Multifunctionality of agricultural channel vegetation : A review based on community functional parameters and properties to support ecosystem function modeling

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Abstract

Vegetation living in agricultural channels (drainage ditches or irrigation channels) supports ecosystem functions such as water flow regulation; retention of sediments, agricultural pollutants and plant propagules; and bank strengthening. The review focuses on plant community functional parameters (aggregations of plant functional traits) and community properties that need to be considered to study the dynamics of these ecosystem functions, to support further modeling work on the functioning of these semiaquatic ecosystems. It also provides an up-to-date overview of the effects of channel management practices on vegetation, because these practices are a potential lever with which to drive plant community functional parameters and properties and, in turn, ecosystem functions. The review points out that the mean height, density, and flexibility of the plant cover, sometimes integrated in the "blockage factor", mainly influence the average components of the water flow associated with the functions of water regulation, and retention of sediments and non-floating propagules. The density of plants, or area of the plant cover at the water surface, are generally used to explain floating propagule retention. The biomasses of living and dead vegetation are the properties used to assess the retention of agricultural pollutants. Root density and root length density, as well as tensile strength of the root system, are parameters generally associated with bank strengthening. Regarding the effects of channel management practices, this work highlights that research generally has focused on the resulting plant richness and diversity, but has not provided much information on associated plant community functional parameters and properties.

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1. Introduction

Networks of agricultural channels (irrigation channels and drainage ditches) play a considerable role in the abiotic and biotic fluxes in agricultural landscapes. Irrigation channels are built to conduct water from a source to its place of use (López-Pomares et al., 2015). Ditches are built to transfer excess water from agricultural plots (Levavasseur et al., 2012). They also play an antierosive role in places where high water velocities occur, such as in Mediterranean landscapes with steep slopes (Ramos and Porta, 1997; Roose and Sabir, 2002), and play a drainage role (Carluer and Marsily, 2004; Krause et al., 2007) in places where the water table has to be lowered to enable cultivation. Their existence results from human decision making, and sometimes their establishment took place hundreds of years ago (Berger, 2000). They are organized into networks; i.e., they are connected to each other hydraulically as well as ecologically. Their density can reach 200 m/ha in Mediterranean landscapes (Levavasseur et al., 2015). Agricultural channels cover a limited surface area of landscapes. For example, ditch networks in Mediterranean areas never represent more than 4 % of cultivated areas, based on data from Levavasseur et al. (2014b). Most of these agricultural channels are uncoated (earth channels), and especially the small ones (no more than 1.5 meters in width) that are located upstream of the network for drainage ditches and downstream of the network for irrigation channels. These small agricultural channels therefore can host flora and fauna species (Herzon and Helenius, 2008). They also are generally subject to intermittent flows associated with rainfall frequency and intensity, or irrigation.

₆₉ The flora encountered in channels are not exclusive, i.e. they are encountered

₇₀ in other places of the catchment, although in some contexts, we can find plants

₇₁ of conservation interest (Mountford and Arnold, 2006). Agricultural networks

₇₂ are important habitats for floral species (Herzon and Helenius, 2008) that were

₇₃ located in natural freshwater bodies and floodplains in the past (Armitage et al.,

₇₄ 2003) because they often represent the only sources of open water in agricultural

₇₅ landscapes. Channels and ditches generally have a high plant diversity (Meier

₇₆ et al., 2017). Plants living in agricultural channels are generally terrestrial or

₇₇ semiaquatic, composed mainly of forbs and graminoids (Bouldin et al., 2004;

₇₈ Clarke, 2015; Levavasseur et al., 2014a; Maheu-Giroux and Blois, 2006; Rudi

₇₉ et al., 2018b; Szymura et al., 2009), and sometimes strictly aquatic (Clarke,

₈₀ 2015; Janse, 1998; Milsom et al., 2004), according to the topographic, climatic,

₈₁ and pedological contexts, as well as location in the channels' network.

₈₂ The vegetation must be managed regularly by users (farmers and irrigation

₈₃ managers) to restore its hydraulic capacity for transport (Dollinger et al., 2015).

₈₄ In Mediterranean agricultural areas, one or two practices such as mowing, burn-

₈₅ ing, clearing, and chemical weeding are conducted every year (Levavasseur et al.,

₈₆ 2014a; Sánchez Martín et al., 2018). Dredging is carried out every 5 to 10 years

₈₇ to remove the deposited sediments. These frequencies can vary according to pe-

₈₈ doclimatic context (Milsom et al., 2004; Twisk et al., 2003). These management

₈₉ practices, according to their typology, frequency, and location in the channel,

₉₀ can alter the ditch bed material (Dollinger et al., 2015) and vegetation. In the

₉₁ short term, they directly affect the shape of the plant cover (Dollinger et al.,

₉₂ 2017; Levavasseur et al., 2014a), but in the medium and long term, manage-

₉₃ ment practices have the additional effect of modifying the composition of plant

₉₄ communities and their dynamics (Manhoudt et al., 2007; Milsom et al., 2004;

₉₅ Leng et al., 2011; Rudi, 2019; Sánchez Martín et al., 2018; Twisk et al., 2003).

Nowadays, studies have highlighted the multifunctionality of agricultural channels' vegetation (Dollinger et al., 2015; Herzon and Helenius, 2008; Pierce et al., 2012), which is a significant provider of functions such as water flow regulation and bank strengthening as well as sediment, agricultural pollutant and plant propagule retention (a propagule is any structure for dispersal or reproduction, i.e., seeds, spores, and rhizomes). This multifunctionality of vegetation living in agricultural channels explains why these infrastructures are often referred to as "agroecological". Relying properly on these ecosystem functions could decrease intervention time and costs for farmers by reducing soil loss from farmed areas, decreasing the frequency of bank failure and reducing weed spreading while limiting overflows. It could also help decrease the concentrations of sediments and agricultural pollutants in receiving ecosystems, which could result in lower water treatment costs for society. These functions are mainly influenced by physical (and to a lesser extent chemical/biological) interactions between vegetation and water flow fields in the channel. As a consequence, the dynamics of the functions result mainly from (i) the spatiotemporal dynamics of vegetation in the agricultural channels and (ii) the spatiotemporal components of water flow fields, which especially depend on the frequency and intensity of rainfalls and irrigations, as well as the topological, pedological and morphological characteristics of the channel (Dollinger et al., 2015). It seems reasonable to think that vegetation would be a powerful lever with which to optimize channels' ecosystem functions because (i) vegetation is already managed by farmers regularly and (ii) the management of vegetation produces few negative impacts on the ecosystem if properly conducted.

For studying and modeling channels' ecosystem functions, a relevant spatial scale has to be chosen (Nepf, 2012b). When estimating channels' functions at the landscape scale, the resolution at which the channels need to be studied is

the reach scale (Rudi, 2019) (in this paper, the term "reach" refers to a channel section with homogeneous properties, as defined in Lagacherie et al. (2006)), which generally corresponds to a description of vegetation at the community-level. Community functional parameters are plant functional traits aggregated at the level of the community (for example, mean height), and a community property is a feature estimated at the community level (for example, density) (Violle et al., 2007). Better consideration of these plant community functional parameters and properties in the modeling of ecosystems functioning should enhance our ability to predict the spatiotemporal dynamics of the ecosystem functions that they provide (Diaz et al., 2003; Lavorel et al., 2017; Mori et al., 2013), and it would provide us with information on the parameters and properties that we need to measure and monitor in the field. Additionally, it would allow us to know which type of vegetation is desirable in channels, in terms of parameters/properties rather than species, which would provide more generic rules to managers and stakeholders for managing ecosystems functions (Rudi, 2019). Although these types of approaches are currently encouraged, several challenges remain, as the community functional parameters and properties responsible for the dynamics of ecosystem functions have not been clearly identified. Moreover, if management practices (anthropogenic drivers) represent a lever with which to manage the dynamics of these parameters and properties, and, in turn, ecosystem functions (Dollinger et al., 2016, 2017; Vinatier et al., 2018), it would be useful to collect data on the effects of these practices on plant community parameters and properties.

