



**HAL**  
open science

## **Impact of maintenance operations on the seasonal evolution of ditch properties and functions**

Jeanne Dollinger, Fabrice Vinatier, Marc Voltz, Cécile Dagès, Jean-Stéphane Bailly

► **To cite this version:**

Jeanne Dollinger, Fabrice Vinatier, Marc Voltz, Cécile Dagès, Jean-Stéphane Bailly. Impact of maintenance operations on the seasonal evolution of ditch properties and functions. *Agricultural Water Management*, 2017, 193, pp.191-204. <10.1016/j.agwat.2017.08.013>. <hal-01591538>

**HAL Id: hal-01591538**

**<https://hal.science/hal-01591538v1>**

Submitted on 21 Sep 2017

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

2  
3 **Impact of maintenance operations on the seasonal evolution of ditch**  
4 **properties and functions**

5  
6 *Jeanne Dollinger\*<sup>1</sup>, Fabrice Vinatier<sup>1</sup>, Marc Voltz<sup>1</sup>, Cécile Dagès<sup>1</sup>, Jean-Stéphane Bailly<sup>2</sup>*

7 *<sup>1</sup>INRA, UMR LISAH, 2 place Pierre Viala, 34060 Montpellier Cedex 1, France*

8 *<sup>2</sup>AgroParisTech, UMR LISAH, 2 place Pierre Viala, 34060 Montpellier Cedex 1, France*

9  
10 DOI: <http://dx.doi.org/10.1016/j.agwat.2017.08.013>

11  
12 **Abstract:** Ditch networks were traditionally designed to protect fields from soil erosion or control  
13 waterlogging. They are still frequently managed by either mowing, chemical weeding, dredging or  
14 burning to ensure their optimal hydraulic capacity. Ditches were recently reported also to improve  
15 water quality and sustain biodiversity. These ditch functions are related to specific ditch properties. By  
16 contrastingly modifying ditch properties, maintenance operations were supposed to regulate these  
17 functions. There is, therefore, a need to re-examine the design and maintenance strategies of ditches  
18 to optimize the whole range of ecosystem services that they provide. In this study, we address the  
19 innovator question of how maintenance operations affect the yearly evolution of ditch properties, and  
20 in turn, the panel of functions that ditches support. During one year, we monitored the vegetation,  
21 litter, soil properties, and ash cover of five ditches that were being unmanaged, dredged, mowed,  
22 burned, and chemically weeded, respectively, with timing and frequency as generally operated by  
23 farmers in the study area. We then used indicators to evaluate the effect that the evolution of these  
24 properties has on the ditch water conveyance, herbicide retention and biodiversity conservation  
25 functions. We found that the evolution of these properties significantly contrasted among the 5  
26 maintenance strategies. All the maintenance operations cleared the vegetation, which improves the  
27 hydraulic capacity by up to 3 times. The optimal hydraulic capacity is maintained longer after chemical  
28 weeding and dredging, but these operations have negative impacts on the herbicide retention and  
29 biodiversity conservation functions. The litter and ash layers generated by mowing and burning,  
30 respectively, improve the herbicide retention by up to 45%. Our results confirm that maintenance can

31 be an efficient tool for optimizing ditch functions. The choice of maintenance operation and timing are  
32 key to successfully optimizing most of the functions that ditches can support.

33

34 **Keywords:** Maintenance operations; intermittently flooded ditch; ecosystem services; herbicides  
35 retention; water conveyance; biodiversity conservation

36

37 **Highlights:**

- 38 • We used indicators to evaluate the evolution of ditch functions after maintenance.
- 39 • Maintenance is an efficient and operational tool for optimizing ditch functions.
- 40 • The choice of maintenance operation and timing are key to optimize multiple functions.
- 41 • The primary 4 maintenance operations generate contrasted ditch properties evolution.
- 42 • Burning and mowing improved the best water quality and biodiversity functions.

43

## 44 **1. Introduction**

45 Farm ditches are infrastructures that have been used for centuries by farmers to regulate excess water  
46 fluxes in cropped areas, which, depending on the pedoclimatic context, were used either to protect  
47 crop fields from soil erosion or to control waterlogging (Dollinger et al., 2015; Levvasseur, 2012;  
48 Levvasseur et al., 2014). The design of these human-made channels, which are arranged as networks  
49 in cropped catchments, was optimized over time to efficiently collect runoff and drainage fluxes and  
50 rapidly evacuate them towards receiving water bodies (Levvasseur et al., 2014, 2016). Additionally,  
51 these infrastructures have also recently been reported to sustain biodiversity, buffer agricultural non-  
52 point source pollutions or participate in groundwater recharge and flood regulation, depending on  
53 their properties (e.g., Dollinger et al., 2015; Herzon and Helenius, 2008; Needelman et al., 2007).

54 As part of a more global strategy that aims to limit the adverse effects of intensive agriculture on the  
55 environment, the interest in promoting those ditch functions that are not directly involved in  
56 protecting crops from waterlogging and soil losses is growing (Dollinger et al., 2015; Herzon and  
57 Helenius, 2008; Needelman et al., 2007). This interest is particularly the case for non-point source  
58 pollution buffering and biodiversity conservation ditch functions. For instance, pesticides sprayed in  
59 intensive crop systems to protect crops from pests and weeds may be partly dissolved by runoff and  
60 drainage fluxes and then transferred towards surface water bodies or groundwater via ditch networks  
61 (Louchart et al., 2001; Tang et al., 2012). This non-point source pollution threatens the quality and

62 ecological health of these water bodies, thereby restricting specific usages, such as drinking water  
63 supply, and engendering significant depollution costs around the world ([Reichenberger et al., 2007](#);  
64 [Schultz et al., 1995](#)). Therefore, there is a need to re-examine the design and maintenance strategies  
65 of ditches to optimize the whole range of ecosystem services that they provide. In this paper, we  
66 address the specific issue of the impact of maintenance practices on the ditch functions. Ditches are  
67 distinguished here from irrigation channels, as, even though they might share design and maintenance  
68 similarities, their flooding regime is greatly contrasted.

69 Ditch maintenance strategies originally aimed to preserve an optimal hydraulic capacity thanks to  
70 frequent vegetation clearance ([Dollinger et al., 2015](#); [Levvasseur et al., 2014, 2016](#)). Ditch  
71 maintenance primarily consists of the succession in time and location of some of the 4 basic  
72 operations, which are ditch mowing, dredging, chemical weeding and burning ([Dollinger et al., 2015](#);  
73 [Levvasseur, 2012](#)). The frequency and timing of these maintenance operations differ. Ditch dredging  
74 is usually performed once every 5 to 10 years but can be more frequent in the case of small in-field  
75 ditches that are designed to protect sloping croplands from erosion ([Bailly et al., 2015a](#); [Levvasseur,](#)  
76 [2012](#); [Smith and Pappas, 2007](#)). Mowing, chemical weeding and burning are usually performed at least  
77 once a year ([Bailly et al., 2015a](#); [Levvasseur, 2012](#); [Levvasseur et al., 2014](#); [Smith and Pappas, 2007](#)).  
78 Moreover, a given ditch is very likely to undergo a combination of maintenance operations every year.  
79 While chemical weeding, mowing and dredging are usually performed from spring to late summer,  
80 burning is performed in winter when the vegetation dries out. This operation is thereby restricted to  
81 the highland or semi-arid areas where there is no base-flow in the ditches during winter (e.g., [Bailly et](#)  
82 [al., 2015a](#)).

83 The maintenance of ditches, by modifying their properties, also modulates the occurrence and  
84 intensity of the biogeochemical processes involved in the multiple functions supported by ditches  
85 ([Dollinger et al., 2015](#)). The change in ditch properties after maintenance may favour certain functions  
86 over others as an intensity shift of a given biogeochemical process may favour a function or a group of  
87 functions and be disadvantageous to others ([Dollinger et al., 2015](#)). Designing ditch maintenance  
88 strategies for sustaining a panel of functions, including those for which the ditches were created,  
89 requires a good knowledge of how each maintenance operation modifies the ditch properties, not only  
90 immediately but also after their mid-term evolution. Few studies have attempted to describe the  
91 spatial and temporal variability of ditch properties along networks and link them to maintenance  
92 strategies ([Bailly et al., 2015a](#); [Lecce et al., 2006](#); [Levvasseur et al., 2014](#)). However, to our knowledge,  
93 the effect of the maintenance operations on the mid- evolution of ditch properties and how this  
94 evolution affects a panel of functions has never been described in the literature.

95 In accordance with these gaps of knowledge, the objectives of this study are to i) experimentally assess  
96 the mid-term evolution of ditch properties after each maintenance operation, ii) evaluate with semi-  
97 quantitative indicators the influence of these ditch property evolutions on the hydraulic capacity,  
98 herbicide retention and biodiversity of the ditches, and iii) try to identify maintenance operations or  
99 strategies that could jointly sustain a panel of functions. The study was conducted during one year in  
100 South of France in a vineyard area that is subjected to rare but highly intensive rainfall events and  
101 where ditch networks were originally designed to prevent soil erosion.

102

103

## 104 **2. Materials and methods**

105

### 106 **2.1 Experimental design**

#### 107 **2.1.1 Study site**

108 The study site is located in the downstream part of the Bourdic catchment in South of France (43°5'  
109 Nord, 3°3' East). This 6.4 km<sup>2</sup> catchment, primarily covered by vineyards, is subject to a Mediterranean  
110 climate, which is characterized by rare but high-intensity rainfall events that occur mostly in spring and  
111 fall ([Levavasseur et al., 2012](#)). The dense ditch network is managed in the catchment with the principal  
112 aim of preventing soil loss by erosion ([Levavasseur et al., 2016](#)).

113 The study site is a ditch receiving both drainage (groundwater exfiltration flux) and runoff (overland  
114 flow) water from the surrounding vineyards. The ditch length is approximately 120 m, its bottom width  
115 64 cm, its top width 160 cm, its depth 54 cm and its slope 0.33%. As described in Fig. 1, for the  
116 experiments, the ditch was divided into 4 sections or "patterns", each sub-divided into 5 quadrats  
117 being 4 m long each. The first quadrat of each pattern is an un-managed control. Then, proceeding  
118 from the upstream to downstream direction, the quadrats are dredged, mowed, burned and  
119 chemically weeded, respectively. Moreover, the quadrats are separated from each other by 2-m long  
120 unmanaged buffer sections.

121 The ditch was equipped, in the middle unmanaged area, with a capacity sensor ([Crabit et al., 2011a](#);  
122 [Crabit et al., 2011b](#)), which monitored the water level fluctuations with a 60-min frequency. Two water  
123 wells, one located upstream and the second 100 m downstream from the ditch outlet, allowed the  
124 manual monitoring of the groundwater level. Rainfall data were obtained from the Roujan catchment  
125 meteorological station located only 1.5 km from the study site.

126 The monthly cumulated rainfall amounts during the experiment period were compared to the rainfall  
127 distributions observed at the same meteorological station from 1992 to 2016 (Fig. S1). This comparison  
128 shows that fall 2015 was dryer than usual. Indeed, the cumulated rainfall amounts for September,  
129 October and November were in the very bottom range of the rainfall distributions for these months.  
130 Moreover, spring 2015 was slightly dryer than usual, particularly in May, but spring 2016 was slightly  
131 wetter.

