

# Effect of Aquatic Plant Patches on Flow and Sediment Characteristics: The Case of *Callitriche platycarpa* and *Elodea nuttallii*

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**Abstract** In lotic ecosystems, submerged aquatic vegetation has important effects on hydrodynamic and sediment processes. These effects depend on plant morphology and patch structure. This study aimed to test the effect of 2 aquatic plant species on flow and sediment characteristics. For this purpose we measured under natural conditions 3D velocity profiles and sediment characteristics along the main axis of one patch of each species. The 2 species presented contrasting effects on velocity, turbulence profiles and sediment characteristics: one species had significant effects on hydrodynamics and accumulation of fine sediment also further downstream of the patch, whereas the second one accumulated very fine sediment mainly in the upstream half of the patch. These results emphasize the role of plant morphology on hydrodynamics and sediment physico-chemical characteristics.

## 1 Introduction

In freshwater lotic environments, interfaces between biota and sediment or flow are recognised as important regions where many critical biophysical processes occur, as recently reviewed by Marion et al. (2014). Particularly, complex and fundamental physical and biogeochemical processes occur at the plants-water-sediment interfaces (Carpenter and Lodge 1986). For instance, rooted submerged plants reduce velocity and increase sedimentation inside plant patches, and some species are able

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to oxygenate the substrate, influencing the microbial activity and hence the biogeochemical processes in the sediment. Submerged plants also induce important modification of flow conditions, acting as ecosystem engineers (*sensu* Jones et al. 1994) and increasing structural complexity and heterogeneity of lotic ecosystems. Plant patches behave as porous walls: on the one hand, they form an obstacle deviating the flow above and towards the sides of the canopy, locally increasing the velocity, whereas, on the other hand, the flow going through the patch shows a reduced velocity (Sand-Jensen and Mebus 1996; Sand-Jensen and Pedersen 2008, Vandenbruwaene et al. 2011). Consequently, the near-bed velocity, shear stress (James et al. 2004) as well as turbulence are significantly reduced inside the patches.

The changes in hydrodynamic conditions due to flow-plant interactions have indirect cascading effects on sediment dynamics: potential of resuspension and erosion are reduced, favouring sedimentation and reducing water turbidity (Hendriks et al. 2009; Sand-Jensen 1998; Schulz et al. 2003). Submerged plants also induce direct trapping of suspended particles and transported in bed-load through collisions with stem and leaf surfaces (Hendriks et al. 2008; Pluntke and Kozerski 2003). As a consequence, sediment accumulates inside the vegetation patches, with an increased proportion of fine particles compared to non-vegetated areas (Sand-Jensen 1998; Schoelynck et al. 2013).

The effect of aquatic plants on flow and sediment deposition depends on plant morphology and patch structure. For instance, species with dense canopies, as *Callitriche cophocarpa* Sendtn. and *Elodea canadensis* Michx., induce a high reduction of flow velocity inside their patches, increasing sediment retention (Sand-Jensen 1998; Sand-Jensen and Mebus 1996). On the contrary, species with open canopy, as *Sparganium emersum* Rehm., have less impact on flow and sediment dynamics (Sand-Jensen 1998; Sand-Jensen and Mebus 1996). Plant flexibility also influences the interactions: reconfiguration of flexible plants minimizes the surface area in contact with water, reducing the resistance to flow (Miler et al. 2012; O'Hare et al. 2007; Sand-Jensen 2003). At the plant level, the leaf area index (*i.e.* the ratio of leaf surface area to the ground area covered by the plant canopy) is an example of morphological traits that have been demonstrated to have a significant effect on the amount of fine sediment accumulated in submerged patches (Petticrew and Kalf 1992). However, only a few studies (Sand-Jensen 1998) have investigated simultaneously the effect of different plant morphologies on both flow and sediment characteristics (e.g. grain size, organic matter content, nutrient content ...). Sand-Jensen (1998) has analysed the effect of vegetation patches only on the streamwise component of velocity, although the flow can also be impacted on the lateral and vertical components.

