time of the experimental sediment block increased with increasing vegetation density and growth duration (Figure 3a). The vegetation reduced the bank erosion as vegetation stems were hanging in front of the sediment block, which increased the resistance along the channel bank (Figure 3c). Erosion for the nonvegetated bank occurred along the entire bank (Figure 3b), whereas the erosion rate differed along the sediment block for the experiments with vegetation (Figure 3c).

[24] After 2 days of vegetation growth, there was no measurable reduction of erosion on the experimental sediment blocks (Figure 3a). After 4 days, the effect of vegetation increased and after 6 days there was a significant effect with increasing vegetation density. The strength of vegetation after 8 days was so large that the half-life time was not reached within 2 h even for the low vegetation density of 0.5 seeds/cm^2. The half-life time was doubled for a seed density of 2.2 seeds/cm^2 and multiplied by 10 for a seed density of 4.4 seeds/cm^2, i.e., half-life time of more than 2 h, during a growth duration of 6 days. At a seed density of 1 seed/cm^2, the half-life time was higher compared to the experiments with a seed density of 2.2 seeds/cm^2. We did not find a clear reason for this.

3.2. River Morphology

[25] Two experiments were conducted to test the effect of different vegetation distribution methods on the channel dynamics. These experiments were compared to several control experiments which had no vegetation. The addition of vegetation resulted in a different river morphology compared to the experiment without vegetation (Figures 4 and 5).

3.2.1. Control Experiments

[26] The control experiments were characterized by successions of meander growth and migration reset by chute cutoffs. Alternate bars formed and continuous lateral expansion led to formation of bends. Later, these bends were cutoff and new bends formed. A sinuous channel formed in a floodplain with old channel remnants, which abandoned when a plug bar blocked the flow in the residual channel (Figures 4a and 4b). The experiment with a variable discharge, i.e., floods with a ratio of 1:5, showed more channel cross cuts. Due to these cross cuts, the original bars were more fragmented compared to the experiments with constant discharge (Figure 4c). Later, the bars in the experiment with constant discharge became more fragmented as well, due to reoccupation of the depressions from the residual channels [*Van de Lageweg et al.*, 2013b]. The flood duration was reduced for the experiment with seeds distributed by the flow, so that there was less effect of bar fragmentation.

3.2.2. Uniformly Distributed Seeds Experiment

[27] The addition of uniformly distributed vegetation to the floodplain resulted in a change in the shape of the meander bends. Initially, bars and bends formed like in the

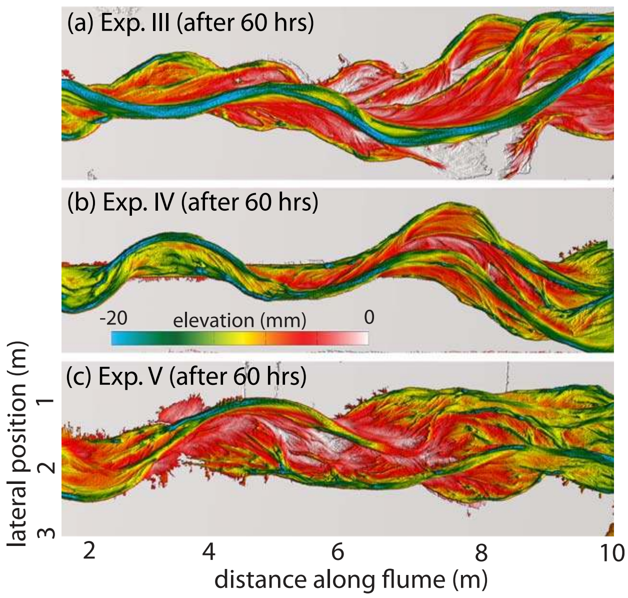

Figure 4. Digital elevation models of the control experiments (III, IV, and V). (a) Abandoned and active sinuous channels in experiment III. (b) Abandoned and active sinuous channels in experiment IV. (c) The long duration floods in experiment V reworked the floodplain more and shows more smaller abandoned morphological units but no clear scroll bars.

control experiment without vegetation (Figure 5a, 30 h). After the floodplain became vegetated, the bends became tighter (Figure 5a, 62 h), which resulted in a sinuosity increase to 1.4. The tighter bends with the deeper channel fitted well to predicted transverse bed slope, but differed strongly from the control experiment (III) and meander experiment with the same sinuosity formed in a cohesive floodplain of fine material (Figure 6).

[28] The establishment of vegetation and mortality affected the morphology of the river. When the vegetation died, the bend migrated downstream and the channel was shortened by chute cutoffs (Figure 5a, 85 h). After channel shortening, new bends developed slowly from upstream. The expansion of new bends was first limited by germination of new sprouts, which were sown on the floodplain after 89 h. Later, vegetation died and several bends developed in downstream direction (Figure 5a, 134 h).

3.2.3. Seeds Distributed by Flow Experiment

[29] Initially, alternate bars formed in the straight channel before vegetation was added to the water and sediment feed. The amplitude of the alternate bars grew and an incipient meandering river developed with a characteristic scroll bar topography in the inner bend (Figure 5b, 32 h). The downstream bend grew slowly by overbank flow and avulsion in contrast to the more upstream bends that grew in lateral and longitudinal direction (Figure 5b, 60 h). After the vegetation establishment the dynamics decreased and

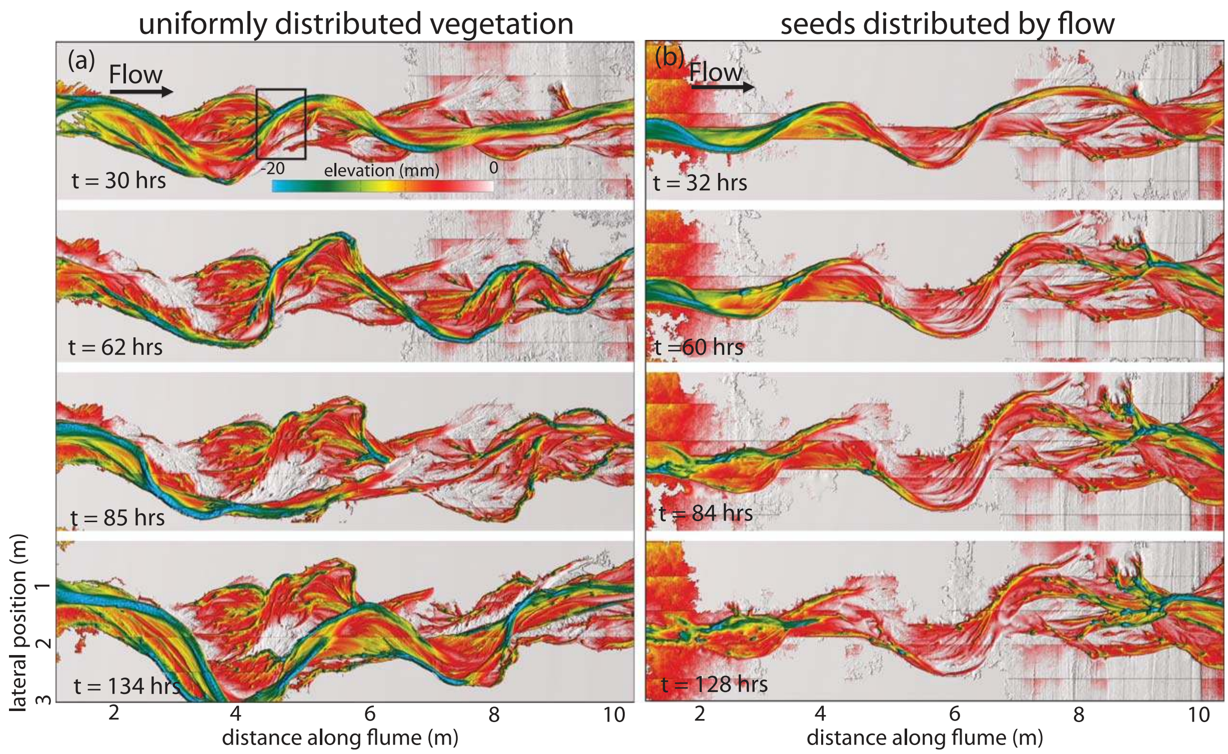

Figure 5. Digital elevation models of experiments I and II. (a) Experiment I with uniformly distributed vegetation shows the development of the same bar-bend shape compared to the experiment without vegetation (exp. III). Later, vegetation tightened the bends. A large chute cutoff (85 h) reset the system. The box indicates the location of Figure 13. (b) Experiment II with seeds distributed by the flow shows initial growth of meanders (32 h), local avulsion and lateral migration (60 h) before the addition of vegetation seeds at the upstream inlet (60 h). Afterward, less cutting and migration occurred as the dynamics decreased (84 and 128 h). Gray shades indicate elevation that did not change.