132

### 133 **2.1.2 Maintenance design**

134 The maintenance strategy was designed to mimic the frequencies and timings typically used by farmers  
135 in the study area (Levvasseur et al., 2014). The first maintenance campaign was initiated on April 7<sup>th</sup>,  
136 2015 with burning and chemical weeding. The dredging operations were spread between April 23<sup>rd</sup>  
137 and May 5<sup>th</sup>, 2015 because of the greatly differing soil humidity conditions among the patterns.  
138 Mowing was performed on June 4<sup>th</sup> and then again on September 7<sup>th</sup>, 2015. The second campaign  
139 started on February 17<sup>th</sup>, 2016 with burning, then chemical weeding on April 13<sup>th</sup>, 2016. A given  
140 quadrat was submitted only to one maintenance operation type throughout the experiment. Figure 2  
141 depicts how each management operation was performed for this study.

142

### 143 **2.1.3 Monitoring of ditch properties**

144 The ditch properties were surveyed on each quadrat using a semi-quantitative method (Bailly et al.,  
145 2015a; Dollinger et al., 2016; Levvasseur et al., 2014). This method consists of first, precisely  
146 measuring the morphological properties of the ditch in each pattern. The cross-section profile (upper  
147 width, lower width and depths) was measured manually, whereas the length and slope were measured  
148 with a theodolite and a differential GPS. Second, in each quadrat, the proportion of the ditch bottom  
149 and walls covered by vegetation, litter and ash (in %) and the depths of these respective layers (in cm)  
150 were visually estimated. The visual estimations were initially performed by 2 independent observers  
151 and then calibrated against each other. The precision of the estimates was approximately 10 to 15%  
152 for the covering area and 1 cm for the material layer depth. Last, the litter was classified into 3 different  
153 types (dead leaves, hay, and decayed plant residues) and the vegetation into either an herbaceous or  
154 ligneous type. During the surveys, the vegetation height was classified as <15 cm, >15 cm or mixed  
155 (several vegetation heights all between 0 and 15 cm) and then, converted to 10 cm (maximal  
156 vegetation height in this class), 54 cm and 15 cm (maximal vegetation height in this class) height for  
157 each class, respectively. The vegetation classified as >15 is, most of the time, as high or even higher  
158 than the ditch depth (54 cm) which was thereby taken as default value for this class as it's the maximum

159 vegetation height that can influence the various ditch functions. The presence or absence of flowers  
160 was also monitored.

161 The surveys were conducted every 15 days between April and July and then every month the  
162 remainder of the year. In total, 19 ditch property monitoring surveys were conducted between April  
163 2015 and May 2016.

164 Soil samples were collected in the upper horizon (0-2 cm) of the 4 control quadrats during July 2015  
165 for physicochemical properties measurements. The particle size distributions, pH values, cation  
166 exchange capacities (CEC) and organic carbon content of the soil samples were measured at the INRA  
167 Soil Analysis Laboratory in Arras (France) using normalized methods. Particle size distribution was  
168 measured with the standardized method NF X 31-107, pH<sub>H2O</sub> with the method NF ISO 10390, CEC  
169 Metson with the method NF X 31-130 and OC content with the method NF ISO 10694. To detect any  
170 change in soil properties according to the maintenance operations, these properties were again  
171 measured on the soil samples collected from the upper 2 cm layer on all quadrats during April 2016,  
172 i.e., after approximately 9 months of the distinct maintenance strategies.

173 The soil bulk densities were estimated by sampling a known volume of soil and measuring the dry  
174 weight after oven drying for 24 h at 105°C. Six replicates were performed for each quadrat during April  
175 2016.

176

## 177 **2.2 Calculation of the pesticide retention indicator**

178 For a given pesticide, the retention capacity of a ditch depends on its properties and more specifically,  
179 on the abundance and characteristics of the ditch materials in contact with the water column ([Dollinger  
180 et al., 2016](#)). Dollinger et al. ([2016](#)) proposed the sorption-induced pesticide retention indicator (SPRI),  
181 which is based on a pesticide mass balance equation and integrates the influence of several factors to  
182 evaluate the proportion of pesticides that is potentially retained by sorption processes as it passes  
183 through a ditch during a flood event. The factors integrated into the calculation of the SPRI indicator  
184 are i) the amount and properties of ditch materials in contact with the water column, ii) the pesticide  
185 sorption properties and iii) the flood characteristics (volume, water level). For the purpose of this  
186 study, this indicator was used as a means to compare how the different implemented maintenance  
187 designs affect the herbicide retention functions of the ditches.

$$188 \quad SPRI(\%) = \frac{\sum_{i=1}^n M_i K d_i}{\sum_{i=1}^n M_i K d_i + V} 100 \quad (\text{Equation 1})$$

189 where  $M_i$  is the mass of material  $i$  and  $i$  is one of the ditch materials [soil (s), decaying (DV) and living  
190 vegetation (veg) (g)];  $Kd_i$  is the sorption coefficient of material  $i$  and  $V$  is the volume of water flowing  
191 through the ditch during a flood event ( $\text{cm}^3$ ).

192 The theory and hypotheses underlying the estimation of pesticide retention in ditches during a flood  
193 event with SPRI are detailed in Dollinger et al. (2016). The SPRI indicator was calculated for 2  
194 herbicides, glyphosate (N-(Phosphonomethyl)glycine) and diuron (3-(3,4-dichlorophenyl)-1,1-  
195 dimethyl-urea), which are frequently detected in the water columns of ditches in the study area at  
196 concentrations reaching up  $1,000 \mu\text{g l}^{-1}$  (Dages et al., 2015; Louchart et al., 2001). The SPRI values were  
197 calculated for both herbicides on the 19 dates during the year when the ditches were surveyed and for  
198 all 20 quadrats. The sorption coefficients of diuron used for the SPRI calculation were  $8.6 \text{ l kg}^{-1}$  for soil,  
199  $3.2 \text{ l kg}^{-1}$  for plants,  $46.5 \text{ l kg}^{-1}$  for dead leaves,  $28.6 \text{ l kg}^{-1}$  for mowing residues and  $1,009.1 \text{ l kg}^{-1}$  for ash;  
200 those of glyphosate were  $26.2 \text{ l kg}^{-1}$  for soil,  $2.0 \text{ l kg}^{-1}$  for plants,  $4.4 \text{ l kg}^{-1}$  for dead leaves,  $0.8 \text{ l kg}^{-1}$  for  
201 mowing residues and  $23.6 \text{ l kg}^{-1}$  for ash (Dollinger et al., 2016).

202 The masses of the soil, vegetation, litter and ash materials were calculated as described in Dollinger et  
203 al. (2016) from the ditch properties estimated during the surveys, namely, the percentages of the ditch  
204 bottom coverage, depths, porosities and bulk densities of all material layers. The values of porosity  
205 factors used were those described in Dollinger et al. (2016) for each type of material. The volume of  
206 flowing water was set to  $122 \text{ m}^3$ , which corresponds to a typical flood event in the study area generated  
207 by a one-month return period rainfall event (Bailly et al., 2015a). The flood usually generated by this  
208 type of event lasts approximately 12h and 20 min, and its flow rate is approximately  $2.75 \cdot 10^{-3} \text{ m}^3 \text{ s}^{-1}$ .

209

210

### 211 **2.3 Calculation of the hydraulic capacity**

212 The waterlogging control and soil erosion prevention functions, for which ditches were created and  
213 managed, both rely on an efficient water conveyance capacity of the ditches (Dollinger et al., 2015).

214 The water conveyance capacity of ditches is related to their shape and roughness (Boutron et al., 2011;  
215 Crabit et al., 2011b). The maximal flow rate ( $Q_{\text{max}}$ ), which is reached when the water level equals the  
216 ditch depth, is also called the hydraulic capacity or water conveyance capacity. This value was  
217 calculated using the Manning-Strickler equation (Strickler, 1923) and assuming flow uniformity (Eq. 2)

$$218 \quad Q_{\text{max}} = K S R h^{2/3} i^{1/2} \quad (\text{Equation 2})$$

219 where  $Q_{\max}$  is the water conveyance capacity ( $\text{m}^3 \text{s}^{-1}$ ),  $K$  is the Strickler coefficient ( $\text{s}^{-1}$ ),  $i$  is the slope ( $\text{m}$   
220  $\text{m}^{-1}$ ),  $S$  is the ditch wet cross-section area ( $\text{m}^2$ ),  $Rh$  is the hydraulic radius (m) or the  $S/P$  ratio, and  $P$  is  
221 the wetted perimeter (m).

222 The primary source of roughness in the ditches is the vegetation (e.g., [Jarvela, 2002](#); [Wu et al., 1999](#)).  
223 The roughness coefficients (Strickler coefficients,  $K$ ) were estimated from the vegetation cover data  
224 using the empirical Strickler database developed by Bailly et al., ([2015b](#)) from measurements in an  
225 hydraulically equipped ditch with variable vegetation patches ([Vinatier et al., In Press](#)).

226 The ditch cross-section was considered trapezoidal and is characterized by the ditch bottom and top  
227 widths and by the ditch depth. The wet cross-section area ( $S$ ) is equivalent to the ditch cross-section  
228 surface area as the water level equals the ditch depth in the calculation of the hydraulic capacity. The  
229 wetted perimeter ( $P$ ) is the sum of the ditch bottom and sidewalls length and the hydraulic radius ( $Rh$ )  
230 is the ratio between  $S$  and  $P$  ( $S/P$ ).

231 The water conveyance capacity of the 20 quadrats was calculated for the 19 dates during the year  
232 when ditches were surveyed.

233

#### 234 **2.4 Establishment and calculation of the ecological indicators**

235 The ditches sustain biodiversity in croplands by providing shelter, food and protected pathways for  
236 connecting different populations of auxiliary insects, mammals, frogs or birds ([Herzon and Helenius,](#)  
237 [2008](#); [Marja and Herzon, 2012](#)). The link between the ditch properties and the abundance of certain  
238 categories of insects or macrofauna has never been empirically quantified but can be approached  
239 thanks to the work conducted on riverine landscapes ([Ward, 1992](#)), dry riverbeds ([Steward et al., 2012](#);  
240 [Wishart, 2000](#)), non-perennial streams ([Chester and Robson, 2011](#)) and riparian vegetation ([Stella et](#)  
241 [al., 2013](#)). We assumed that the relations between systems characteristics and the biodiversity  
242 described in those studies could be extended to Mediterranean ditches. The works of Dangles et al.  
243 ([2004](#)), Johnson et al. ([2003](#)) and Murphy et al. ([2012](#)) show that detritivore insects are the primary  
244 consumers of litter in several types of ecosystems. This category of insects relies on a sufficient litter  
245 cover as their food sources. We thereby assumed that the litter layer in ditches favours these insects.  
246 Second, the linear vegetated elements of landscapes improve the survival and development of insects  
247 ([Meier et al., 2005](#)) and macrofauna ([Andreassen et al., 1996](#)) populations by providing sheltered  
248 corridors. However, the surface of the ditch covered by vegetation and the vegetation height modulate  
249 the shelter effect of a given ditch. Last, the blooming vegetation provides sources of nectar for auxiliary  
250 insects ([Nicholls et al., 2001](#); [Sarhou et al., 2005](#)).