The objective of the present study was to evaluate the effects of 2 submerged plant species having contrasting morphologies on different directional components of flow velocity and sediment characteristics. For this purpose, we carried out an in situ investigation of natural patches, combining 3D velocity, sediment grain size distribution and organic matter content measurements. An interdisciplinary

approach was applied for this study, as it is recognised fundamental to fully understand plants-water-sediment interactions (Marion et al. 2014). These complex interactions were then addressed and presented in an ecological perspective.

## 2 Materials and Methods

### 2.1 Study Sites and Plant Species

The study was conducted in two drainage channels of the Upper Rhône River (France), near the localities of Brégnier-Cordon (45° 38' 43"N, 5° 36' 29"E) and Peyrieu (45° 40' 46"N, 5° 42' 3"E). Drainage artificial channels were selected because they present uniform structure (cross-section, water depth) with long straight sections and natural colonization by submerged aquatic vegetation. The 2 channels presented similar length (2.1 and 2.8 km for Brégnier-Cordon and Peyrieu channels, respectively), width (6.0–8.0 m) and depth (0.6–0.7 m). These channels are fed by Rhône river seepage and hillslope aquifers. Cover by aquatic vegetation ranges from 30 to 90 % depending on season and channel section. The most abundant submerged species are *Callitriche platycarpa* Kütz., *Berula erecta* (Huds.) Coville, *Myriophyllum spicatum* L. and *Groenlandia densa* (L.) Fourr. in the site of Brégnier-Cordon, and *Veronica anagallis-aquatica* L. and *Elodea nuttallii* (Planch.) St.-John in the site of Peyrieu.

We selected two species with contrasting morphology and patch architectural structure: *Callitriche platycarpa* and *Elodea nuttallii*. *C. platycarpa* has thin, flexible and highly branched stems that can be 10–200 cm long (Tison and de Foucault 2014) and is heterophyllous: submerged leaves are opposite (*i.e.* two leaves per node), linear to narrowly oblanceolate and emergent ones are rhomboidal to obovate. At shoot apex, leaves get densely packed at the apex other forming a rosette. Plants of *C. platycarpa* tend to be organized in elliptic patches as flow pushes downstream the long stems generating an overhanging canopy. Patches are dense as stems get entangled, with most of the biomass concentrated in the upper part of the canopy. *E. nuttallii* has relatively rigid stems, 10–50 cm up to 150 cm long (Tison and de Foucault 2014), with few or no ramifications. Stems present three-leaved whorls densely packed and distributed almost uniformly along all their length. Patches of *E. nuttallii* are dense and compact with an elongated shape in direction of the flow and do not present an overhanging canopy.

### 2.2 Field Sampling

During summer 2014, one patch of *C. platycarpa* was sampled in Brégnier-Cordon and one patch of *E. nuttallii* in Peyrieu. These patches were selected because they

presented similar lengths (respectively 1.6 and 1.3 m) and were located as far as possible from the channel banks and from other patches to avoid hydrodynamical interferences.

For each patch, coupled measurements of hydrodynamics and sediment collection were carried out at five sampling points all along its central axis (2 outside and 3 inside plant patch). The 2 sampling points outside the patch were located approximately 1 m upstream from its leading edge (U) and 1 m downstream its rear edge (D). The 3 sampling points inside the patch were located at 10, 50, and 90 % of the canopy length. For each position, the velocity profile was measured and a core of sediment was collected (5 cm in diameter and 10 cm deep).

