

1 **Particle size segregation of turbidity current deposits in vegetated canopies**

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18

19 **Abstract**

20

21 Interactions between ecology, hydrodynamics and sediments play central roles in the
22 evolution of coastal and freshwater ecosystems. We set out to characterise
23 interactions of a specific hydrodynamic phenomenon – turbidity currents – with
24 vegetation and sediment dynamics. We measured hydrodynamics and sediment
25 deposition rates when turbidity currents flowed into plant canopies in a lock-
26 exchange flume experiment, using simulated vegetation and three real plant species,
27 and varying the turbidity current's initial sediment concentration in the range 1.0-6.0
28 gL^{-1} . The natural sediment used had an essentially bimodal size distribution, with
29 coarse (6.2-104 μm) and fine (2.2-6.2 μm) fractions. In all cases, on entering the
30 vegetation canopy, the turbidity current was initially inertially-dominated, but
31 subsequently became drag-dominated. In the inertial regime, there was no size
32 segregation in the deposited material. In the drag-dominated regime, the deposited
33 material became increasingly dominated by fine sediment, at a rate dependent on
34 the vegetation type. The transition between these two regimes occurred at a
35 distance equivalent to 5.1 to 7.6 times the total water depth downstream of the lock
36 gate. The size segregation of deposited sediment is posited to have important
37 consequences for substrate evolution, which in turn may affect vegetation growth.
38 Thus, our findings point to a non-linear feedback mechanism between the spatial
39 heterogeneity of vegetation canopies and that of the substrate they help to engineer.

40

41 **Keywords:** Turbidity current, drag-dominated regime, inertial regime, natural
42 vegetation, sediment deposition, particle segregation

43

44 ***Introduction***

45

46 Bio-geomorphic processes and their associated scale-dependent feedbacks play an
47 important role in the evolution of the ecosystems in many contexts (Bouma et al.
48 2013; Corenblit et al. 2015; Manners et al., 2015). The high spatial heterogeneity
49 and time variability of coastal and freshwater vegetation canopies make them some
50 of the most dynamic ecosystems on Earth (Corenblit et al. 2015). These systems
51 respond to externally-forced disturbances by adapting their geomorphology and
52 forming effective sediment retention structures, i.e. roots or rhizomes (Stallins, 2006;
53 Gurnell, 2014), making possible the recovery of the vegetation after damage or
54 disturbance (Balke et al. 2014). The structure and function of many disturbed coastal
55 and freshwater vegetation canopies result from feedbacks between plant dynamics
56 and the water- and wind-induced transport of sediment (Stallins, 2006; Corenblit et
57 al. 2015). Plants ‘engineer’ geomorphic processes in a scale-dependent way by
58 developing specific response traits and therefore modifying ecosystem functioning
59 (Corenblit et al. 2015; Diehl et al., 2017; Curran et al., 2013). They can generate
60 local positive feedback, when flow deceleration occurs promoting sediment accretion
61 and thereby plant survival and growth, but negative feedback at larger scales, when
62 flow accelerates around vegetation patches enhancing the risk of erosion inhibiting
63 plant growth (Bouma et al. 2013; Rietkerk & van de Koppel, 2008; Vandenbruwaene
64 et al. 2011; Zong & Nepf, 2011). Thus, bio-geomorphic feedbacks are a major
65 determinant of coastal and freshwater landscape evolution (Bouma et al. 2013).
66 Flow-vegetation interactions in these systems not only drive their geomorphic
67 structure (Van Katwijk et al. 2010; Manners et al. 2015) but also their nutrient

68 cycling, sedimentary microbial processes and the successional distribution of plant
69 species across land-water gradients. Vegetation affects water quality positively by
70 increasing bed stability, removing pollution, increasing light availability and
71 decreasing turbidity (Schulz et al. 2003; Folkard 2011, Vilas et al. 2017).

72

73 The bio-mechanical properties and structure of plants (density, height, cover and
74 flexibility) mediate interactions between vegetation, hydrodynamics and sedimentary
75 processes (Serodes & Troude 1984; Wilson et al. 2003; Venterink et al. 2006; Wilson
76 et al. 2008; Manners et al. 2015; Diehl et al. 2017). The ratio of plant height to water
77 depth, particularly whether plants are emergent or submerged, is an important factor
78 in determining rates of sediment transport and deposition (Follett & Nepf. 2012;
79 Nepf, 2012). Seasonal evolution of plants shapes their morphology through changes
80 in the number and the characteristics of stems and leaves. That, in turn, produces a
81 change in the frontal canopy area. Increased plant density, frontal area and stiffness
82 reduce mean flow speed (Kadlec 1990; Västilä & Järvelä 2014), decrease near-bed
83 turbulence intensity (Pujol et al. 2010; 2013), promote sediment deposition (Soler et
84 al. 2017) and reduce sediment resuspension (Ward et al. 1984; Leonard & Luther
85 1995). These effects determine bed characteristics, and feed back to determine plant
86 growth due to the different tolerances of different plant species to burial or scouring
87 (Kui and Stella, 2016).