251 To evaluate the influence of the ditch properties evolution on their ecological functions, we derived  
252 qualitative indicators from these general ecological principles. These indicators are not designed to  
253 quantify or qualify the progression of the biodiversity based on the progression of the ditch properties,  
254 which would require more empirical work. The indicators only intend to describe the progression of  
255 the conditions sustaining or disadvantaging the biodiversity as a function of the ditch properties. Based  
256 on the ecological principles, we divided the ditch into 3 layers, the litter, vegetative and canopy layers  
257 and computed an ecological indicator for each. The three indicators were calculated for each quadrat  
258 as binary functions with thresholds for the respective layers based on i) the litter and surface covering,  
259 ii) the vegetation height and surface covering, and iii) the presence of flowers. Considering the absence  
260 of experimental data on these ecological functions in the ditches, we arbitrarily chose the thresholds  
261 in accordance with the works on closed ecosystems ([Andreassen et al., 1996](#); [Chester and Robson,](#)  
262 [2011](#)) and to emphasize the difference between the maintenance treatments. The thresholds for the  
263 litter layer were defined as 5 cm and 50% for height and cover, respectively. The thresholds for the  
264 vegetation layer were defined as 20 cm and 50% for height and cover, respectively. Finally, the  
265 threshold for the canopy layer was defined as the presence of at least 1 flower in the quadrat. For a  
266 given quadrat, the value of every indicator is either 0 or 1. The value 1 represents a situation favouring  
267 the biodiversity. For a given treatment, the value of every indicator is the average of the 4 replicates  
268 and can, therefore, take the values 0, 0.25, 0.5 and 1.

269

270

### 271 **3. Results**

272

#### 273 **3.1 Influence of the maintenance operations on the mid-term evolution of ditch properties**

274 Figure 3 describes the evolution of the living vegetation layer in all the treatments throughout the year.  
275 It must be noted that the high variability of the vegetation height that can be observed among the 4  
276 replicates of a given treatment is partly due to the conversion of vegetation height classes into  
277 vegetation height. Figure 4 describes the contrasted evolution of the litter layers and Figure 5 the  
278 difference in soil physicochemical properties among the treatments.

279 At the beginning of the experiments in April 2015, vegetation covered only approximately 30% of the  
280 ditch bottom surface area and was short and scattered. At that time, the vegetation cover was  
281 homogeneous all along the ditch. No litter or ash covering could be observed on any of the 20 quadrats  
282 and the soil physicochemical properties were relatively homogeneous among the 4 control quadrats.

283 The evolution of the ditch properties for the 5 treatments, namely, no management, dredging,  
284 mowing, burning and chemical weeding between April 2015 and May 2016 are described hereafter.

285 For the control treatment, the bottom surface areas of the quadrats were progressively colonized by  
286 vegetation during the spring and summer (Fig. S2). The total vegetation covering was reached by about  
287 September for all the control quadrats and persisted throughout the fall. Then, the vegetation cover  
288 progressively decreased from December 2015 to April 2016. It must be noted that the vegetation  
289 covering and density was higher in April 2016 than at the beginning of the experiments in April 2015.  
290 This difference is probably due to the contrasting maintenance history in the previous year. Indeed,  
291 before April 2015, the ditch was intensively managed, whereas between April 2015 and 2016, it was  
292 left unmanaged. The evolution of the relative surface area covered by vegetation was progressive  
293 throughout the year, but the vegetation growth and densification was very quick for this treatment.  
294 Moreover, the litter layers on the control quadrats were scattered and thin until December, when the  
295 progressive vegetation senescence generated a few litter inputs. The major litter inputs were due to  
296 the collection of dead leaves from the surrounding vineyards during January 2016. The amount of dead  
297 leaves collected considerably varied among the patterns because of their different orientation  
298 regarding the dominant wind direction and vine rows. The control quadrats from patterns 2 to 4  
299 collected most of this litter, whereas the control quadrat of the first pattern, which was not  
300 perpendicular to the wind direction, collected almost nothing. The decrease of the litter layer depth  
301 with time can be attributed to a progressive biotransformation and the settling generated by the  
302 successive floods. Furthermore, the topsoil physicochemical properties only slightly evolved between  
303 July 2015 and April 2016 on the control quadrats. A slight decrease in the clay fraction in favour of the  
304 silt fraction can be reported as well as a slight pH rise. The organic carbon content and CEC did not  
305 significantly change.

306 After the dredging treatment operation in April 2015, the vegetation recolonized the bottom surface  
307 area of the quadrats very progressively throughout the year and stayed relatively short and scattered  
308 (Fig. S3). The vegetation senescence during winter was weak and generated only very few litter inputs.  
309 Similar to the control treatments, the primary litter provision was ensured by the collection of dead  
310 leaves from the surrounding vineyards. These litter inputs were also heterogeneous among the  
311 patterns, and an identical decrease in the litter layer depth was observed for both the control and  
312 dredged quadrats. The particle size distribution of the topsoil on the dredged quadrats was very similar  
313 to that of the controls on the same date and so were the pH values. However, the bulk density, CEC  
314 and organic carbon content were slightly lower. During the dredging, a layer of 15 cm of soil was  
315 excavated, which corresponded to the first horizon enriched in organic matter compared to the deeper

316 layers. Accordingly, the values of CEC and organic carbon content were similar for the dredged top soil  
317 and the second horizon in 2015 (data not shown).

318 For the mowing treatment, the vegetation recolonization and growth after each maintenance  
319 operation were very quick, particularly after the second operation in September due to more  
320 favourable hydric conditions (Fig. S4, Fig. 6). Both of the mowing operations generated consequent  
321 litter layers that were supplemented during winter by the collection of dead leaves. These mowed  
322 quadrats were partly or even completely covered by more or less deep litter layers throughout the  
323 year. The physicochemical properties of the topsoil of these quadrats were very similar to that of the  
324 control.

325 For the burning treatment, the vegetation recolonization in the months following the two burnings  
326 was very progressive, but the vegetation growth and densification were very quick (Fig. S5). For this  
327 treatment, the litter layer in the quadrats was quasi-inexistent until the dead leaves collection during  
328 January 2016. This litter was then rapidly eliminated in February 2016 during the second burning  
329 operation. The burning residues or ashes covered the ditch surface until July and then progressively  
330 dissipated until the end of August when the ash residues could no longer be observed at the ditch  
331 surface. The majority of these ashes were not washed out by the big floods during August (Fig. 6) but  
332 were found by visual inspection to be infiltrated and bound to soil down to 2 to 5 cm depth. The ashes  
333 seem to have undergone a similar fate after the burning operations that occurred before the  
334 experiments, as several soil-bound ash layers were observed at different depths in the soil profile. The  
335 physicochemical properties of the topsoil of these quadrats were very similar to those of the control  
336 except the pH values, which were higher. The higher pH is consistent with the alkaline properties of  
337 ashes ([Dollinger et al., 2016](#)).

338 Finally, for the chemical weeding treatment, vegetation senescence was observed during the 2 months  
339 following each maintenance operation, and then, the vegetation started to recolonize the ditch  
340 surface. The dynamic of the vegetation recolonization was relatively rapid afterwards, but the plants  
341 stayed rather short and scattered (Fig. S6). The vegetation decay after the chemical weeding generated  
342 a wide but thin litter layer. For the other treatments, the litter layer increased during January on the  
343 chemically weeded quadrats due to the dead leaves collected from neighbouring fields. The  
344 physicochemical properties of the topsoil of these quadrats were very similar to that of the control.

345

346

347 **3.2 Influence of the maintenance operations on the processes and functions sustained by ditches**

348

### 3.2.1 Hydraulic capacity

349 The estimated hydraulic capacity or maximal flow rate that a ditch can carry without overflowing ( $Q_{\max}$ )  
350 varied only slightly, i.e., from 7.6 to 14 l s<sup>-1</sup>, on average, for the control quadrats (Fig. 7). Indeed, these  
351 quadrats contained a dense vegetation cover from April 2015 to May 2016 (Fig. 3). The dense  
352 vegetation fills the ditches and thereby limits the water volume that they can carry and induces flow  
353 resistance (e.g., Crabit et al., 2011b; Jarvela, 2002). By clearing the vegetation cover, all the  
354 maintenance operations rapidly improved the hydraulic capacity of the ditches (Fig. 7). However, the  
355 different dynamics of the ditch recolonization by vegetation after the four maintenance strategies  
356 generated diverse evolutions of the hydraulic capacity as described in Fig. 6. These contrasting changes  
357 are not only due to the type of maintenance operation but also to the maintenance calendar.

358 The effect of dredging, mowing and burning on the hydraulic capacity immediately resulted in an  
359 increased  $Q_{\max}$ , i.e., by 4 times compared to the control treatment. In contrast, after the chemical  
360 weeding operations, a vegetation clearing took longer than for the other maintenance operations and  
361 the optimal hydraulic capacity was reached only approximately a month after each operation. The  
362 hydraulic capacity dropped (Fig. 7) as the vegetation recolonized the ditches (Fig. 3). Generally, the  
363  $Q_{\max}$  decreased to the level of the control quadrat within 1 to 3 months, depending both on the  
364 maintenance operations performed and on the calendar. As an example, when the mowing was  
365 performed during June, i.e., during the dry season, this operation helped maintain an optimal  $Q_{\max}$   
366 during the following 2 months, whereas the  $Q_{\max}$  dropped to the control treatment level within a  
367 month when performed during September.

368 Dredging was performed in spring, and therefore, the hydraulic capacity of these quadrats was optimal  
369 during spring and early summer. This maintenance design optimizes the ditch hydraulic capacity for  
370 the storms that generate massive runoff amounts and have a high occurrence frequency during spring  
371 in the study area (Fig. S1) (Levavasseur et al., 2014; Moussa et al., 2002). On the other hand, the  
372 hydraulic capacity is minimal under this maintenance design during late summer and fall when the  
373 highest intensity rainfall events generally occur in the study area (Fig. S1) (Moussa et al., 2002).  
374 Mowing was performed in June and September, and  $Q_{\max}$  was optimal from June to the beginning of  
375 August and from September to October. The occurrence probability of high-intensity rainfall events in  
376 June and July is very low. However, this maintenance design optimizes the ditch hydraulic performance  
377 for the big storms that usually occur between late summer and fall. The optimal hydraulic capacity was  
378 maintained longer under the chemical weeding design than under the others. However, the chemical  
379 weeding was performed once a year during April, and thus the hydraulic capacity of the ditches was at  
380 the level of those of the control treatment during the periods when big floods likely occur. Last, burning

381 was performed during April 2015 and then again during February 2016, which generated an optimal  
382 hydraulic capacity for the floods occurring in spring but not for those in fall.

383

384

### 385 **3.2.2 Herbicide retention**

386 At the scale of a flood event, sorption was reported to be the primary pesticide retention mechanisms  
387 in ditches (Dollinger et al., 2015; Stehle et al., 2011). The SPRI indicator provides estimations of the  
388 herbicide fractions potentially retained by sorption on the ditch bottom during a flood event (Dollinger  
389 et al., 2016). Figure 8 shows the evolution of the SPRI values for the 2 herbicides, diuron and  
390 glyphosate, on the control quadrats and the difference, which is either positive or negative, that the  
391 changes in the ditch properties due to the different maintenance strategies imply regarding herbicide  
392 retention.

393 For the control quadrats, the glyphosate SPRI values did not evolve between April 2015 and May 2016.  
394 This outcome is consistent with the relative affinity and masses of the different ditch materials  
395 (Dollinger et al., 2016). Indeed, glyphosate has a very high sorption affinity for soils and a reduced  
396 sorption affinity for litters and living vegetation. Moreover, the mass of living vegetation and litters is  
397 slight compared to the mass of soil in contact with the ditch water column. The glyphosate sorption  
398 capacity of ditches is thereby mostly driven by the properties of their soils. Soil properties did not  
399 significantly change during the study period. The average glyphosate SPRI value for the control  
400 treatments was 29%. The SPRI values of diuron for the control treatment did not evolve until January  
401 2016 but then increased by approximately 3%. The sorption affinity of diuron for the different ditch-  
402 bed materials is different than that of glyphosate, i.e., low for living vegetation, moderate for soil, high  
403 for litters and very high for ash. The soil properties did not evolve, and the litter layer was very scarce  
404 until January 2016, when the ditch collected dead leaves from the surrounding vineyards, which  
405 improved the diuron retention capacity.