### 2.3 Velocity Profiles

Velocity vertical profiles were measured using a 3D Acoustic Doppler Velocimeter (ADV) (FlowTracker Handheld-ADV, SonTek). Vertical profiles consisted in depth steps of less than 12 cm, reduced to 1–4 cm near plants-water-sediment interfaces. For technical reasons, measurements closest to the sediment (near-bed) were taken at 4 cm above the channel bed. Velocity was recorded over 100 s at 1 Hz. For each component of velocity (streamwise,  $u$ ; spanwise,  $v$ ; vertical,  $w$ ), mean velocity profiles ( $\bar{u}$ ,  $\bar{v}$ ,  $\bar{w}$ ) were obtained and the turbulence intensity was quantified as the velocity variation around the mean (standard deviation). Standard deviation was then divided by the mean velocity to calculate the relative turbulence intensity.

### 2.4 Sediment Characterisation

The collected sediment cores were stored at 4 °C until measurements. To perform grain size analyses, sediments were wet sieved with distilled water at 1.6 mm and then dried at 70 °C for 48 h, to allow sample conservation until analyses were completed. Grain size analyses of sediment were carried out in aqueous phase by laser diffractometry, using a Malvern Mastersizer 2000 G (diameter range: 0.01–2000  $\mu\text{m}$ ). The analytical model used is based on the Fraunhofer theory and considers particles equal to spheres. Prior to the measurements, sediments were exposed to a treatment of ultrasound for 2 min to destroy the aggregated particles developed during the drying process, necessary for the preservation of the samples. The results of the analysis were displayed as grain size distributions curves. The mode of the curve indicates the most abundant grain size in volumic percentage present in the sample. The curves were then transformed in cumulative curves and the percentile values  $d_{0.1}$ ,  $d_{0.3}$ ,  $d_{0.5}$  were calculated (maximum diameter corresponding to 10, 30 and 50 % of particle volume). The 3 values were correlated and only the percentile value  $d_{0.3}$  was kept for analyses.

Finally, organic matter content was measured by weight loss after ignition at 550 °C for 2 h.

All the measurements were triplicated for each sample.

For each species, comparisons of sediment parameters relative to different positions were tested by one-way ANOVA, followed by a post hoc Tukey HSD correction. Linear regressions were performed to test the correlation between flow (near-bed velocities and relative turbulence intensities) and sediment parameters (grain size and organic matter content).