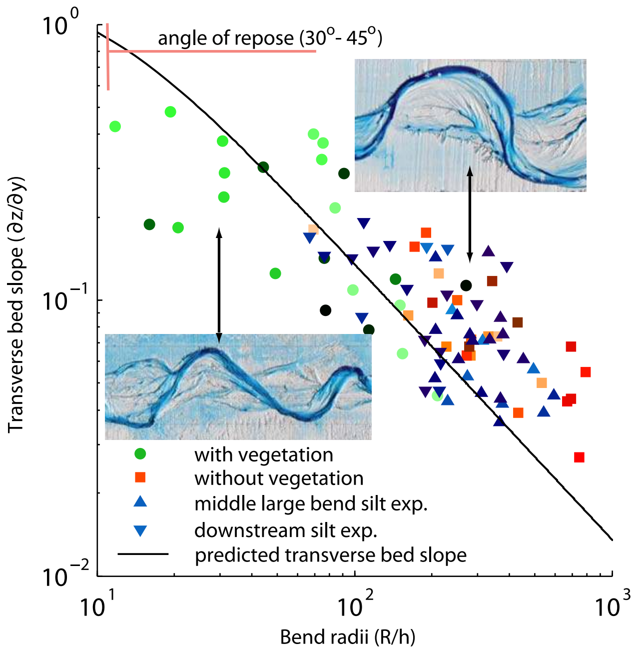

Figure 6. Transverse bed slopes in bends. Comparison between experiments I (circles), III (squares) and the experiment with high amplitude meander bend from [*Van Dijk et al.*, 2013, triangles]. Experiment III and *Van Dijk et al.* [2013] experiment have bend radii and transverse bed slopes in the same range, whereas the experiment I with vegetation had tighter bends and a steeper transverse bed slopes. For the predicted transverse bed slope, we used a constant water depth of 10 mm and the White-Colebrook equation for the Chezy coefficient with a Nikuradse roughness length equal to the D_{90} of the sediment. Note that the color intensity indicates experimental time (darker is later).

were limited to scouring in the downstream section and shortening of the bend in the upstream section (Figure 5b, 84–128 h).

3.2.4. Characteristic Similarities and Differences Between Experiments

[30] Each experiment started with a straight channel and showed similarities in formation of alternate bars and channel belt widening. As the channel belt widened, its complexity increased and multiple parallel channels became active (Figures 7a and 7b). All five experiments showed that the *ABI* increased, but remained below 2. Experiment III with the constant discharge and coarser sediment exceeded 2, which was mainly due to a large shift occurring in a 6 h time span (Figure 7b). Afterward, the *ABI* lowered and reached a stable braiding intensity of 1.7, as in the other experiments (with and without vegetation).

[31] The addition of vegetation reduced the morphodynamics of the river and reduced widening of the channel belt compared to the experiments without vegetation (Figure 8a). Bank erosion decreased due to vegetation in the experiment with uniformly distributed vegetation, while channel dynamics decreased due to shallower flow that led to no sediment mobility in the experiment with seeds distributed by the flow. The experiments with higher discharges, i.e., experiments III and V, showed faster widening of the channel belt compared to the experiment with a low constant discharge (experiment IV).

[32] The distributions of detrended bed elevation differed slightly between the five experiments. The median surface elevation remained constant most of the time for all experiments (Figure 8b). The topographical height distribution for experiments with a lower constant discharge was narrower (Figure 8c), which indicated that the bars were less high and the channel scours less deep. In the experiment with uniformly distributed vegetation, the range of elevations increased (Figure 8c, $Z_5 - Z_{95}$), while the mean channel depth remained at the same surface elevation even after mortality of the vegetation. This indicated that the bars and/or channel scours were slightly higher and/or deeper, respectively, than for the other experiments.

3.3. Effects of Vegetation Dispersal

3.3.1. Uniformly Distributed Seeds

[33] Vegetation was uniformly distributed on a river planform formed during a constant discharge for 30 h. The low flow during germination led to minor lateral migration of the channel. Initially, the vegetation covered about 45% of the flume and was mostly found on the pristine floodplain (Figures 9a and 10a). Vegetation on the inner bend was overtopped when the discharge

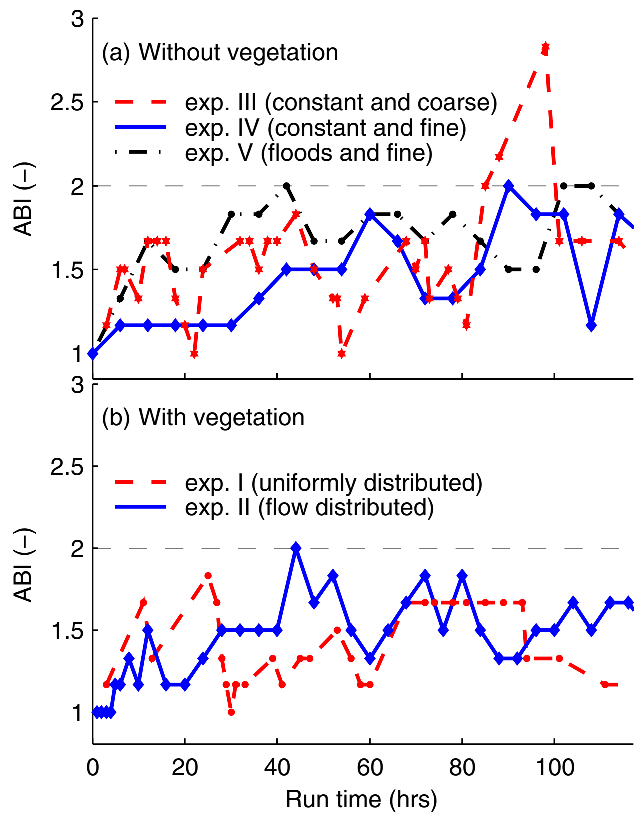

Figure 7. Time series of the Active Braiding Index (*ABI*). (a) *ABI* for the experiments without vegetation. The *ABI* increases rapidly due to floods in experiment V compared to the experiment IV with constant discharge, but the difference decreases over time. (b) *ABI* for the experiments with vegetation shows no significant difference in the number of active channels.

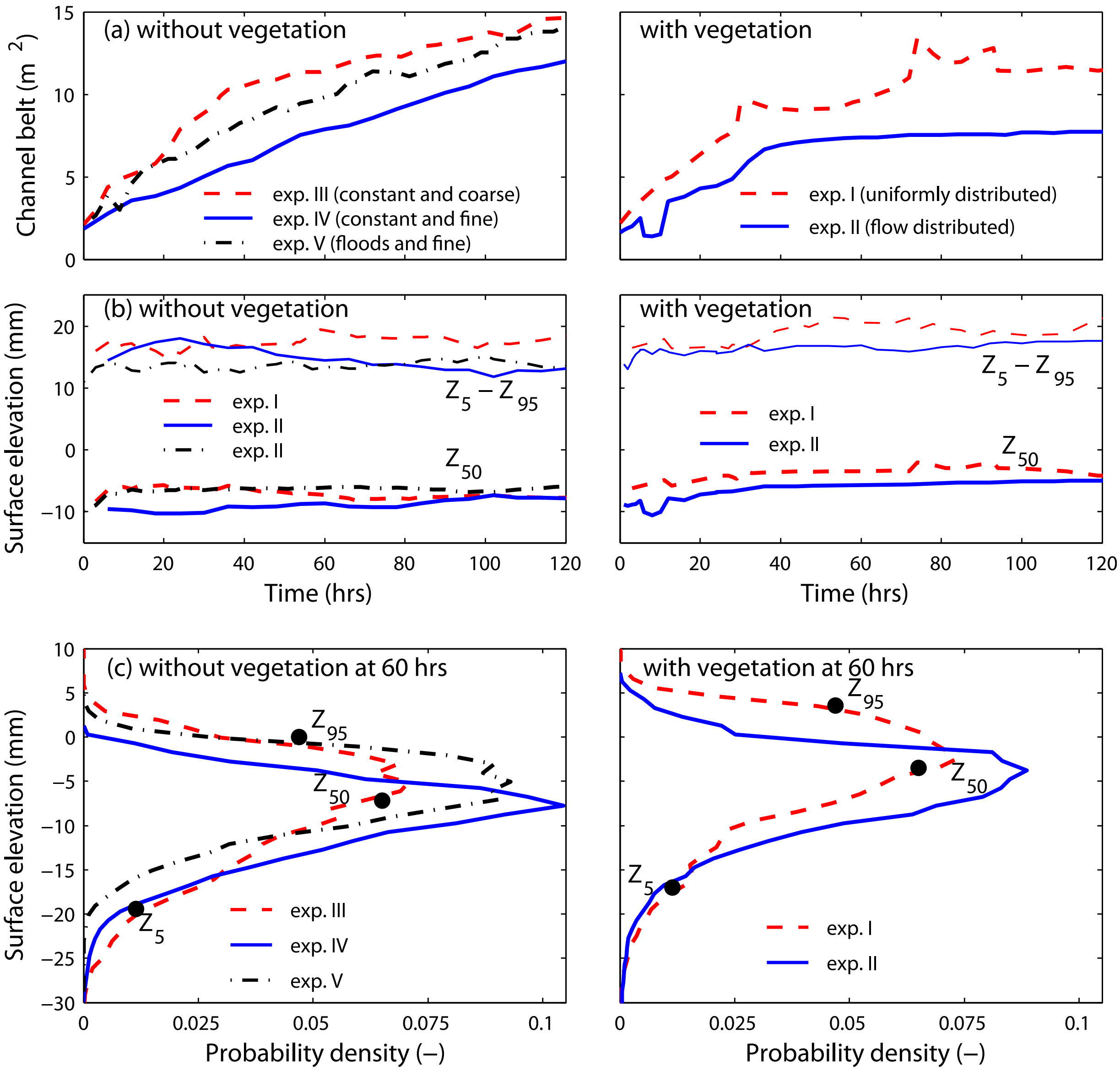

Figure 8. Descriptive statistics of the experiments, (left) without vegetation and (right) with vegetation. (a) Channel belt area increases in all experiments without vegetation, while the vegetation reduces the channel belt increase. (b) Time series of the detrended median surface elevation and of the spatially averaged range of detrended surface elevations of the channel belt area showing no clear differences between experiments. (c) Probability distribution of detrended channel belt surface elevation at 60 h of the flume experiments indicates that elevation was more skewed for the lower discharge experiments. The experiment with uniformly distributed vegetation has a wider range with deeper channels and higher bars. Dots indicate percentiles plotted in Figure 8b.