406 Chemical weeding and mowing had no effect on the glyphosate retention capacity of the ditches  
407 estimated with SPRI. On the other hand, the dredging slightly decreased the glyphosate retention  
408 capacities while burning increased the retention by approximately 3% during the periods when ashes  
409 are covering the ditch surface. For diuron, the impact of chemical weeding and mowing on the  
410 evolution of the ditch retention capacities was also limited. The inputs of litter after chemical weeding  
411 and particularly after mowing slightly increased the retention capacity of ditches. For glyphosate,  
412 dredged ditches had lower diuron retention capacities than the control ditches throughout the year.

413 Burning, however, increased the diuron retention capacity of the ditches by almost 50% during the  
414 period when ashes are covering the ditch surface.

415 In the study area, the herbicide spraying period stretches from April to June ([Levavasseur, 2012](#);  
416 [Louchart et al., 2001](#)) during the growth of the vines. Accordingly, the peak of herbicide concentrations  
417 in runoff water is monitored in April/May, whereas from August to March, the concentrations are  
418 relatively low ([Louchart et al., 2001](#)). Optimizing the herbicide retention capacity of ditches is therefore  
419 particularly important during the growth season, particularly if over the same period there is a high  
420 risk of storm events as in the study area. In this respect, the burning practices are welcome since, when  
421 ditches are burned in winter, the ashes are covering the ditch surface during spring and summer, which  
422 slightly increases the retention of glyphosate and substantially increases that of diuron during that  
423 crucial period.

424

### 425 **3.2.3 Biodiversity conservation**

426 Figures 9 represents the evolution of the ecological indicators or, more precisely, of the ditch  
427 conditions that influence the detritivore and auxiliary insects and macrofauna populations. Due to the  
428 non-additivity of the three ecological indicators, we present their evolution separately. The duration  
429 of the study was divided into three periods to facilitate the description of the indicator evolutions. The  
430 period from March to May is a crucial period for animal and insect biodiversity, as it corresponds to  
431 the breeding season of most species in the study area. This duration includes the beginning of the first  
432 and the third periods.

433 In the control treatment, the vegetation was dense in late summer and fall, and blooming flowers were  
434 abundant in the ditch until December 2015 and again from March 2016, but the litter layer was rather  
435 scattered throughout the year. In accordance, the indicator scores were high for the canopy and  
436 vegetation layer during spring to fall but were low for the litter layer. This treatment thus most likely  
437 generates conditions that favour the development and the survival of pollinators and small animals  
438 (e.g., [Herzon and Helenius, 2008](#); [Meier et al., 2005](#); [Murphy et al., 2012](#)). However, this treatment  
439 does not provide ideal conditions for detritivore insects populations ([Dangles et al., 2004](#); [Johnson et  
440 al., 2003](#); [Murphy et al., 2012](#))

441 For the dredging treatments, the vegetation remained scattered throughout the year, and the litter  
442 layer and blooming flower were only abundant at the beginning of the second period. Accordingly, the  
443 indicator scores for all layers were low and only reached the same values as the control during the last  
444 period. Thus, as could be expected, this treatment is unlikely to efficiently sustain the biodiversity in  
445 ditches and can even reduce this factor (e.g., [Herzon and Helenius, 2008](#)).

446 For the mowing treatment, the ecological indicators were highest in the canopy and vegetation layer  
447 from April to June, which covers the breeding season. The mowing operations in June and September  
448 drastically decreased these scores but increased those of the litter layer. Overall, this treatment most  
449 likely generates conditions that favour the development and the survival of auxiliary and detritivore  
450 insects (Dangles et al., 2004; Johnson et al., 2003; Murphy et al., 2012) and small animals (e.g., Herzon  
451 and Helenius, 2008; Meier et al., 2005; Murphy et al., 2012).

452 The burning treatment exhibited the same behaviour as the control for the two first periods due to the  
453 quick recolonization of the vegetation after the maintenance operation. However, the second burning  
454 operation in February 2016 led to very low indicator scores during the third period. Due to the timing  
455 of the burning, it can be concluded that this operation, when performed in late winter or spring, can  
456 reduce the biodiversity.

457 The chemical weeding treatment generated low ecological indicator scores during the breeding season  
458 and overall improved scores in summer. This treatment is, along with dredging, the least able to sustain  
459 a rich biodiversity and can even be detrimental.

460 In summary, we can rank the management operations in increasing order on biodiversity conservation:  
461 dredging, chemical weeding, burning and finally mowing. The differences observed among the  
462 different strategies could be related to the maintenance calendar constraints and the plant  
463 recolonization dynamics after each treatment.

464

465

## 466 **4. Discussion**

467

### 468 **4.1 Representativeness and accuracy of the empirical and indicator data**

469 To our knowledge, the yearly evolution of ditch properties after the common maintenance operations  
470 has not yet been described in the literature. However, the literature contains few studies where ditch  
471 maintenance strategies and properties were punctually surveyed. In accordance with the literature,  
472 our results show that all of the maintenance operations have a direct effect on the removal of the  
473 living vegetation (Dollinger et al., 2015). As in our study, the surveys performed by Levavasseur et al.  
474 (2014) in the same region also highlighted that the chemically weeded and mowed ditches had higher  
475 litter layers than the other types and that all the ditches, regardless of their maintenance design,  
476 tended to collect dead leaves during winter. The decrease in the organic carbon content of the ditch

477 soil after dredging was similarly reported by several studies across the world (e.g., [Smith and Pappas,](#)  
478 [2007; Vaughan et al., 2008](#)).

479

480 The estimated values of the hydraulic capacity ( $Q_{max}$ ) can be associated with the high uncertainties that  
481 stem from both the estimation of vegetation cover ([Levavasseur et al., 2014](#)) and the derivation of the  
482 Strickler coefficients from the vegetation cover data ([Bailly et al., 2015b](#)). However, it must be  
483 underlined that the Strickler coefficients over the range of vegetation densities were similar to those  
484 measured by Crabit et al. (2011) in similarly vegetated ditches or presented in the Chow tables for  
485 small channels ([Arcement and Schneider, 1989; Lagacherie et al., 2006](#)). This estimation yields the  
486 confidences in the hydraulic capacity trends obtained with this semi-quantitative approach.

487 The estimation of glyphosate and diuron retention in ditches might also be associated with some  
488 uncertainties due, in the one hand, to precision of the ditch properties data and, on the other hand, to  
489 the hypotheses underlying the calculation of the SPRI indicator ([Dollinger et al., 2016](#)). We found no  
490 studies reporting measurement of glyphosate retention rates in ditches that would allow assessing the  
491 accuracy of the indicator. However, the average diuron SPRI value for the control treatments was 12%,  
492 which is in the range of the diuron retention measured in vegetated ditches with variable litter layers  
493 by Margoum et al. (2003). Therefore, the estimation yields the confidences in the herbicide retention  
494 capacity trends obtained with this semi-quantitative approach.

495 The indicators developed to compare the evolution of the biodiversity conservation function in ditches  
496 among treatments are entirely qualitative. These indicators allow the discrimination of properties that  
497 would either favour or reduce the biodiversity function. However, these indicators do not allow the  
498 estimation of the presence or absence of certain categories of insects or animals. Moreover, the  
499 thresholds were set based on expert estimations and should be confirmed by additional empirical  
500 work.

501

## 502 **4.2 Designing maintenance strategies for sustaining multiple functions**

503 In the study area, the hydraulic capacity of the ditches needs to be optimal during spring, late summer  
504 and fall when high-intensity storms have a high probability of occurrence ([Levavasseur et al., 2014;](#)  
505 [Moussa et al., 2002](#)). Second, the herbicide retention capacity of the ditches needs to be optimal during  
506 the growth period and particularly during spring when herbicides are sprayed, which results in high  
507 concentrations in the runoff water ([Levavasseur, 2012; Louchart et al., 2001](#)). Last, biodiversity must

508 be especially sustained in spring and early summer during the breeding season ([Herzon and Helenius,](#)  
509 [2008](#)).

510 In this area, dredging and chemical weeding performed once a year in the early spring do not allow the  
511 simultaneous optimization of the water conveyance capacity, herbicide retention and biodiversity  
512 conservation of the ditches (Table 1). These maintenance designs only allow for the optimization of  
513 the hydraulic capacity of the ditches for the spring storms. However, the designs have a null or negative  
514 impacts on the other functions during the critical periods when they should be optimal, which includes  
515 the hydraulic performance during the late summer and fall storms. However, mowing performed in  
516 June and September and burning performed in the winter allows for the optimization of the three  
517 investigated functions at least for some of the critical periods (Table 1). Indeed, if mowing is performed  
518 too late for the optimization of the hydraulic performance of ditches during the spring floods, the  
519 hydraulic performance is still optimized for the late summer and fall floods. Moreover, the dense litter  
520 layer produced during the mowing operations increase the retention of hydrophobic herbicides such  
521 as diuron. The rapid recolonization by the vegetation after mowing along with the dense litter layer  
522 and late flowering sustain biodiversity in ditches from fall until the end of spring. Conversely, burning  
523 optimizes the hydraulic capacity for the spring floods but not for the late summer and fall floods.  
524 Burning is the maintenance operation that has the greatest impact on herbicides retention and  
525 biodiversity during the spring and summer.

526 For this study, only the succession of single maintenance operations (as opposed to a combination of  
527 operations) was investigated on a given ditch. Successions in a period of the two different operations  
528 are relatively frequent in the study area ([Levvasseur et al., 2014](#)). Successions of burning plus mowing  
529 during the year in the same ditch has a probability of occurrence even greater than each operation  
530 alone in the study area. The impact of this succession on the multiple functions supported by ditches  
531 can be extrapolated from the ditch properties evolution data. Burning performed in February would  
532 cover the ditch with ashes during spring and early summer, which optimizes the herbicides retention  
533 and limits the vegetation coverage in early spring, which optimizes the hydraulic capacity. The  
534 subsequently rapid vegetation recolonization and flowering in spring would help sustain biodiversity.  
535 Then, in the late summer when the ditch properties are equivalent to those of an unmanaged ditch,  
536 mowing would clear the vegetation. This operation would thereby optimize the hydraulic performance  
537 for the late summer and fall floods and generate a dense litter layer that would improve the retention  
538 of hydrophobic pesticides. This common succession thereby appears to optimize all the considered  
539 functions during all important periods.

540 The 4 maintenance operations have similar short-term impacts on ditch vegetation but contrasting  
541 impacts on the mid-term evolution of the ditch properties (Fig. 3 to 5). The different biochemical  
542 processes involved in the multiple functions supported by ditches are modulated by the ditch  
543 properties and thereby by the maintenance operations (Dollinger et al., 2015). These modulations of  
544 the water conveyance capacity, herbicide sorption and biodiversity conservation of ditches related to  
545 the evolution of ditch properties assessed with the semi-quantitative indicators may be associated  
546 with significant uncertainty related both to the precision of the ditch properties data and to the  
547 simplification hypothesis inherent to the calculation of the various indicators. However, the range of  
548 Strickler coefficients or diuron retention was where the estimated values correspond well to those  
549 measured in similar ditches or channels (Crabit et al., 2011b; Margoum et al., 2003), which yields  
550 confidence in the trends derived from these indicators.

