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*Highlights

We propose a classification for monitoring hydrological soil surface characteristics (H-SSC) in vineyards.

This multitemporal classification relies on expert knowledge about possible H-SSC transitions.

As compared to a monotemporal approach, it improved discrimination of H-SSC related to crusting processes.

It also allowed detecting soil management practices such as mechanical and chemical weeding.

1 **Multitemporal analysis of hydrological soil surface characteristics using aerial photos: a case**
2 **study on a Mediterranean vineyard.**

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19 **Abstract**

20

21 Soil surface characteristics (SSC) constitute an important land surface property that drives the
22 partitioning between infiltration and runoff. Therefore, knowledge of SSC is crucial for runoff-
23 forecasting in hydrology. However, the difficulties in measuring spatial variabilities and temporal
24 dynamics of SSC have limited the use of this property in operational hydrology at the catchment
25 extent. Recent progresses have permitted to characterize hydrological SSC classes (H-SSC) with
26 distinct infiltration rates, by implementing monotemporal classifications along with aerial photos.
27 However, when dealing with Mediterranean vineyards, some classes still are difficult to discriminate
28 on the basis of remotely sensed spectral and spatial information only.

29

30 The objective of the current study was to propose a multitemporal classification that integrates
31 a priori information about possible H-SSC evolutions, such as it is possible improving their
32 characterization. H-SSC evolutions could be either natural, depending on rainfall events, or
33 anthropogenic, driven by soil management practices. Knowledge of possible H-SSC evolutions was
34 translated in the form of decision rules. It was applied to a time series of H-SSC class maps derived
35 from a monotemporal classification of monthly aerial photos. As compared to the monotemporal
36 classification, the multitemporal classification had two advantages for the identification of H-SSC
37 classes. First, it allowed improving the discrimination of classes related to crusting processes, with
38 increased performances between 35 and 48% relative. Second, it was able to detect H-SSC temporal
39 evolutions in relation to soil management practices.

40

41 **Keywords:** hydrological soil surface characteristics (H-SSC), Mediterranean vineyards, expert
42 knowledge, H-SSC evolutions, multitemporal classification, aerial photos.

43

44 1. INTRODUCTION

45
46 Soil surface characteristics (SSC) are currently among the best available indicators for soil structural
47 stability and partitioning between infiltration and runoff. Therefore, SSC knowledge gives partial
48 evidence about catchment production function and erosion magnitude, which is essential for
49 hydrological modelling (Auzet et al., 2001; Cerdan et al., 2001; Jetten et al., 1996; Liu et al., 2003).
50 Within farmed Mediterranean catchments, the dominant influence of SSC has already been
51 demonstrated for overland flows (Moussa et al. 2002) and pesticide transport (Lennartz et al., 1997;
52 Louchart et al., 2001). In the context of operational hydrology at the catchment extent, it is therefore
53 necessary monitoring SSC spatiotemporal variabilities in relation to anthropogenic and natural forcing.

54
55 In vineyard fields, the crucial role of SSC on infiltration rates was tested and validated under
56 simulated rainfalls by Léonard and Andrieux (1998). By combining usual SSC attributes, Andrieux et
57 al. (2001) proposed a typology of hydrological SSC (H-SSC) classes, where the classes correspond to
58 distinct infiltration rates for Mediterranean cultivated areas without cracking soils. These usual SSC
59 attributes were related to (i) surface crusting such as structural and sedimentary crust (Boiffin and
60 Monier, 1986), (ii) stoniness (Poesen et al., 1990), (iii) micro-topography such as soil roughness which
61 depends upon soil treatment (Lelong et al., 1993), and (iv) soil cover such as mulching, organic litter
62 density and vegetation cover (Dunne and Dietrich, 1980).

63
64 The spatial heterogeneity of H-SSC was assessed in Mediterranean vineyards by Corbane et
65 al. (2008a) who showed that H-SSC depicted considerable variability between rows and inter-rows.
66 This was ascribed to the coupling effect between local topography, vegetation row structure, rainfall /
67 runoff characteristics and soil management practices. This strong spatial variability, to be taken into
68 account during field surveys of H-SSC, makes the latter labour intensive and costly. Thus, H-SSC
69 monitoring requires alternative methods that compromise both a fine spatial resolution to capture
70 spatial heterogeneities and the catchment extent to address operational hydrology.

72 Remote sensing is the most promising technique to monitor H-SSC in a spatially distributed
73 manner, where satellite or aerial imagery can collect spatial and temporal information at the catchment
74 extent with fine spatial resolution. Remote sensing techniques were successfully used for the retrieval
75 of surface roughness (Baghdadi et al., 2002), humidity (Wang et al., 1997) and soil organic matter
76 (Wiegand et al., 1992), especially under specific conditions such as bare soil or sparse vegetation.
77 Later, relationships between reflectance and surface crusting (Goldshleger et al., 2002; Ben-Dor et al.,
78 2003; 2004; Goldshleger et al., 2004) or infiltration rates (Goldshleger et al., 2001; 2002) were
79 highlighted for bare soil conditions only. Overall, most studies have focused on single SSC attributes.
80 However, infiltration / runoff partitioning are conditioned by a combination of several SSC attributes
81 (Descroix et al., 2001; 2002), as taken into account by the H-SSC typology of Andrieux et al. (2001).

82
83 Among the remote sensing studies that addressed hydrological SSC (H-SSC), Wassenaar et
84 al. (2005) investigated the potential of multiangular information at very high spatial resolution over
85 Mediterranean vineyards. They showed several H-SSC could be distinguished (e.g., crusted mineral
86 soil surfaces or half to fully covered surfaces with litter and / or weed), although some of them
87 remained difficult to discriminate due to the influences of illumination and viewing conditions. Later,
88 Corbane et al. (2008b) demonstrated that several classes could be distinguished on the basis of spectral
89 and spatial information collected with aerial photographs. The method proposed by Corbane et al.
90 (2008b) relied on an object-oriented multiscale classification that links H-SSC observed in the field to
91 image-objects identified with an image segmentation process. The use of spatial information partially
92 allowed overcoming inconsistent discriminations of H-SSC induced by similar spectral behaviours.
93 Overall, several H-SSC classes still are difficult to separate with the monotemporal methods discussed
94 above, where the monotemporal dimension refers to separately analysing each image independently
95 from any chronological order of acquisition.

96
97 Given the current limitations of the H-SSC monotemporal classifications presented above, two
98 main improvements can be foreseen. The first one relies on using richer spectral information, since
99 spectroscopy (Bartholomeus et al., 2007; 2011) and hyperspectral imagery (Ben-Dor et al., 2002;

100 Lagacherie et al., 2008; Weber et al., 2008) have provided promising results for characterizing
101 physicochemical properties of soil surface, including crusts (de Jong et al., 2011). A second
102 improvement relies on incorporating a priori information about H-SSC evolution, where using aerial
103 cameras with few spectral bands is attractive for operational hydrology at the watershed extent. The
104 current paper investigates this second way of improvement.

105
106 A priori information about the temporal evolution of land surface characteristics has been
107 successfully used for classification purposes. It has taken form of expert knowledge or ancillary
108 databases, where the associated uncertainties required using probabilistic approaches. Matrices of
109 probable state transition were used by Janssen and Middelkoop (1992) who designed a knowledge-
110 based classifier that integrated crop information for current and past years. Largouet and Cordier
111 (2001) developed a probabilistic classification that relied upon (i) time dependencies of classes
112 derived from a satellite image sequence, (ii) knowledge about the field locations and (iii) expertise on
113 possible land-cover evolutions. Raclot et al. (2005) proposed a per-field land-cover classification,
114 where a rule-based decision system incorporated yearly satellite imagery acquired during the growing
115 period along with ancillary data such as cropping history (inter-annual crop rotations), context
116 (altitude, soil type) and structure (field sizes and shapes). Mota et al. (2007) integrated temporal class
117 dependencies by means of a transition diagram based on fuzzy possibility values, in order to classify
118 land use and land cover. Lucas et al. (2007) implemented temporal decision rules based on fuzzy logic
119 for mapping semi-natural habitats and agricultural land cover during an annual cycle. Overall, these
120 multitemporal methods allowed improving performances as compared to monotemporal methods,
121 although they depended upon complex modelling for handling temporal relationships.

122
123 In order to provide an efficient remote sensing monitoring of H-SSC for the benefit of
124 operational hydrology at the catchment extent, the current study aims to propose and assess a
125 multitemporal image classification that incorporates a priori information about H-SSC temporal
126 evolutions. A priori information consisted in expert knowledge about possible evolutions of H-SSC
127 classes, in relation to environmental conditions (i.e., rainfall regime) and soil management practices.