The first objective of the review was to determine the plant community functional parameters and community properties involved in three main functions of agricultural channels : (i) water flow regulation, (ii) retention, and (iii) bank strengthening. We focused on parameters and properties that have a clearly

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established relationship with the studied functions that has been documented in research papers. The second objective was to collect data on the effect of management practices on plant community functional parameters and properties. The review first presents an overview of ecosystem functions provided by vegetation in agricultural channels. Then, it presents an up-to-date overview of plant community functional parameters and properties generally associated with the studied ecosystem functions. In the last section, the review presents what we currently know about the effect of management practices on the dynamics of plant community functional parameters and community properties in agricultural channels. The review focuses on uncoated and therefore vegetated channels, located in temperate climatic contexts, with a focus on Mediterranean agricultural areas.

2. Material and Methods : Methodology

The review focuses on vegetated channels that can generally be found in agricultural areas under temperate climatic contexts. Their width is generally between 50 to 120 cm and depth between 30 and 80 cm in Mediterranean agricultural landscapes (Levavasseur et al., 2012). As underlined in the introduction, they can be intermittent or permanent, according to the climatic context and location according to the network. Regarding irrigation channels, the discharges transported to the plots are generally between 30 to 150 $L.s^{-1}$ downstrean of the network (Rudi, 2019). Regarding agricultural ditches, the mean discharge was estimated from 2 to 11 $L.s^{-1}$ for an agricultural Mediterranean ditch for rainfall events with return times respectively of 1 and 12 months (Dollinger, 2016). However, these values are temporally-averaged and peak values can be drastically higher (occasionnally above 100 $L.s^{-1}$ for ditches bordering plots). In this study, we will focus on agricultural channels with slopes under 5 ‰because

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channels with steep slopes were poorly studied to this day. Turbulent flow conditions are often observed in agricultural channels. The networks under study often transport water on distances from tens to hundreds of kilometers across the agricultural landscape.

To gather data on plant community functional parameters and properties involved in water flow regulation, retention, and bank strengthening, as well as on the effect of management practices on plant communities in agricultural channels, we relied on four scientific databases : Science Direct, Wiley Online Library, Springer Link and Google Scholar. We then collected all papers that contained the keyword "ditch", "irrigation channel" and "irrigation canal", with "vegetation" or "plant", resulting in 5087 papers. We then sorted the relevant papers, resulting in 146 papers dealing with the interactions between vegetation and the studied ecosystem functions, and with their management practices, in agricultural channels or flumes. These 146 papers were read and studied carefully. Note that papers relying on flume experiments, although not conducted in agricultural areas, were considered relevant for understanding some of the studied functions due to the physical similarity and comparable morphologies and hydraulic conditions of flumes and small agricultural channels.

The relationships between individual plant traits, community functional parameters and properties, and ecosystem functions are presented in Figure 1.

3. Overview of the functions of vegetation in agricultural channels

Agricultural channel vegetation is generally composed of terrestrial and semi-aquatic species (Bouldin et al., 2004; Clarke, 2015; Maheu-Giroux and Blois, 2006; Rudi et al., 2018b; Szymura et al., 2009), and sometimes of strictly aquatic species (Cassan et al., 2015; Clarke, 2015; Janse, 1998; Milsom et al., 2004; Sabbatini et al., 1998), according to the flow regime (especially intermittence or
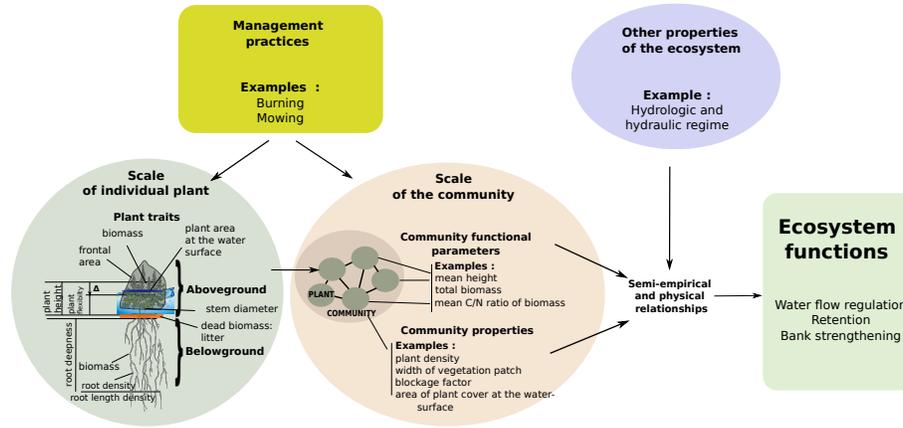
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Figure 1: Conceptual representation of the link between plant traits, plant community functional parameters and plant community properties, and ecosystem functions

not), and other conditions (topographic, climatic, and pedological). They form sparse or dense cover that is homogeneously distributed in the channel or forms patches, as illustrated in Figure 2. Vegetation is involved in ecosystem functions that have already been highlighted in other research works focusing on agricultural channels (Aspe et al., 2016; Dollinger et al., 2015; Herzon and Helenius, 2008; Needelman et al., 2007; Pierce et al., 2012). Three main types of functions provided by agricultural channels vegetation have been identified (Figure 3).

The first of these functions is water flow regulation. Water flow regulation in agricultural channels can be assessed through average components of water flow, such as velocity and water height. The modification of these components in a plurality of locations in the network can in turn affect the discharge and hydrograms at the outlet of the networks of channels. The presence of vegetation usually generates hydraulic resistance and therefore reduces water velocity and increases water height. The effect of vegetation on water flow regulation is particularly interesting under conditions of heavy rainfalls and steep slopes, as can be found in Mediterranean landscapes, because vegetation in agricul-

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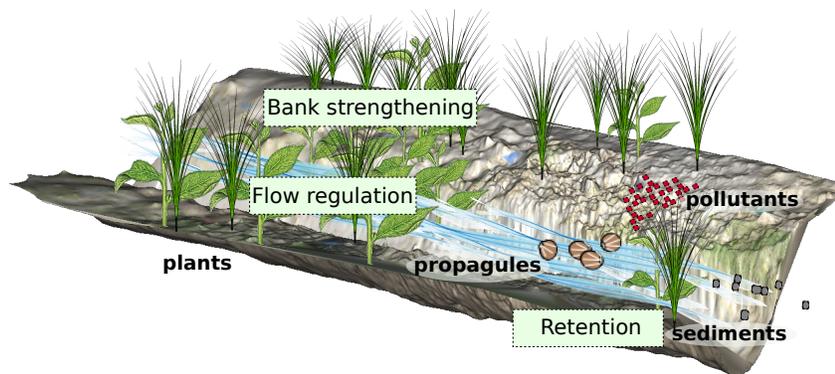Figure 2: Illustrations of vegetation living in agricultural channels

Figure 3: Ecosystem functions provided by vegetation in agricultural channels : (i) water flow regulation (ii) retention of sediments, pollutants and plant propagules, (iii) bank strengthening.