## 3 Results

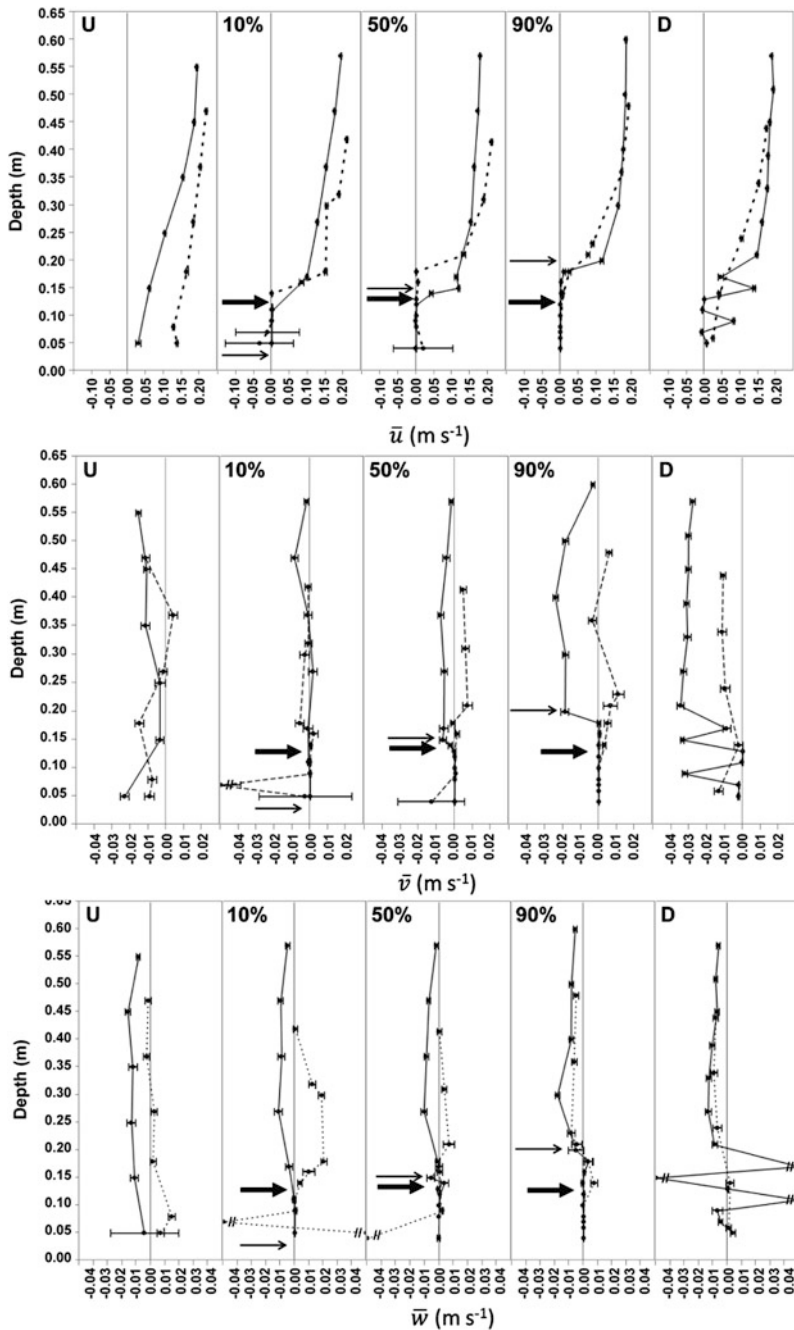
### 3.1 Velocity Profiles

Both species presented a different pattern of canopy height: the canopy height was relatively constant all over the patch length for *E. nuttallii*, whereas for *C. platycarpa* the canopy height gradually increased from the upstream to the downstream part of the patch (Fig. 1). For both species, velocity profiles upstream plant patch (U position) presented a steep decrease in streamwise velocity ( $\bar{u}$ ) near the flow-sediment interface (Fig. 1). The profiles were more linear than logarithmic. For both species, the profiles downstream the patches (D position) were very similar to the upstream ones, except regarding the higher variability observed for *C. platycarpa*. For both species,  $\bar{u}$  decreased immediately above the canopy, reaching approximately 0 within the canopy.

Profiles of mean spanwise velocity ( $\bar{v}$ ) showed little variation for *E. nuttallii*, with values ranging between 0 and 0.01 m s<sup>-1</sup>. For *C. platycarpa*,  $\bar{v}$  increased above the canopy at the 50 and 90 % sampling points, due to flow deviation. At the D position, the velocity profile was more similar to the 90 % profile than to the U one but with a much higher variability.

For *E. nuttallii*, the  $\bar{w}$  slightly increased above the canopy at the 10 % position, due to upwelling, whereas at the 90 % position  $\bar{w}$  became negative, due to downwelling. For *C. platycarpa*,  $\bar{w}$  profiles were similar along its axis and presented mainly negative values, except a slight increase just above the canopy, at the 90 % position. At the D position, the velocity profile was very similar to the 90 % profile but with a higher variability.

For each direction and species, relative turbulence intensity increases at the flow-canopy and flow-sediment interfaces (Fig. 2). In the streamwise direction, relative turbulence intensity was higher for *E. nuttallii* than for *C. platycarpa*. The highest relative turbulence intensity was observed in the streamwise direction for *E. nuttallii*, and in the spanwise direction, above the canopy, for *C. platycarpa*.