551

552

## 553 **5. Conclusion**

554

555 This study aimed at characterizing the influence of maintenance on the yearly dynamics of ditch  
556 properties in order to identify strategies that would allow simultaneous optimization of a panel of  
557 agricultural and ecological functions. The primary maintenance operations of i.e., dredging, chemical  
558 weeding, mowing and burning, were shown in this work to lead to significant changes the ditch  
559 properties. They all induce vegetation clearance that increases the hydraulic capacity of ditches but  
560 decreases their biodiversity support. Moreover, the chemical weeding, and even more mowing  
561 generate dense litter layers that improve the retention of hydrophobic herbicides such as diuron and  
562 sustain detritivore insects. Furthermore, burning covers the ditch bottom with ashes that greatly  
563 increase their herbicide retention capacity. The hydraulic capacity of ditches has to be optimal during  
564 the periods when big floods are likely to occur in a given area, while their herbicides retention  
565 capacities should be increased during the herbicide-spraying season when concentrations in runoff are  
566 likely to be high. Biodiversity should be preferentially sustained during the breeding season. The  
567 periods of the year over which these respective ditch functions should be optimal may not overlap. As  
568 such, not only the type of maintenance operation but also the calendar of maintenance, by modifying  
569 ditch properties at given periods during a year, can help optimizing the multiple ditch functions. The  
570 combination of different operations at critical periods of the year allows for the optimization of  
571 successively most of the functions that ditches can support. In the Mediterranean context, for  
572 example, burning in winter and mowing in late summer is the combination of operation and timing  
573 that appears to improve the best of the functions during the crucial periods.

574 The evolution of ditch properties after the 4 primary maintenance operations may differ under various  
575 pedoclimatic contexts, particularly because the maintenance calendar and operation type chosen are  
576 likely to be constrained by the climate. The period over which the different functions of the ditch  
577 should be optimized may vary as well. This study, performed in the specific Mediterranean context,  
578 provides trends of ditch properties evolutions and of their impact on the ditch hydraulic performance,  
579 herbicide retention and biodiversity conservation that may help design maintenance strategies.  
580 However, maintenance design should be site-specific and should consider the local problematics of  
581 agricultural water management, the environmental problematics and the pedoclimatic context.

582

### 583 **Acknowledgments**

584 We would like to cheerfully thank Mr. Cros and Mr. Boulade for kindly letting us perform the  
585 experiments on their ditch. This work was performed in the framework of a research and development  
586 project co-funded by the French Office for Water and Aquatic Bodies (ONEMA) and INRA.

587

### 588 **References**

- 589 Andreassen, H.P., Ims, R.A., Steinset, O.K., 1996. Discontinuous Habitat Corridors: Effects on Male  
590 Root Vole Movements. *J. Appl. Ecol.* 33, 555–560. doi:10.2307/2404984
- 591 Arcement, G.J., Schneider, V.R., 1989. Guide for selecting Manning's roughness coefficients for  
592 natural channels and flood plains, United State Geological Survey. ed, Water-Supply. Denver,  
593 USA.
- 594 Bailly, J.S., Dages, C., Dollinger, J., Lagacherie, P., Voltz, M., 2015a. Protocole de spatialisation et  
595 d'évolution d'états de surface de fossés (No. 3). INRA.
- 596 Bailly, J.S., Vinatier, F., Belaud, G., Combemale, D., 2015b. Vegetation patch effects on flow resistance  
597 at channel scale, in: E-Proceedings of the 36th IAHR World Congress. IAHR, The Hague,  
598 Netherlands, pp. 1–5.
- 599 Boutron, O., Margoum, C., Chovelon, J.-M., Guillemain, C., Gouy, V., 2011. Effect of the submergence,  
600 the bed form geometry, and the speed of the surface water flow on the mitigation of  
601 pesticides in agricultural ditches. *Water Resour. Res.* 47, n/a–n/a.  
602 doi:10.1029/2011WR010378
- 603 Chester, E.T., Robson, B.J., 2011. Drought refuges, spatial scale and recolonisation by invertebrates in  
604 non-perennial streams. *Freshw. Biol.* 56, 2094–2104. doi:10.1111/j.1365-2427.2011.02644.x
- 605 Crabit, A., Colin, F., Bailly, J., Ayroles, H., Garnier, F., 2011. Soft Water Level Sensors for  
606 Characterizing the Hydrological Behaviour of Agricultural Catchments. *Sensors* 11, 4656–  
607 4673. doi:10.3390/s110504656
- 608 Crabit, Colin, F., Moussa, R., 2011. A soft hydrological monitoring approach for comparing runoff on a  
609 network of small poorly gauged catchments. *Hydrol. Process.* 25, 2785–2800.
- 610 Dages, C., Samouëlian, A., Negro, S., Storck, V., Huttel, O., Voltz, M., 2015. Seepage patterns of  
611 Diuron in a ditch bed during a sequence of flood events. *Sci. Total Environ.* 537, 120–128.  
612 doi:10.1016/j.scitotenv.2015.07.130
- 613 Dangles, O., Gessner, M.O., Guerold, F., Chauvet, E., 2004. Impacts of stream acidification on litter  
614 breakdown: implications for assessing ecosystem functioning. *J. Appl. Ecol.* 41, 365–378.

615 Dollinger, J., Dagès, C., Bailly, J.-S., Lagacherie, P., Voltz, M., 2015. Managing ditches for  
616 agroecological engineering of landscape. A review. *Agron. Sustain. Dev.* 35, 999–1020.  
617 doi:10.1007/s13593-015-0301-6

618 Dollinger, J., Dagès, C., Negro, S., Bailly, J.-S., Voltz, M., 2016. Variability of glyphosate and diuron  
619 sorption capacities of ditch beds determined using new indicator-based methods. *Sci. Total*  
620 *Environ.* 573, 716–726. doi:10.1016/j.scitotenv.2016.08.168

621 Herzon, I., Helenius, J., 2008. Agricultural drainage ditches, their biological importance and  
622 functioning. *Biol. Conserv.* 141, 1171–1183. doi:10.1016/j.biocon.2008.03.005

623 Jarvela, J., 2002. Flow resistance of flexible and stiff vegetation: a flume study with natural plants. *J.*  
624 *Hydrol.* 269, 44–54. doi:http://dx.doi.org/10.1016/S0022-1694(02)00193-2

625 Johnson, B.R., Cross, W.F., Wallace, J.B., 2003. Long-term resource limitation reduces insect  
626 detritivore growth in a headwater stream. *J. North Am. Benthol. Soc.* 22, 565–574.  
627 doi:10.2307/1468353

628 Lagacherie, P., Diot, O., Domange, N., Gouy, V., Floure, C., Kao, C., Moussa, R., Robbez-Masson, J.M.,  
629 Szleper, V., 2006. An indicator approach for describing the spatial variability of artificial  
630 stream networks with regard to herbicide pollution in cultivated watersheds. *Ecol. Indic.* 6,  
631 265–279. doi:10.1016/j.ecolind.2005.02.003

632 Lecce, S.A., Pease, P.P., Gares, P.A., Wang, J., 2006. Seasonal controls on sediment delivery in a small  
633 coastal plain watershed, North Carolina, USA. *Geomorphology* 73, 246–260.  
634 doi:10.1016/j.geomorph.2005.05.017

635 Levavasseur, F., 2012. Structure du paysage et fonctionnement hydrologique : application aux  
636 réseaux de fossés en zone viticole méditerranéenne. Montpellier SupAgro, Montpellier,  
637 France.

638 Levavasseur, F., Bailly, J.S., Lagacherie, P., 2016. Are ditch networks optimised for mitigating rill  
639 erosion in cultivated Mediterranean landscapes? A numerical experiment. *Land Use Policy*  
640 50, 441–448. doi:10.1016/j.landusepol.2015.08.033

641 Levavasseur, F., Bailly, J.S., Lagacherie, P., Colin, F., Rabotin, M., 2012. Simulating the effects of  
642 spatial configurations of agricultural ditch drainage networks on surface runoff from  
643 agricultural catchments. *Hydrol. Process.* doi:10.1002/hyp.8422

644 Levavasseur, F., Biarnès, A., Bailly, J.S., Lagacherie, P., 2014. Time-varying impacts of different  
645 management regimes on vegetation cover in agricultural ditches. *Agric. Water Manag.* 140,  
646 14–19. doi:10.1016/j.agwat.2014.03.012

647 Louchart, X., Voltz, M., Andrieux, P., Moussa, R., 2001. Herbicide Transport to Surface Waters at Field  
648 and Watershed Scales in a Mediterranean Vineyard Area. *J. Environ. Qual.* 30, 982–991.

649 Margoum, C., Gouy, V., Laillet, B., Dramais, G., 2003. Rétention des produits phytosanitaires dans les  
650 fossés de connexion parcelle-cours d'eau. *J. Water Sci.* 16, 389–405.

651 Marja, R., Herzon, I., 2012. The importance of drainage ditches for farmland birds in agricultural  
652 landscapes in the Baltic countries: does field type matter? *Ornis Fenn.* 89, 170–181.

653 Meier, K., Kuusemets, V., Luig, J., Mander, Ü., 2005. Riparian buffer zones as elements of ecological  
654 networks: Case study on *Parnassius mnemosyne* distribution in Estonia. *Ecol. Eng.* 24, 531–  
655 537. doi:10.1016/j.ecoleng.2005.01.017

656 Moussa, R., Voltz, M., Andrieux, P., 2002. Effects of the spatial organization of agricultural  
657 management on the hydrological behaviour of a farmed catchment during flood events.  
658 *Hydrol. Process.* 16, 393–412. doi:10.1002/hyp.333

659 Murphy, S.M., Wimp, G.M., Lewis, D., Denno, R.F., 2012. Nutrient Presses and Pulses Differentially  
660 Impact Plants, Herbivores, Detritivores and Their Natural Enemies. *PLoS ONE* 7, e43929.  
661 doi:10.1371/journal.pone.0043929

662 Needelman, Kleinman, P.J.A., Strock, J.S., Allen, A.L., 2007. Improved management of agricultural  
663 drainage ditches for water quality protection: An overview. *J. Soil Water Conserv.* 62, 171–  
664 178.