88

89 Variations in vegetation structure result in heterogeneous landscape patterns
90 (Stallins 2006). For example, dense coastal vegetation provides sheltering for fine
91 particles, leading to an increase of fine sediments and organic matter within the
92 substrate, while sparse vegetation in higher energy environments cause a decrease

93 in fine sediments and organic content (Van Katwijk et al., 2010). Conversely, flooding
94 and sediment deposition can have non-linear effects on riparian vegetation in
95 freshwater environments. They can increase the mortality of smaller plants but cause
96 a compensating growth response in survivors, which, as they grow in age and size,
97 become less vulnerable to hydro-geomorphic processes such as burial, scour and
98 prolonged inundation (Kui and Stella 2016). Coastal and freshwater vegetation also
99 plays a crucial role in providing food, habitat and substrate for aquatic invertebrates
100 (Wilson et al. 2003). *Ruppia cirrhosa*, for example, is a floating plant that helps to
101 create a substrate for macro and microalgae, which are food sources for a range of
102 invertebrates and nurseries for resident fauna and migrating organisms (Mannino &
103 Sará, 2006).

104

105 Gravity currents are an important type of transport process associated with the fate
106 and distribution of sediments in coastal and fluvial environments. They are driven by
107 horizontal pressure gradients due to spatial variations in fluid density. This density
108 variation can be due to differences in water temperature, or particulate or solute
109 concentration. The subset of gravity currents in which the density differences are due
110 to particulate concentration are called “turbidity currents”. These particle-laden
111 currents persist for long distances and can induce significant modifications in
112 substrate characteristics by scouring and depositing sediment (Kneller & Buckee,
113 2000; Hogg & Woods, 2001; Felix, 2002). Diverse examples can be found in aquatic
114 environments such as lakes (Roget & Colomer 1996; Serra et al, 2002a; Serra et al.,
115 2005; Soler et al., 2009), reservoirs (Chikita, 1989), rivers (Jackson et al., 2008;
116 Lyubimova et al., 2014) and oceans (Kneller and Buckee 2000; Felix, 2002;
117 Meiburg and Kneller, 2010).

118

119 In the present paper, we focus on interactions between turbidity currents and natural
120 vegetation in land-water transition zones and shallow marine and freshwater
121 environments. There is a lack of knowledge of the effect of the vertical structure of
122 natural aquatic plants on both the hydrodynamics and sediment dynamics of turbidity
123 currents. This study provides understanding of the effects of natural vegetation on
124 the hydrodynamics of turbidity currents propagating through plant canopies typical in
125 coastal marine systems and freshwater environments, and compares the currents'
126 evolution in these canopies to that found in simulated vegetation canopies and over
127 non-vegetated beds. In addition, the sediment transport and deposition rates from
128 turbidity currents in these canopies are investigated and compared. This is an
129 advance over previous studies of interactions between turbidity currents and
130 canopies of obstacles, which have considered only continuous-release turbidity
131 currents flowing through idealized emergent vegetation (Soler et al., 2017) and non-
132 Newtonian mud flows (Testik and Yilmaz (2015).

133

134 ***Theoretical background***

135

136 ***Gravity current hydrodynamics***

137

138 Gravity currents have been analysed for many years, both theoretically (Benjamin,
139 1968) and experimentally (Simpson, 1982; Shin et al., 2004). The latter approach
140 has most commonly used lock-exchange flume studies. These experiments begin
141 with two fluids of different densities, at rest and separated by a vertical barrier or
142 'lock gate'. When the lock gate is removed, differences in the hydrostatic pressure

143 cause the denser fluid to flow as a gravity current beneath the less-dense fluid, along
144 the bottom boundary of the flume, forcing the less-dense fluid to flow in the opposite
145 direction over the denser fluid. Gravity currents pass through three phases while
146 advancing along the flume (e.g. Huppert and Simpson 1980; Maxworthy et al. 2002).
147 In the initial, 'inertial' phase, the current proceeds as if released from an infinite
148 reservoir, at constant velocity i.e. its frontal position x_c varies in direct proportion to
149 time, and depends on g' and H , such that (Tanino et al., 2005)

150

$$151 \quad x_c \propto \left(\frac{g'H}{4} \right)^{1/2} t \quad (1)$$

152

153 where g' is the reduced gravity $g' = g(\rho_c - \rho_a)/\rho_a$, ρ_c and ρ_a are the current and ambient
154 fluid densities respectively, and H is the total water depth. This phase lasts until the
155 motion is affected by the reflection of an interfacial wave generated by the removal of
156 the lock gate. This wave sets off in the opposite direction to the gravity current,
157 reflects off the back wall of the flume, and then catches up with the front of the
158 gravity current. When it does so, the current passes into its second phase, in which
159 motion is determined by a balance between buoyancy and inertial forces, and the
160 flow slows over time such that the position of the front varies as $t^{2/3}$ (Maxworthy et al.
161 2002). The third and last phase occurs when the current has spread so far that it has
162 become thin enough for viscous forces between the two fluids to become important.
163 In this phase, the dominant force balance is between viscous and buoyancy forces
164 and the position of the front varies as $t^{1/5}$.

165

166 The propagation of gravity currents through arrays of obstacles (usually intended to
 167 simulate vegetation) has been studied by several recent laboratory and numerical
 168 investigations (e.g. Tanino et al., 2005; La Rocca et al., 2008; Zhang and Nepf,
 169 2008, 2011; Gonzalez-Juez et al., 2009; 2010; Nogueira et al., 2013, 2014;
 170 Bhaganagar 2014; Soler et al, 2017). In these conditions, gravity currents are
 171 affected by drag forces exerted by the obstacles, and these tend to dominate over
 172 both inertial forces and drag forces caused by the flume bed and sidewalls. When a
 173 gravity current produced by a finite-volume release from a reservoir of denser fluid
 174 flows through an array of obstacles, the position of the current's front, x_c , evolves
 175 following as (Hatcher et al. 2000)

176

$$177 \quad x_c = k \left(\frac{q_0 g' d}{C_{Da} \phi} \right)^{1/4} t^{1/2} \quad (2)$$