₂₁₈ tural channels can contribute to mitigating the peak of floods according to the
₂₁₉ topological conditions and organization of the channels' network (Moussa et al.,
₂₂₀ 2002).

₂₂₁ The second ecosystem function provided by agricultural channel vegetation
₂₂₂ is retention (sediments, agricultural pollutants, and plant propagules). The
₂₂₃ presence of vegetation can enhance retention by three main means : (i) it can
₂₂₄ affect the components of the water flow and then favor sedimentation of parti-
₂₂₅ cles transported in the water column, (ii) it can mechanically retain particles,
₂₂₆ and (iii) dissolved pollutants can be absorbed or adsorbed by vegetation. The
₂₂₇ retention of sediments can reduce the turbidity of water in receiving ecosys-
₂₂₈ tems (at the outlet of the ditch networks) (Fiener and Auerswald, 2003; Flora
₂₂₉ and Kröger, 2014). Vegetation also slows the transfer of pesticides to receiving
₂₃₀ ecosystems (Dollinger et al., 2015, 2016; Margoum et al., 2003; Lagacherie et al.,
₂₃₁ 2006), and therefore favors their degradation in the channels. Last, standing
₂₃₂ vegetation influences the dispersal of species through agricultural channels by
₂₃₃ retaining plant propagules (seeds and other propagules such as rhizomes) trans-
₂₃₄ ported by water (Rudi et al., 2018a; Soomers et al., 2010). This limits the
₂₃₅ spread of adventitious propagules in cultivated areas (Rudi et al., 2018a) but
₂₃₆ consequently also limits the dispersal of non-adventitious or protected species.

₂₃₇ The last type of function is bank strengthening. Terrestrial and semiaquatic
₂₃₈ vegetation plays a part in maintaining the banks of waterways through the
₂₃₉ dissipation of hydraulic energy due to the presence of the aboveground part
₂₄₀ of the plants, but also through the stabilization, and limitation of soil bank
₂₄₁ loss, due to the development of the root system (De Baets et al., 2006; Ghestem
₂₄₂ et al., 2011; Mamo and Bubenzer, 2001; Pollen-Bankhead and Simon, 2010). We
₂₄₃ therefore assume that the effects of vegetation are similar between agricultural
₂₄₄ channels and natural waterways.

In the following paragraphs, we aim to characterize plant functional community parameters and properties involved in the ecosystem functions described above.

4. Characterization of plant community functional parameters and properties involved in ecosystem functions of vegetation

4.1. Plant community functional parameters and properties involved in water flow regulation

The function of water regulation is generally assessed through the velocity of the water flow and the height of the water column. Water velocity and height mainly rely on imposed hydraulic conditions (inflow, downstream conditions), as well as on a physical quantity called hydraulic resistance. In agricultural channels, hydraulic resistance is largely driven by vegetation when it is present in the channels. Hydraulic resistance induced by vegetation in channels can be studied at different spatial resolutions : (i) at the plant resolution (or lower resolution such as the stem or leaf scale when relevant), but this approach is not practicable when estimating ecosystem functions in a whole network of channels, (ii) at the resolution of small homogeneous plant covers (iii) at the reach resolution : in this case the total hydraulic resistance is generally encompassed in a global resistance coefficient.

4.1.1. Characterization of the hydraulic resistance of homogeneous plant covers in small sections of channels

Plant cover in agricultural channels exerts a drag force opposite to the motion of the water. A quadratic drag law can be used to assess this spatially averaged drag force f (Equation 1):

$$f = \frac{1}{2} \times C_d \times A \times \rho \times V^2 \tag{1}$$

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where C_d is the drag coefficient $[-]$, A is the area of plants projected in the flow direction $[L^2]$, ρ is the density of water $[M.L^{-1}]$ and V is the local flow velocity $[L.T^{-1}]$.

The coefficient C_d is dependent on community parameters and properties such as the projected area A (Nepf, 2012a), and, therefore, on density D (Li and Shen, 1973), mean diameter d (Li and Shen, 1973) and morphology (James et al., 2004; Nepf, 2012a), as well as flexibility (James et al., 2004). Nepf (2012b) explains that for large Reynolds numbers (calculated at the stem scale), it is reasonable to choose a constant drag coefficient C_d between 0.7 and 1.5. This drag coefficient is often fixed at 1 when no data are available for estimating it more accurately. In contrast, for small stem Reynolds' numbers, C_d can take larger values and increases as the Reynolds number decreases (Tanino and Nepf, 2008).

Velocity fields are heterogeneous within plant cover (Nepf, 2012a). Generally, studies differentiate emergent and submerged plant covers because the mean velocity and turbulence fields can be truly different in these two conditions (Defina and Bixio, 2005; Finnigan, 2000; Nepf and Vivoni, 2000) (Figure 4). The scale of turbulence is also dependent on the density of the cover, which is generally defined as sparse or dense (Table 1). Sparse covers are covers with approximately $C_d a h_p < 0.04$ and dense covers are covers with approximately $C_d a h_p > 0.1$ (Belcher et al., 2003; Nepf et al., 2007), with a representing the frontal area of the plant cover by volume and h_p the height of the plant cover. Note that all conditions (sparse and dense plant covers, as well as submerged and emergent covers) are commonly found in agricultural channels.

In emergent conditions, the mean velocity inside the vegetation is always lower than that for a bare-bed channel. However, the vegetation concomitantly creates an increase in turbulence. The turbulence inside the plant cover is
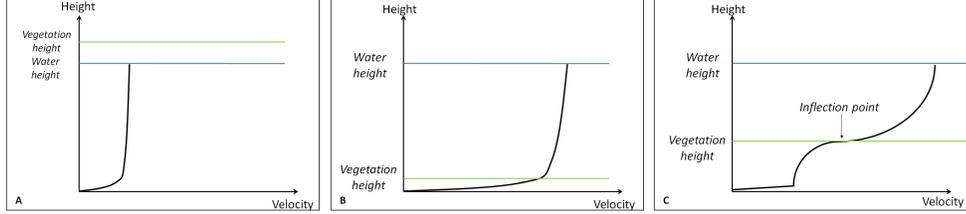
Figure 4: Vertical profiles of flow velocity in emergent (A), submerged and sparse (B), and submerged and dense (C) plant covers. In (A) and (B), there is a turbulent boundary layer profile. In (C), there is a region of shear at the top of the plant cover and an inflection point. The shear layer at the top of the plant cover is present when momentum absorption by the vegetation layer is sufficient. The characteristics of the three flow configurations (A), (B) and (C) are detailed in Table 1.

(A) Emergent conditions	(B) Submerged conditions - Sparse $C_d a h_p < 0.04$	(C) Submerged conditions - Dense $C_d a h_p > 0.1$
Flow driven by potential gradients from bed slope and water-surface slope	Flow driven by both potential gradients and turbulent stress at the top of the plant cover	
	Bed drag $>$ Vegetative drag	**Vegetative drag $>$ Bed drag**
Turbulent boundary layer profile	Turbulent boundary layer profile	Region of shear at the top of the plant cover and inflection point
Turbulence at the scale of stems	Turbulence at the scale of stems	Turbulence at the scale of stems and turbulence at the scale of the plant cover

Table 1: Characteristics of velocity-fields in submerged or emergent conditions

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₂₉₆ greater than that due to bed friction, and therefore, the total turbulence cannot
₂₉₇ be predicted from only the bed shear velocity (Nepf, 2012b), as is commonly
₂₉₈ done in studies on bare beds.