- 665 Nicholls, C.I., Parrella, M., Altieri, M.A., 2001. The effects of a vegetational corridor on the abundance  
666 and dispersal of insect biodiversity within a northern California organic vineyard. *Landsc.*  
667 *Ecol.* 16, 133–146.
- 668 Reichenberger, S., Bach, M., Skitschak, A., Frede, H.-G., 2007. Mitigation strategies to reduce  
669 pesticide inputs into ground- and surface water and their effectiveness; A review. *Sci. Total*  
670 *Environ.* 384, 1–35. doi:10.1016/j.scitotenv.2007.04.046
- 671 Sarthou, J.P., Ouin, A., Arrignon, F., Barreau, G., Bouyjou, B., 2005. Landscape parameters explain the  
672 distribution and abundance of *Episyrphus balteatus* (Diptera: Syrphidae). *Eur. J. Entomol.*  
673 102, 539–545.
- 674 Schultz, R.C., Collettil, J.P., Isenhardt, T.M., Simpkins, W.W., Mize, C.W., Thompson, M.L., 1995. Design  
675 and placement of a multi-species riparian buffer strip system. *Agrofor. Syst.* 29, 201–226.  
676 doi:10.1007/BF00704869
- 677 Smith, D.R., Pappas, E.A., 2007. Effect of Ditch Dredging on the Fate of Nutrients in Deep Drainage  
678 Ditches of the Midwestern United States. *J. Soil Water Conserv.* 62, 252–261.
- 679 Stehle, S., Elsaesser, D., Gregoire, C., Imfeld, G., Niehaus, E., Passeport, E., Payraudeau, S., Schäfer,  
680 R.B., Tournebize, J., Schulz, R., 2011. Pesticide risk mitigation by vegetated treatment  
681 systems: a meta-analysis. *J. Environ. Qual.* 40, 1068–1080. doi:10.2134/jeq2010.0510
- 682 Stella, J.C., Rodríguez-González, P.M., Dufour, S., Bendix, J., 2013. Riparian vegetation research in  
683 Mediterranean-climate regions: common patterns, ecological processes, and considerations  
684 for management. *Hydrobiologia* 719, 291–315. doi:10.1007/s10750-012-1304-9
- 685 Steward, A.L., von Schiller, D., Tockner, K., Marshall, J.C., Bunn, S.E., 2012. When the river runs dry:  
686 human and ecological values of dry riverbeds. *Front. Ecol. Environ.* 10, 202–209.  
687 doi:10.1890/110136
- 688 Strickler, A., 1923. Contributions to the question of a velocity formula and roughness data for  
689 streams, channels and closed pipelines.
- 690 Tang, X., Zhu, B., Katou, H., 2012. A review of rapid transport of pesticides from sloping farmland to  
691 surface waters: Processes and mitigation strategies. *J. Environ. Sci.* 24, 351–361.  
692 doi:10.1016/S1001-0742(11)60753-5
- 693 Vaughan, R.E., Needelman, B.A., Kleinman, P.J.A., Rabenhorst, M.C., 2008. Morphology and  
694 Characterization of Ditch Soils at an Atlantic Coastal Plain Farm. *Soil Sci. Soc. Am. J.* 72, 660.  
695 doi:10.2136/sssaj2006.0102
- 696 Vinatier, F., Bailly, J.-S., Belaud, G., In Press. From 3D grassy vegetation point cloud to hydraulic  
697 resistance grassy vegetation point cloud to hydraulic resistance: Application to close-range  
698 estimation of Manning coefficients for intermittent open channels. *Ecohydrology*.  
699 doi:10.1002/eco.1885
- 700 Ward, S.A., 1992. Environmental Uncertainty and Polyphagy in Herbivorous Insects. *Oikos* 63, 506–  
701 512. doi:10.2307/3544978
- 702 Wishart, M.J., 2000. The terrestrial invertebrate fauna of a temporary stream in southern Africa. *Afr.*  
703 *Zool.* 35, 193–200. doi:10.1080/15627020.2000.11657090
- 704 Wu, F.C., Hsieh Wen, S., Chou, Y.-J., 1999. Variation of roughness coefficients for unsubmerged and  
705 submerged vegetation. *J. Hydraul. Eng.* 125, 934–942.

706

707

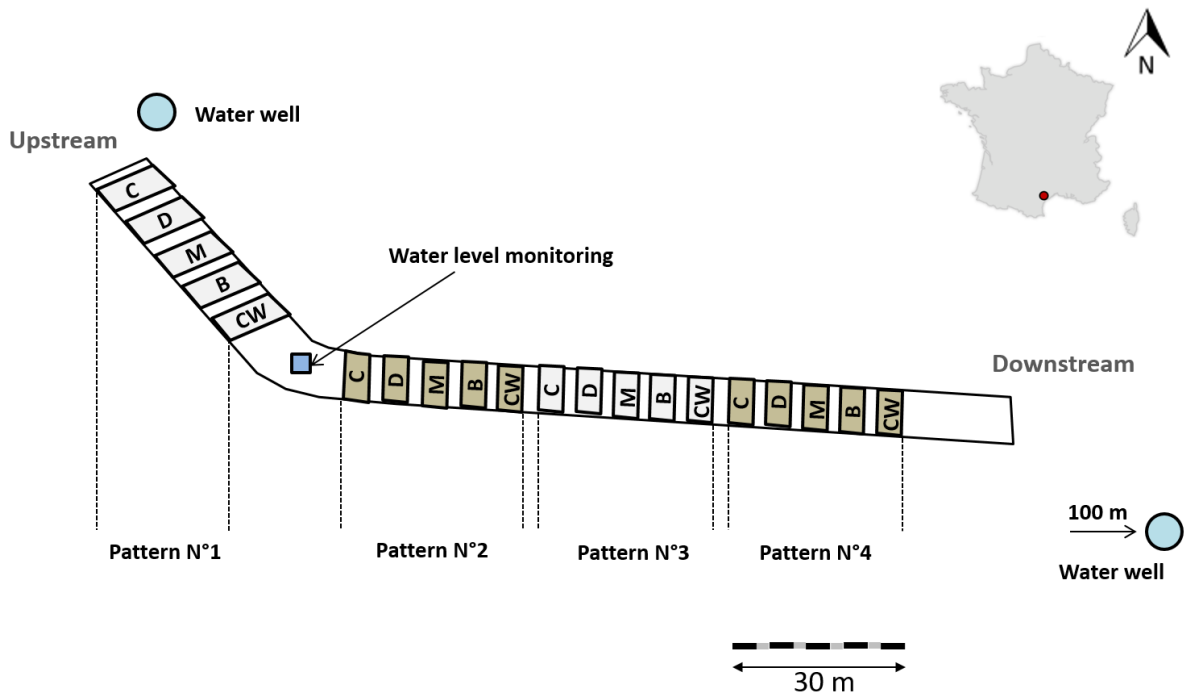
708

709

710

711

712  
713  
714  
715



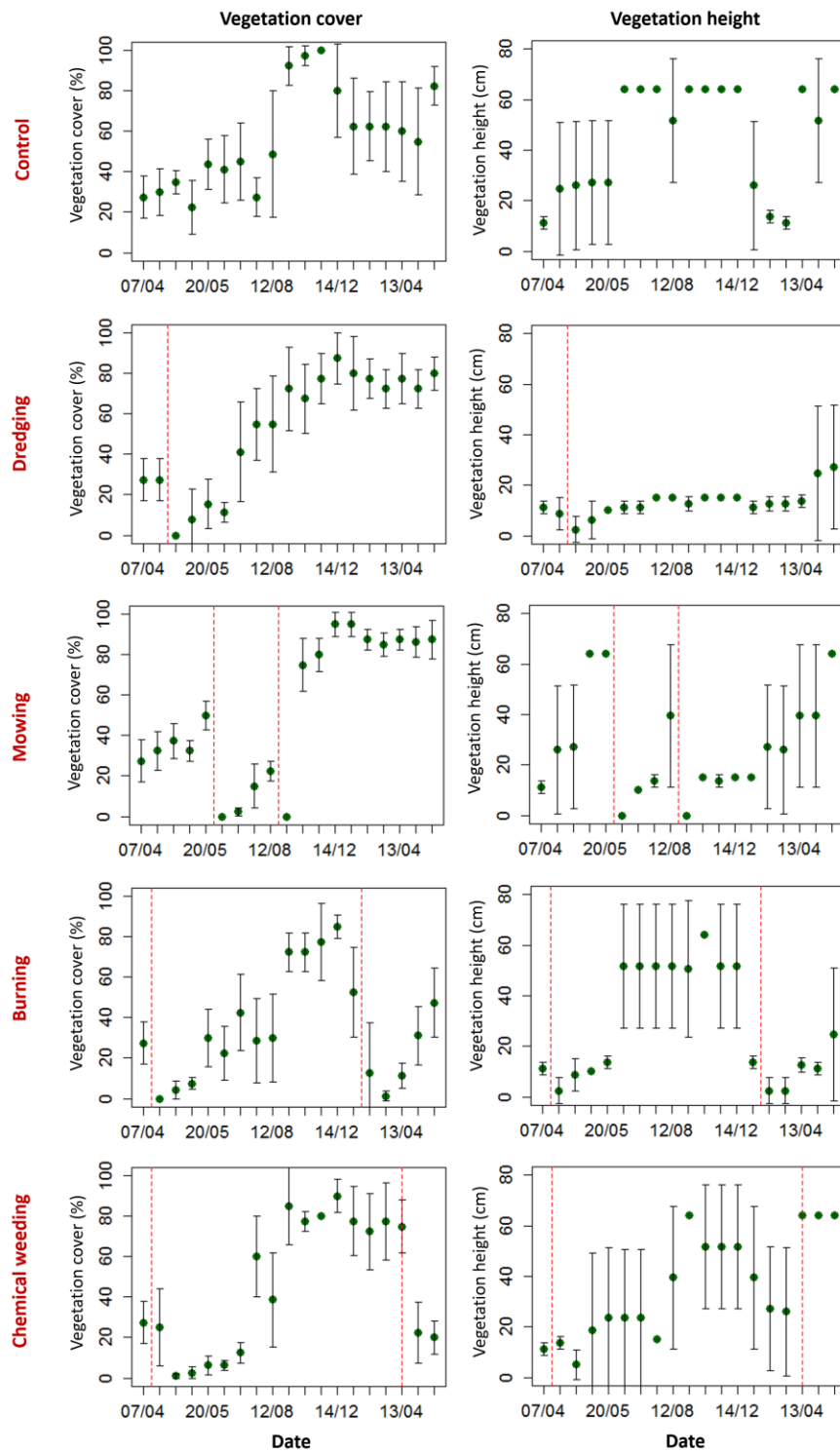
716  
717  
718  
719  
720  
721  
722

**Fig. 1: Experimental design.** For each pattern, the quadrats C, D, M, B, CW were respectively unmanaged (control), dredged, mowed, burned and chemically weeded with frequencies and timing that apply to farmers in the study area. Each pattern is 30 m long, quadrats are 4 m long each and are separated by 2 m long buffer sections.