178

179 where q_0 is the total volumetric flow rate per unit across-flume distance; g' is the
 180 reduced gravity (see above); d is the individual obstacle width (cylinder diameter); $\phi =$
 181 $(\pi/4) \cdot ad$ is the volume fraction of the obstacles; $a = Nd/A$ is the frontal area of
 182 cylinders per unit volume (Nepf, 1999), N is the number of cylinders, A is the bed
 183 area occupied by the array of cylinders (or stems); and $C_{Da} = C_D / 1.16 \cdot (1.16 -$
 184 $9.31 \cdot ad + 38.6 \cdot ad^2 - 59.8 \cdot ad^3)$ is the drag coefficient of the randomly-distributed array
 185 (Ghisalberti and Nepf, 2004), where C_D is the drag coefficient for smooth isolated
 186 circular cylinders which is a function of the cylinder Reynolds number Re_c , such that
 187 $C_D = 1 + 10Re_c^{-2/3}$ (White, 1991). This expression for C_D applies for Re values ranging
 188 from 1 to 10^5 and dimensionless array density $ad < 0.03$ (Nepf, 1999).

189

190 ***Turbidity currents***

191

192 The spatial structure and temporal evolution of turbidity currents are determined by
193 both their grain-size distribution – which is commonly quantified as the ratio of fine to
194 coarse grains that they contain – and their total particle concentration (Felix 2002). A
195 preponderance of fine particles favours extended propagation of the turbidity current
196 and results in sedimentation further downstream than in coarse grain-dominated
197 currents (Harris et al., 2002). Moreover, the runout distance to which coarse particles
198 are transported within turbidity currents increases substantially when the proportion
199 of fines in the turbidity current is increased (Gladstone et al., 1998).

200

201 Turbidity current dynamics can be more complicated than those of gravity currents in
202 which the density-varying agent is conservative (e.g. heat or solute concentration),
203 because of the possibility of sediment entrainment due to bed scouring or loss due to
204 deposition (Francisco et al., 2017). These processes can change the density
205 differences that drive the propagation of turbidity currents, altering their temporal
206 evolution. Based on earlier work on lock releases of oil slicks (Hoult 1972; Fanelop
207 and Waldman 1972) and other hazardous fluids (Chen 1980), Bonnecaze et al.
208 (1993) found that the position of the front of a turbidity current of finite volume
209 spreading over a rigid, un-obstructed horizontal surface in shallow water, evolved
210 following $x_c \propto t^{2/3}$.

211

212 Turbidity currents are commonly found in shallow regions of coastal waters and
213 lakes. For example, they can be generated by sediment-bearing runoff of rainfall
214 from surrounding land. In these environments, their interactions with vegetation such

215 as saltmarshes, lake-fringing plants and seagrass meadows reduce the currents'
216 speed, altering sediment transport, deposition and entrainment within them. In
217 general, the presence of vegetation results in reduction of bed erosion (Madsen et
218 al., 2001) and increased deposition of sediment (Agawin and Duarte, 2002; Zong
219 and Nepf 2011; Montakhab et al., 2012). The experiments carried out in this study go
220 beyond these previous studies by simulating turbidity currents in vegetated
221 environments in a more realistic way, by using natural sediment and vegetation.

222

223 ***Material and methods***

224

225 ***Flume set-up***

226

227 The experiments were carried out in a methacrylate flume (4.0 m long, 0.3 m high
228 and 0.3 m wide) with a removable vertical lock gate that separated the flume into two
229 sections (Figure 1). The shorter section was filled with a mixture of sediment and
230 water that would form the turbidity current, while the longer section was filled with
231 water only. In the latter, a vegetation canopy was distributed along the flume bed.

232

233 ***Vegetation canopies***

234

235 Three species of natural vegetation with differentiated vertical structure, and a single
236 run of simulated vegetation canopy were used. The simulated vegetation consisted
237 of vertical PVC dowels with a diameter of 6 mm and was intended as a generic
238 model of the rigid stems of plants in an emergent vegetation canopy. The three
239 species of natural vegetation used (Figure 2) are native to Mediterranean and

240 temperate climatic zones: *Arthrocnemum fruticosum* and *Juncus maritimus* are found
241 in marine inter-tidal environments; *Ruppia cirrhosa* is found in freshwater, marshy
242 environments.

243

244 Due to the different morphology of the three natural plant species, different frontal
245 areas, and different vertical distributions of frontal area, resulted from the same
246 canopy density. *Ruppia cirrhosa* (Figure 2A) is an emergent but flexible plant, with
247 long, buoyant, thread-thin stems, which are highly branched and cause a dense
248 obstruction near the water surface where they generate a mesh. *Arthrocnemum*
249 *fruticosum* (Figure 2B) is a rigid and emergent plant, which branches out over its
250 height. *Juncus maritimus* (Figure 2C) is a rigid emergent plant with a slight vertical
251 variation in its stem diameter. The plants were collected from field sites in the
252 Empordà Marshes Natural Park, NE Spain. To construct each canopy, a PVC base
253 sheet was perforated at positions selected by means of a random number generator,
254 following Pujol et al. (2013), and a single plant stem secured in each hole. The
255 density of the canopies was quantified using their solid plant fraction (SPF), which is
256 defined as the fraction of the bed area occupied by the vegetation stems, $SPF =$
257 $100N\pi(d/2)^2/A$ (Pujol et al., 2010). The canopy density for all the experiments with
258 natural or simulated plants was $SPF = 1\%$, i.e. 128 plants m^{-2} . Experiments without
259 plants were also carried out as controls.