increased and sediment deposited on the inner bar (Figure 11a). Extensive wetting by overbank flow and the poorly light conditions of our facility resulted in high mortality of the riparian vegetation on the floodplain (Figure 9a, 60 h). The uniformly distributed vegetated floodplain decreased extensive erosion and channel shifts, i.e., chute cutoffs, compared to the control experiment. The riparian vegetation stabilized the outer bank, so that outer bank erosion decreased and the bank became irregular to differences in erodibility (Figure 11b). Here bank undercutting and bank collapsing were dominant bank erosion processes (Figure 11d).

[34] The vegetation on the floodplain decreased bank erosion rates. Mortality of the riparian vegetation caused an increase in overbank flow due to less flow resistance, which led to a chute cutoff of the bend in the middle of the experiment (Figures 5a and 11c, 85 h). The flow direction shift, caused by this cutoff, initiated several chute cutoffs downstream (Figures 5a and 9, 85 h). Then the chute channel developed to the same width-depth ratios as observed in the control experiment. After the large chute cutoff, new seeds were uniformly distributed on the floodplain with the same density as in the first seeding event (Figure 9a, 89 h). The decayed vegetation and fungi resulted in less successful

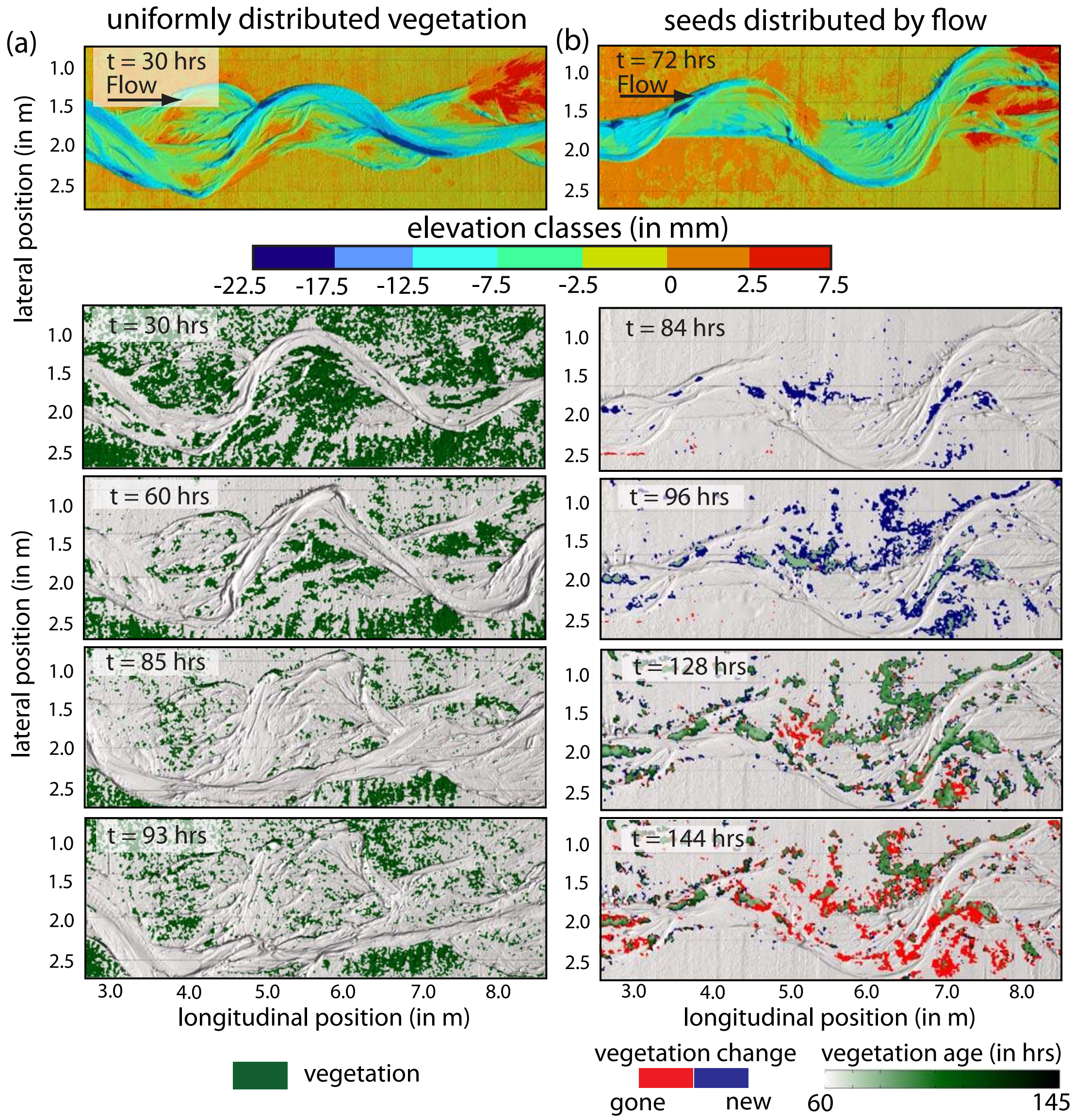

Figure 9. Shaded DEM with vegetation map during (a) uniformly distributed seeds and (b) seeds distributed by flow. (a) The top part shows the elevation classes before seeds were uniformly distributed. Below are vegetation maps showing a decrease in active vegetation until a new seeding event (93 h). (b) In the top part elevation classes are given that are used in Figure 10. Below maps illustrated locations of newly germination (blue colors), germination time (lightness of the green colors) and the mortality (red colors) of vegetation. Note that no new germination took place.

germination of seeds. The vegetation density was 0 seeds/cm^2 on the floodplain, instead of 0.64 seeds/cm^2 3 weeks after the seeding event. Although less seeds germinated, decaying seeds and fungi (mycelium hyphae) seemed to increase bank stability. We observed slow lateral migration which led to a low-sinuous river and deeper outer pools than during the first seeding event.

3.3.2. Seeds Distributed by Flow

[35] Vegetation seeds were distributed by the flow on a river planform formed during a constant discharge. These seeds were added in the sediment and water feed during floods, so that the seeds deposited on the higher floodplain. Vegetation seeds were added after 60 h until the end of the experiment. The first seeds settled in the lows of the point bar and downstream of the crevasse splay on the outer bends. Seeds on the point bar were transported as bed load and helical flow pushed the seeds to the inner bend. Seeds deposited downstream of the splays on the outer bends due to flow dispersion which likely resulted in a decrease in flow velocity from the splay to the floodplain (Figure 9b, 84 h). The vegetation developed on lower areas and the elevation distribution was more skewed to the lower elevation compared to the experiment with uniformly distributed vegetation (Figure 10a).