128 This expert knowledge was found in field and laboratory experiments that focused on the monitoring
1 of H-SSC under natural or simulated rainfalls, as reviewed by Pare et al. (2011). Focusing on
2 129 of H-SSC under natural or simulated rainfalls, as reviewed by Pare et al. (2011). Focusing on
3
4 130 Mediterranean vineyards, the proposed method is applied to a time series of H-SSC class maps, where
5
6 131 the latter are beforehand derived from a monotemporal classification of monthly aerial photos. The
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8 132 benefit of incorporating a priori information about H-SSC temporal evolution is evaluated by
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10 133 comparing performances of multitemporal and monotemporal classifications.
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15 135 **2. STUDY BACKGROUND: TYPOLOGY OF HYDROLOGICAL SSC (H-SSC)**

17 136

19 137 Among the various definitions suggested in the literature for characterizing SSC, we focused in the
20 138 current study on the typology of hydrological SSC (H-SSC) proposed by Andrieux et al. (2001). This
21 139 typology is devoted to Mediterranean vineyards. It combines usual SSC attributes. It was established
22 140 according to field measurements of infiltration rates from Léonard and Andrieux (1998).
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30 142 The SSC attributes to be selected because of their significant influence on infiltration as
31 143 observed within Mediterranean vineyards are soil micro-topography, surface crusting (structural and
32 144 sedimentary crust), soil cover (grass, mulching and organic litter), and stoniness. The typology
33 145 disregards some usual SSC attributes (i.e., soil moisture, soil clay content and soil organic matter);
34 146 since Leonard and Andrieux (1998) demonstrated their influences are of second order for
35 147 Mediterranean vineyards. The typology also disregards cracks that are not systematic in Mediterranean
36 148 vineyards, as in the case of the study area we considered here (Section 4.1).
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47 150 For the selected SSC attributes, the typology relies on the following distinctions. Soil micro-
48 151 topography of tilled surfaces is determined by considering four classes of soil clod size: (i) lower than
49 152 1 cm, (ii) from 1 to 5 cm, (iii) from 5 to 10 cm, and (iv) larger than 10 cm. A distinction is also
50 153 conducted between (i) clods of a recently tilled soils that can be clearly individualized, (ii) clods with a
51 154 slightly formed thin structural crust and (iii) tilled soil surfaces slightly sealed by raindrop impacts.
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155 Two types of surface crusts are distinguished, structural and sedimentary crust. Soil cover is
156 characterized using vegetation and litter fraction cover, with a thresholding of 50%.

157
158 Hydrological SSC (H-SSC) classes are finally obtained by applying association rules that
159 combine the SSC attributes discussed below. Table 1 displays the involved SSC attributes, the
160 association rules, and the resulting H-SSC classes with their distinct infiltration rates. As compared to
161 the original version of the typology proposed by Andrieux et al. (2001), we removed the class related
162 to stoniness since the latter was a minor attribute within the study area (Section 4.1).

[Table 1 about here]

3. A NEW KNOWLEDGE-BASED MULTITEMPORAL CLASSIFICATION OF H-SSC

167
168 We propose here a new multitemporal classification that aims to provide H-SSC maps as accurate as
169 possible. For this, the proposed method analyses pairs of consecutive H-SSC class maps within a time
170 series by integrating expert knowledge about possible H-SSC evolutions in accordance to ancillary
171 information about daily rainfall. This multitemporal classification is designed for Mediterranean
172 vineyards where H-SSC evolutions are driven by two types of soil management practices (mechanical
173 and chemical weeding) combined with rainfall forcing. Then, the proposed method must be able to
174 detect these management practices that are supposed to impact significantly H-SSC evolutions.
175 Besides, the time delay between two consecutive maps within the time series must hold with the H-
176 SSC dynamics, which is presumably close to the monthly timescale.

177
178 The proposed multitemporal classification consists of correcting H-SSC class maps,
179 previously derived from any monotemporal classification, where maps are pixel or image-object
180 based. The flowchart of the multitemporal classification is displayed in Figure 1. The first step is the
181 design of the rule-based system that defines the possible H-SSC successors in accordance with expert
182 knowledge about H-SSC evolutions (Section 3.1). The second step is the comparative analysis of the

183 H-SSC successors against the output of the monotemporal classification (Section 3.2). This second
184 step is twofold. By considering the field scale that corresponds to soil management practices
185 (Section 3.3.1); the dominant H-SSC evolution is first identified. The monotemporal classification is
186 next corrected when it is inconsistent with the dominant evolution at the field scale (Section 3.2.2).

[Figure 1 about here]

190 In addition to its capability in generating time series of reliable H-SSC maps, the method we
191 propose here also detects evolution drivers between natural and anthropogenic, including an
192 identification of soil management practices between mechanical and chemical weeding. We detail
193 hereafter each step of the proposed multitemporal classification.

195 3.1. Expert knowledge on possible H-SSC evolutions

196
197 The underlying concept is derived from recurrent in-situ observations of similar evolutions for various
198 surface crusts. Figure 2 shows an example of temporal H-SSC class successions when restricting to
199 natural evolutions. According to the H-SSC typology we considered in the current study (Section 2), a
200 recently tilled soil with large clods (class T), evolves progressively into a previously tilled soil with a
201 slightly sealed surface (class TC), then into a structural crust (class STC), before reaching the state of
202 sedimentary crust (class SDC). This evolution is conditioned by rainfall amounts between two
203 successive dates (time t_{i-1} and time t_i).

[Figure 2 about here]

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205
206
207 Additionally, farmers' soil management practices can occur and modify natural evolutions.
208 Thus, a mechanical weeding / tillage operation just before t_3 or t_4 on Figure 2 would result in H-SSC
209 class T. Knowledge of temporal evolution of H-SSC may be found in field studies about the
210 monitoring of H-SSC under natural or simulated rainfall (Andrieux et al., 2001; Marques, 2004;

211 Corbane, 2006; Pare et al., 2011). From this knowledge, H-SSC evolution can be derived for a given
1 surface, to predict the set of possible successors $PS(t_i)$ at time t_i according to:

- 212
- 213 • the antecedent H-SSC class $C(t_{i-1})$ at time t_{i-1} , as obtained from the previous iteration that
214 processed the preceding pair of consecutive H-SSC class maps within the time series (Figure 1),
- 215 • the rainfall amount P_i between time t_{i-1} and time t_i , as obtained from ancillary rainfall data such as
216 those provided by usual and easy-to-access meteorological databases, and
- 217 • the soil management practices between time t_{i-1} and time t_i , which has to be detected by the
218 method we proposed here.

219 We discuss hereafter the distinction between natural and anthropogenic evolution rules.

220

221 3.1.1. Natural evolution rules

222

223 The knowledge-based rules are compiled in Table 2 in the case of a natural evolution. This table
224 presents the set of possible natural successors **S_{nat}** related to each combination of antecedent H-SSC
225 class $C(t_{i-1})$ and rainfall amount P_i . The natural successors for T, TC, STC and SDC are established
226 according to the evolution scenario for the vineyard soil structure displayed in Figure 2, provided the
227 initial conditions resulted from tillage (class T). These natural successors correspond to different
228 stages in relation to reconsolidation by raindrop impact and redistribution of soil particles by splash
229 and flow (Robinson and Phillips, 2001).

230

231 [Table 2 about here]

232

233 Precipitations on STC can induce grass growing, and thus the evolving of STC into GC.
234 Although this evolution is also possible for SDC, it has not been observed on the field and it is
235 therefore disregarded. LC class can evolve into STC or SDC since heavy precipitations can induce
236 litter removal (leach effect) and upslope to downslope transport. The threshold values on rainfall
237 amount are setup according to Andrieux et al. (2001) and Léonard and Andrieux (1998).

239 3.1.2. Anthropogenic evolution rules

240

241 Once conducted, a soil management practice induces specific anthropogenic evolutions that must be
242 considered. A mechanical weeding induces all H-SSC classes evolve into class T, whereas a chemical
243 weeding is usually applied on class GC and can result either in STC or LC, since it induces grass cover
244 death. Table 3 summarizes the possible successors following a soil management practice.

245

246 [Table 3 about here]

247

248 As the soil management practice can occur at any time between image acquisitions at time t_{i-1}
249 and t_i , a natural evolution can also take place. In accordance to usual soil management practices for
250 Mediterranean vineyards, it is reasonable assuming one practice only can occur within one month, as
251 shown later in Section 4.4. Therefore, any set of possible anthropogenic successors to be considered in
252 the evolution rules combines (i) possible successors resulting from an anthropogenic evolution
253 (Table 3) and (ii) possible successors resulting from a natural evolution (Table 2).

254

255 An example of final set of possible anthropogenic successors **Sant** induced by a soil
256 management practice is represented in Table 4 for antecedent H-SSC classes of structural crust (STC)
257 and sedimentary crust (SDC). For the STC instance, a mechanical weeding on STC can result in T, TC
258 or STC according to rainfall amount. Similarly, STC can evolve into GC and then, following a
259 chemical weeding, evolve into LC. In its turn, LC evolves into STC or SDC according to rainfall
260 amount (leach effect). For the SDC instance, the chemical weeding is not considered since the change
261 of SDC into GC has not been observed in the field (see natural evolutions in Section 3.1.1).

262

263 [Table 4 about here]

264

265 Given the number of possible successors for a unique antecedent H-SSC class, expert
266 knowledge is finally used to define the most probable successor, in accordance with field observations

267 (Leonard and Andrieux, 1998, Andrieux et al., 2001, Corbane et al., 2008a). For instance, based on the
1
2 268 example given in table 4, following a mechanical weeding and rainfall amount of 30 mm, the most
3
4 269 probable successor for STC is T.
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6 270

7 271 **3.2 Rule-based decision system for incorporating expert knowledge**

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11 273 3.2.1. Detection of dominant evolution process at the field extent

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13 275 The evolution rules outlined in the previous section are applied on each H-SSC class $C(t_{i-1})$ at time t_{i-1} ,
14
15 276 to define the set $PS(t_i)$ of possible H-SSC successors at time t_i , where the possible successors are
16
17 277 natural (Snat in Table 2) or anthropogenic (Sant in Table 4). Next, a comparative analysis is conducted
18
19 278 between the set of possible successors $PS(t_i)$ and the class $C_{mono}(t_i)$ obtained from the monotemporal
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21 279 classification. The comparative analysis consists of checking the presence of $C_{mono}(t_i)$ within the set
22
23 280 of possible successors $PS(t_i)$, to next identify an evolution scenario among six possible cases of
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25 281 evolutions: natural evolution, mechanical weeding, chemical weeding, combined natural evolution and
26
27 282 mechanical weeding, combined natural evolution and chemical weeding, inconsistency (Table 5).
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36 284 [Table 5 about here]

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38 286 The occurrences of the six cases are counted at the field extent. For any field, three surface
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40 287 percentages are calculated, in relation to the H-SSC classes that are the most likely to be observed:

- 41 288 • percentage of Sant-MW as the total surface belonging to cases 2 or 4 (mechanical weeding)
42
43 289 divided by the field surface;
- 44 290 • percentage of Sant-CW as the total surface belonging to cases 3 or 5 (chemical weeding) divided
45
46 291 by the field surface;
- 47 292 • percentage of Snat as the total surface belonging to cases 1 or 4 or 5 (natural evolution) divided by
48
49 293 the field surface.