In submerged conditions, two main configurations are observed (Nepf, 2012b)
(Figure 4). If the plant cover is sparse, the velocity profile has the shape of
a turbulent boundary layer. In this case, turbulence intensity increases with
vegetation density (Nepf, 2012a). If the plant cover is dense, the velocity profile
has an inflection point as observed in Figure 4. When the vegetation is dense and
thus an inflection point occurs in the velocity profile, plant cover-scale vortices
are expected to appear (Brown and Roshko, 1974). It is possible to predict the
length of penetration δe of these Kelvin-Helmholtz vortices in the plant cover
(Nepf et al., 2007). This length of penetration decreases with an increasing
density of stems. For $0.2 < C_d a h_p < 1$, $\delta e \sim (C_d a)^{-1}$ (Nepf et al., 2007). When
$C_d a h_p < 0.2$, $\delta e = h_p$ and the vortex penetrates to the bed. Lastly, when
$(C_d a)^{-1} < 2d$, $\delta e \approx 2d (White and Nepf, 2008)$.

₂₉₉ In both emergent and submerged conditions, flexible vegetation can bend
₃₀₀ under the effect of water velocity. This phenomenon is called reconfiguration
₃₀₁ (Vogel, 1996) and is dependent on water velocity. The streamlining of the veg-
₃₀₂ etation with increasing water velocity might also change the friction coefficient
₃₀₃ C^* at the interface of the top of the plant cover and the free layer of water
₃₀₄ (Aberle and Järvelä, 2013). Luhar and Nepf (2011) then Chapman et al. (2015)
₃₀₅ proposed the prediction of drag coefficients for plants or flexible elements with
₃₀₆ different flexibilities. In real conditions in agricultural channels, most of the
₃₀₇ vegetation is flexible because it is composed mainly of nonligneous species. To
₃₀₈ the best of our knowledge, no estimation of flexibility for a whole plant com-
₃₀₉ munity has been conducted, and research has generally considered individual
₃₁₀ plants, despite the importance of this property for understanding flow patterns.

The flexible cover can move according to the mean and turbulent fields (Nepf and Ghisalberti, 2008). The progressive waving of the vegetation due to the passage of the Kelvin-Helmholtz vortices is named "monami" and was first observed for seagrasses (Fonseca and Kenworthy, 1987; Grizzle et al., 1996), and then experimentally characterized in flumes (for example see Okamoto et al. (2016)). In their study, Okamoto et al. (2016) revealed that the quantity of vegetation waving at the same time was associated with the lenght-scale of the turbulence in the mixing-layer zone.

4.1.2. Characterization of hydraulic resistance in real plant cover at the reach scale

Hydraulic resistance at the reach scale is generally described by a resistance coefficient, which is commonly the Manning n, Darcy-Weisbach or Chezy coefficient, but some authors have proposed other coefficients (for example James et al. (2004)). In traditional hydraulic engineering, resistance coefficients were assessed through visual aspect of channel, then refering to tables linking channels' features (including vegetation) to resistance coefficient values (see Chow (1959) for example). Manning's coefficient n is widely used and is associated to flow characteristics by Manning's equation (Manning, 1890) (Equation 2) :

$$n = \frac{R^{2/3} \times i^{1/2}}{u} \tag{2}$$

However, vegetation presenting very different morphologies and characteristics according to the context, this approach was considered as limiting, and led to inaccurate values of resistance coefficients (Green, 2005b). This led many authors to propose formulas allowing to predict resistance from measurable plant community parameters and properties. Note that as underlined by Folkard (2011), it seems that the use of resistance coefficient n to account for vegetation

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³³⁵ resistance is only valid when the height of vegetation cover is low compared to
³³⁶ the height of water. However, despite the lack of theoretical validity, n is still
³³⁷ really used in practice.

³³⁸ Research focusing on flow resistance caused by vegetation at the reach scale
³³⁹ increased approximately around 15 years ago. First, Luhar et al. (2008) high-
³⁴⁰ lighted that in natural channels, the architecture of the submerged vegetation
³⁴¹ was of low importance for predicting the resistance coefficient. Luhar and Nepf
³⁴² (2013) showed that the individual description of all patches with their own
³⁴³ properties did not give very different results for resistance coefficient predictions
³⁴⁴ compared to those obtained with an average description at the reach scale. Ac-
³⁴⁵ cording to Green (2005b); Nikora et al. (2008); Luhar et al. (2008), the blockage
³⁴⁶ factor B had the best explanatory power for three resistance coefficients (Man-
³⁴⁷ ning, Darcy-Weisbach and Chezy). The blockage factor B is the fraction of
³⁴⁸ channel cross-section occupied by vegetation ($B = wh_p \ / \ WH$). The relation-
³⁴⁹ ship between the resistance coefficient and B has been reported as nonlinear by
³⁵⁰ many authors (Nepf, 2012a; Nikora et al., 2008; Vinatier et al., 2017). Nikora
³⁵¹ et al. (2008) interpreted this nonlinearity as the result of a decrease of bed
³⁵² contribution to total resistance with an increase in vegetation and suggested
³⁵³ that linear formulas were thus poorly accurate. In emergent conditions, Fathi-
³⁵⁴ Maghadam and Kouwen (1997) showed that the shape and distribution of veg-
³⁵⁵ etation were poor descriptors of resistance equations and highlighted the role of
³⁵⁶ vegetation density D. Aberle and Järvelä (2013) argued that the density and
³⁵⁷ ability for reconfiguration were the most important properties for determining
³⁵⁸ the resistance. This was empirically inferred with decreasing exponential laws
³⁵⁹ in Bailly et al. (2015). Recently, Rubol et al. (2018) successfully modeled the
³⁶⁰ resistance by representing the vegetation as a porous medium. Many formu-
³⁶¹ las predicting resistance coefficients based on plant community parameters and

362 properties have been developed (some of them are presented in Table 2).

363 In practice, at the network scale, few hydraulic or hydrological models con-
364 sider the resistance created by vegetation, especially its spatialization at the
365 resolution of reaches. When vegetative resistance is considered, its relationship
366 with vegetation properties is highly simplified as in Doncker et al. (2009) or
367 Bertoldi et al. (2014), who considered a really simplified relationship between
368 vegetation biomass and the resistance coefficient. These last two examples have
369 been found for natural waterways: no studies on this subject were found for
370 agricultural channels.

371 *4.2. Plant community functional parameters and properties involved in retention*
372 *of sediments, agricultural pollutants and plant propagules*

373 *4.2.1. Sediment transport and deposition*

374 It is generally considered that the presence of vegetation is associated with
375 increased sedimentation of suspended particles in rivers, flumes and agricultural
376 channels (Abt et al., 1994; Cotton et al., 2006; López and García, 1998) and
377 decreased bed-load transport (Kothyari et al., 2009). However, some researchers
378 have observed the opposite, such as van Katwijk et al. (2010), who reported
379 negative net sedimentation in patches of sparse vegetation (seagrass) compared
380 with a bare bed.