260

261 In order to quantify the frontal obstruction caused by each species, their vertically-
262 averaged plant diameter, d , was calculated. To do this, each species canopy was
263 placed, in turn, into the flume, which was filled with water to 12 cm. A plain, grey
264 background was placed 5 cm behind the vegetation to differentiate it from the

265 background and side-view photographs taken at five evenly-distributed locations
266 (Figure 3). Image processing software was used to transform the photographs into
267 binary images, with pixels indicating either vegetation or no vegetation, to compute
268 the obstruction percentage at each height, z , from these binary images, and thus to
269 find the equivalent plant diameter, d_z , at each height, following Neumeier (2005)
270 (Figure 3). This was averaged over the full depth to give the vertically-averaged
271 diameter, d , for these canopies. Values of d were 0.60 cm, 1.10 cm, 1.28 and 1.50
272 cm for the simulated vegetation, *J. maritimus*, *A. fruticosum* and *R. cirrhosa*
273 respectively. Therefore, the dimensionless array densities, ad , varied from 0.02 to
274 0.09, and all fell within the range observed in natural vegetation canopies, $ad = 0.01$
275 to 0.1 (Kadlec, 1990).

276

277 ***Sediment characteristics***

278

279 To generate the turbidity current, the flume was filled with water to a height $H = 12$
280 cm and the lock gate was lowered to separate the two sections. A volume of 3 litres
281 of water from the left channel section (Figure 1) was collected in a container, into
282 which sediment was then added. The sediment-water mixture was stirred vigorously
283 for five minutes to ensure a homogeneous sediment suspension. The sediment-
284 laden water sample was then returned to the left-hand section of the flume and
285 mixed with the remainder of the water therein to give an initial sediment
286 concentration for each run, C_0 . Three values of $C_0 - 1.0, 3.0$ and $6.0, \text{gL}^{-1}$ – were
287 used.

288

289 In order to mimic natural conditions, the sediment was taken from the Pletera ponds
290 at the Empordà Marshes Natural Park. The collected sediment was sieved to remove
291 leaves and roots and then sieved with a finer mesh to remove particles larger than
292 0.5 mm. The particle size distribution of the remaining sediment was measured with
293 a LISST-100 particle size analyser (Sequoia Scientific, Inc., Bellevue, WA, USA).
294 The sample of the sediment in suspension was taken directly from the lefthand
295 section of the channel before starting the experiment. It was found to have an
296 essentially bimodal size distribution, the coarse fraction having diameters of 6.2 to
297 104 μm and forming the majority of the sediment volume (77.7%), and the fine
298 fraction having diameters 2.2 to 6.2 μm and accounting for 18.2% of the sediment
299 volume. The coarse particles fell into the category of weakly cohesive particles (fine
300 to coarse silts and small sand particles), and the fine particles into the category of
301 very cohesive particles (clays and very fine silts) according to the classification of
302 Van Rijn (2007) and Blott and Pye (2012). The remaining 4.1% of the sediment
303 volume consisted of only a few particles with large volumes, which quickly dropped
304 out of the turbidity currents and therefore were not considered in the analysis (Figure
305 4).

306

307 ***Development of the turbidity current***

308

309 For each experimental run, once the sediment-water mixture had been introduced
310 into the left-hand section of the flume, and was well mixed with the rest of the water
311 therein, the lock gate was lifted to release it into the longer, experimental flume
312 section, into which it flowed as a turbidity current. In all runs, the initial (inertial
313 regime) speed of the turbidity current front was two to three orders of magnitude

314 greater than the settling velocity of the coarse particles, and three to four orders of
315 magnitude higher than settling velocities of the fine particles. Thus, the current was
316 essentially conservative in this stage of its evolution. At intervals of 20 cm, fourteen
317 sediment traps (ST0 to ST13) were located on the flume bed, each with a volume of
318 21.3 mL. ST0, the furthest upstream (defined in relation to the direction of flow of the
319 turbidity current) was placed in the reservoir section, 20 cm upstream of the lock
320 gate (Figure 1B), and the furthest downstream, ST13, was positioned 10 cm from the
321 downstream end of the flume. Traps ST1 to ST13 were deployed to analyse the
322 sediment deposited from the turbidity current as it travelled along the flume. Trap
323 ST0 was used to determine the particle size distribution of sediment that settled from
324 the turbidity current before it entered the canopy. As soon as the particle-laden
325 current arrived at the end of the canopy, the traps were covered with lids to avoid
326 collection of sediment that settled out of the current after it had been reflected by the
327 end wall. The sediment collected in each trap was analysed with the LISST-100 to
328 obtain the particle volume distribution and the particle volume concentration (Serra et
329 al. 2002b, 2005). As the major sediment constituent in all the traps was silt particles
330 (77.7%, see Figure 4), the particle volume concentration ($\mu\text{l/l}$) was transformed into
331 deposited sediment mass by assuming that the density of the particles was 2.798
332 $\text{g}\cdot\text{cm}^{-3}$, the standard value for the density of silt particles (Mandal and Maiti, 2015).
333 No flocculation of fine sediment was observed, so its potential effects were not taken
334 into account in this conversion. Finally, deposited mass per unit bed area was
335 converted to a depositional flux rate (DF hereafter) at each sediment trap by dividing
336 by the time over which the deposition occurred.

337

338 The speed of the current front was determined from images taken by two CCD
339 cameras, which were mounted on stationary tripods over the tank (Figure 1A). The
340 position of the front was located on these images by using edge detection (parallax
341 error was less than 3% in these images and was not corrected for in the analysis).