294 The highest percentage value (%max) indicates the dominant evolution at the field extent. However, if
1
2 295 %max is lower than a threshold value, i.e., 70%, the system interrupts and indicates an inconsistency.
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4 296 Finally, the identification of the dominant evolution permits the detection of the soil management
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6 297 practice among mechanical and chemical weeding, when occurring.
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10 299 3.2.2. Correction of H-SSC class

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14
15 301 The final stage consists in replacing $C_{mono}(t_i)$ by one element within the set of possible successors
16
17 302 $PS(t_i)$, when $C_{mono}(t_i)$ is inconsistent with the dominant evolution process at the field extent. In this
18
19 303 case $C_{mono}(t_i)$ is replaced by the most probable H-SSC class within $PS(t_i)$, as identified from expert
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21 304 knowledge (Section 3.1.2) and given the dominant evolution detected at the field extent. Thus, the
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23 305 rule-based decision system assigns a unique H-SSC class to each pixel or image-object.
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27 28 29 307 **4. CASE STUDY AND IMPLEMENTATION**

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32
33 309 This section reports all the materials involved in the implementation and assessment of the proposed
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35 310 multitemporal classification. We present the study area, the in-situ observations of H-SSC classes to
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37 311 be used for validation, the time series of H-SSC class maps obtained from a monotemporal
38
39 312 classification of aerial photos, as well as the dataset of rainfall and soil management practices. Finally
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41 313 are presented the implementation and the assessment of the multitemporal classification.
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44 314

45 46 315 **4.1. Study Area**

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51 317 The experiment was carried out within a vineyard site at Puisserguier (43°22'N–3°2'E), located in
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53 318 Languedoc-Roussillon which is a Southern France region of wine production. The climate is
54
55 319 Mediterranean sub humid, with a long dry season. The annual rainfall over the last 20 years is about
56
57 320 650 mm. High intensity storms are common in summer. The soil is fairly homogeneous with a sandy
58
59 321 loam texture and a dominant brownish yellow colour overlaying sandy clayey molasses. It is neither
60
61

322 stony nor cracking. During the experiment, the cropping system included bilateral wire trained Syrah
1
2 323 vine stocks covering an area of 8000 m². Spacing between and along rows were 2.5 and 1.0 m.
3

4 324
5
6 325 This experimental site concentrated the main soil management practices for Mediterranean
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8 326 vineyards (Figure 3): bare soil controlled by chemical weeding (Field 1, 2000 m²), natural grassing
9
10 327 controlled by chemical weeding (Field 2, 2100 m²), natural grassing controlled by mechanical weeding
11
12 328 (Field 3, 2100 m²), and sowed grass controlled by mow (Field 4, 1800 m²). Among the three different
13
14 329 soil management practiced that were encountered on this site (i.e., chemical weeding, mechanical
15
16 330 weeding, mow), chemical and mechanical weeding only had a direct impact on H-SSC evolution.
17
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21
22 332 [Figure 3 about here]
23

24 333 25 26 334 **4.2. Ground-truthing of H-SSC classes for classification training and validation** 27

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29
30 336 A set of ground truth data was acquired on each date included in the time series of H-SSC class maps,
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32 337 where each date corresponded to an acquisition of remote sensing data (Section 4.3.1). The ground
33
34 338 truth data were collected according to a sampling strategy which accounted for the geometrical
35
36 339 features of the study site (Corbane et al., 2008a; b). Each of the four fields was sampled by setting
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38 340 around 25 transects with 1.25 m lengths. Each transects included 25 visual observations of SSC
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40 341 attributes with a 5 cm step, and was assigned to an H-SSC class according to (i) the fraction cover of
41
42 342 each SSC attribute observed within the transect and (ii) the association rules presented in Table 1.
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48 344 The resulting data set included, for each day of remote sensing data acquisition, about 100
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50 345 transects equally distributed over the four fields, where each transect corresponded to a unique H-SSC
51
52 346 class. Each daily set of about 100 transects with 1 m² sizes provided a ground truth database that
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54 347 covered between 1 and 2% of the whole study area. This set of ground truth data was randomly split in
55
56 348 two equal parts devoted to training classification and to assessing classification accuracy.
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350 **4.3. H-SSC maps derived from a monotemporal classification of aerial photos**

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4 352 4.3.1. Airborne images

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9 354 A series of airborne images was acquired around solar noon using a remotely controlled Unmanned

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11 355 Airborne Vehicle (UAV) called Pixy© (Asseline et al., 1999). The images were collected on five days

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13 356 in 2004 that corresponded to dry soil conditions (January 04, March 27, May 18, June 15 and July 23).

14
15 357 The monthly frequency of photo collection was supposed to capture the temporal dynamics of H-SSC.

16
17 358 The UAV flew at an altitude of 150 m, yielding a 0.10 m spatial resolution. The digital camera was a

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19 359 Minolta DiMAGE 7Hi, featuring a 2/3 in. type CCD sensor with five megapixels. The airborne nadir

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21 360 viewing images were collected using filters centred on 450 (blue), 550 (green) and 650 (red) nm.

22
23 361 Reflectance over these three filters were supposed to provide sufficient information for the mapping of

24
25 362 H-SSC classes (Corbane et al., 2008b), whereas using an aerial camera with few spectral bands was

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27 363 attractive for operational hydrology at the watershed extent.

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32
33 365 Performing H-SSC classification at several dates required normalizing the images collected at

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35 366 different dates. The pre-processing of the raw airborne images included geometric and radiometric

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37 367 corrections, and was completed by spatial and radiometric filtering (Corbane et al. 2008b). Geometric

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39 368 corrections aimed to remove distortions from the camera lens, the camera tilt and the topography

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41 369 effects. Radiometric corrections were twofold. Date-to-date changes in sun illumination were

42
43 370 corrected using the method from Richter and Schlaepfer (2002). Date-to-date changes in instrumental

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45 371 response were corrected using daily linear regressions based on invariants. Finally, vine canopy and

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47 372 shadow were removed using a radiometric thresholding on red reflectance (Wassenaar et al., 2005).

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53 374 4.3.2. Monotemporal classification method

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58 376 When selecting the monotemporal classification to be used for deriving time series of H-SSC class

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60 377 maps from aerial photos, two approaches devoted to hydrological SSC could be foreseen, as listed in

378 the introduction. We selected the method proposed by Corbane et al. (2008b). First, it allowed a better
1
2 379 discrimination of some H-SSC classes as compared to that of Wassenaar et al. (2005). Second, it was
3
4 380 already tested on the considered study area. We give here an overview of the monotemporal
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6 381 classification. Method rationales, implementations and performance analysis are discussed in Corbane
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8 382 et al. (2008b), who also addressed the relevance of the underlying assumptions.

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13 384 The monotemporal classification proposed by Corbane et al. (2008b) assumes SSC attributes
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15 385 are more easily identified from remote sensing images than H-SSC classes, because of greater
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17 386 homogeneities. This object-oriented classification is based on a multiscale segmentation that involves
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19 387 two nested spatial scales (Figure 4): a fine scale to isolate SSC attributes, and a coarse scale to identify
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21 388 each H-SSC class that is a combination of several SSC attributes. The multiscale segmentation
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23 389 spectrally outlines homogeneous image-objects at the two spatial scales, and a two scale classification
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25 390 assigns image-objects to SSC attributes at the fine scale and to H-SSC classes at the coarse scale.

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31 392 [Figure 4 about here]
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35 394 SSC attributes are assigned at the fine spatial scale by using a nearest neighbour classifier in
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37 395 an object-oriented framework along with preselected training sets, which relies on both spectral and
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39 396 spatial behaviours. Assigning objects at the coarser scale to H-SSC classes relies on (i) the image-
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41 397 objects identified from the segmentation at both scales, and (ii) the spatial relations between the two
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43 398 scales within the image-objects' hierarchy. The spatial relations are based on a set of decision rules
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45 399 that follow those designed for characterizing ground-based estimates of H-SSC classes (Table 1).

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51 401 4.3.3. Time series of H-SSC class maps

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55 403 The time series of H-SSC class maps was obtained by implementing the monotemporal classification
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57 404 described in Section 4.3.2 over the data set of aerial photos described in Section 4.3.1. The
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59 405 classification training was conducted using half of the ground-truth observations described in Section

406 4.2. A portion of the obtained time series is displayed in Figure 5. Significant heterogeneities were
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2 407 observed, in time between the five dates and in space between the four fields.

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6 409 [Figure 5 about here]

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11 411 Accuracy assessment was performed by Corbane et al. (2008b) using the other half of the
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13 412 ground-truth observations along with confusion matrices. The best classification accuracy was
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15 413 obtained on January image (Overall accuracy = 0.86). For the other dates, classification accuracies
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17 414 decreased: 0.80 in March, 0.84 in May, 0.69 in June and 0.63 in July.