381 At the local scale, Palmer et al. (2004) described the capture by a plant stem
382 of small suspended particles (range 177-210 μm) relying on a metrics named the
383 particle capture efficiency η, using an empirical formula (Equation 3) of the form
384 :

$$\eta = aRe_c^b R^c \tag{3}$$

385 with a, b and c positive constants, Re_c the "collector Reynolds number"

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Source	Equation for resistance	Experimental conditions	Parameters or properties of the plant community
James et al., 2004	$\frac{1}{F_f} = \sqrt{\frac{1-\frac{N\pi d^2}{4}}{\frac{F_{dw}}{8}+C_d\frac{1}{2}NHd}gH}$ and $u = \frac{1}{F_f}\sqrt{S}$	Emergent vegetation • Both Rigid and flexible	**Parameters and properties:** C_d,d,D
Kouwen et al., 1969; Kouwen and Unny, 1973	$\sqrt{\frac{8}{F_{dw}}} = C_1 \ln\left(\frac{1}{B}\right) + C_2$ with C_1 and C_2 coefficients depending respectively on stiffness and vegetation density	Submerged vegetation • Flexible • Uniform cover	**Parameters and properties :** **Flexibility,**D,B
Baptist et al., 2007	$n = \frac{H^{1/6}}{\sqrt{\frac{2g}{f_v}}+\frac{\sqrt{g}}{\kappa}\ln\left(\frac{H}{h_p}\right)}$	Submerged vegetation • Rigid	**Parameters and properties :** h_p
Yang and Choi, 2010	$n = \dfrac{H^{2/3}}{\sqrt{\frac{2gH}{DC_d h_p}}+\frac{C_u}{K}\sqrt{g(H-h_p)}\ln\left(\frac{H}{h_p}\right)-\left(\frac{H-h_p}{H}\frac{\sqrt{g(H-h_p)}}{\kappa}\right)}$ with: • $C_u = 1$ with $D \leq 5m^{-1}$ • $C_u = 2$ with $D > 5m^{-1}$	Submerged vegetation	**Parameters and properties :** h_p, D, **flexibility**
Green, 2005b,a; Nepf, 2012b	For $B = 1$: $n\left(\frac{g^{1/2}}{KH^{1/6}}\right) = \sqrt{\frac{C_d aH}{2}}$ For $B < 1$: $n\left(\frac{g^{1/2}}{KH^{1/6}}\right) = \sqrt{\frac{C^*}{2}}(1-B)^{-3/2}$	Submerged vegetation • Flexible • Non uniform cover	**Parameters and properties :** a,B,C^* **or** C_d

Table 2: Examples of equations used in literature to link plant community parameters and properties to resistance

described as $Re_c = ud \ / \ \nu$ and $R = d_p \ / \ d$ with d_p the particle diameter. Based on the same formalisms, Fauria et al. (2015) showed the significant role of the biofilms developing in vegetation in small particles capture (range 1.25 - 250 μm) in some aquatic systems. Note that these biofilms developing on fresh-water vegetation have been mainly characterized in streams (Besemer, 2015) and marshes (Buesing et al., 2009) and have an important diversity affected by several factors, although abundance and community assemblage of biofilms seems specifically affected by the presence of inorganic nutrients and dissolved organic matter (Olapade and Leff, 2005). Relying on plant density conditions relevant to the ones found in agricultural channels (2724 and 7209 $stems.m^{-2}$) and on a natural biofilm devloped in eutrophic conditions, Fauria et al. (2015) have determined new coefficients for the formulation of the particle capture effi-ciency (especially with b a negative exposant, highlighting the fact that particle retention is decreased with increased flow velocity).

For bare beds, the settling velocity of the particles and the minimal shear stress for entrainment are generally used to model entrainment and transport. To understand the interactions between sediment transport and vegetation in channels more deeply, Nepf (2012a) reported that sediment transport was linked not only to the mean bed stress (as for bare-bed sediment transport) but also to the profile of turbulence. Indeed, Luhar et al. (2008) found that in sparse plant cover, the turbulent stress remained elevated close to the bed, whereas it was reduced in dense plant cover. For plant cover for which $C_d a h_p < 0.1$, the resuspension is of the same order of magnitude as that for bare-bed channels. In other words, plant cover below this threshold has a limited influence on sediment retention. Moore (2004) even noted enhanced erosion under these conditions due to the augmentation of stem-scale turbulence. For plant cover above this threshold, we observed in paragraph 4.1.1 that the penetration scale

of the Kevin-Helmholtz vortices was dependent on the density of the stems. In this case, the higher the density, the more important the sheltering between adjacent stems. As a consequence, the bed is protected from the turbulent stress caused by Kevin-Helmholtz vortices, and the momentum transfer is therefore extremely reduced. Additionally, the mean bed stress is generally reduced in the presence of vegetation (Nepf, 2012a), but the methods used to characterize it are still controversial (Nepf, 2012a; Yang et al., 2015). Recently, Yang et al. (2015) presented a formula (Equation 4) for estimating this bed shear stress in the presence of vegetation, but only for plant covers with frontal areas per volumetric unit a up to 4.3 m^{-1}.

$$U_{eff*} = max\left(\sqrt{C_f} < V_0 >, 2\sqrt{\frac{\nu < V_0 >}{d}}\right) \qquad (4)$$

with V_0 the local time-averaged velocity in the uniform layer $(m.s^{-1})$, C_f the drag coefficient for the bare-bed (-), ν the kinematic viscosity of water $(m^2.s^{-1})$ and d the diameter of the stems (m).

Under these conditions, stem diameter d is considered a determining parameter for bed shear stress, independent of density.

Other studies focused on the effects of patches of vegetation on sediment transport and deposition (Zong and Nepf, 2011; Ortiz et al., 2013). In the wake behind a patch, it seems that sedimentation is increased, but this appears to be true only for emergent and rigid patches (Ortiz et al., 2013). However, at the leading edge of the patch, where the flow is generally deflected, the net deposition is reduced compared to that of the bare-bed (Zong and Nepf, 2011). Bouma et al. (2007) and Sand-Jensen and Vindbæk Madsen (1992) reported that these two mechanisms explained why patches generally grow in length but rarely grow in width along open channels.

Nepf (2012a) and Solari et al. (2016) reported that no general model cur-

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rently exists for sediment transport in vegetated channels. First, most of the models are based on the estimation of bed shear stress. However, as stated before, the bed shear stress in vegetated flows is very difficult to calculate (Nepf, 2012a; Yang et al., 2015). Second, as turbulence is reported as an influential parameter for resuspension and transport under some conditions, bed shear stress might not be sufficient to take into account the effect of vegetation on sediment transport (Vollmer and Kleinhans, 2007).

4.2.2. Agricultural pollutants (pesticides and nutrients) retention

Sorption is a major mechanism involved in pesticides retention in agricultural areas (Dousset et al., 2010; Stehle et al., 2011), in particular in farmed ditches (Dollinger et al., 2015). This has been demonstrated for an insecticide (pyrethroid) (Bennett et al., 2005) and a herbicide (diuron) (Dollinger et al., 2016; Margoum et al., 2006). Sorption increases with increasing organic content for most pesticides, namely hydrophobic ones (Margoum et al., 2006). This explains that an effective retention has been observed not only in the presence of living vegetation but also in the presence of litter (dead vegetation) at the bottom of agricultural channels. Based on these principles, Margoum et al. (2003) proposed a retention index based on the relative cover (in the wetted section of channel) of living vegetation, dead vegetation and sediments, reported as Herbicide Retention Power (HRP) in Lagacherie et al. (2006) (Equation 5) :

$$HRP = LV + 2DV + 0.5S \tag{5}$$

with LV the relative cover of living vegetation (%), DV the relative cover of dead vegetation (%) and S the relative cover of sediments (%).