◀ **Fig. 1** Mean vertical profiles of the three components of velocity ( $\bar{u}$ ,  $\bar{v}$ ,  $\bar{w}$ ) for *E. nuttallii* (dashed line) and *C. platycarpa* (solid line), in the positions upstream (U), inside the patch at 10, 50 and 90 % of its length and downstream (D). The thick and thin arrows indicate the height of the patch for *E. nuttallii* and *C. platycarpa*, respectively

### 3.2 Sediment Characterisation

The grain size distribution curves were overall different for each species (Fig. 3). For *E. nuttallii*, two main modes were observed in each sampling position: a main mode around 350  $\mu\text{m}$  and a secondary one around 60  $\mu\text{m}$ . The sediment in the D position was the coarsest with a very homogeneous particle size around 450  $\mu\text{m}$ . For *C. platycarpa*, the sediments texture was distributed around one main mode. The upstream sediment was the coarsest (main mode around 350  $\mu\text{m}$ ), whereas the sediment collected in the others positions were enriched in fine particles leading to an increase of particles with a silty texture (20–100  $\mu\text{m}$ ).

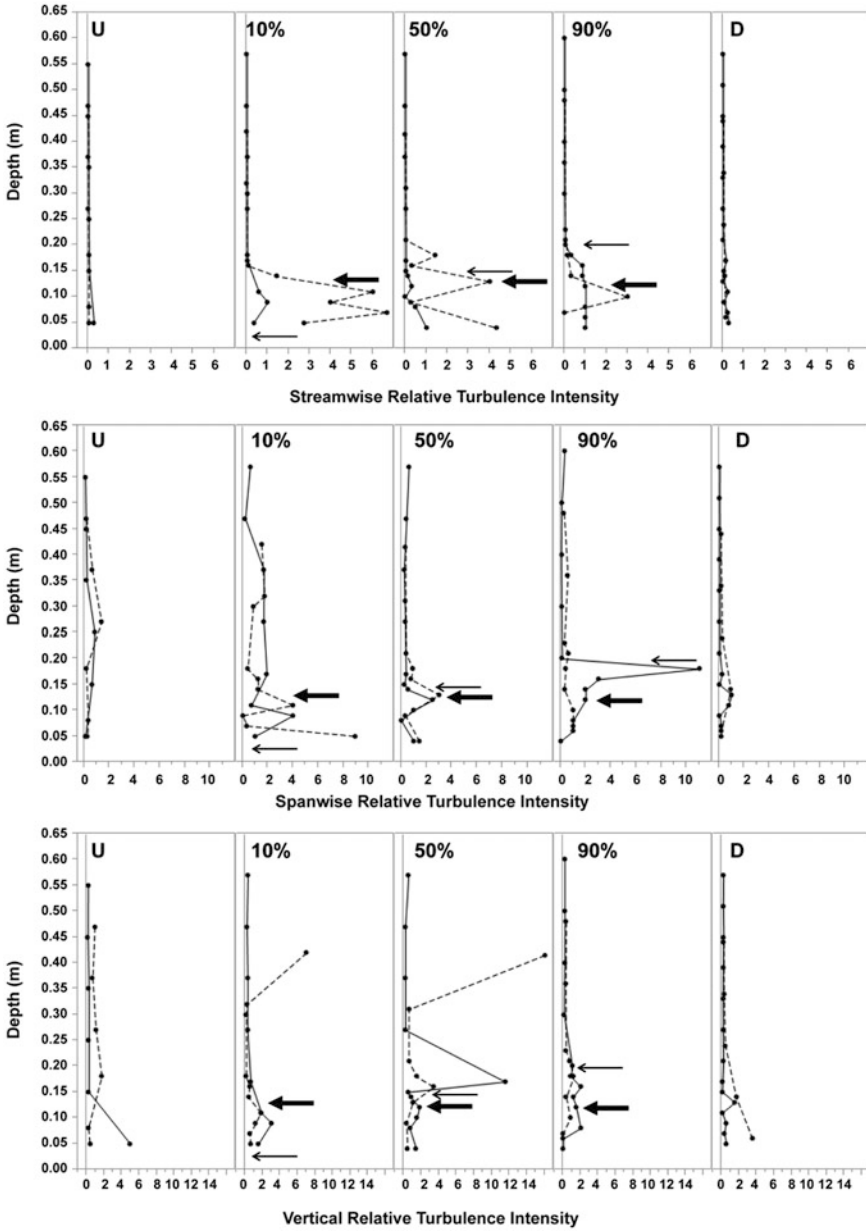
The two species presented different patterns of accumulation of fine sediment. For *E. nuttallii*, it decreased from the upstream position to a minimum at the 50 % position and then increased to a maximum reached at the D position (Fig. 4). For *C. platycarpa*, the  $d_{0.3}$  was significantly higher at the U position than at all other positions.