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20 416 **4.4. Calendar on rainfall data and agricultural practices**

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25 418 In order to characterize possible H-SSC evolutions between two dates of consecutive maps of H-SSC
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27 419 classes, the multitemporal classification required as input ancillary data on cumulative rainfall. The
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29 420 later were derived from measurements collected by a rain gauge located within the site.

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34 422 The chronological diagram presented in Figure 6 displays the dates of image acquisitions in
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36 423 addition to the cumulative rainfall. It also includes the calendar of soil management practices
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38 424 throughout the period of experiment, derived from farmer interviews. The soil management practices
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40 425 were significantly different from one field to another. With regards to the H-SSC temporal dynamics
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42 426 induced by rainfall and soil management practices, the monthly time scale was considered as relevant
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44 427 for monitoring H-SSC temporal evolution from aerial photos. This calendar was used for validating
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46 428 the soil management practices detected with the multitemporal classification.

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49 430 [Figure 6 about here]

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433 **4.5. Implementation and assessment of the proposed multitemporal classification**

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4 435 The multitemporal classification was applied on the time series of H-SSC maps derived from the
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6 436 monotemporal classification of monthly aerial photos (Section 4.3). It was initialized with the first
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8 437 map obtained from the January 2004 flight (classification accuracy of 0.86). It was then tested on the
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11 438 four images of March, May, June and July 2004 acquired over the four fields of the vineyard site.
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15 440 The performances of the multitemporal classification were assessed in the same way as were
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17 441 those of the monotemporal classification (Section 4.3.3), such as the comparison between both
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19 442 classifications was possible. Accuracies were assessed using half of the ground-based dataset, i.e. the
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21 443 part that was not used for training the monotemporal classification (Section 4.2 and 4.3.3). The
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23 444 pairwise test statistic based on the Kappa coefficients was used to evaluate the significance of
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25 445 differences between the two classification approaches (represented by their respective confusion
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27 446 matrices), as recommended by Cohen (1960).
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33 448 **5. RESULTS AND DISCUSSION**

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37 450 We report here the results obtained when analysing the performances of the multitemporal
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39 451 classification. First, we analyse the potential of the multitemporal approach to detect the considered
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41 452 soil management practices (i.e., mechanical and chemical weeding). Next, we compare the
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43 453 performances of the monotemporal and multitemporal classifications, for both each of the four fields
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45 454 and each of the six H-SSC classes. Finally, we discuss the implications of the proposed approach.
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53 456 **5.1 Detection of soil management practices**

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57 458 Table 6 represents the calculated surface percentages that were assigned to natural evolution (%nat),
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59 459 anthropogenic mechanical weeding (%antMW) and anthropogenic chemical weeding (%antCW), for
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61 460 each date between March and July 2004 on the four fields. For each date, the maximum percentage
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461 (%max) that corresponds to the detected dominant evolution process is highlighted in grey. It is shown
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2 462 that all the values of %max were larger than the 70% threshold value.

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6 464 [Table 6 about here]

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11 466 Knowledge soil management practice calendar (Figure 6) allowed verifying the results
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13 467 obtained with the multitemporal classification. The later correctly identified the two mechanical
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15 468 weeding interventions on Field 3, the first one around mid-May and the second one around mid-June
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17 469 (%antMW = 87 and 72, respectively). In July, a mechanical weeding was also detected on Field 3
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19 470 (%antMW = 92) which actually corresponded to the former soil management practice applied around
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21 471 mid-June over this field. The results of the multitemporal classification also indicated that a chemical
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23 472 weeding had been applied on Field 2 in May and July (%antCW = 74 and 80, respectively).

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29 474 Comparing to the actual calendar of soil management practices displayed by Figure 6, the
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31 475 detection of chemical weeding was not straightforward. On the one hand, the first intervention around
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33 476 the end of March was detected lately on the image acquired in May. On the other hand, the second and
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35 477 the third interventions applied around the end of June and at the beginning of July, respectively, were
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37 478 successfully identified on the image acquired in July. The differences in the detection timing for
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39 479 mechanical and chemical weeding could be explained by the delay in chemical weeding effect that did
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41 480 not appear immediately after the herbicide application, as compared to the effect of mechanical
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43 481 weeding which was observable right after the passage of the spring-tine rotovator.

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47 483 **5.2 Evaluation of classification improvement**

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53 485 We next compared the performances of the monotemporal and multitemporal classifications. Figure 7
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55 486 displays the H-SSC class maps obtained with both classifications in May 2004. For the four dates,
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57 487 Table 7 describes the results of classification assessments obtained on individual fields, and the overall
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59 488 accuracy calculated over the whole vineyard site.

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[Figure 7 about here]

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[Table 7 about here]

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The absolute values of the test Z statistic were larger than the critical value of 1.96, which suggested that all the classification results obtained by the multitemporal approach were significantly better than those obtained by the monotemporal classification, at a 95% confidence level. The multitemporal classification outperformed the monotemporal classification for the whole dataset. The higher performance achieved with the multitemporal classification was obtained on Field 2 for the image acquired in March with an overall accuracy of 0.98. On the other hand, the lowest improvement achieved with the multitemporal classification was obtained for the image acquired in May (0.84 overall accuracy for monotemporal versus 0.89 overall accuracy for multitemporal). This might be attributed to the relatively good level of accuracy already reached by the monotemporal approach.

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Another evaluation of improvements in classification performances is proposed in Figure 8, where relative values are reported for each H-SSC class. As depicted in this graph, a significant improvement in the identification of class SDC was observed on Field 1 (relative improvement about 39% in March, 17% in May and 48% in June) and on Field 2 (21% in June). An important increase in accuracy was also observed for class STC in March (relative improvement about 35% on Field 2; 37% on Field 3 and 20% on Field 4). Similarly, the identification of classes GC, LC and TC from the multitemporal classification over-performed that from the monotemporal classification, mainly in June for classes GC (31% on Field 4) and LC (37% on Field 1) and in July for class TC (18% on Field 3). On the other hand, accuracy result of class T did not vary as much with the multitemporal classification, because this class was already well detected by the monotemporal classification.

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[Figure 8 about here]

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517 The comparison between the results of monotemporal and multitemporal classifications
1 showed that using expert knowledge about H-SSC evolutions satisfactorily improved the identification
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3 of misclassified H-SSC classes, mainly classes related to crusting processes (SDC and STC). The
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5 improvement was manifest (i) in the overall accuracy assessments per field and for the whole vineyard
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7 site and (ii) in the identification of individual H-SSC classes.
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13 523 **5.3 Advantages and limits of the knowledge-based multitemporal classification**

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17 525 The method based on expert knowledge on possible H-SSC evolutions is worthwhile for detecting
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19 both natural and human induced evolutions, such as the effects of chemical and mechanical weeding
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21 on H-SSC dynamics. Since mechanical weeding has an instantaneous effect on the evolution of H-
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23 SSC, it was correctly identified using the multitemporal reasoning. On the other hand, the delayed
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25 effects of chemical weeding induced the date of image acquisition becomes very critical for the
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27 detection of this specific practice. This explains the ineptitude of the system in identifying the first
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29 chemical weeding on Field 2 in March when the image was acquired three days after the application of
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31 glyphosate. Yet, the first chemical weeding was identified lately on the image acquired in May. Thus,
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33 the knowledge-based multitemporal classification has potential in detecting soil management
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35 practices, provided the remotely sensed observations are collected with an adequate frequency in
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37 relation to these practices.
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44 537 This case study demonstrates that the timing of image acquisitions is not that critical for an
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46 adequate detection of the dominant evolution process. However, with respect to the natural evolution
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48 of H-SSC in relation to the rainfall amount and to the frequency of soil management practices, an
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50 acceptable time interval for multitemporal monitoring would be an aerial photograph acquisition per
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52 month. On the other hand, the aerial photographs had a spatial resolution of 0.1 m, which raises the
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54 question of portability to spaceborne remote sensing systems. Indeed, the best spatial resolution for
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56 multispectral sensor is 1.84 metres with WorldView-2, to be compared with the 2.5 m inter-row
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58 spacing of the vineyard we studied here.
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2 546 The quantitative evaluation of classification improvements indicated the superiority of the
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4 547 results produced when employing expert knowledge, as compared to the outcomes of the
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6 548 monotemporal classification. The knowledge-based multitemporal classification presented in this
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8 549 paper has strengths in straightforwardness and simplicity. The ancillary data required as inputs, i.e.,
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10 550 amount of rainfall and expert knowledge, can be easily acquired at a relatively low cost. This is
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12 551 consistent with the consideration of UAVs carrying cameras with few spectral bands, thus constituting
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14 552 an attractive tool for operational hydrology at the watershed extent.
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20 554 A particular attention must be given to the geometric accuracy and the precision in image-
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22 555 overlay database, which requires an accurate georeferencing procedure. In the multirate approach,
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24 556 uncertainty is mostly related to the superimposition process. For instance, in the case of vineyards, a
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26 557 vine and shadow mask was applied on the images, because we were interested in the sunlit soil
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28 558 surfaces only. The size of the mask generally increases from January to July with the increase of
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30 559 vineyard canopy density, thus always ensuring the existence of an antecedent H-SSC $C(t_i-1)$ for all
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32 560 image-objects. The problem would arise when the size of the mask decreases during the senescence
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34 561 season, although remotely sensed acquisitions around solar noon mitigate shadow effects. In this case,
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36 562 we advocate applying the monotemporal classification on this particular period in order to reset the
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38 563 multitemporal classification schema and to avoid the difficulties induced by the absence of antecedent
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40 564 H-SSC class, where the latter is an essential input for the rule-based decision system.
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46 566 An important critical point is linked to the choice of a reliable map for initializing the
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48 567 multitemporal classification. Ideally, an exhaustive thematic map on H-SSC could be used for
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50 568 initialization. Practically, it is impossible to obtain such information, and we initialised the
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52 569 multitemporal approach with the H-SSC class maps obtained from the monotemporal classification on
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54 570 the first date, given the accuracy was larger than 0.8. However, because the quality of the results is
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56 571 subject to progressive deviation, the error propagation has to be analysed in future works, such as it is
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58 572 possible evaluating its impact on the outcomes of the multitemporal classification.
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2 574 In this case study, the H-SSC evolution rules that were implemented into the multitemporal
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4 575 classification framework were obtained from previous and exploratory field studies. Field research on
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6 576 H-SSC evolutions in relation to rainfall intensity is currently being conducted (Pare et al., 2011). The
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8 577 expert knowledge could then be complemented by obtaining quantitative information on evolutions of
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10 578 H-SSC classes, from the typology of Andrieux et al. (2001), and by implementing this information
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12 579 into the multitemporal classification system. Refining the expert knowledge would obviously improve
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14 580 the classification performances, adding more interest to the approach proposed in this paper. Finally,
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16 581 progressing towards genericity requires first addressing other agricultural practices.
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21 583 **6. Concluding remarks**