More recently, Dollinger et al. (2016) proposed a "Sorption induced Pesticide Retention Indicator" (SPRI) directly based on masses of the different elements

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composing the bottom and banks of the channel, including living and dead vegetation 6) :

$$SPRI(\%) = \frac{\sum_i^n M_i Kd_i}{\sum_i^n M_i Kd_i + V} 100 \tag{6}$$

with i being material i composing the channel (ie living vegetation, dead vegetation, soil, ash), M_i the corresponding mass of material i (g), Kd_i the linear adsorption coefficient ($cm^3.g^{-1}$) and V the volume of water flowing during a flow-event (cm^3).

such as Dollinger et al. (2016); Margoum et al. (2003); Lagacherie et al. (2006) proposed retention indicators partly based on living and dead biomasses of vegetation in agricultural channels. Additionally, absorption of pesticides by vegetation is also expected to play a role in retention, but it is not easy to differentiate between absorption and adsorption in field experiments (Moore et al., 2011). Vegetation can also indirectly drive the retention of pesticides prone to adsorption on sediments by influencing sedimentation rates under some conditions (see paragraph 4.2.1). Vegetation can also increase water retention times and therefore favor sorption (Dollinger, 2016) and biodegradation mechanisms (Liu et al., 2012).

Regarding nutrients, Castaldelli et al. (2015) showed that N uptake by agricultural channel vegetation was low but that vegetation played a role in microbial denitrification by providing interfaces favoring the activity of bacteria. To the best of our knowledge, only Janse (1998) proposed a model assessing nutrient uptake by vegetation in agricultural channels based on the biomasses of plant functional groups. As for pesticides, nutrients that tend to be transported bounded on sediments (for example P), might also be retained by vegetation through increased sedimentation (Bouldin et al., 2004; Liu et al., 2008).

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4.2.3. Plant propagule retention

Traditionally, studies on hydrochorous plant propagule dispersal distinguishes nonfloating and floating propagules (usually seeds). Indeed, seeds can be transported in the bedload, suspended in the flow or at the water surface (Carthey et al., 2016; Chambert and James, 2009; Jager et al., 2019). For nonfloating seeds, Gurnell (2007) established an analogy between sediment and seed transport. This was confirmed by an experiment led by Chambert and James (2009) who concluded that the main factors explaining the entrainment and deposition of nonfloating seeds were minimum critical shear stress necessary for their entrainment and the settling velocity. Therefore, the plant community functional parameters and properties of the standing vegetation involved in the retention of nonfloating seeds are the same as those described in paragraph 4.2.1.

For floating seeds, Defina and Peruzzo (2010) reported the four main mechanisms governing the seed-plant interactions in an artificial flume : the Cheerios effect, when a seed is attracted by the meniscus around the stem due to surface tension forces (Vella and Mahadevan, 2005); inertial impaction, when a collision between a seed and plant results in a change in the direction of the seed (Palmer et al., 2004); wake trapping, when the seed is temporarily trapped in the recirculation zone behind a stem (White and Nepf, 2003); and net trapping, when plants form a net that stops the seeds (Defina and Peruzzo, 2010). Many studies, mainly focused on the Cheerios effect, highlighted the role of stem density (more precisely the mean centre-to-centre spacing) in the rate of propagules' retention (Defina and Peruzzo, 2012; White and Nepf, 2003; Liu et al., 2019). Net trapping depends on the density, height, and spatial distribution of plants in the reach (homogeneous distribution or existence of patches), as well as on plant architectures at the water surface (Rudi and Vinatier, personnal observation). At low velocities, the Cheerios effect is important but it disappears

progressively as turbulent diffusion phenomena become too important (Chambert and James, 2009; Defina and Peruzzo, 2012; Peruzzo et al., 2012, 2016). Net trapping is generally predominant when stem density and water turbulence are important (Defina and Peruzzo, 2010).

In addition, for floating seeds, the velocity fields at the water surface significantly influence the deposition of seeds (Soomers et al., 2010). In this context, emergent vegetation can be considered a porous obstacle modifying the velocity fields (Defina and Peruzzo, 2010), and the presence of vegetation is susceptible to creating recessional flows, recirculating flows, or eddies, which are generally associated with high rates of seed deposition (Merritt and Wohl, 2002; Nilsson et al., 1991).

Due to the inherent difficulty of taking into account some plant parameters such as the specific architecture of plants at the scale of the community in heterogeneous plant covers, Rudi et al. (2018a); Vinatier et al. (2018) relied on a measure of the area of vegetation at the water surface (at the scale of a section of approximately one meter), accounting for the porosity of vegetation, because this property was assumed to explain seed deposition with good performance. These metrics were assessed through image analysis (Structure-from-Motion using Multi-View Stereo algorithm). Note however that this approach is less performing in case of abundant vegetation because the highest strata of vegetation might hide the water surface in some images.

4.3. Plant community functional parameters and properties involved in bank strengthening

Plants growing in agricultural channels have root systems that develop on the channel bottom or bank soil substrates. Most monocotyledons have fibrous root systems, and dicotyledons generally have taproot systems, from which other roots sometimes grow laterally. Beyond this coarse differentiation, channels'

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plants exhibit a gradient of root systems, differing in length, deepness, diameter, architecture, junction and spatial distribution in soils. These root parameters and properties, in interaction with soil properties, channel morphology, and hydrologic/hydraulic regimes, greatly influence the stability of channels' banks.

Some parameters and properties of root systems, such as root density (RD) (De Baets et al., 2006); root length density (RLD), corresponding to the cumulative length of root per soil unit volume (De Baets et al., 2006; Pollen-Bankhead and Simon, 2010); root biomass and total root volume (Pollen-Bankhead and Simon, 2010), have been reported to have an effect on the limitation of the erosion rates of banks, and therefore on bank strengthening. It has been shown that the volume of eroded soil is a negative exponential of RLD or RD (De Baets et al., 2006; Pollen-Bankhead and Simon, 2010). Due to this nonlinearity, there appears to be a threshold of RLD above which an increase in RLD has little effect on the eroded volume of soil. This threshold was found to be approximately 50 $km_{roots}.m_{soil}^{-3}$ by Pollen-Bankhead and Simon (2010) for switchgrass (*Panicum virgatum*) and approximately 400 $km_{roots}.m_{soil}^{-3}$ by De Baets et al. (2006) for a mixture of *Lolium sp* and *Festuca sp*. The difference in the values of the threshold could arise not only from differences in root properties (especially diameter distributions in the soil profile) but also from differences in experimental conditions. The negative exponential shape observed between RLD (and RD) and the volume of eroded soil led De Baets et al. (2006) to propose a power and a hill curve functions for this relationship, for which they obtained good correlation coefficients (equations 7 and 8).

$$RSD = 16.38RLD^{-0.78} \tag{7}$$

$$RSD = \frac{RLD^{-2.22}}{RLD^{-2.22} + 0.000026} \tag{8}$$

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₅₆₃ with RSD being the Relative Soil Detachment rate.

₅₆₄ However, it seems difficult to experimentally differentiate the influence of the

₅₆₅ aboveground and belowground parts of the plant (Mamo and Bubenzer, 2001;

₅₆₆ Zhang et al., 2013). Indeed, aboveground part of the plant community also

₅₆₇ tend to dissipate hydraulic energy and therefore protect the banks' soils from

₅₆₈ hydraulic erosion. Some aboveground plant architectures, such as the presence

₅₆₉ of rosettes, can also protect the soil (Kramer and Weaver, 1936).