No positive relationship was found between near-bed velocity ( $\bar{u}$ ,  $\bar{v}$ ,  $\bar{w}$ ) and  $d_{0.1}$  and  $d_{0.3}$  for both species, whereas a positive linear relation was found between near-bed vertical relative turbulent intensity and  $d_{0.3}$  (*E. nuttallii*  $r^2 = 0.82$ ,  $p < 0.05$ ; *C. platycarpa*  $r^2 = 0.77$ ,  $p = 0.05$ ).

The organic matter content ranged between 0.97 and 6.18 % of dry mass for *E. nuttallii*, and between 1.33 and 2.78 % for *C. platycarpa* (Fig. 5). For *E. nuttallii*, the organic matter content was maximal at the 50 % position and minimal at the D one. For *C. platycarpa*, the organic matter content was generally significantly higher within (10, 50 or 90 %) and downstream the patch. Organic matter tended to be inversely related to  $d_{0.3}$  for both species (linear regression,  $r^2 = 0.89$ ,  $p = 0.01$ , for *C. platycarpa* and  $r^2 = 0.78$ ,  $p = 0.06$ , for *E. nuttallii*).

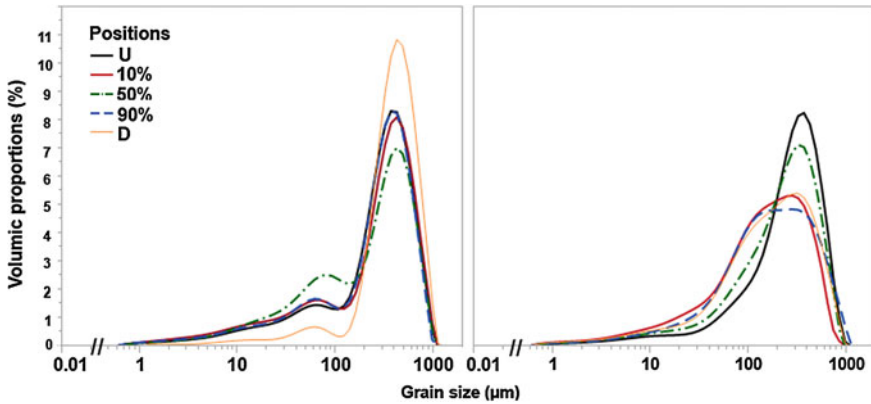
## 4 Discussion

In accordance with our expectations, the present results demonstrated that the two species had different effects on hydrodynamics, probably due to their differences in morphology and patch structure. *E. nuttallii* had a uniform canopy height and relatively rigid stems and deviated the flow towards the surface at the beginning of the patch, and then towards the streambed at the end of the patch. The upstream flow conditions were mainly restored downstream the patch. Relative turbulence intensity was higher inside the canopy and especially at the sediment-flow and canopy-flow interfaces. On the contrary, *C. platycarpa* had gradually increasing