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26 585 Some directions for future work would consist of (i) refining the expert knowledge by acquiring new
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28 586 information on possible evolution of all H-SSC classes and (ii) analysing error propagation. Further
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30 587 investigations are also required (i) to apply this approach on other sequences of H-SSC maps derived
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32 588 from any monotemporal classification of H-SSC and (ii) to monitor H-SSC over larger areas and
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34 589 under different soil management and cultivation conditions. Finally, the current paper investigated one
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36 590 way of improvement for the monotemporal classification of H-SSC, by incorporating a priori
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38 591 information about H-SSC evolution. Using richer spectral information from spectroscopy and
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40 592 hyperspectral imagery is the other potential direction to be deepened for improvement, since it is a
41
42 593 promising alternative for characterizing physicochemical properties of soil surface, including crusts.
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47 595 **Acknowledgments**

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52
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55 599 Hydrosystème) technicians for their participation in the field campaigns. This research is supported by
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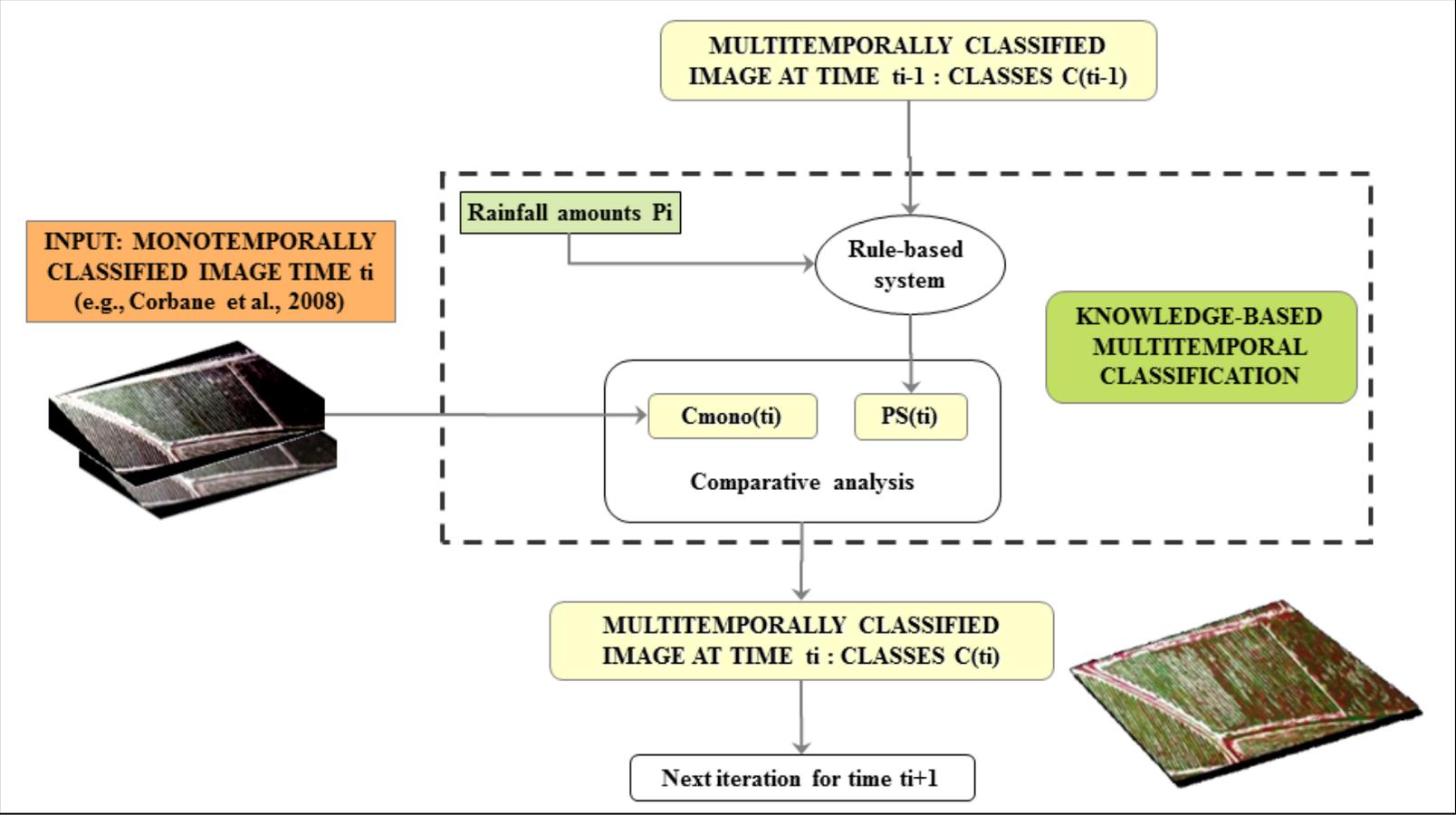
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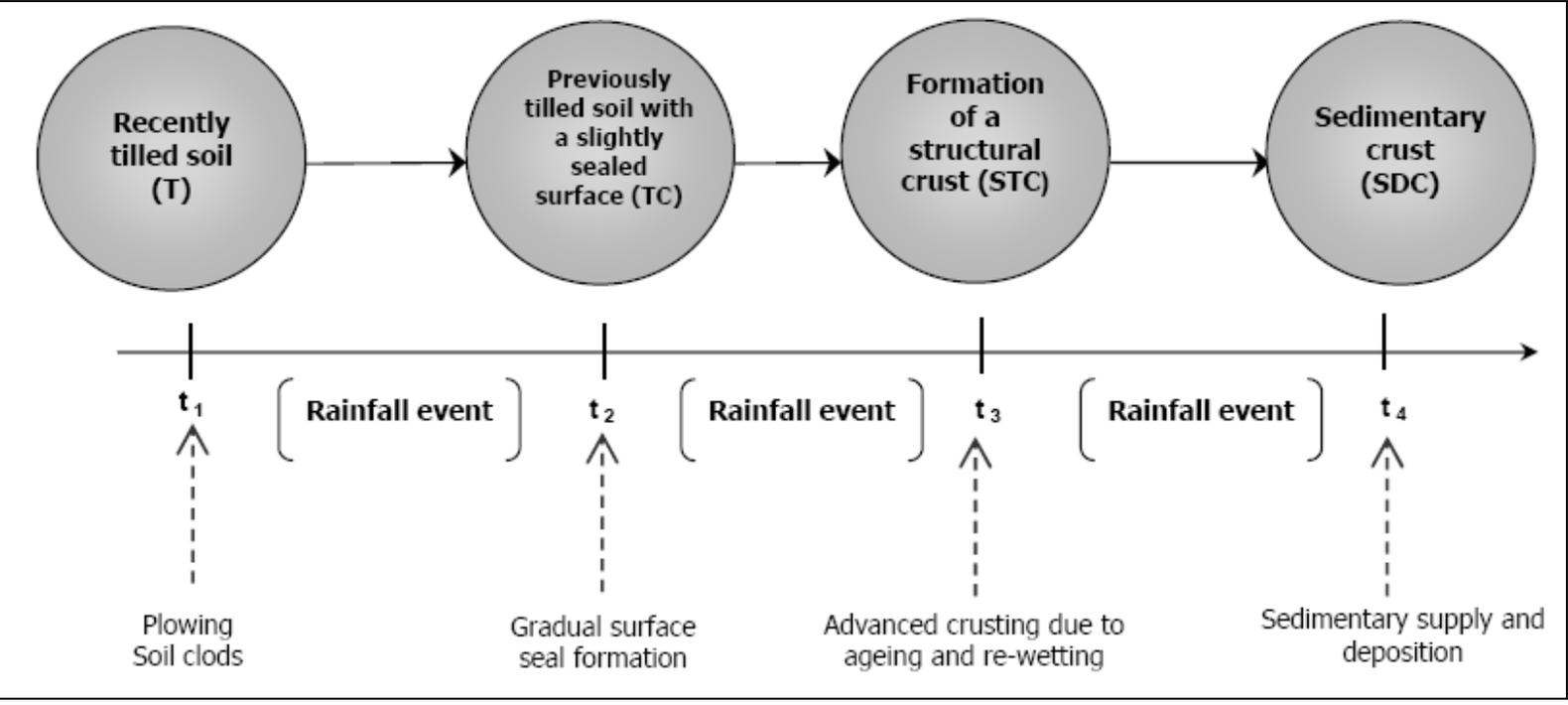


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Figure 1: flow-chart of the multitemporal classification at time t_i . $C(t_{i-1})$ is the antecedent H-SSC class obtained from the multitemporal classification at previous time t_{i-1} . “PS(t_i)” is the set of Possible Successors at time t_i when applying the H-SSC evolution rules to $C(t_{i-1})$. “Cmono(t_i)” is the classification result from the monotonically method at time t_i . Comparative analysis of “Cmono(t_i)” and “PS(t_i)” provides $C(t_i)$ at time t_i . The design of the rule-based system for H-SSC evolution is presented in Section 3.1. The comparative analysis between Cmono(t_i) and PS(t_i) is presented in section 3.2. It includes (i) the detection of the dominant H-SSC evolution at the field scale (Section 3.2.1) and (ii) the possible correction of H-SSC assignment when necessary (3.2.2).