342

343 Fifteen experimental runs were carried out, covering the full matrix of combinations
344 of three values of initial sediment concentration, C_0 , (1.0, 3.0, and 6.0 gL^{-1}), and five
345 different canopy conditions (no canopy, and 1% SPF canopies of simulated
346 vegetation, *A. fruticosum*, *J. maritimus* and *R. cirrhosa*).

347

348 **Results**

349

350 **Advance of the turbidity current**

351

352 Initially, for all the experiments carried out, the temporal advance of the turbidity
353 current (x_c) was linear with time, $x_c \propto t$ (i.e. flow speed was constant), as predicted
354 by (1), indicating that the current was in the inertial regime at this stage (Figure 5).

355 For this initial period of turbidity current development, the relationship between the
356 non-dimensional position of the turbidity current x_c/H and non-dimensional time
357 $(g'/4H)^{1/2} \cdot t$ was linear (Figure 5):

$$358 \quad \frac{x_c}{H} = 0.44 \left(\frac{g'}{4H} \right)^{1/2} t \quad (3)$$

359 and therefore the current had a constant velocity of

$$360 \quad v_c = 0.44 \left(\frac{g'H}{4} \right)^{1/2} \quad (4)$$

361 where $v_c = x_c/t$ is the speed of advance of the front of the current. Subsequently, the
 362 flow slowed, taking on a time dependence, $x_c \propto t^{2/3}$ in the non-vegetated case
 363 (Figure 5). In the vegetated runs, the turbidity current was further slowed by the
 364 vegetative drag. In the drag-dominated regime, the frontal position of the current
 365 followed $x_c \propto t^{1/2}$, as predicted by (2), and the non-dimensional position of the
 366 turbidity current x_c/H followed a linear dependence with the non-dimensional time
 367 $(q_0 g' d / C_{Da} \phi H^4)^{1/4} t^{1/2}$ (Figure 6B) such that

$$368 \quad \frac{x_c}{H} = 0.6 \left(\frac{q_0 g' d}{C_{Da} \phi H^4} \right)^{1/4} t^{1/2} \quad (5)$$

369 and therefore the velocity of the turbidity current varied with time following,

$$370 \quad v_c = 0.3 \left(\frac{q_0 g' d}{C_{Da} \phi} \right)^{1/4} t^{-1/2} \quad (6)$$

371 The hydrodynamic regimes through which the turbidity currents developed (the
 372 inertial and drag-dominated regimes) were separated by a transitional regime, which
 373 occurred in the range $5 < C_{Da} x_c < 7$, starting at the end of the inertial regime (Figure
 374 6A) and ending at the start of the drag-dominated regime (Figure 6B).

375

376 ***Sediment transport and deposition***

377

378 The DF was divided by the initial flux – which was calculated by multiplying the initial
 379 concentration (as prepared in the left hand section of the flume before releasing the
 380 lock gate) by the initial current velocity at the lock gate – to give the normalized DF.

381 For all cases studied, the normalised DF decreased with x , indicating a loss of
 382 sediment from the turbidity current as it propagated through the vegetation. For both
 383 fine and coarse particles, the greater the initial sediment concentration the greater

384 the normalised DF (Figure 7). The DF of coarse particles (which represent 77.7% of
385 the mass of sediment of the turbidity current, see Figure 4) was ≈ 1.5 times that of the
386 fine particles. It can also be seen that the DFs for all values of C_0 and for both
387 particle size fractions decreased as the canopy frontal area, a_d , increased from the
388 simulated vegetation to the *R. cirrhosa* vegetation (Figure 7). The fine particle DFs
389 showed small differences between the different vegetated canopies (Figures 7A, B
390 and C) whereas the coarse particle DFs increased with the canopy frontal area
391 (Figures 7D, E and F).

392

393 The ratio of the normalised DF value at each sediment trap to that at ST1 (the “DF
394 ratio”), was calculated for all the experiments conducted and found to be
395 approximately constant (≈ 1) throughout the inertial regime. In contrast, this ratio
396 decreased in a power law fashion with increasing $C_{Da}aX_c$ in the drag-dominated
397 regime with a slope of -0.15 for the fine particles and -0.24 for coarse particles
398 (Figure 8). This indicates that sediment deposition occurred at a constant rate
399 throughout the inertial regime, but decreased with increasing $C_{Da}aX_c$ in the drag-
400 dominated regime.

401

402 Chen et al. (2012) define the distance over which turbidity currents deposit sediment
403 at a constant rate as the Constant Sedimentation Length (L_{CS}). To determine how
404 this length changed with the canopy characteristics, L_{CS} was plotted against the
405 canopy drag coefficient, $C_{Da}a_d$ (Figure 9). In our vegetated canopy experiments, the
406 canopy drag coefficient has been calculated taking into account the vertically
407 averaged equivalent stem diameter instead of the width of the patch relative to the
408 flow width, as used by Rominger et al. (2011) and Chen et al. (2012). The non-

409 dimensionalized form L_{cs}/H is constant with respect to the canopy drag coefficient in
410 the inertial regime (Figure 9A), i.e. it is not a function of vegetation type. It does vary
411 according to particle size category: $L_{cs}/H = 7.6 \pm 0.2$ for fine particles and 5.1 ± 0.2 for
412 coarse particles. Thus, fine particles deposit inside the canopy at a constant rate
413 over a distance $\approx 50\%$ longer than that over which coarse particles maintain a
414 constant rate of deposition.