₅₇₀ In addition, some parameters, such as the distribution of root diameters (in

₅₇₁ a soil unit) and the number of roots, were reported to be related to the full-

₅₇₂ root tensile strength, which is frequently used in models evaluating the stability

₅₇₃ of stream banks and based on mechanical reinforcement (Pollen-Bankhead and

₅₇₄ Simon, 2009). Fibrous roots (Operstein and Frydman, 2000), and fibrils (Li

₅₇₅ et al., 1991), are considered more efficient than taproots (Zhang et al., 2013), in

₅₇₆ increasing soil resistance. The technical literature on waterway bank strength-

₅₇₇ ening suggests sowing the banks with perennial and fibrous-rooted vegetation,

₅₇₈ such as *Festuca sp, Lolium sp, Trifolium sp, Elymus sp, Carex sp, Potentilla*

₅₇₉ *sp*, and *Mentha sp* (APEL, 2015) or *Tripsacum dactyloides* (Ghestem et al.,

₅₈₀ 2011). However, according to Reubens et al. (2007), it seems that for slope

₅₈₁ stabilization, plants with deep anchorage and many lateral roots, for example

₅₈₂ dicotyledons, would be more effective than plants with only fibrous roots.

₅₈₃ Ghestem et al. (2011) also stressed the importance of considering the network

₅₈₄ of macropores (pores up to 30 µm), generally of biotic origin, in the mechanisms

₅₈₅ governing slope stability and therefore bank strengthening. Indeed, high con-

₅₈₆ vergence of macropores or dead-end macropores can generate high pore water

₅₈₇ pressure, in turn destabilizing the banks. Root orientation (upslope or downs-

₅₈₈ lope) is also of great importance. Deep-rooted plants generally perform better

₅₈₉ than shallow-rooted plants in terms of driving water away from unstable areas.

₂₇

However, well-developed fibrous and shallow root systems can help dissipate pore water pressures that could otherwise concentrate in one location (Ghestem et al., 2011).

Finally, Pollen-Bankhead and Simon (2010) highlighted the hydrological effect of root systems on bank stability. Total evapotranspiration, driven by the composition of the plant community, removes water from the soil and therefore influences soil matrix suction. This is assumed to influence apparent soil cohesion, but this hydrological effect of plants on bank stability is still difficult to quantify (Pollen-Bankhead and Simon, 2010).

5. Effects of channel management practices on plant community functional parameters and properties

The main aim of managing a ditch or a channel is to restore its hydraulic capacity (Dollinger et al., 2015; Sánchez Martín et al., 2018). Different management practices (mowing, dredging, burning, chemical weeding, and clearing) affect the communities in the short term (less than one year) and medium (between one and five years) and long term (more than five years). In the short term, the practices of mowing, dredging, burning and chemical weeding affect the dynamics of height, density and porosity of vegetation, as was illustrated by Dollinger et al. (2017); Vinatier et al. (2018) (see Figure 5). These two studies related the dynamics of functional parameters and properties of plant communities driven by management practices throughout the year, to the dynamics of ecosystem functions in which vegetation is involved (especially water regulation and pollutant and propagule retention). The two papers suggested that both the temporality and type of practice are determinant of the resulting ecosystem functions.

In the medium term, dredging allows a return to the early stages of veg-
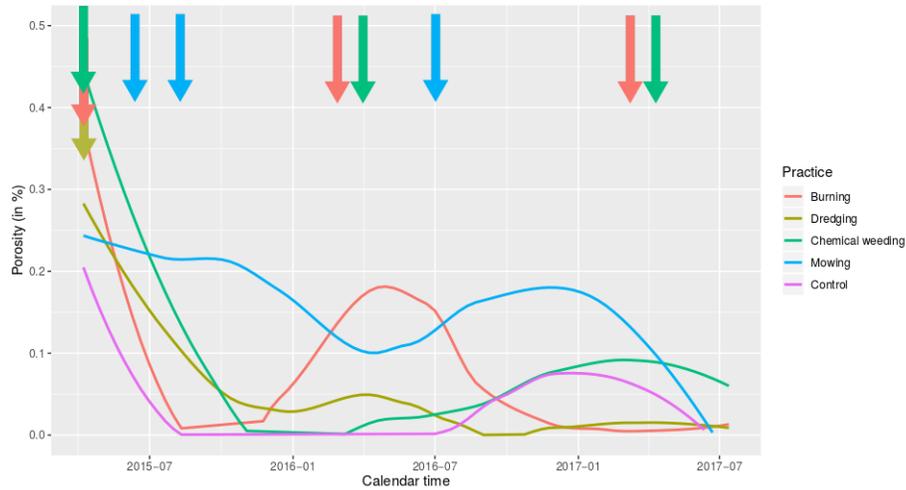
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Figure 5: Evolution of porosity (%) of an agricultural channel plant cover in a ditch from Spring 2015 to Summer 2017. The arrows report the temporality of the practices throughout the year. The lines report the evolution of the porosity. The four practices and the control are represented with different colors. The figure was made based on data from Vinatier et al. (2018).

etation succession (Clarke, 2015) and therefore allows more replacements of plant species (Teurlincx et al., 2018). Mowing and burning generally maintain or improve richness and diversity (Chaudron et al., 2016; Milsom et al., 2004; Sánchez Martín et al., 2018). These practices influence competitive interactions betweens species because the distribution of water, nutrients and light is modified. Indeed, frequently disturbed ecosystems have been reported to be less competitive than natural ones (Connell, 1978; Odum, 1969). Successions at a multiyear scale after management are generally characterized by strictly aquatic plants in the early stages and emergent facultative plants and herbs in the late stages (Clarke, 2015; Milsom et al., 2004), which implies different parameters and properties. Janse (1998) showed that the level of nutrient (N and P), that depends on management practices in adjacent fields and inside the ditch, influenced the composition of the plant community : duckweed was mainly found in highly loaded ditches and submerged plants were found in poorly loaded

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ditches. They showed that there was a critical level in nutrient input that triggered the shift in plant community composition. Note that most studies on channel management practices focused on general indices of richness, diversity or productivity and did not clearly evaluate the response of vegetation in terms of community parameters or properties. Moreover, the long-term effect of management practices on community composition has been poorly studied and is difficult to predict (Blomqvist et al., 2006).

6. Discussion

In conclusion, the vegetation in agricultural channels is involved in three main ecosystem functions : (i) water regulation, (ii) retention of sediments, propagules and agricultural pollutants, (iii) bank strengthening. At the local scale, parameters and properties such as the drag coefficient, frontal area, density, height, stem diameter, and flexibility, are generally used to assess the effect of vegetation on water flow. At the reach scale, the parameters and properties used to assess water flow regulation are mainly the mean height of the plant cover, porosity, flexibility and the density of the plant community. These parameters and properties are sometimes integrated in a global property named the "blockage factor", which is the fraction of channel cross-section occupied by vegetation. The mean height and density of plant cover are easily measurable; it is far more complicated to measure the flexibility (Rudi, 2019), porosity (Vinatier et al., 2018) or blockage factor (Vinatier et al., 2017) of vegetation cover. Regarding the retention function (sediments and nonfloating seeds), the parameters and properties generally used to assess the effect of vegetation on the function, are those affecting the mean velocity and the turbulence (especially the drag coefficient, density, diameters of stems and height), as well as the width of patches. However, this function has been generally studied in small

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sections of channels due to the complexity of the processes involved. Indeed, the calculation of bed shear stress in the presence of vegetation and the quantification of turbulence and its influence on particle transport are far from being elucidated. For floating propagules (especially floating seeds), the height of the plant cover is the most influencial parameter because only emergent vegetation is involved in retention. The architecture of individual plants and the spatial distribution of the plants play a significant role in net trapping. In practice, the total area of the plants at the water surface is generally associated with seed retention. For agricultural pollutants, the biomass of living or dead vegetation in contact with them is the plant community property generally used to assess the retention function. For N and P retention, biomass is also influential because vegetation can both absorb nutrients and create interfaces for biodegradation, but the quantification of N and P decay in agricultural channels has mainly been demonstrated experimentally. Only a few studies have proposed to model it to date (see for example (Janse, 1998)). For bank strengthening, aboveground community parameters and properties involved in the control of the average components of water flow are those associated with the dissipation of hydraulic energy. Aboveground parts of the plant community play a role in protecting the banks' soils from hydraulic erosion. Belowground community functional parameters, such as root density and root length density, are frequently used for the prediction of soil loss under different hydraulic conditions, and the number of roots per unit area of soil and the total tensile strength associated with these roots are often used in bank stability models. The plant parameters and properties involved in the studied ecosystem functions are summarized in Table 3.