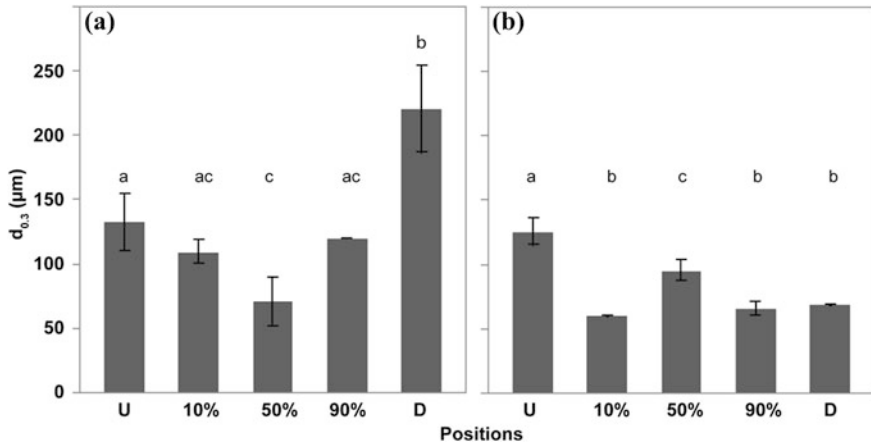


**Fig. 2** Relative Turbulence Intensity of the three components of velocity ( $\bar{u}$ ,  $\bar{v}$ ,  $\bar{w}$ ) for *E. nuttallii* (dashed line) and *C. platycarpa* (solid line). The thick and thin arrows indicate the height of the canopy for *E. nuttallii* and *C. platycarpa*, respectively. Positions are described in the legend of Fig. 1





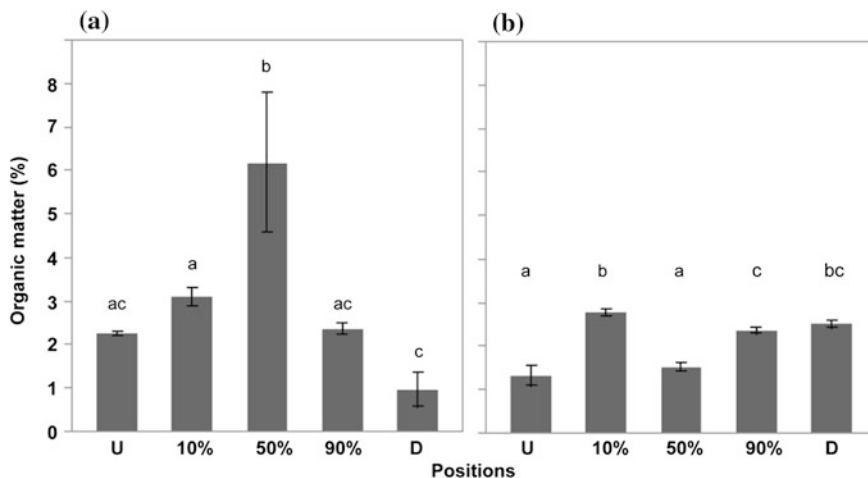
**Fig. 3** Mean grain size distributions of sediment in different positions along the main axis of the patch of: (a) *E. nuttallii* and (b) *C. platycarpa*. Positions are explained in the legend of Fig. 1



**Fig. 4** Mean value of  $d_{0.3}$  in sediment collected in different positions along the main axis of the patches of: (a) *Elodea nuttallii* and (b) *Callitriche platycarpa*. The positions are described in the legend of Fig. 1. Bars with different letters are significantly different (one way ANOVA, followed by post hoc Tukey’s HSD correction,  $p < 0.05$ )

biomass and canopy height from upstream to downstream. When the flow encountered the dense canopy, the flow was deviated on patch side, creating high spanwise relative turbulence at the canopy-flow interface. The effects of the patch of this species on hydrodynamics were also observed further downstream the patch. Similar effects of *C. platycarpa* on hydrodynamics were previously reported in literature (Schoelynck et al. 2012, 2013).