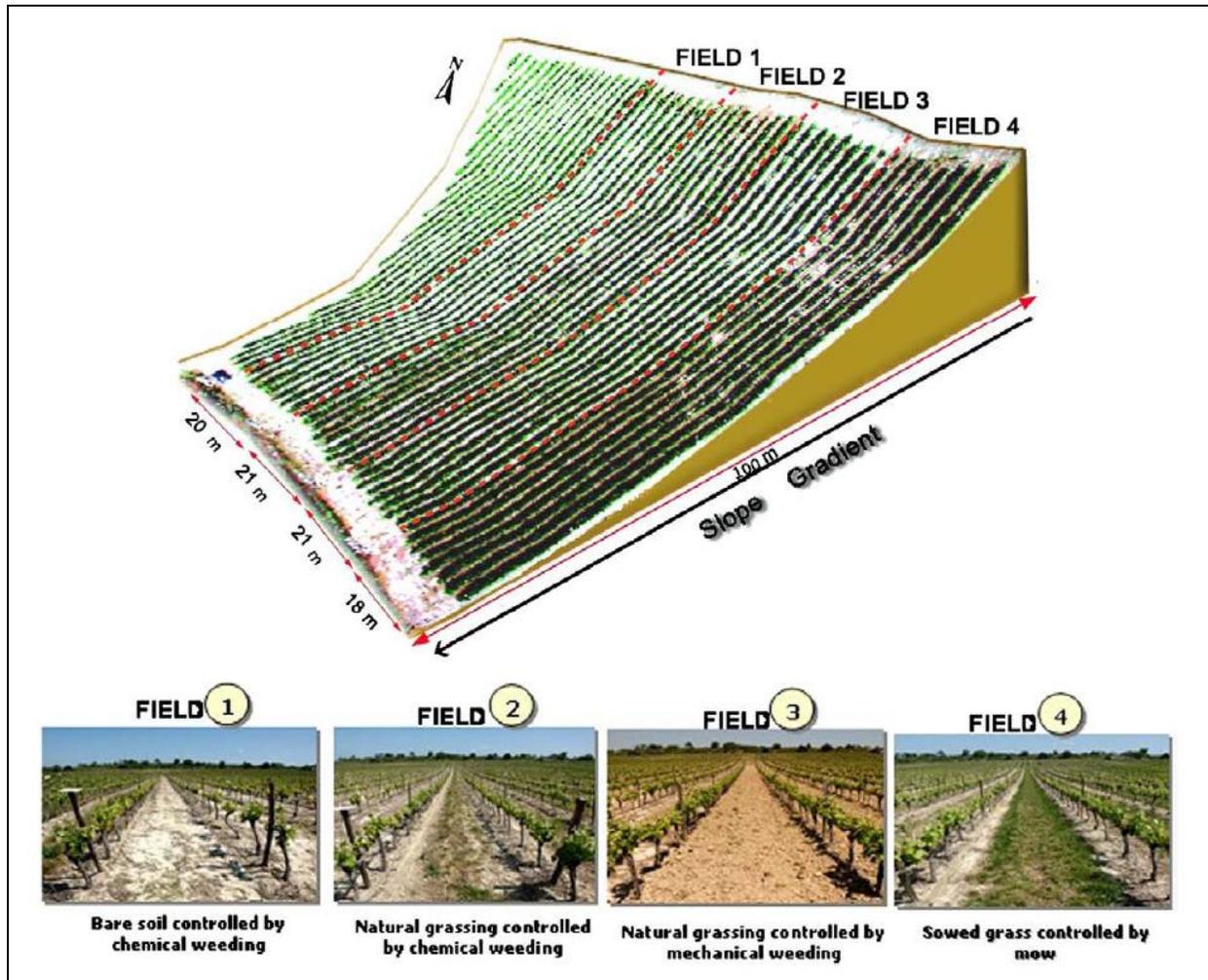
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Figure 2: example of a temporal scenario for successive states of soil surface characteristics.

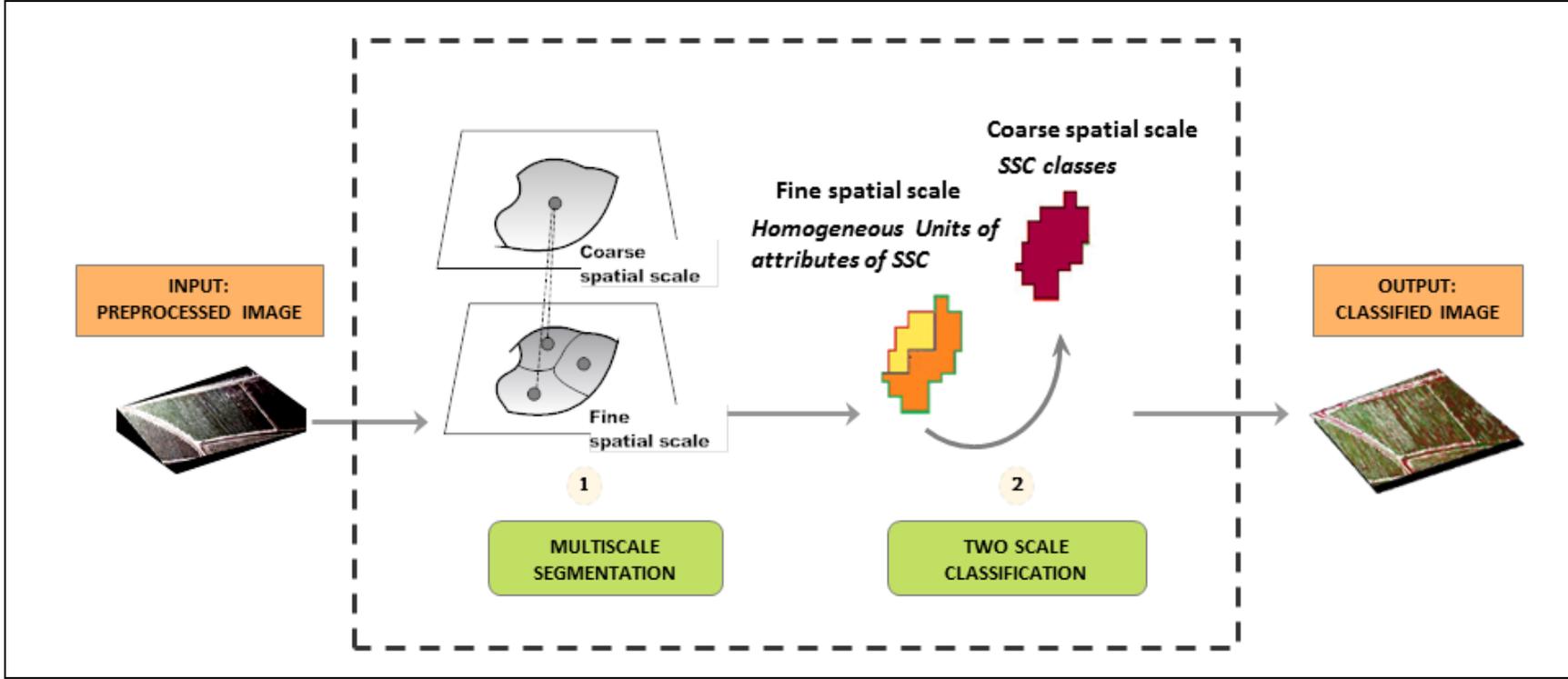
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Figure 3: the experimental vineyard site. This site is divided into four fields, each subject to a specific soil management practice.