415

416 In the drag dominated regime, we considered the non-dimensional parameter
417 $L_{50\%settled}/H$, where $L_{50\%settled}$ is the distance at which the deposition rate falls to half
418 of its initial value. This parameter is plotted against C_{Daad} for both the fine and the
419 coarse particles in Figure 9B. In both cases, $L_{50\%settled}/H$ is a decreasing linear
420 function of C_{Daad} : $L_{50\%settled}/H = -39.2 \cdot C_{Daad} + 8.9$ ($r^2=0.77$) for the fine particles, and
421 $L_{50\%settled}/H = -71.7 \cdot C_{Daad} + 8.7$ ($r^2=0.93$) for the coarse particles. Finally, the
422 values of C_{Daad} corresponding to $L_{50\%settled}/H = 0$, calculated from the linear functions
423 were found to be 0.23 and 0.12 for the fine and coarse particles, respectively. They
424 correspond to stem densities of 27.7% and 16.0% for *J. maritimus*, 13.0% and 7.3%
425 for *A. fruticosum*, and 10.5% and 6.0% for *R. cirrhosa* and represent the minimum
426 canopy densities for which the turbidity current deposition rate falls to half of its initial
427 value by the time it enters the canopy.

428

429 **Discussion**

430

431 The hydrodynamics and depositional sediment fluxes of turbidity currents travelling
432 through canopies have been analysed in terms of both biotic (plant morphology) and
433 abiotic (initial sediment concentration) variations. For the non-vegetated case, the

434 turbidity current's loss of speed is attributed to particles settling out as it progressed
435 forward, causing a reduction of the buoyancy force driving the current. The
436 propagation of the front followed a time dependence, $x_c \propto t^{2/3}$, as found by
437 Bonneau et al. (1993), for the same flow configuration. In the vegetated cases,
438 the greater the frontal canopy area, a_d , the more difficult it was for the turbidity
439 current to flow through the vegetation. This effect caused a loss of sediment from
440 the turbidity current before even entering the canopy. For instance, for a turbidity
441 current with $C_o = 6 \text{ gL}^{-1}$ the amount of sediment deposited in the sediment trap ST0
442 in the *R. cirrhosa* canopy run was 4.2 times the amount deposited in the simulated
443 canopy run, 3.1 times the amount deposited in the *J. maritimus* canopy run and 1.6
444 times the amount deposited in the *A. fruticosum* run. Once the turbidity current
445 penetrated the canopy, its speed decreased. This deceleration was more
446 pronounced for *R. cirrhosa* than for *A. fruticosum* and *J. maritimus*, and was least in
447 the simulated vegetation runs, which had the lowest canopy frontal area.

448

449 The advance of the turbidity current along the canopy, transitioned from the inertial
450 regime to the drag-dominated regime in accordance with previous studies (Tanino et
451 al., 2005; Zhang and Nepf, 2008). The slopes of the regression equations for the
452 front development in the inertial regime and the drag-dominated regime with time
453 were of 0.44 and of 0.67 (Figure 6), respectively. They are similar to those found by
454 Soler et al. (2017) for turbidity currents developing in simulated rigid cylinder
455 canopies, but lower than those found by Tanino et al. (2005) for the inertial regime
456 and Hatcher et al. (2000) for the drag-dominated regime. The difference might be
457 because Tanino et al. (2005) and Hatcher et al. (2000) worked with salinity-driven
458 gravity currents, whereas Soler et al. (2017) and the present study were concerned

459 with turbidity currents. The strong linear correlation between the non-dimensional
460 front development and the non-dimensional time (Figure 6B) indicates that the
461 vertically-averaged equivalent stem diameter, d , and the height of water, H , are
462 appropriate parameters to represent the characteristics of spatially-heterogeneous
463 natural plant canopies with complex vertical structures, as they can be for simpler
464 simulated canopies (Soler et al., 2017). While the turbidity current directly interacts
465 only with the lower parts of the vegetation, the return flow that travels above the
466 current will be strongly slowed by the drag forces exerted by the dense upper parts
467 of the plants, which in turn will reduce the turbidity current speed. The $x_c \propto t^{1/2}$
468 dependency for the drag-dominated regime is in agreement with the findings of
469 Hatcher et al. (2000) for saline currents and with Soler et al. (2017) for turbidity
470 currents, both of which used arrays of vertical cylinders as a model of vegetation.
471 The effect of the plant morphology on the currents' evolution was quantified in terms
472 of its influence on the drag coefficient of the canopy, the frontal area, and the
473 vertically-averaged equivalent stem diameter. Regardless of the type of canopy, the
474 sediment depositional flux rate was found to be independent of C_{Daad} in the inertial
475 regime. In contrast, in the drag-dominated regime the DF rate decreased in a power
476 law fashion with increasing C_{Daad} .