As expected, both species also induced contrasting effects on sediment characteristics. The effects observed for the patch of *C. platycarpa* were consistent with its



**Fig. 5** Mean value of organic matter content (%) in sediment collected in different positions along the main axis of the patches of: (a) *Elodea nuttallii* and (b) *Callitriche platycarpa*. The positions are described in the legend of Fig. 1. Bars with different letters are significantly different (one way ANOVA, followed by post hoc Tukey's HSD correction,  $p < 0.05$ )

effect on hydrodynamics:  $d_{0.3}$  revealed that very fine sand and coarse silt were trapped not only within the patch, but deposited also downstream the patch, consistently with previous results (Schoelynck et al. 2013). On the contrary, the patch of *E. nuttallii* trapped most of the sediment in the upstream half of the patch and the finest sediment in the middle part of the patch. No fine sediment was accumulated in the downstream half of the patch, possibly because the trapping was high enough to deplete the suspended sediment that moved inside the patch. Similar patterns were observed for species *E. canadensis*, morphologically similar to *E. nuttallii* (Sand-Jensen 1998).

The two species influenced also the accumulation of organic matter inside and downstream the patch, showing contrasting patterns. The negative relation observed between the  $d_{0.3}$  and the organic matter seemed to indicate that the finer sediments were enriched in organic matter. Moreover, the two species showed a significant difference in the amount of organic matter percentage accumulated within and downstream the patch. *E. nuttallii* and *C. platycarpa* thus had contrasted action on organic matter content in sediment. High concentration of organic matter in anaerobic conditions can lead to the accumulation of soluble organic compounds and other substances that are potentially toxic for plants (Barko and Smart 1983). Therefore, differences in organic matter could have consequences for the growth of both species, especially in the downstream part of the patch, where patch usually tends to develop. For *E. nuttallii*, the sediment downstream patches had a low organic matter content, possibly without limitation for plant growth. For *C. platycarpa*, instead, the sediment downstream the patch presented a similar value than within the patch and higher than upstream, potentially limiting plants growth.

Contrary to previous studies, no positive relationship was found between near-bed velocity and  $d_{0.1}$  and  $d_{0.3}$  for both species (Sand-Jensen 1998). This lack of correlation could be due to the too low number of sampling points in our study. However a positive correlation was found between near-bed vertical relative turbulent intensity and  $d_{0.3}$ , underlining the importance of the vertical component of turbulence in the processes of deposition (and resuspension) of fine sediment particles.

Our results emphasize the role of morphological and structural factors in the effects of submerged vegetation on flow and sediment processes. For instance *E. nuttallii* has relatively rigid stems and almost a uniform height all over the patch length. On the contrary *C. platycarpa* has flexible stems and most of the biomass located in the upper part of the canopy: the upstream part of the canopy, with less biomass, is more subject to flow pressure and is then compressed near the sediment bed, whereas further downstream plants gradually increment their biomass acquiring buoyancy and then increasing the patch height. This morphological and structural difference influences the relative depth of submergence ( $H/h$ , flow depth to canopy height ratio; Nepf 2012). The patch of *E. nuttallii*, with a uniform height, had a constant relative depth of submergence, corresponding to shallow submerged ( $H/h < 5$ ). On the contrary, the patch of *C. platycarpa* presented a varying relative depth of submergence along the length ranging from deeply submerged ( $H/h > 10$ ) to shallow submerged ( $H/h < 5$ ) or even to emergent ( $H/h = 1$ ) when the patches reach the surface. As differences in relative depth of submergence correspond to different flow and turbulence structures (Nepf 2012), they could explain the contrasting effects on both hydrodynamics and sediment composition (*i.e.* mass transport) for the two species. As other morphological and structural properties of vegetation have an effect on hydrodynamics and sediment composition (*e.g.* stem/leaf length, leaf surface, flexibility, patch size ...), further in situ studies with combined measurements of several morphologies, hydrodynamics and sediment composition are necessary to understand the relative effect of these characteristics on flow and sediment dynamics.

This study showed how morphology and patch structure substantially controlled the effects of vegetation on flow and sediment dynamics, not only inside the patch but also downstream the patch. The presence of different species in lotic ecosystems as streams may contribute to the hydrodynamical and geomorphological heterogeneity of these systems.

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