[36] The germination and growth of vegetation occurred at several specific locations. The first clear establishment of vegetation occurred on the outer banks where seeds deposited during overbank flow (Figures 11f and 11g). The second vegetation cover was observed downstream of the point bar which developed between the former scroll and

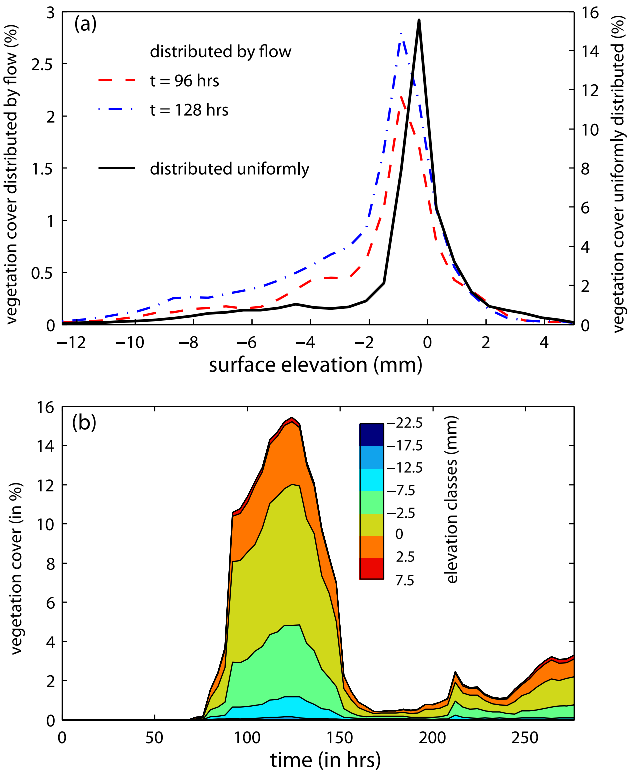

Figure 10. Time series of vegetation distribution as a function of elevation. (a) Vegetation distributed on a lower level during the experiment where vegetation seeds were distributed by the flow during floods. Note that the vegetation cover for the uniformly distributed vegetation experiment is denser. (b) Vegetation distribution on different elevations over time.

the new scroll (Figure 11f). The third germination location was along the outer bend on the pristine floodplain (Figures 9b and 11f). The seeds probably settled when overbank flow converged back to the main channel and seeds deposited due to a change in hydraulic roughness. The final location where vegetation established was at the plug bar in the upstream section of the flume (Figure 11e). Closure of the former channel by a plug bar captured seeds, so that the plug bar became vegetated.

[37] Later, seeds settled within and close to the initial vegetation patches and therefore these patches grew (Figures 9b, 96 h and 10b). The maximum vegetated cover (15%) was observed after 128 h. Here most vegetation deposited on the pristine plain area (orange) and on the reworked floodplain area (green). Mortality of the vegetation after 3 weeks reduced the vegetated cover as the old vegetation was not renewed and limited the effective experimental time.

3.3.3. Morphological Effect of Different Seed Distribution

[38] Initially, experiments were characterized by channel cutting and lateral migration changing the morphology of the nonvegetated floodplain. The morphological changes in the experiment with uniformly distributed vegetation remained high after the establishment of vegetation on the floodplain (Figure 12b). However, in the experiment with seeds distributed by the flow, the morphological activity was low after the addition of vegetation (Figure 12a). Here the vegetation was distributed on lower areas and did not lead to focused flow in the main channel.

[39] The vegetation density as well as the morphological changes varied in longitudinal direction. We observed that the vegetation density affected the volume of morphological changes in longitudinal direction. A higher vegetation cover (Figure 12a) in the experiment with uniformly distributed vegetation resulted in more concentration of the flow in the channel (Figure 12b). This concentrated flow led to more morphological changes (Figure 12b). In contrast, in the experiment with seeds distributed by the flow, there were less morphological changes (Figure 12c) in the denser vegetated areas (Figure 12a), as the flow was less concentrated in the channel. Here the flow was dispersed over the nonvegetated floodplain, which resulted in a shallow flow and no sediment mobility.

[40] The effect of concentration of the flow in the lows of the river was observed during tracer measurements. During bankfull condition in the experiment with uniformly distributed vegetation we observed that flow was focused in the main channel and floodplain lows, while flow was not concentrated on the bars (Figure 13a). After the floodplain was vegetated, the flow was mainly in the channel and in the floodplain lows (Figure 13b). During flow conditions that exceeded bankfull, the flow was dispersed over the floodplain (Figure 13a). These results indicated that the distribution of vegetation was important in the concentration of the flow in the channel and on the floodplain. Furthermore, the vegetation distribution determined the morphological changes of the river.

4. Discussion

[41] These experiments highlight the effect on river pattern and dynamics by the process of vegetation distribution. The main findings of the different vegetation distribution experiments are: (1) vegetation decreases the dynamics of the river, due to bank stabilization and flow resistance; (2) vegetation distribution by the flow occurs predominantly on bars close to the channels, so that flow disperses around the bars and over the floodplain; and (3) flow concentration determines channel dynamics and the resultant pattern.

4.1. Ecosystem Engineering

[42] The addition of vegetation leads to bank stabilization and reshapes the meander bends. The effect of bank stabilization by vegetation was tested in earlier work and showed that bank stabilization reduced the number of active channels [*Gran and Paola*, 2001; *Tal and Paola*, 2010]. This study shows that the outer bank vegetation leads to a tighter bend with a steeper transverse bed slope and hence stronger outer banks, compared to an experiment without vegetation [*Van Dijk et al.*, 2013, Figure 6]. Bank erosion is focused at the point where the main flow converges [*Ikeda et al.*, 1981]. At the point where flow diverges, flow strength decreases and the stronger vegetated banks lead to tighter bends and local erosion as illustrated in the bank erosion test. The transverse bed slope for the tight bends differs from the predicted transverse bed slope, which is the result of weaker secondary flow in sharp bends [*Ottevanger et al.*, 2013]. The bends were so sharp

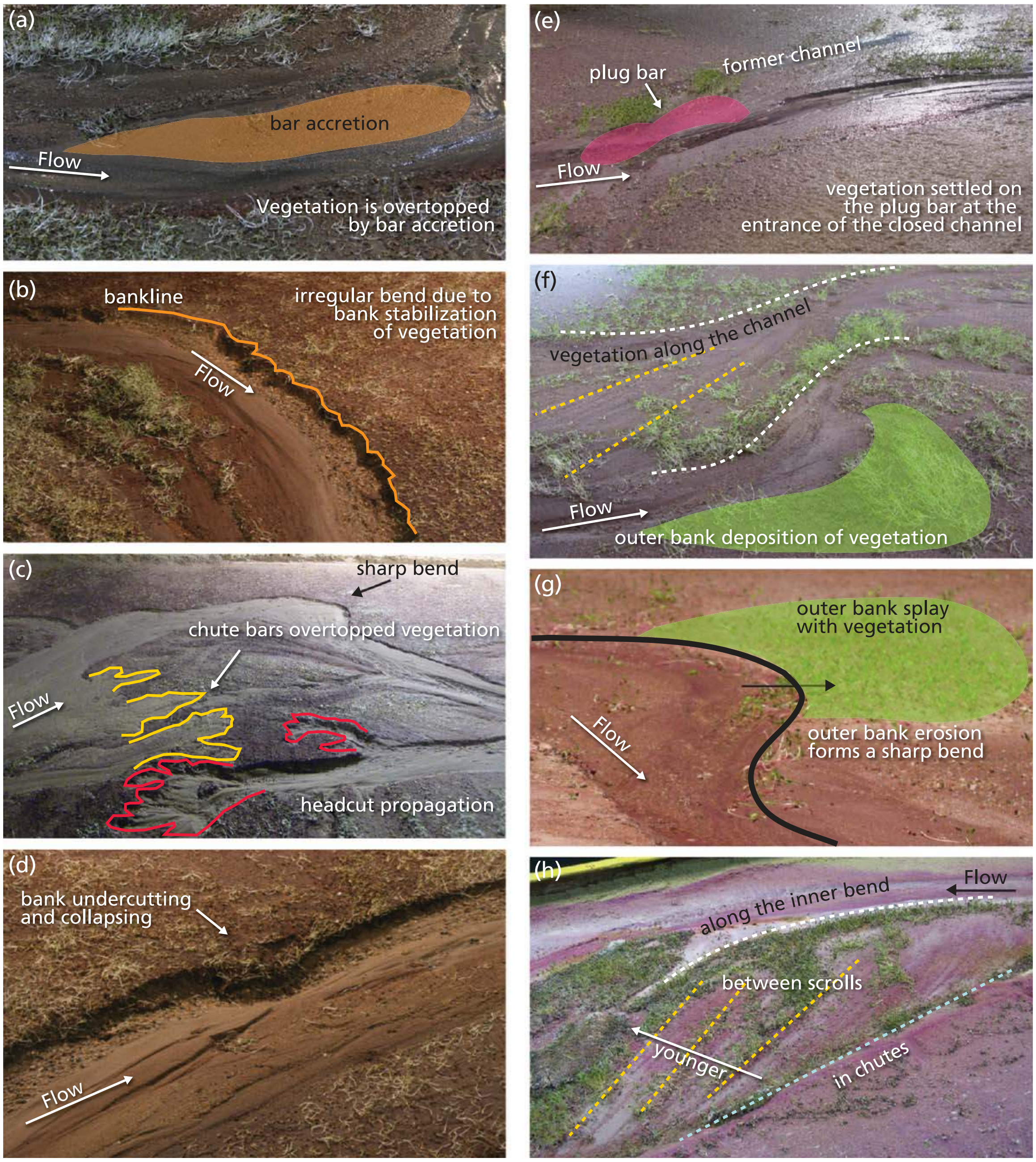

Figure 11. Observed vegetation patterns in our experimental setup. (a) Vegetation near the channel is overtopped by sediment that deposited on the inner bend. (b) Local stabilization by vegetation leads to local differences in bank erosion rates and an irregular bank. (c) Mortality of vegetation increases erosion rates and the occurrence of chute cutoffs. (d) Bank undercutting leads to bank collapse of large vegetated banks. (e) Vegetation is distributed in the former channel and deposited at the plug bar. (f) Vegetation deposited on the outer bank, along the inner bend and in the scroll swales. (g) Vegetation on deposited at the outer bank splay stabilized the bank and increases the sharpness of the bend. (h) In a stream table experiment we observed successions of vegetation in the inner bend, between the scrolls and in the chutes.

that they had flow recirculation over the inner-bend bar and a bank-detached flow hitting the opposite bank just downstream of the apex [cf. *Ferguson et al.*, 2003; *Blanckaert et al.*, 2013].