477

478 Our results can be summarized in a conceptual model (Figure 10). The inertial
479 regime is characterized by a downstream advance of the front of the current at a
480 constant velocity, which depends on the initial sediment concentration of the turbidity
481 current (and therefore the reduced gravity, g') and the water depth, H . Within this
482 regime, the settled sediment remained homogeneously distributed until a distance
483 5.1 times the water depth, regardless of the plant morphology. At this point, the

484 coarse sediment started to settle faster than the fine sediment. The position within
485 the inertial regime at which segregation occurred between the fine and coarse
486 sediment ranged from 5.1H to 7.6H. In contrast to the inertial regime, when the
487 turbidity currents moved into the drag-dominated regime, their speed decreased as t
488 $^{1/2}$, leading to increased sedimentation. Under this hydrodynamic condition, coarse
489 particles settle faster than fine particles, increasing the segregation between the
490 particle size fractions, especially where canopies are denser (higher C_{Dad}). We infer
491 that this will lead to a “muddification” of the substrate of the inner canopy region, i.e.,
492 an overall increase in the fine sediment fraction along the canopy, since coarse
493 particles will deposit out before the current reaches this region (near the canopy
494 edge). From this, it may be concluded that, within drag-dominated regimes, there is a
495 strong interaction between plant morphology and the resulting sedimentation is such
496 a way that denser vegetation canopies cause higher sedimentation of coarse
497 particles than fine particles. If the turbidity current does not have a preferential
498 direction, vegetation canopies of horizontal extents greater than two times 5.1H (i.e.
499 10.2H) will be characterized by an outer region where the deposited sediment is
500 made up of both fine and coarse fractions, and an inner region where only the fine
501 sediment fraction is found. If canopies are shorter than 10.2H in horizontal extent,
502 segregation would not occur and the deposited sediment would be a combination of
503 fine and coarse fractions throughout. If the turbidity current does have a preferential
504 direction, then the mixed sediment region would be found up to 5.1H into the canopy
505 at its upstream side, and fine sediment only beyond that point.

506

507 Providing that a canopy is long enough and has a high enough C_{Dad} , segregation by
508 size dominates the sedimentation of turbidity currents. This is in accordance with the

509 conclusions of studies of how plants species traits (such as stiffness, density or
510 height) can modulate the evolution of bio-geomorphic systems such as saltmarshes
511 (Bouma et al., 2013, Corenblit et al., 2015). As has been seen in several laboratory
512 experiments (Bouma et al., 2013) and field studies of seagrasses (van Katwijk et al.,
513 2010) or riparian ecosystems (Diehl et al, 2017), there are positive and negative
514 feedbacks between vegetation, hydrology, hydrodynamics and sediment transport,
515 which can drive landscape changes in coastal marine environments (Larsen et al.,
516 2010) and freshwater environments (Bywater-Reyes et al., 2017). In these dynamic
517 environments, plants act as ecosystem engineers, increasing sediment retention
518 (Corenblit et al., 2009; Bouma et al., 2013; Corenblit et al., 2015; Brodersen et al.,
519 2017). This affects surface elevation, which can lead to significant changes in
520 ecosystem structure, function, and stability (see Morris et al., 2002; Kirwan et al.,
521 2016 regarding coastal environments and Naiman and Décamps, 1997 regarding
522 freshwater environments). Finally, salt marsh plants such as *J. maritimus* or *A.*
523 *fruticosum* have the capacity to take up metal contaminants via their roots (Micaelo
524 et al., 2003; Mucha et al., 2008). Almeida et al. (2004) studied the role of *J.*
525 *maritimus* canopies as sink of contaminants, finding that metal concentration
526 increased with decreasing grain size within them. This implies that the
527 “muddification” effect described above would lead to higher metal concentrations in
528 sediment in the inner canopy region, and if plant density increased (increasing
529 $C_{Da} \alpha X_c$), this effect would be observed near the edges of the canopy.

530

531 **Conclusion**

532

533 The experiment reported here sheds new light on the way in which vegetation
534 canopies affect the deposition of sediment from turbidity currents flowing through
535 them. Specifically, it explores the effects of the different morphologies of three
536 species of plant, and their differences from artificial vegetation and a control case of
537 no vegetation. The main finding of this study is summarised in Figure 10: at the
538 upstream end of a vegetation canopy, there is a region where fine and coarse
539 sediment fractions are deposited homogeneously, and there is no size segregation in
540 the deposited material. Subsequently, there is an increasing degree of segregation,
541 such that the deposited material becomes increasingly dominated by fine sediment
542 as the current proceeds downstream through the vegetation canopy. We refer to this
543 as a process of “muddification” of the canopy interior. The upstream, non-segregated
544 region corresponds to turbidity current’s inertial regime, where it flows with constant
545 speed, and the nature of the deposited sediment is not a function of C_{Daad} . The
546 downstream, segregated region corresponds to the current’s drag-dominated
547 regime. Here, the nature of the deposited sediment is a function of C_{Daad} , and is
548 thus dependent on the morphological characteristics of the vegetation making up the
549 canopy. The transition region between these two occurs at downstream distances
550 with Constant Sedimentation Length of 5.1 to 7.6 times the total water depth.

551

552 This segregation of deposited sediment particle sizes may have important
553 consequences for geomorphic evolution of ecosystems, as well as for local
554 concentrations of nutrients and pollutants bound to the particles, thus playing the
555 same role as sediment focussing in lakes, and downstream sediment fining in rivers.
556 The differences in the extent to which this occurs for different plant species will
557 exacerbate this tendency to geomorphic and biogeochemical heterogeneity, which in

558 turn will affect the ability of vegetation to thrive. Thus, our findings point to a non-
559 linear feedback mechanism between the spatial heterogeneity of vegetation
560 canopies and that of the substrate they help to engineer and its physical and
561 biogeochemical properties.

562

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872

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874

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879

880 **Captions to figures**

881 Figure 1 (a) Side view of the laboratory flume, which is divided prior to the start of
882 each experimental run by a removable, sealing partition (lock gate) into two sections.
883 The smaller, left-hand, section is a reservoir for preparation of the turbidity current
884 fluid. The right-hand section contains the real or simulated vegetation and is the
885 experimental test section. Water depth in both is $H = 12\text{cm}$. The vertical coordinate is
886 z , with $z = 0$ at the bed (increasing upwards); the longitudinal coordinate is x , with $x =$
887 0 at the lock gate (increasing to the right). (b) Top view of the laboratory flume
888 showing the locations of fourteen sediment traps (ST0 to ST13) on the flume bed;
889 ST0 is 20 cm to the left of the lock gate, ST1 is 20 cm to the right of the lock gate,
890 and each subsequent trap is a further 20 cm to the right. The canopy is a randomly-
891 distributed array of obstacles with solid plant fraction (SPF) of 1.0%.