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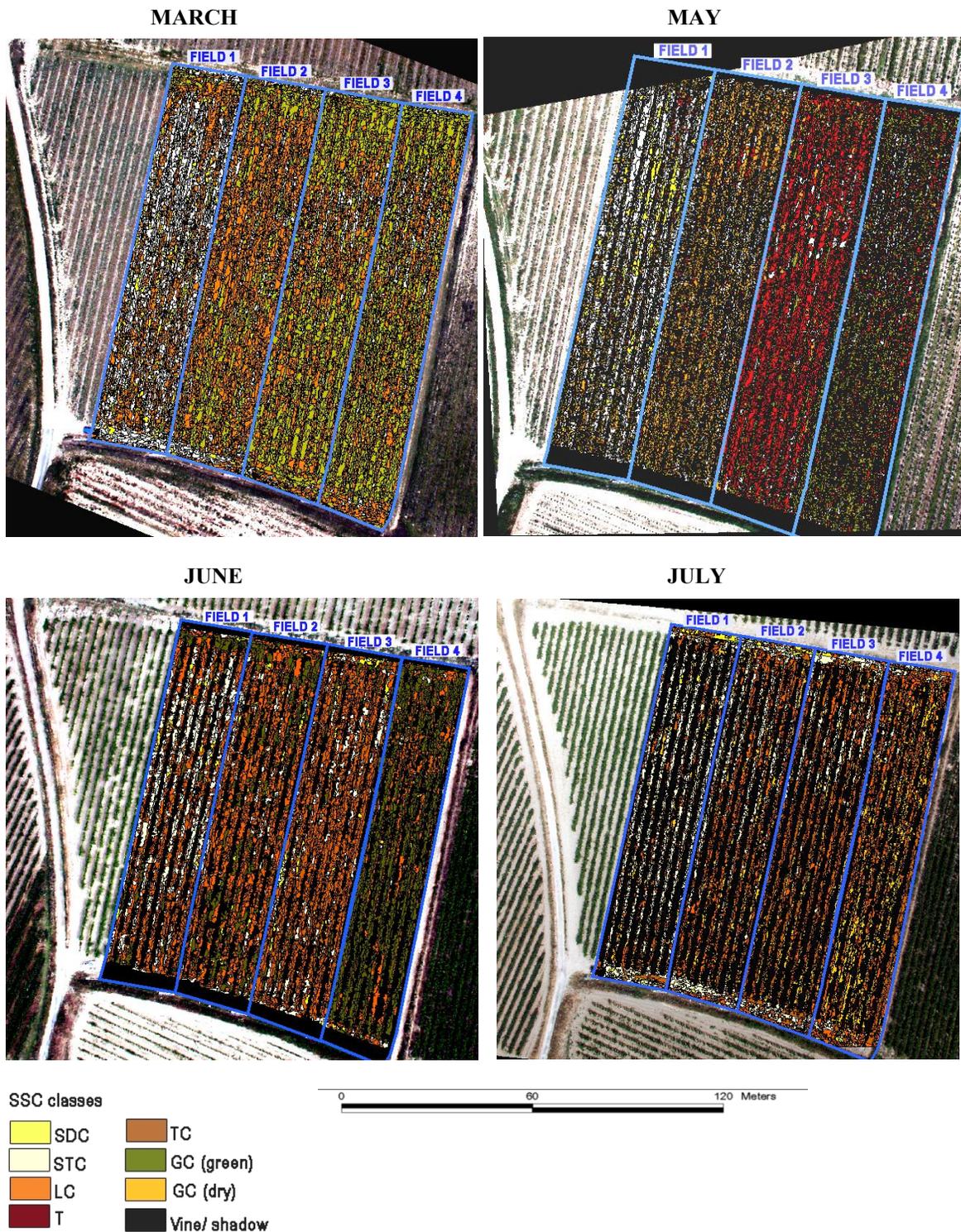


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Figure 4: flow-chart of the H-SSC monotemporal classification methodology. From Corbane et al. (2008b).

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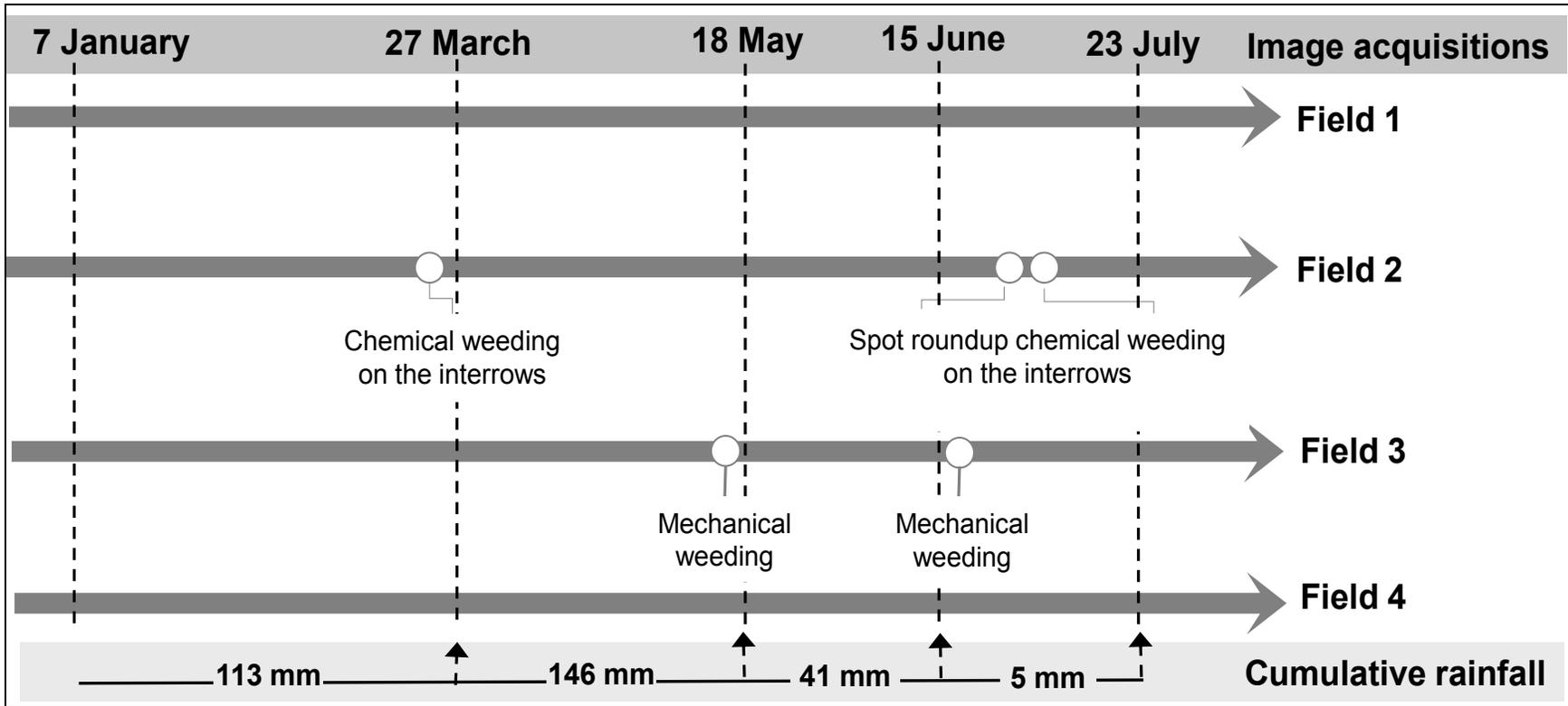
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Figure 5: time series of H-SSC class maps obtained when applying the monotemporal classification to the aerial photos monthly collected over the Puisserguier vineyard site. From Corbane et al. (2008b).

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Figure 6: calendar of soil management practices and cumulative rainfall amounts registered between two dates of consecutive image acquisitions.

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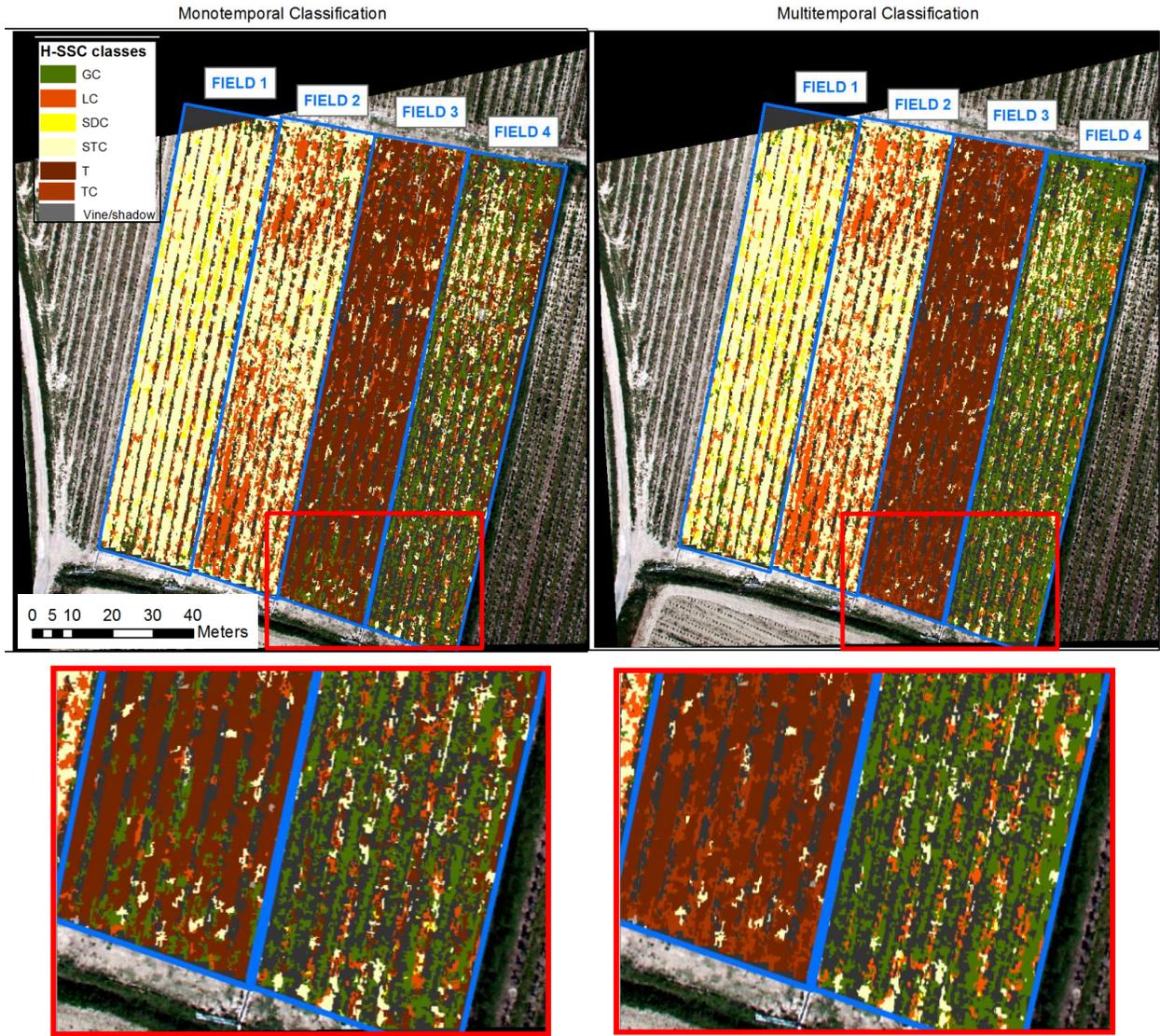
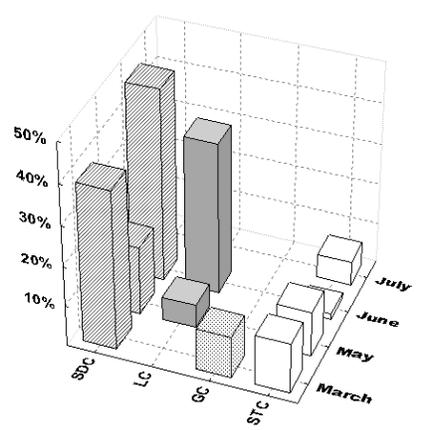
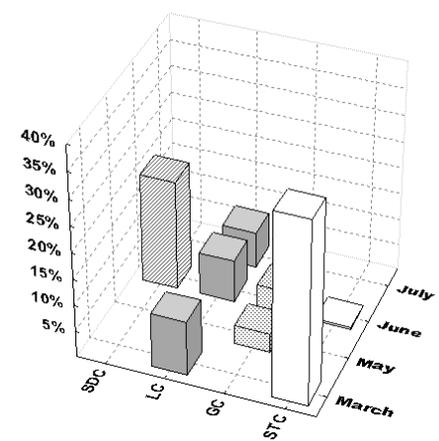