[43] The alfalfa stems lead to flow resistance, while the roots of the alfalfa sprouts provided cohesion. The resistance of the vegetation depends on the stem height of the alfalfa sprouts. The resistance and the strength of vegetation patches at the bar level leads to flow diversion resulting in multiple channels [cf. *Coulthard*, 2005; *Perona et al.*, 2012]. In the experiment with seeds distributed by the flow, patches of vegetation diverted the flow to higher banks or the floodplain. This led to reduced dynamics, as the flow became shallower and below the critical shields

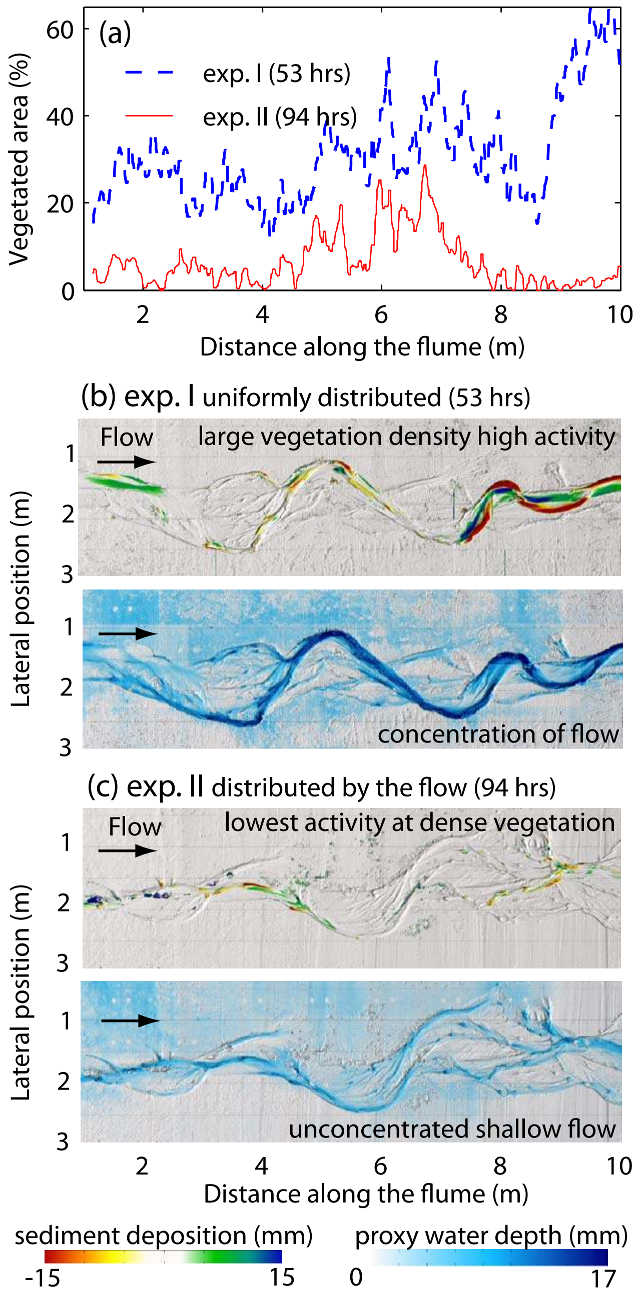

Figure 12. Morphological changes after the establishment of vegetation in experiments I and II. (a) Vegetation distribution along the flume. (b) A DoD and a waterdepth map for experiment I showing concentrated flow and more activity at higher vegetation density. (c) A DoD and a water depth map for experiment II showing low shallow flow and less activity in the channel at the location of higher density vegetation.

number and showed a multithread system. In contrast, in the experiment with uniformly distributed vegetation, resistance of vegetation on the entire floodplain resulted in increased flow velocity and deeper scours, which is important for the meandering channel [cf. *Bennett et al.*, 2008; *Braudrick et al.*, 2009].

[44] Plants are often suggested to have modified the environment to the benefit of their own species. The question whether these observed differences amount to ecosystem engineering depends on the environmental requirements of particular species. Clearly, the different seed distribution styles affect the dynamics and spatial pattern thereof of the river morphology. In the meandering case the vegetation on the outer banks enhanced cyclic rejuvenation with creation of a pristine and high-dynamic substrate for pioneers, whereas in the case that can perhaps be characterized as island braiding the vegetation caused more spreading of water. If such patterns in nature are caused by species that also benefit from the conditions that this creates then they can be considered true ecosystem engineers. This question has importance for a wide range of fields from assessment of the effects of invading species to interpretation of extinct species in the geological past [*Davies and Gibling*, 2011].

4.2. Effects of Vegetation Distribution on Channel Dynamics and Pattern

[45] In the experiment with seeds distributed by the flow, the vegetation patches became that dense [like colonization in natural systems; *Van Splunder et al.*, 1995], that the bank was hardly erodible. The initial colonization of gravel bars by the riparian vegetation is a fundamental process for floodplain formation and habitat dynamics in alluvial rivers [e.g., *Gregory et al.*, 1991; *Stanford et al.*, 2005]. The riparian vegetation patches formed bar islands in the experiments, comparable with pioneer islands initiated around a deposited tree, i.e., large woody debris (LWD), in natural systems [e.g., *Tockner et al.*, 2009; *Gurnell et al.*, 2012]. Trees on the active bars are more pronounced in braided rivers and affect the bars by increasing sediment deposition and stabilizing the bar behind the tree [e.g., *Gurnell et al.*, 2001; *Bertoldi et al.*, 2011]. Our results suggest that the vegetation establishment on these bars increases the tendency of the river to braid. Hydraulic resistance of the vegetation and flow diversion around these bars had a different effect than simple bank stabilization by cohesive fine material [*Van Dijk et al.*, 2013]. The stability of these bars is stronger than for braided river experiments of *Federici and Paola* [2003] and *Egozi and Ashmore* [2009] without vegetation.

[46] Uniformly distributed vegetation on the floodplain reduced the number of channels as flow was concentrated [cf. *Gran and Paola*, 2001; *Tal and Paola*, 2010]. The strength of the vegetated bank reduced channel widening and limited the formation of midchannel bars. The strength of the vegetation by the roots and hydraulic resistance of the stems hanging over the bank reduced the erosion rate, but led to local erosion and the formation of sharper bends. These sharp bends were also observed in the meander experiment of *Braudrick et al.* [2009], who also had chute cutoffs when vegetation density decreased. The addition of vegetation resulted in a different river pattern compared to experiments without vegetation. The experiments without vegetation slightly differed due to a variation in the flow regime. Floods mainly affected the reorganization of channels and bars, but not the geometry of the channel width and depth (also shown in *Van de Lageweg et al.* [2013b]). The reason for this is that as soon as the bankfull level is reached and the floodplain inundates, bed shear stresses increase at a lower rate. The flood is often simply stored in the floodplain,