Ecosystem function	Associated plant community functional parameters or properties
Water flow regulation - Local scale - Reach scale	 Drag coefficient C_d, frontal area A, stem diameter d, height h_p, density of the plant cover D, flexibility Height h_p, density of the plant cover D, flexibility, blockage factor B
Sediments' retention	Same parameters and properties as water flow regulation, and width of vegetation patch w
Pollutants' retention - Adsorbed on sediments - Dissolved - Absorbed	 Same as for sediments' retention Living and dead biomass Living biomass
Propagules' retention - Non floating propagules - Floating propagules	 Same as for sediments' retention Density D, height h_p, plant architectures, spatial distribution of plants in the channel, area of plant cover at the water surface
Bank strengthening - Due to aboveground parts - Due to belowground parts	 Same parameters and properties as water flow regulation, and plant architectures (for example presence of rosettes protecting the soils from hydraulic erosion) Hydraulic effect : Root Density, Root Length Density, total root biomass, total root volume - Mechanical effect : Type of root systems (taproot or fibrous roots), number of roots, tensile strenth, distribution of diameters in the soil profile - Hydrological effect : Composition and stage of development of the plant community

Table 3: Recapitulative table of plant community functional parameters and properties generally used to assess the studied ecosystem functions. The reported parameters and properties are those for which there is a clearly established relationship between the parameter/property and the function, established by research studies

⁶⁸¹   This review pointed out that knowledge of the effect of functional parameters
⁶⁸² and properties on channel ecosystem functions is far more developed for water
⁶⁸³ regulation than for the other functions. Mechanisms underlying water regula-
⁶⁸⁴ tion have been described both at the local scale and at the reach scale, using
⁶⁸⁵ physical and semiempirical approaches, although research on the effect of het-
⁶⁸⁶ erogeneous vegetation cover on water flow fields remains to be conducted. Bank
⁶⁸⁷ strengthening has been explored, especially for waterways, with models based
⁶⁸⁸ on the number of roots and tensile strength, which do not explicitly take into
⁶⁸⁹ account the complexity of the relationships between soil texture/structure, root
⁶⁹⁰ systems and their effect on the hydrological status of the soil matrix. This can
⁶⁹¹ be partly explained by (i) the complexity of the relationships between soils and
⁶⁹² roots that involve physical, biological and chemical processes, (ii) the difficulty
⁶⁹³ of measuring belowground properties and parameters, and (iii) the dynamic
⁶⁹⁴ nature of the contributions of the different effects of roots on bank stability
⁶⁹⁵ (Pollen-Bankhead and Simon, 2010). Moreover, regarding root systems, other
⁶⁹⁶ properties/parameters such as root system architecture and orientation with
⁶⁹⁷ respect to the banks of the channel, as well as the hydrological effect of root
⁶⁹⁸ systems on soil reinforcement, have been poorly explored. Nonfloating propag-
⁶⁹⁹ ules and sediment retention is still difficult to model at the reach scale due to
⁷⁰⁰ the complexity of the processes involved, especially due to the effect of turbu-
⁷⁰¹ lent phenomena in vegetated channels. The retention of pesticides, as well as
⁷⁰² nutrients, is generally related to total plant biomass, which is an integrative
⁷⁰³ parameter, due to the difficulty to disentangle the processes involved in the
⁷⁰⁴ function (e.g. both dissolved and bound particle transport, quantification of
⁷⁰⁵ the role of absorption, effect of water residence times on sorption processes,...).
⁷⁰⁶ Similarly, the retention of floating propagules in vegetated channels is influenced
⁷⁰⁷ by the specific features of the propagules (e.g. roundness, density, and shape)

(Carthey et al., 2016), as well as by hydrodynamic conditions at the free surface of water and other environmental factors (such as the intensity and direction of wind (Soomers et al., 2010)) that make it even more difficult to study. Therefore, research efforts still need to be made to be able to quantify accurately the effect of vegetation and of its dynamics on the three studied ecosystem functions.

Channel management practices (mowing, dredging, burning, clearing and chemical weeding) influence the dynamics of vegetation (composition and properties/parameters) in the short and long term. However, except for a few studies (Dollinger et al., 2017; Vinatier et al., 2018), the effect of management practices on the dynamics of these properties and parameters has not been clearly addressed because research traditionally focused on the effect of management practices on preserving the richness and diversity of plant communities. This review therefore identifies a lack of knowledge of the potential for management practices to drive the properties and parameters of plant communities that are involved in the three ecosystem functions studied.

7. Conclusion

Water regulation; retention of sediments, agricultural pollutants and plant propagules; and bank strengthening are essential ecosystem functions that support the agroecological transition because they help limit the harmful effects of agriculture on ecosystems. It would be interesting to adopt an approach based on community parameters/properties to understand how vegetation influences the functioning of agricultural channels because doing so would allow generical conclusions about the effect of vegetation on these ecosystem functions to be drawn and support the subsequent modeling of these functions. This review provides insights into the parameters/properties that have been clearly associated with the studied ecosystem functions in the literature and that can be measured

in the field or modeled to study the dynamics of these ecosystem functions in space and time. Modifying plant community parameters and properties through agricultural channel management could be a powerful lever with which to manage ecosystem functions and optimize them in space and time. However, the potential role of agricultural channel vegetation remains largely underestimated and underexploited.

Notations

Notation	Definition	Unit (SI)
a	Frontal area per volume unit	m^{-1}
A	Projected area	m^2
B	Blockage factor	$-$
$C*$	Interfacial shear between vegetated and unvegetated flows	$-$
C_d	Drag coefficient of the vegetation	$-$
C_f	Drag coefficient of the bare-bed	$-$
D	Vegetation density	m^{-1}
d	Stem diameter	m
f	Total drag force	N
F_f	Resistance coefficient of James et al. (2004)	$-$
$F_d w$	Darcy-Weisbach friction factor	$-$
f_v	Vegetative resistance parameter	$-$
g	Gravitational acceleration	$m.s^{-2}$
H	Height of water	m
h_p	Plant height	m
i	Channel slope	$-$
K	Constant equal to 1	$m^{1/3}.s-1$
N	Number of stems per unit area	$-$
n	Manning coefficient	$s.m^{-(1/3)}$
R	Hydraulic radius	m
RD	Root (mass) density	$g.m^{-3}$
RLD	Root Length density	$m.m^{-3}$
S	Wetted surface	m^2
u	Mean velocity	$m.s^{-1}$
U_{eff*}	Effective friction velocity	$m.s^{-1}$
V	Local flow velocity	$m.s^{-1}$
V_0	Local time-averaged stream-wise velocity in the uniform layer	$m.s^{-1}$
w	Width of vegetation patch	m
W	Width of channel section	m
ΔS	Spacing between plant stems	m
δe	Length of penetration of Kelvin-Helmholtz vortices	m
κ	Von Karman constant	$-$
ν	Kinematic viscosity	$m^2.s^{-1}$
ρ	Density of water	$kg.m^{-3}$
τ_r	Critical shear stress acting on a channel bed	$N.m^2$

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