Figure 7: H-SSC class maps obtained with monotemporal (left) and multitemporal (right) classifications for May 18, 2004. Top subplots are H-SSC class maps obtained over the whole study area, where the squares indicate the specific areas that are zoomed in bottom subplots to illustrate changes between monotemporal (left subplots) and multitemporal (right subplots) classifications.

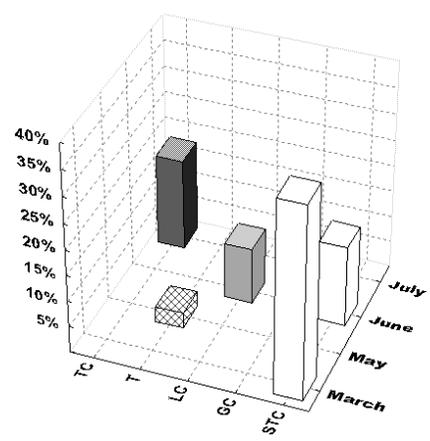
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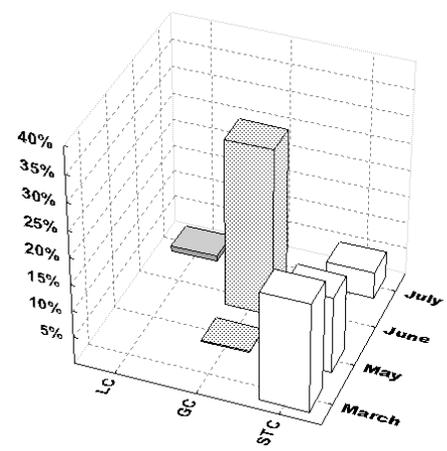
a) Field 1



b) Field 2



c) Field 3



d) Field 4

Figure 8: comparison of the results of monotemporal and multitemporal classifications by H-SSC class in terms of relative accuracy improvements on Field 1 (5-a), Field 2 (5-b), Field 3 (5-c) and Field 4 (5-d).

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	Label	Definition	Mean Infiltration rate
H-SSC classes	T	The surface is mainly composed of 5-10 cm size clods	31 (SD = 4.3; N = 5)
	TC	More than 50% of the surface is composed of clods with a slightly sealed surface	21 (SD = 6.5; N = 7)
	GC	More than 50% of the surface is composed of grass AND the rest is predominantly composed of structural crust	20.3 (SD = 10.8; N = 9)
	LC	More than 50% of the surface is composed of litter AND the rest is predominantly composed of structural crust	18.2 (SD = 6.3; N = 20)
	STC	More than 50% of the surface is composed of structural crust	10.8 (SD = 3.4; N = 8)
	SDC	More than 50% of the surface is composed of sedimentary crust	7.6 (SD = 2.6; N = 19)

Table 1: the six H-SSC classes we considered in the current study. Each H-SSC class is defined through its constituting SSC attributes. The related infiltration rates measured in situ with a rainfall simulator (Léonard and Andrieux, 1998) are also presented. SD stands for standard deviation and N for measurement number.

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Antecedent H-SSC class C(ti-1)	Possible Successors S _{nat}		
	Rainfall amount P _i		
	[0 - 20 mm[[20 - 40 mm[≥ 40 mm
T	T	TC/STC	STC/SDC
TC	TC	TC/STC	STC/SDC
STC	STC/GC	STC/GC	STC/SDC/GC
SDC	SDC	SDC	SDC
GC	GC	GC	GC
LC	LC	LC	LC/STC/SDC

Table 2: possible H-SSC successors (S_{nat}) related to natural evolutions.

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Antecedent H-SSC class C(ti-1)	Anthropogenic successors Sant
T	T
TC	T
STC	T
SDC	T
GC	<i>T/STC/LC</i>
LC	T

Table 3: possible H-SSC successors related to soil management practices. In bold: possible successors after mechanical weeding. In italic: possible successors after chemical weeding.

Antecedent H-SSC class C(ti-1)	Possible Successors Sant		
	Rainfall amount P _i		
	[0 - 20 mm[[20 - 40 mm[≥ 40 mm
STC	T	T/TC/STC	T/TC/STC/SDC/
SDC	T	T/TC/STC	T/TC/STC

Table 4: examples, for antecedent H-SSC classes C(ti-1) STC and SDC, of sets of possible anthropogenic successors Sant related to soil management practices. These H-SSC successors are obtained by considering possible combinations of natural forcing (Table 2) and anthropogenic forcing (Table 3). In bold: possible successor(s) Sant-MW for Mechanical Weeding (MW). In italic: possible successor(s) Sant-CW for Chemical Weeding (CW).

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Cmono(ti) versus PS(ti)	Corresponding cases
$Cmono(ti) \in S_{nat} \wedge \notin S_{ant-MW} \wedge \notin S_{ant-CW}$	Case 1: natural evolution
$Cmono(ti) \notin S_{nat} \wedge \in S_{ant-MW}$	Case 2: mechanical weeding
$Cmono(ti) \notin S_{nat} \wedge \in S_{ant-CW}$	Case 3: chemical weeding
$Cmono(ti) \in S_{nat} \wedge \in S_{ant-MW}$	Case 4: mechanical weeding and natural evolution
$Cmono(ti) \in S_{nat} \wedge \in S_{ant-CW}$	Case 5: chemical weeding and natural evolution
$Cmono(ti) \notin S_{nat} \wedge \notin S_{ant-MW} \wedge \notin S_{ant-CW}$	Case 6: inconsistency

Table 5: the six possible cases when checking the presence of $Cmono(ti)$ within the set of possible successors $PS(ti)$. Sign \in reads “is an element of”, sign \notin reads “is not an element of”, sign \wedge reads “and”.

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DATE	Occurrence	Field 1	Field 2	Field 3	Field 4
MARCH					
27/03/2004	% nat	92	78	75	72
	% antMW	40	21	16	15
	% antCW	60	27	30	30
MAY					
18/05/2004	% nat	74	31	42	74
	% antMW	49	28	87	26
	% antCW	05	74	21	23
JUNE					
15/06/2004	% nat	89	86	21	71
	% antMW	23	19	73	14
	% antCW	55	36	30	29
JULY					
23/07/2004	% nat	81	31	37	84
	% antMW	14	19	92	16
	% antCW	36	80	19	24

Table 6: results from calculations of surface percentages of natural evolution (%nat), anthropogenic mechanical weeding (%antMW) and anthropogenic chemical weeding (%antCW) obtained over the four fields for dates between March and July 2004. Bold numbers correspond to maximum value for a given field and a given date.

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	MARCH		MAY		JUNE		JULY	
	Mono-temporal	Multi-temporal	Mono-temporal	Multi-temporal	Mono-temporal	Multi-temporal	Mono-temporal	Multi-temporal
Field 1	0.75	0.87	0.76	0.87	0.70	0.86	0.78	0.81
Field 2	0.90	0.98	0.92	0.96	0.86	0.89	0.76	0.79
Field 3	0.60	0.68	0.89	0.92	0.50	0.53	0.42	0.59
Field 4	0.86	0.93	0.87	0.92	0.83	0.90	0.76	0.79
Overall	0.79	0.85	0.84	0.98	0.69	0.76	0.63	0.70

Table 7: overall accuracy improvement for Fields 1, 2, 3 and 4 following the multitemporal classification. The performance of the multitemporal classification was significantly different (z-value always superior to 5.59) in the four classification outputs (March, May, June and July).