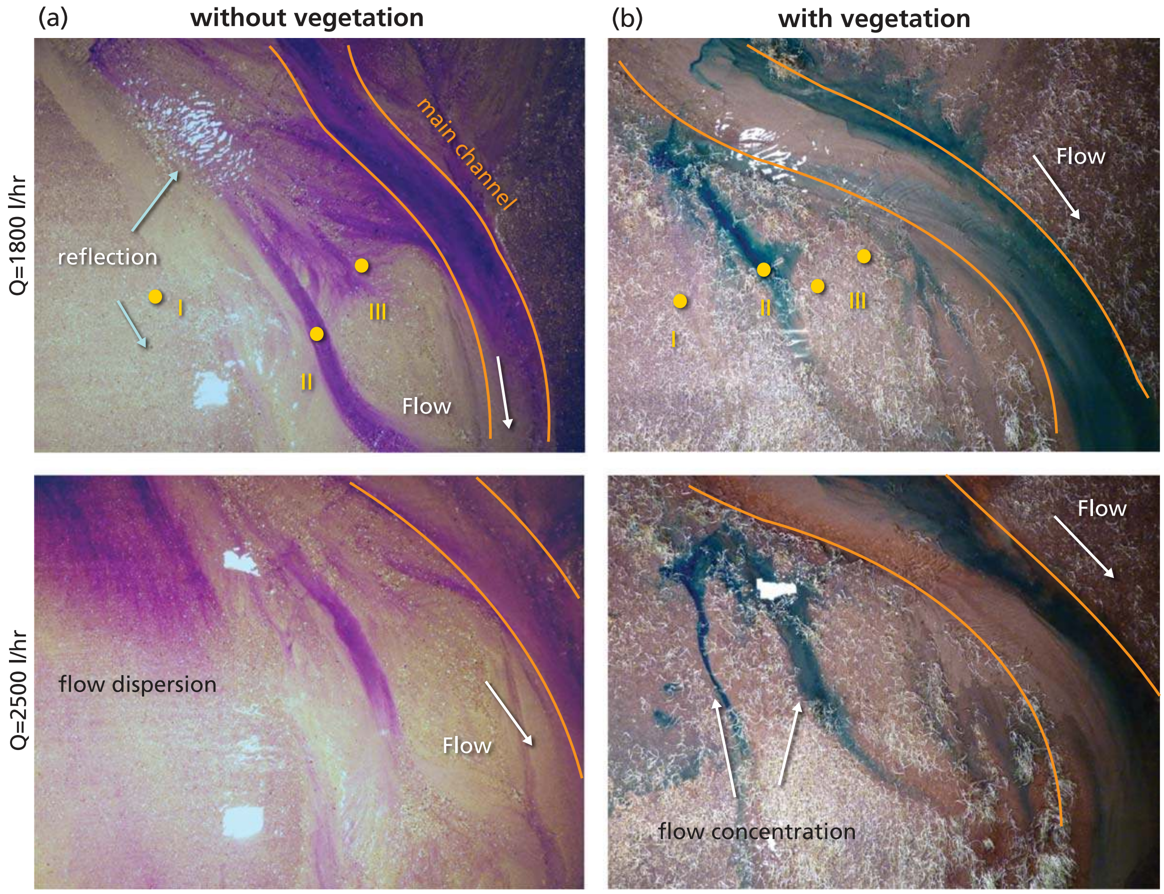

Figure 13. Hydrological changes after the establishment of vegetation in the experiment. (a) Dyed water shows the flow path for the nonvegetated floodplain on the floodplain (I), in the chute channel (II) and on the bar (III). (b) Dyed water shows the flow path just after establishment of vegetation on the floodplain. Note that the location slightly changed due to lateral migration of the channel during low flow of 600 L/h (0.17 L/s).

which affects deposition of fine sediments in *Van Dijk et al*. [2013], and vegetation dispersal in this paper.

4.3. Vegetation Distribution Processes

[47] The variation in water depth and curvature of meander bends resulted in different disturbances and affected the distribution of the vegetation along the channel. Vegetation predominantly settled on the point bar [also observed by *Tal and Paola*, 2010] and on the outer banks. The distribution of the seeds by the flow is similar to the distribution of fines in the experiment of *Van Dijk et al*. [2013]. This similarity of seed and fine distribution was also suggested by *Gurnell* [2007]. The distribution of fine sediment and the vegetation seeds is determined by flow direction in the channel and on the floodplain of the meandering river. A part of the seeds was distributed on relatively low elevations compared to the uniformly distributed vegetation experiment. This distribution may correspond better with the distribution of aquatic (bench) vegetation instead of riparian vegetation, which otherwise would not survived continuous water levels above the roots.

[48] In the experiment with seeds distributed by the flow, the mechanism of stranding is most important in establishing a vegetation patch, whereas distance traveled and the timing of the dispersal is negligible in the experimental setting. Several mechanisms related to natural rivers [see review *Nilsson et al*., 2010] can be involved for the stranding of seeds in the experiment; water level decrease [cf. *Nilsson et al*., 2002], capture by sprouts protruding above water [cf. *Schneider and Sharitz*, 1988], and seeds that are forced to the inner bend by helical flow related to river sinuosity, hydraulics and channel morphology [cf. *Merritt and Wohl*, 2002; *Gurnell et al*., 2008]. The river planform influences the establishment of vegetation on the outer banks and in the inner scrolls. In the experiment with seeds distributed by the flow, the seeds were dispersed by nautohydrochory, i.e., at the water surface, and by bythisochory, i.e., by spiral flow at the bottom of the channel [also found in nature *Parolin*, 2005]. Clearly seed density, size and shape have a large effect on dispersal style. These two different dispersal processes lead to vegetation establishment on the pristine floodplain and in the inner bend scrolls, respectively. Overbank flow distributes the seeds on top of the outer bank, where a decrease in flow velocity, i.e., hydraulic disturbance, results in deposition of the seeds [cf. *Gurnell and Petts*, 2002].

[49] The alfalfa seeds germinate relatively easily and occupy the alluvial river, which corresponds to pioneer

trees in natural temperate rivers that grow very rapidly, e.g., Cottonwood or Poplars (Populus) or Willows (Salix spp.) [*Van Splunder et al*., 1995; *Rood et al*., 2003]. The dispersion of these riparian trees is driven by water flow, i.e., hydrochorous, and wind, i.e., anemochorous [e.g., *Walker et al*., 1986; *Gurnell et al*., 2004]. The establishment of Cottonwood or other vegetation depends on a combination of root growth and capillary fringe, e.g., moisture content [*Noble*, 1979; *Van Splunder et al*., 1995; *Mahoney and Rood*, 1998]. These trees are often deposited in spring during high flows, where (if the conditions are suitable) plants will grow over the summer, ready to withstand subsequent autumn or spring flows [*Mahoney and Rood*, 1998; *Lytle and Leroy Poff*, 2004]. The alfalfa sprouts in the experiment with floods were able to withstand these floods as well and can therefore fruitfully be used in future experiments dedicated to particular river rehabilitation projects.

[50] Our experiments can also be interpreted in a different manner. The uniform distribution of plants may be seen to represent settings in nature with a high degree of connectivity, high seed dispersion, and wet floodplain, which can be found in temperate or tropical climate zones. The other distribution on the other hand can be seen as representing settings where vegetation settling is limited by moisture so that vegetation growth is stimulated within the river channel at low elevation and at immediate margins, but is limited or inhibited on the floodplain. This could be found in semiarid and Mediterranean climate settings [cf. *Stella et al*., 2013]. It is clear that our approach opens up new possibilities for experimental investigation of the interaction between hydromorphology and ecology. Interesting scenarios in future experiments include combination of different ways of seed dispersion and more realistic flood regimes.

4.4. Ramifications for River Rehabilitation

[51] The dispersal of vegetation seeds at the point bar and on the crevasse splays at the outer bend as well as the germination at the outer banks and downstream parts of the point bar have possible practical applications. The dispersal of vegetation seeds is still unknown for restored or newly created channels [*Gurnell et al*., 2006]. These results can help to predict the sites of aquatic and riparian vegetation propagules deposition and germination. In vegetated channels, propagule dispersal and deposition is strongly influenced by the existing submerged and emergent aquatic vegetation [*Gurnell et al*., 2008; *O'Hare et al*., 2012]. However, in newly created channels, e.g., restored reaches, propagules preferably deposit at the locations identified as potential sites of deposition in this study. An illustrative difference between our experiments and those of *Braudrick et al*. [2009] is that vegetation on the initial floodplain limited the lateral expansion in the experiments of *Braudrick et al*. whereas we developed a higher sinuosity meandering channel before vegetation was allowed to settle.

[52] These results show what effect vegetation has on channel dynamics and channel belt width, but also the effect of different dispersal methods. Creating a new, more natural channel planform is increasingly used as a restoration measure to improve the hydromorphological state of rivers [e.g., *Gurnell et al*., 2006; *Pedersen et al*., 2007]. Moreover, enhancing natural channel dynamics and creating a more natural channel planform are among the most frequently designated hydromorphological measures in the river management [*Kail and Wolter*, 2010]. The results of this study show that a newly created restored channel potentially increases in channel dynamics and hence, sediment output are high until the river banks and floodplain get vegetated with a more pronounced effect if seeds are dispersed by flow compared to a uniform distribution of seeds (which is comparable to planting on the floodplain). Hence, if the objective of the restoration project is to develop a natural channel planform and (vegetated) floodplain and to avoid large sediment output from the restored reach, natural propagule dispersal, deposition, and vegetation growth should be ensured and assisted.

[53] Our experimental approach opens up a wide range of exciting possibilities for exploration with a high degree of control of one-way and mutual interactions between hydrodynamics, morphodynamics, vegetation, and restoration measures. Such experiments complement numerical modeling where a host of dynamic properties and settling conditions for plants and for the interactions between plants and flow at various scales must be specified, and therefore require detailed data [*Schnauder and Moggridge*, 2009; *Camporeale et al*., 2013]. Furthermore, a better understanding of such interactions from these experiments can help interpretation of the significant change of the Earth system when terrestrial plants established in the Palaeozoic era [*Davies and Gibling*, 2011], which is presently interpreted to have caused changes in river patterns.