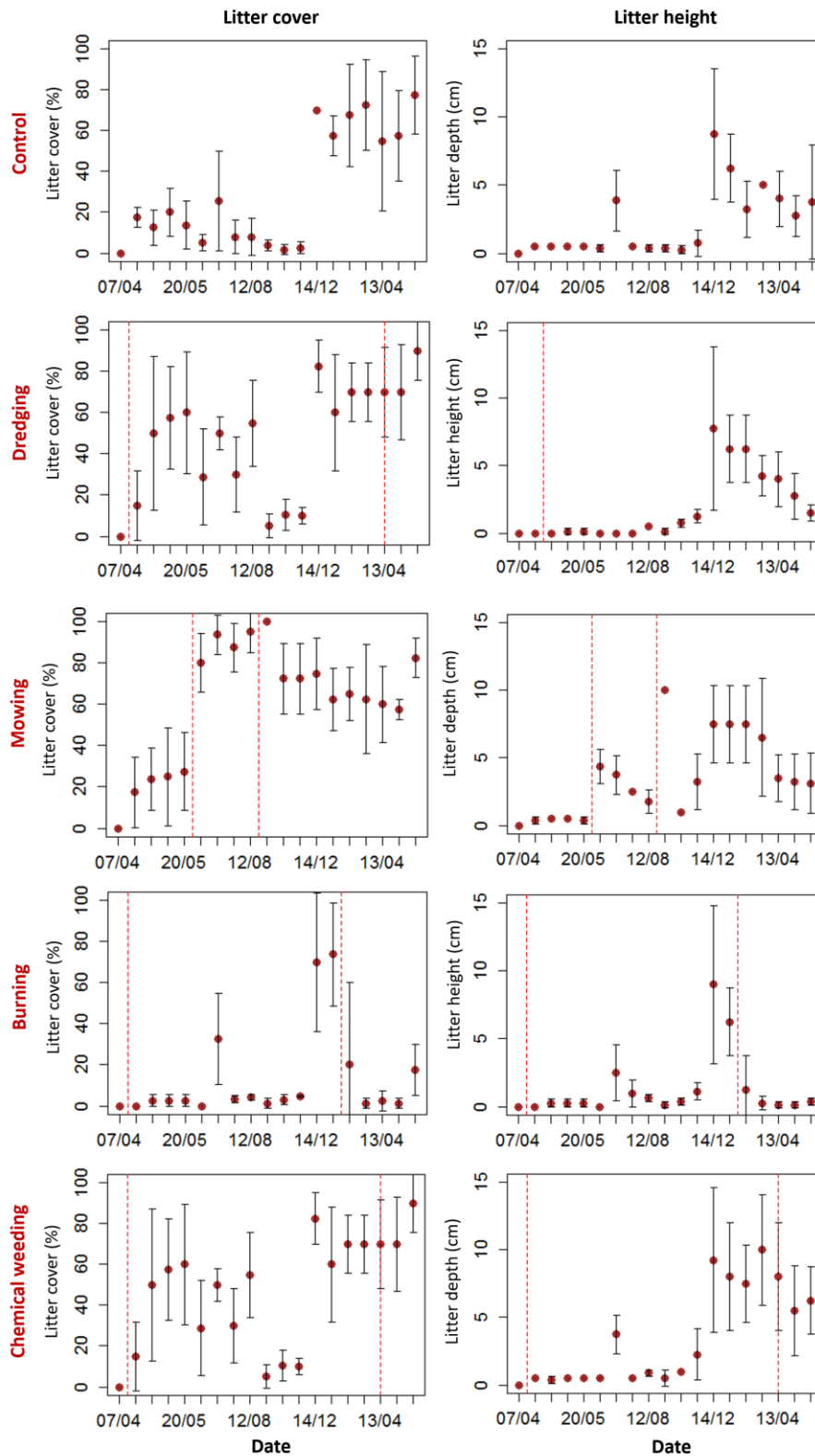
723

724 **Fig. 2: Ditch maintenance.** **A:** burning; **B:** mowing; **C:** chemical weeding and **D:** dredging. During the  
725 burning operation the fire was contained in the 4 m long sections by suffocating the flames with  
726 broom branches. Mowing was done manually using a strimmer. Chemical weeding was performed by  
727 applying glyphosate with a manual sprayer. Dredging consisted in excavating a 15 to 20 cm soil layer  
728 from the ditch bottom and walls.



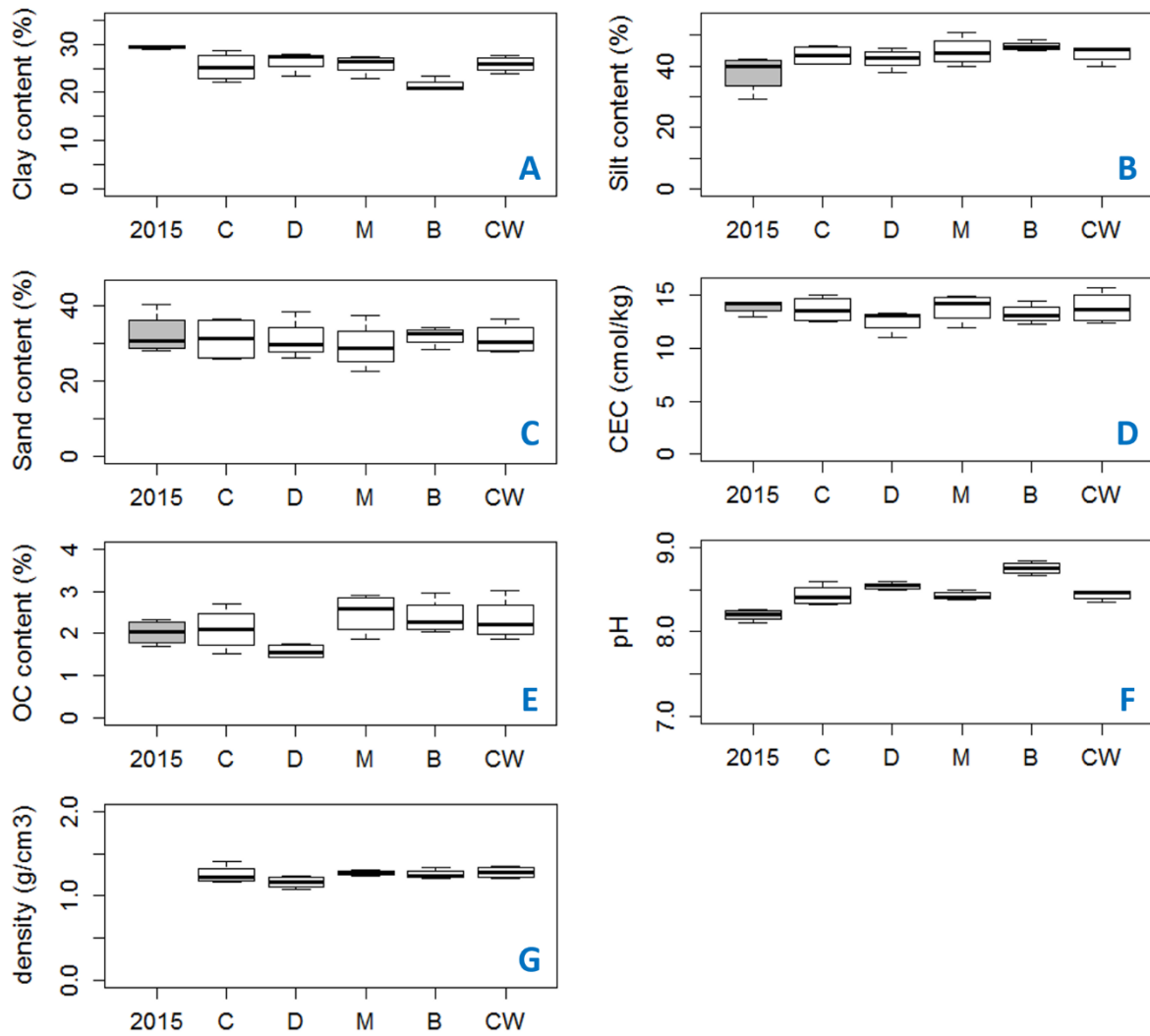
729

730 **Fig. 3: Yearly evolution of vegetation in the ditches.** From top to bottom, the graphs picture the  
 731 evolution of the vegetation cover in the unmanaged, chemically weeded, mowed, dredged and  
 732 burned ditches. The graphs in the left column represent the evolution of the ditch bottom surface area  
 733 covered by vegetation and the graphs on the right the vegetation height. The red dashed lines  
 734 represent the calendar of the maintenance operations. The green dots represent the mean value  
 735 among the 4 replicates of each treatment and the vertical bars represent the standard deviations.



736

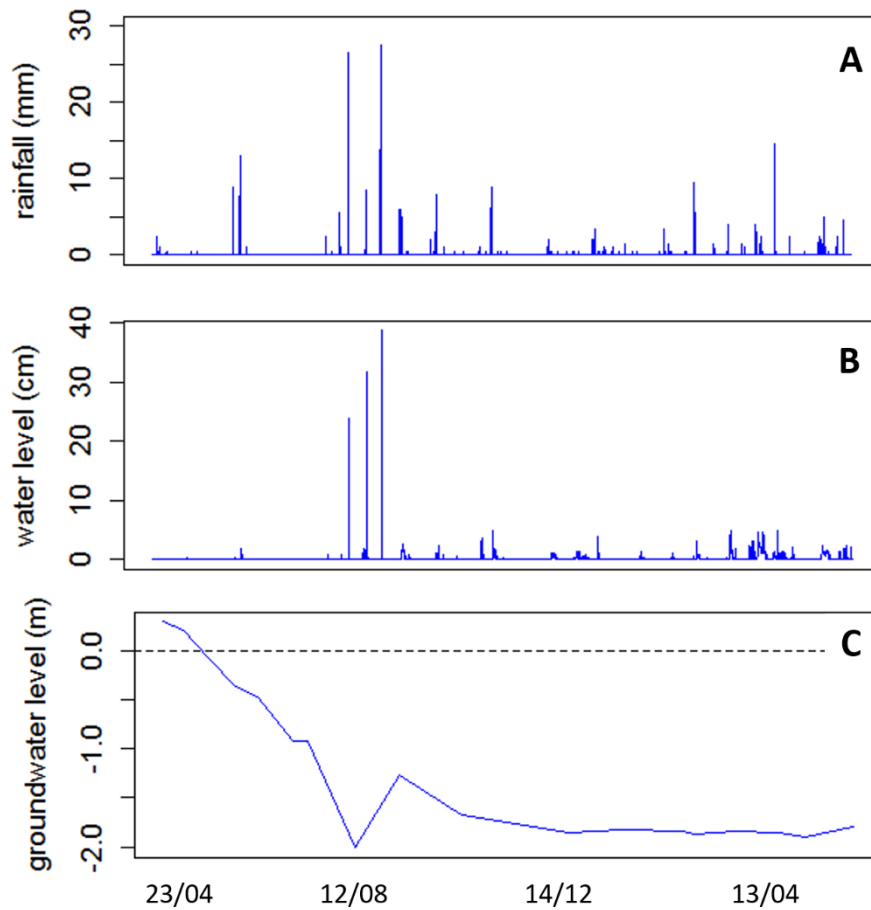
737 **Fig. 4: Yearly evolution of litter in ditches.** From top to bottom, the graphs picture the evolution of  
 738 the vegetation cover in the unmanaged, chemically weeded, mowed, dredged and burned ditches.  
 739 The graphs in the left column represent the evolution of the ditch bottom surface area covered by  
 740 litter, and the graphs on the right represent the litter height. The red dashed lines represent the  
 741 calendar of the maintenance operations. The brown dots represent the mean value among the 4  
 742 replicates of each treatment and the vertical bars represent the standard deviations.



743

744 **Fig. 5: Ditch top soil physicochemical properties. A:** clay content (%), **B:** silt content (%), **C:** sand  
 745 content (%); **D:** cation exchange capacity (cmol kg<sup>-1</sup>), **E:** organic carbon content (%), **F:** pH, **G:** density  
 746 (g cm<sup>-3</sup>). For each soil property, the distribution of the values are given from the left to the right for  
 747 the control quadrats in 2015 (2015), the control quadrats in 2016 (C), the dredged quadrats in 2016  
 748 (D), the mowed quadrats in 2016 (M), the burned quadrat in 2016 (B) and the chemically weeded  
 749 quadrats in 2016 (CW).