892

893 Figure 2 Images of samples of natural vegetation utilised in the experiments: (a)
894 *Ruppia cirrhosa*, (b) *Arthrocnemum fruticosum* and (c) *Juncus maritimus*

895

896 Figure 3 Photographs of the natural vegetation array; subsequent software-
897 processed binary images and vertical profiles of the plant diameter (d_z) values for
898 each of the natural vegetation canopies: (a) *Juncus maritimus*, (b) *Arthrocnemum*
899 *fruticosum* and (c) *Ruppia cirrhosa*.

900

901 Figure 4 Particle size distribution of deposited sediment mass, normalised by unit
902 bed area and the time over which the deposition occurred ($\times 10^{-4} \cdot \text{g} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$), plotted

903 against particle diameter, ϕ , of the natural sediments in the turbidity currents. The
904 distribution is divided into fine-particle ($2.5 \mu\text{m} < \phi < 6.2 \mu\text{m}$) and coarse-particle (6.2
905 $\mu\text{m} < \phi < 104.0 \mu\text{m}$) fractions.

906

907 Figure 5 Temporal evolution of the front of the turbidity current for runs carried out
908 using different vegetation canopy types: non-vegetated (x); simulated rigid emergent
909 vegetation (white circles); *Juncus maritimus* (black circles), *Arthrocnemum*
910 *fruticosum* (black squares) and *Ruppia cirrhosa* (black triangles).

911

912 Figure 6 Evolution of the dimensionless length (x_c / H) of the turbidity current versus
913 the non-dimensional time (a) $(g'/4H)^{1/2} \cdot t$ for the inertial regime and (b)
914 $(q_0 \cdot g' \cdot d / C_{Da} \cdot \Phi \cdot H^4)^{1/4} \cdot t^{1/2}$ for the drag-dominated regime, for runs with all canopies
915 (PVC dowels (white circles), *Juncus maritimus* (black circles), *Arthrocnemum*
916 *fruticosum* (black squares) and *Ruppia cirrhosa* (black triangles)). Dashed lines
917 represents the linear best fit of data for both the inertial regime ($m = 0.44$, $r^2 = 0.84$, n
918 $= 77$, $p < 0.01$) and the drag dominated regime ($m = 0.60$, $r^2 = 0.90$, $n = 185$,
919 $p < 0.01$).

920

921 Figure 7. Semi-logarithmic plot of the non-dimensional depositional flux rate (DF)
922 against downstream distance. Left panels show results for fine sediment particles
923 (particle diameters $< 6.2 \mu\text{m}$) for runs with turbidity current initial particle
924 concentrations: (a) $1\text{g}\cdot\text{L}^{-1}$ (b) $3\text{g}\cdot\text{L}^{-1}$ and (c) $6\text{g}\cdot\text{L}^{-1}$ and right panels for coarse
925 sediment particles ($6.2 \mu\text{m} < \text{particle diameter} < 104.0 \mu\text{m}$) for: (d) $1\text{g}\cdot\text{L}^{-1}$ (e) $3\text{g}\cdot\text{L}^{-1}$
926 and (f) $6\text{g}\cdot\text{L}^{-1}$. Data shown for all canopies: PVC dowels (white circles), *Juncus*

927 *maritimus* (black circles), *Arthrocnemum fruticosum* (black squares) and *Ruppia*
928 *cirrhusa* (black triangles).

929

930 Figure 8. Ratio of the logarithmic dimensionless DF between the trap at x and the
931 trap at ST1 plotted against $\log(C_{Da}x_c)$ for (a) fine particles and (b) coarse particles.
932 The plots are divided into three zones depending on the dynamical regime: inertial,
933 transitional and drag-dominated. The dashed lines illustrate the linear best fit of the
934 data in the drag-dominated regime: (a) $m = 0.15$, $r^2 = 0.24$, $n = 27$, $p < 0.05$; and (b)
935 $m = 0.24$, $r^2 = 0.19$, $n = 26$, $p < 0.05$. Data shown for all canopies: PVC dowels (white
936 circles), *Juncus maritimus* (black circles), *Arthrocnemum fruticosum* (black squares)
937 and *Ruppia cirrhosa* (black triangles).

938

939

940 Figure 9. (a) Dimensionless constant sedimentation length (L_{cs}/H) in the inertial
941 regime; (b) dimensionless distance at which sediment concentration was reduced to
942 50% of the initial concentration ($L_{50\%settled}/H$) versus the canopy drag coefficient,
943 C_{Daad} for both the fine (black squares) and the coarse particles (grey squares). The
944 lines illustrate, in (a) the mean value of L_{cs}/H for fine and coarse particles, and in (b)
945 the linear best fit of the data in the drag-dominated regime for each particle size
946 fraction: fine ($m = -39.2$, $R^2 = 0.77$, $p < 0.01$) and coarse ($m = -71.7$, $R^2 = 0.93$, $p < 0.01$)

947

948 Figure 10. Diagram of a conceptual model defining turbidity current hydrodynamics
949 (inertial and drag-dominated regimes), and sediment deposition regimes in
950 vegetated canopies.

951