5. Conclusions

[54] We conducted several experiments to test the role of vegetation dispersal styles on river morphology. We compared control experiments without vegetation, an experiment with uniformly distributed vegetation seeds and an experiment with vegetation seeds distributed by the flow. In addition, small-scale bank erosion experiments showed that vegetation decreases bank retreat rate depending on vegetation density. The experiments demonstrate that seed dispersal processes and initial morphology determine vegetation pattern. In turn, the vegetation pattern strongly modifies the river morphology pattern. A uniformly vegetated floodplain stabilizes banks, forms tighter meander bends, increases channel sinuosity, and leads to a sustained single-thread channel. In contrast, vegetation establishment from seeds distributed by the flow leads to a very different patchy pattern with flow diversion around patches and bars rather than concentrated channelization. The resulting multithreaded system has shallower flow depths and is no longer dynamic. In general, we conclude that the combination of discharge variations and vegetation settling rules have a large effect on the morphology and dynamics of rivers. Specifically, our results show that:

[55] 1. the channel becomes narrower and deeper for experiments with vegetation;

[56] 2. bank erosion rates decrease for increasingly vegetated banks;

[57] 3. bank stabilization leads to tighter bends with an irregular bank line;

[58] 4. hydraulic resistance due to patchy vegetation leads to sediment deposition upstream of the vegetation;

[59] 5. the establishment of vegetation, where seeds are distributed by the flow, occurs mostly by stranding of

seeds; water level decrease (e.g., on the floodplain), helical flow (e.g., in bends), and germination of sprouts (e.g., increase of vegetation patches).

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References

Abernethy, B., and I. D. Rutherford (2001), The distribution and strength of riparian tree roots in relation to riverbank reinforcement, *Hydrol. Processes*, *15*, 63–79, doi:10.1002/hyp.152.

Baptist, M. J. (2003), A flume experiment on sediment transport with flexible, submerged vegetation, paper presented at International Workshop on Riparian Forest Vegetated Channels: Hydraulic, Morphological and Ecological Aspects, Int. Assoc. for Hydraul. Res., Trento, Italy.

Bendix, J., and C. R. Hupp (2000), Hydrological and geomorphological impacts on riparian plant communities, *Hydrol. Processes*, *14*, 2977–2990, doi:10.1002/1099-1085(200011/12)14:16/17¡2977::AID-HYP130¿3.0.CO;2–4.

Bennett, S. J., T. Pirim, and B. D. Barkdoll (2002), Using simulated emergent vegetation to alter stream flow direction within a straight experimental channel, *Geomorphology*, *44*, 115–126.

Bennett, S. J., W. Wu, C. V. Alonso, and S. S. Y. Wang (2008), Modeling fluvial response to in-stream woody vegetation: Implications for stream corridor restoration, *Earth Surf. Processes Landforms*, *33*, 890–909, doi:10.1002/esp.1581.

Bertoldi, W., L. Zanoni, and M. Tubino (2009), Planform dynamics of braided streams, *Earth Surf. Processes Landforms*, *34*, 547–557, doi:10.1002/esp.1755.

Bertoldi, W., N. A. Drake, and A. M. Gurnell (2011), Interactions between river flows and colonizing vegetation on a braided river: Exploring spatial and temporal dynamics in riparian vegetation cover using satellite data, *Earth Surf. Processes Landforms*, *36*, 1474–1786, doi:10.1002/esp.2166.

Blanckaert, K., M. G. Kleinhans, S. J. McLelland, W. S. J. Uijtewaal, B. J. Murphy, A. Van de Kruijs, D. R. Parsons, and Q. Chen (2013), Flow seperation at the inner (convex) and outer (concave) banks of constant-width and widening open-channel bends, *Earth Surf. Processes Landforms*, *38*, 696–716, doi:10.1002/esp.3324.

Blom, C. W. P. M., and L. A. C. J. Voesenek (1996), Flooding: The survival strategies of plants, *Trends Ecol. Evol.*, *11*(7), 290–295, doi:10.1016/0169–5347(96)10034-3.

Braudrick, C. A., W. E. Dietrich, G. T. Leverich, and L. S. Sklar (2009), Experimental evidence for the conditions necessary to sustain meandering in coarse bedded rivers, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(40), 16,936–16,941, doi:10.1073/pnas.0909417106.

Camporeale, C., E. Perucca, L. Ridolfi, and A. M. Gurnell (2013), Modeling the interactions between river morphodynamics and riparian vegetation, *Rev. Geophys.*, *51*, 379–414, doi:10.1002/rog.20014.

Chambert, S., and C. S. James (2009), Sorting of seeds by hyrdochory, *River Res. Appl.*, *25*, 48–61, doi:10.1002/rra.1093.

Clarke, S. J. (2002), Vegetation growth in rivers: Influence upon sediment and nutrient dynamics, *Prog. Phys. Geogr.*, *26*(2), 159–172, doi:10.1191/0309133302pp324ra.

Corenblit, D., E. Tabacchi, J. Steiger, and A. M. Gurnell (2007), Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches, *Earth Sci. Rev.*, *84*, 56–86, doi:10.1016/j.earscirev.2007.05.004.

Coulthard, T. J. (2005), Effects of vegetation on braided stream pattern and dynamics, *Water Resour. Res.*, *41*, W04003, doi:10.1029/2004WR003201.

Crosato, A., and E. Mosselman (2009), Simple physics-based predictor for the number of river bars and the transition between meandering and braiding, *Water Resour. Res.*, *45*, W03424, doi:10.1029/2008WR007242.

Davies, N. S., and M. R. Gibling (2011), Evolution of fixed-channel alluvial plains in repsonse to Carboniferous vegetation, *Nat. Geosci.*, *4*, 629–633, doi:10.1038/NGEO1237.

Eaton, B. C. (2006), Bank stability analysis for regime model of vegetated gravel bed rivers, *Earth Surf. Processes Landforms*, *31*, 1438–1444, doi:10.1022/esp.1364.

Edwards, P., J. Kollman, A. Gurnell, K. Tockner, and J. Ward (1999), A conceptual model of vegetation dynamics on gravel bars of a large Alpine river, *Wetlands Ecol. Manage.*, *7*, 141–153, doi:10.1023/A:1008411311774.

Egozi, R., and P. Ashmore (2009), Experimental analysis of braided channel pattern response to increased discharge, *J. Geophys. Res.*, *114*, F02012, doi:10.1029/2008JF001099.

Fagherazzi, S., E. J. Gabet, and D. J. Furbish (2004), The effect of bidirectional flow on tidal channel planforms, *Earth Surf. Processes Landforms*, *29*, 295–309, doi:10.1002/esp.1016.

Federici, B., and C. Paola (2003), Dynamics of channel bifurcations in noncohesive sediments, *Water Resour. Res.*, *39*(6), 1162, doi:10.1029/2002WR001434.

Ferguson, R., D. Parsons, S. Lane, and R. Hardy (2003), Flow in meander bends with recirculation at the inner bank, *Water Resour. Res.*, *39*(11), 1322, doi:10.1029/2003WR001965.

Friedkin, J. (1945), *A Laboratory Study of the Meandering of Alluvial Rivers*, U.S. Army Corps of Eng., U.S. Waterways Exp. Stn., Vicksburg, Miss.

Gran, K., and C. Paola (2001), Riparian vegetation controls on braided stream dynamics, *Water Resour. Res.*, *37*(12), 3275–3283, doi:10.1029/2000WR000203.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins (1991), An ecosystem perspective of riparian zones, *BioScience*, *41*(8), 540–551.

Gurnell, A. M. (2007), Analogies between mineral sediment and vegetative particle dynamics in fluvial systems, *Geomorphology*, *89*, 9–22, doi:10.1016/j.geomorph.2006.07.012.

Gurnell, A. M., and G. E. Petts (2002), Island-dominated landscapes of large floodplain rivers, a European perspective, *Freshwater Biol.*, *47*(4), 581–600, doi:10.1046/j.1365–2427.2002.00923.x.

Gurnell, A. M., and G. E. Petts (2006), Trees as riparian engineers: Tagliamento River, Italy, *Earth Surf. Processes Landforms*, *31*, 1558–1574, doi:10.1002/esp.1342.

Gurnell, A. M., G. E. Petts, D. M. Hannah, B. P. G. Smith, P. J. Edwards, J. Kollman, J. V. Ward, and K. Tockner (2001), Riparian vegetation and island formation along the gravel-bed fiume Tagliamento, Italy, *Earth Surf. Processes Landforms*, *26*, 31–62, doi:10.1002/1096–9837(200101)26:1<31::AID-ESP155>3.0.CO;2-Y.

Gurnell, A. M., J. M. Goodson, P. G. Angola, I. P. Morrissey, G. E. Petts, and J. Steiger (2004), Vegetation Propagule Dynamics and Fluvial Geomorphology, in *Riparian Vegetation and Fluvial Geomorphology*, edited by S. J. Bennett and A. Simon, pp. 209–219, AGU, Washington, D. C., doi:10.1029/008WSA15.

Gurnell, A. M., A. J. Boitsidis, K. Thompson, and N. J. Clifford (2006), Seed bank, seed dispersal and vegetation cover: Colonization along a newly-created river channel, *J. Veg. Sci.*, *17*, 665–674.

Gurnell, A. M., K. Thompson, J. Goodson, and H. Moggridge (2008), Propagule deposition along river margins: Linking hydrology and ecology, *J. Ecol.*, *96*, 553–565, doi:10.1111/j.1365–2745.2008.01358.x.

Gurnell, A. M., W. Bertoldi, and D. Corenblit (2012), Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers, *Earth Sci. Rev.*, *111*, 129–141, doi:10.1016/j.earscirev.2011.11.005.

Hughes, F. M. R. (1997), Floodplain biogeomorphology, *Prog. Phys. Geogr.*, *21*(4), 501–529, doi:10.1177/030913339702100402.