750



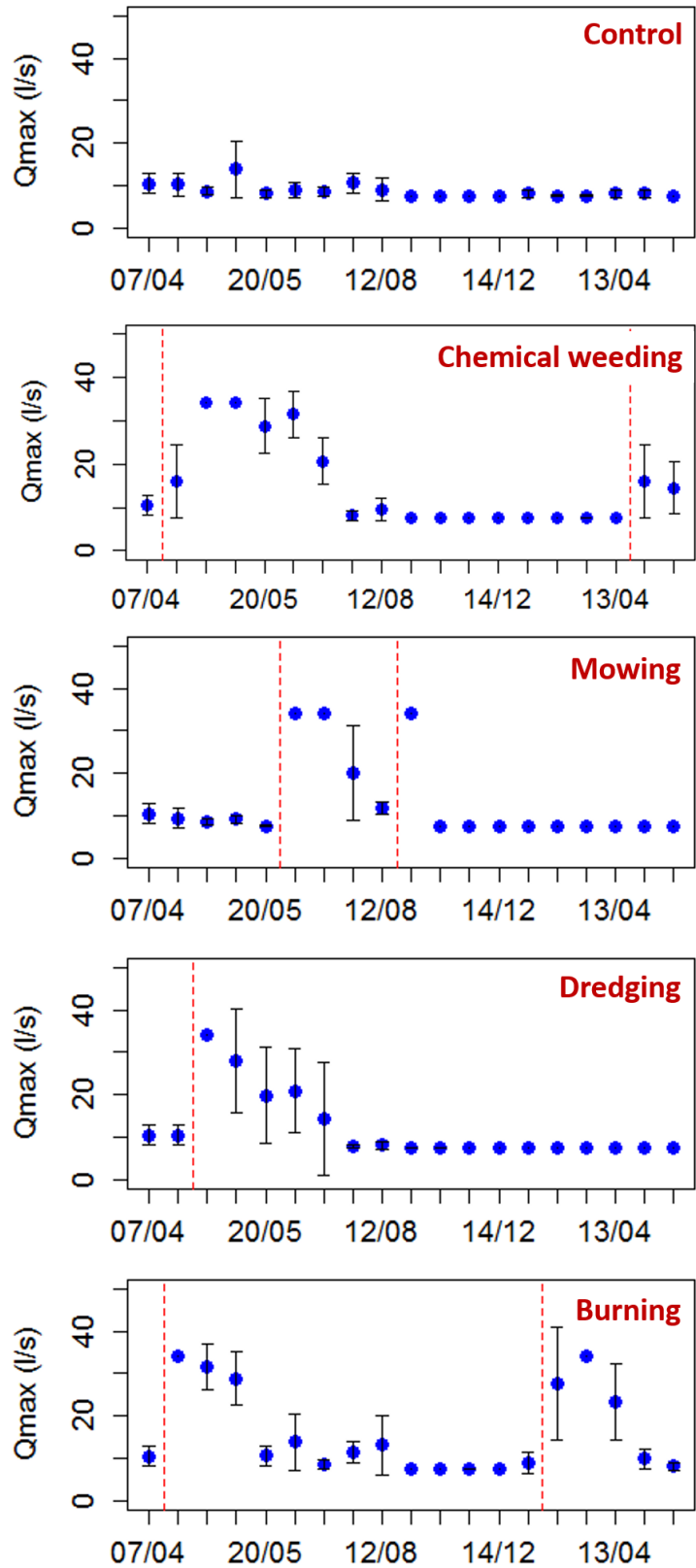
751

752

753

754

**Fig. 6: Hydrology of the study site from April 2015 to May 2016. A: rainfall, B: water level in the ditch, C: groundwater level relative to the ditch bottom. The dashed black line represents the ditch bottom level.**



755

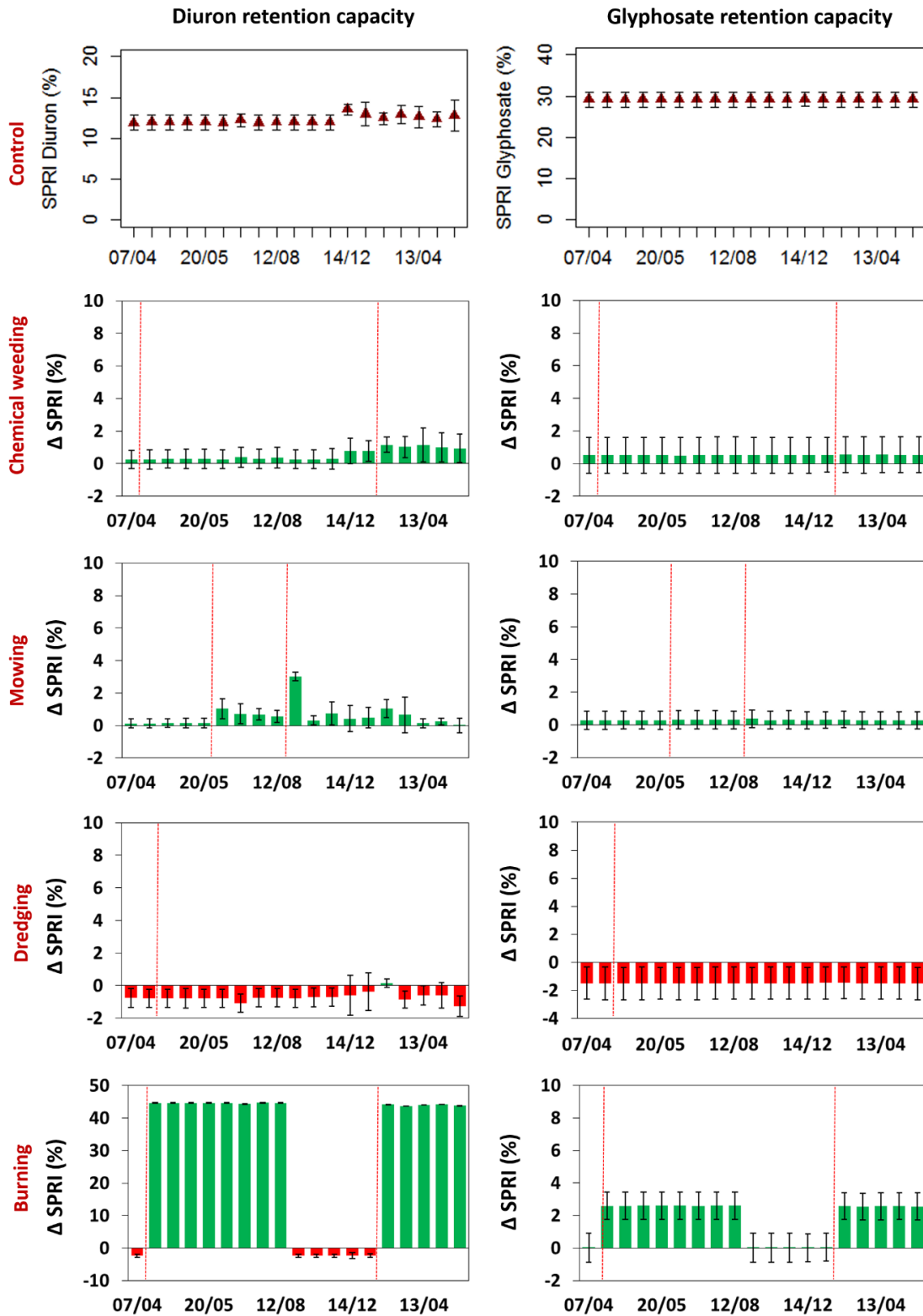
756

757

758

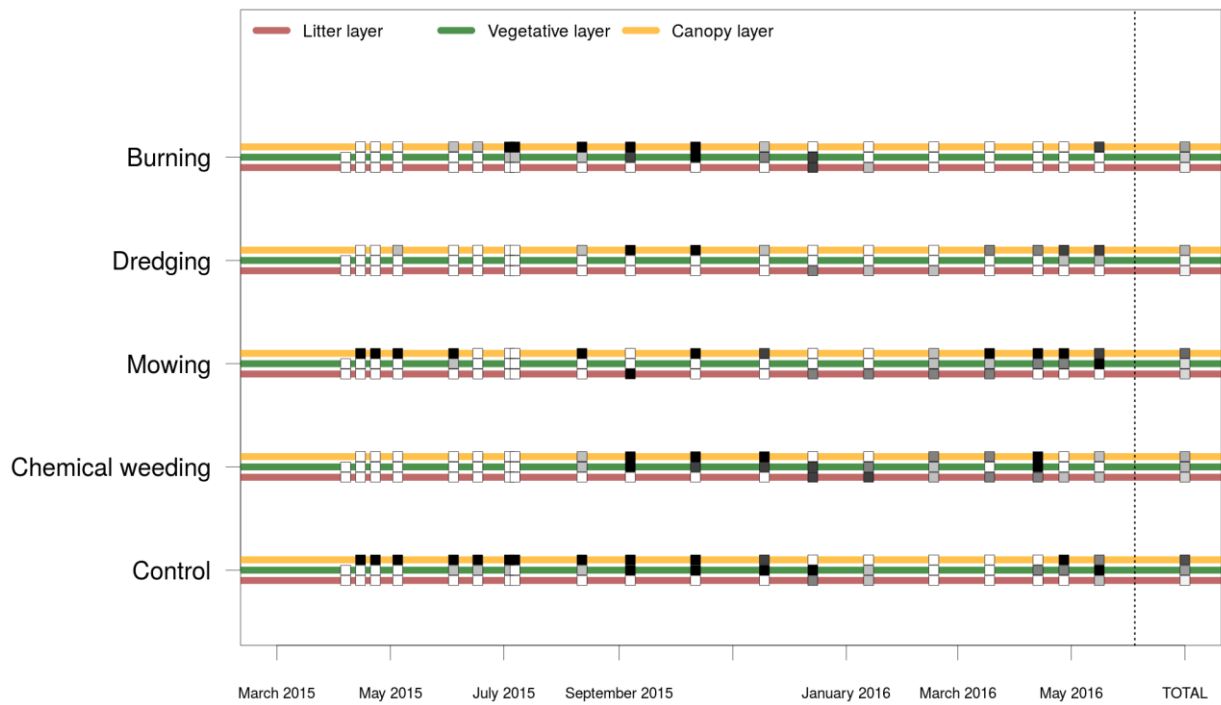
759

**Fig. 7: Ditch hydraulic capacity evolutions.** The red dashed lines represent the calendar of the maintenance operations. The blue dots represent the mean value among the 4 replicates of each treatment and the vertical bars represent the standard deviations.



760



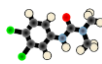

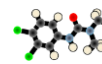
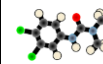
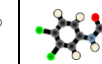






761 **Fig. 8: Herbicide retention capacity (SPRI) evolutions.** The  $\Delta$  SPRI represents the difference between  
 762 the SPRI values of the ditches, which are respectively chemically weeded, mowed, dredged and  
 763 burned relative to the SPRI value of the control ditch at the same dates. The red dashed lines  
 764 represent the calendar of the maintenance operations. The vertical bars represent the standard  
 765 deviations among the 4 replicates of each treatment.



766  
 767  
 768  
 769  
 770  
 771

**Fig. 9: Biodiversity indicator evolution.** Each square is filled with a grey level from 0 (white) to 1 (black) that represents the mean level of biodiversity indicator per layer across the four patterns, except for the last column that represents the mean biodiversity indicator per layer across the four patterns and the 19 dates.

**Table 1: The influence of ditch maintenance strategies on their hydraulic capacity, herbicide retention and ecological functions**

	April	May	June	July	August	September	October	November	December	January	February	March	April	
<b>Key periods during which the hydraulic capacity, herbicide retention and ecological functions should be optimized</b>	 	 												 
<b>Dredging strategy</b>	+	+	+	+									●	●
<b>Mowing strategy</b>	●	●	+	+	Δ	+	+	Δ					●	●
<b>Burning strategy</b>	+	+	Δ	Δ	Δ							+	+	+
	Δ	Δ	Δ	Δ	Δ	●	●	●	●	●	Δ	Δ	Δ	+
<b>Chemical weeding strategy</b>	+	+	+	+										+
						●	●	●					●	Δ

*The blue waves represent the risk of floods and soil erosion, the molecule the periods of high herbicide concentration in runoff and the insect the breeding season in the study area. The months during which each maintenance operations were performed are greyed. The blue crosses represent the periods during which the hydraulic capacity is improved under a given maintenance strategy compared to unmanaged ditches. The red diamonds represent the periods during which the herbicide retention capacity is improved under a given maintenance strategy compared to unmanaged ditches. The green dots represent the periods during which the conditions are favourable for the biodiversity.*