Ikeda, S., G. Parker, and K. Sawai (1981), Bend theory of river meanders. Part 1. Linear development, *J. Fluid Mech.*, *112*, 363–377, doi:10.1017/S0022112081000451.

Kail, J., and C. Wolter (2010), Analysis and evaluation of large-scale river restoration planning in Germany to better link river research and management, *River Res. Appl.*, *27*, 985–999.

Kirkby, M. (1995), Modelling the links between vegetation and landforms, *Geomorphology*, *13*, 319–335, doi:10.1016/0169-555X(95)00065-D.

Kleinhans, M. G. (2010), Sorting out river channel patterns, *Prog. Phys. Geogr.*, *34*, 287–326, doi:10.1177/0309133310365300.

Kleinhans, M. G., W. M. van Dijk, W. I. van de Lageweg, R. Hoendervoogt, H. Markies, and F. Schuurman (2010), From nature to lab: Scaling self-formed meandering and braided rivers, in *Riverflow 2010*, vol. *2*, edited by A. Dittrich et al., pp. 1001–1010, Bundesanst. für Wasserbau, Karlsruhe, Germany.

Lytle, D. A., and N. Leroy Poff (2004), Adaptation to natural flow regimes, *Trends Ecol. Evol.*, *19*(2), 94–100, doi:10.1016/j.tree.2003.10.002.

Mahoney, J. M., and S. B. Rood (1998), Streamflow requirements for cottonwood seedling recruitment: An intregrative model, *Wetlands*, *18*, 634–645.

Merritt, D. M., and E. E. Wohl (2002), Processes governing hydrochory along rivers: Hydraulics, hydrology, and dispersal phenology, *Ecol. Appl.*, *12*(4), 1071–1087.

Murray, A., and C. Paola (2003), Modelling the effect of vegetation on channel pattern in bedload rivers, *Earth Surf. Processes Landforms*, *28*, 131–143.

Nilsson, C., E. Andersson, D. M. Merritt, and M. E. Johansson (2002), Differences in riparian flora between riverbanks and river lakeshores explained by dispersal traits, *Ecology*, *83*(10), 2878–2887, doi:10.1890/0012–9658(2002)083[2878:DIRFBR]2.0.CO;2.

Nilsson, C., R. L. Brown, R. Jansson, and D. M. Merritt (2010), The role of hydrochory in structuring riparian and wetland vegetation, *Biol. Rev.*, *85*, 837–858, doi:10.1111/j.1469-185X.2010.00129.x.

Noble, M. G. (1979), The origin of Populus deltoides and Salix interior zones on point bars along the Minnesota river, *Am. Midland Nat.*, *102*(1), 59–67.

O'Hare, J. M., M. T. O'Hare, A. M. Gurnell, P. M. Scarlett, T. Liffen, and C. McDonald (2012), Influence of an ecosystem engineer, the emergent macrophyte sparganium erectum, on seed trapping in lowland rivers and consequences for landform colonisation, *Freshwater Biol.*, *57*, 104–115.

Osterkamp, W. R., and C. R. Hupp (2010), Fluvial processes and vegetation: Glimpses of the past, the present, and perhaps the future, *Geomorphology*, *116*, 274–285, doi:10.1016/j.geomorph.2009.11.018.

Ottevanger, W., K. Blanckaert, W. S. J. Uijttewaal, and H. J. De Vriend (2013), Meander dynamics: A reduced order non-linear model without curvature restrictions for flow and bed morphology, *J. Geophys. Res.*, *118*, 1118–1131, doi:10.1002/jgrf.20080.

Parker, G., P. R. Wilcock, C. Paola, W. E. Dietrich, and J. Pitlick (2007), Physical basis for quasi-universal relations describing bankfull hydraulic geometry of single-thread gravel bed rivers, *J. Geophys. Res.*, *112*, F04005, doi:10.1029/2006JF000549.

Parolin, P. (2005), Ombrohydrochory: Rain-operated seed dispersal in plants—With special regard to jet-action dispersal in Aizoaceaea, *Flora*, *201*, 511–518.

Pedersen, M., N. Friber, J. Skriver, A. Baattruppedersen, and S. Larsen (2007), Resoration of Skjetn River and its valley: Short-term effects on river habitats, macrophytes and macroinvertebrates, *Ecol. Eng.*, *30*, 145–156.

Perona, P., et al. (2012), Biomass selection by floods and related timescales: Part 1. Experimental observations, *Adv. Water Resour.*, *39*, 85–96, doi:10.1016/j.advwatres.2011.09.016.

Perucca, E., C. Camporeale, and L. Ridolfi (2007), Significance of the riparian vegetation dynamics on meandering river morphodynamics, *Water Resour. Res.*, *43*, W03430, doi:10.1029/2006WR005234.

Pollen, N., and A. Simon (2005), Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model, *Water Resour. Res.*, *41*, W07025, doi:10.1029/2004WR003801.

Rood, S. B., J. H. Braatne, and M. R. Hughes (2003), Ecophysiology of riparian cottonwoods: Stream flow dependency, water relations and restoration, *Tree Physiol.*, *23*, 1113–1124, doi:10.1093/treephys/23.16.1113.

Schnauder, I., and H. L. Moggridge (2009), Vegetation and hydraulic-morphological interactions at the individual plant, patch and channel scale, *Aquat. Sci.*, *71*, 318–330, doi:10.1007/s00027-009-9202-6.

Schneider, R. L., and R. R. Sharitz (1988), Hydrochory and regeneration in a bald cypress-water tupelo swamp forest, *Ecology*, *69*(4), 1055–1063.

Stanford, J. A., M. S. Lorang, and F. R. Hauer (2005), The shifting habitat mosaic of river ecosystems, *Verh. Int. Ver. Limnol.*, *29*, 123–136.

Stella, J. C., P. M. Rodrígues-González, S. Dufour, and J. Bendix (2013), Riparian vegetation research in Mediterranean-climate regions: Common patterns, ecological processes, and consideration for management, *Hydrobiologia*, *719*, 291–315, doi:10.1007/s10750-012-1304-9.

Struiksma, N., K. W. Olesen, C. Flokstra, and H. J. De Vriend (1985), Bed deformation in curved alluvial channels, *J. Hydraul. Res.*, *23*(1), 57–79, doi:10.1080/00221688509499377.

Tal, M., and C. Paola (2010), Effects of vegetation on channel morphodynamics: Results and insights from laboratory experiments, *Earth Surf. Processes Landforms*, *35*(9), 1014–1028, doi:10.1002/esp.1908.

Talmon, A., N. Struiksma, and M. van Mierlo (1995), Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes, *J. Hydraul. Res.*, *33*(4), 495–517.

Thorne, C. R. (1990), Effects of vegetation on riverbank erosion and stability, in *Vegetation and Erosion*, edited by J. B. Thornes, pp. 125–144, John Wiley, Chichester, U. K.

Tockner, K., A. Paetzold, U. Karaus, C. Claret, and J. Zettel (2009), Ecology of braided rivers, in *Braided Rivers: Process, Deposits, Ecology and Management*, edited by G. H. Sambrook Smith et al., Blackwell, Oxford, U. K., doi:10.1002/9781444304374.ch17.

Van de Lageweg, W. I., W. M. Van Dijk, R. Hoendervoogt, and M. G. Kleinhans (2010), Effects of riparian vegetation on experimental channel dynamics, in *Riverflow 2010*, vol. *2*, edited by A. Dittrich et al., pp. 1331–1338, Bundesanst. für Wasserbau, Karlsruhe, Germany.

Van de Lageweg, W. I., W. M. Van Dijk, and M. G. Kleinhans (2013a), Channel belt architecture formed by an experimental meandering river, *Sedimentology*, *60*(3), 840–859, doi:10.1111/j.1365–3091.2012.01365.x.

Van de Lageweg, W. I., W. M. Van Dijk, and M. G. Kleinhans (2013b), Morphological and stratigraphical signature of floods in a braided gravel-bed river revealed from flume experiments, *J. Sediment. Res.*, doi: 10.2110/jsr.2013.70.

Van Dijk, W. M., W. I. Van de Lageweg, and M. G. Kleinhans (2012), Experimental meandering river with chute cutoffs, *J. Geophys. Res.*, *117*, F03023, doi:10.1029/2011JF002314.

Van Dijk, W. M., W. I. Van de Lageweg, and M. G. Kleinhans (2013), Formation of a cohesive floodplain in a dynamic experimental meandering river, *Earth Surf. Processes Landforms*, *38*, 1550–1565, doi: 10.1002/esp.3400.

Van Splunder, I., H. Coops, L. A. C. J. Voesenek, and C. W. P. M. Blom (1995), Establishment of alluvial forest species in floodplains: The role of dispersal timing, germination characteristics and water level fluctuations, *Acta Bot. Neer.*, *44*(3), 269–278.

Walker, L. R., J. C. Zasada, and F. S. Chapin (1986), The role of life history processes in primary succession on an Alaskan floodplain, *Ecology*, *67*, 1243–1253, doi:10.2307/1938680.