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2
3 **15 Abstract**

4
5 **16** Winter soil cover by vegetation is associated with multiple benefits. In this study, winter soil cover rate
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7 **17** before spring-sown crops was estimated for mainland France from multispectral imagery. For 67% and
8
9 **18** 84% of the area under spring-sown crops for years 2018 and 2019, soil cover during the previous winter
10
11 **19** was estimated through the computation of the Normalized Difference Vegetation Index (NDVI), using
12
13 **20** Sentinel-2 multispectral images. At country scale, winter soil cover rate before spring-sown crops was
14
15 **21** estimated between 37% and 48 % for 2018 and between 31% and 43% for 2019, depending on the
16
17 **22** NDVI threshold for a soil to be considered covered by at least 50% of vegetation. Spatial patterns were
18
19 **23** relatively similar between the two years studied, highlighting strong heterogeneities between French
20
21 **24** departments. Cropping systems may explain some of these heterogeneities, as it has been shown that
22
23 **25** there is a large variability in the soil cover rate between spring-sown crops, but also depending on the
24
25 **26** previous crop. Winter soil cover rate was higher for crops associated with livestock production, such
26
27 **27** as maize silage (between 59% and 74% of plots covered before this crop). It was also shown that winter
28
29 **28** soil cover could be ensured by other means than cover crops: temporary grasslands were the previous
30
31 **29** crop with the highest soil cover, probably due to late ploughing. For these reasons, mixed systems
32
33 **30** combining livestock and crop productions may be a solution to increase winter soil cover before spring-
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35 **31** sown crops.

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33 **33 Social media abstract (100 characters)**

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35 **34** For France, winter soil cover rate before spring crops was estimated between 31% and 48%, with
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37 **35** strong spatial heterogeneities.

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36 Introduction

37 Bare soils during winter can result in environmental damage while the introduction of cover crops
38 before spring-sown crops has the potential to increase the ecosystem services provided by agricultural
39 systems [1]. Nutrient uptake by plants reduces losses related to leaching during the winter period,
40 when soils are frequently saturated with water [2]. In this regard, winter soil cover is one of the good
41 agricultural practices promoted by the European Nitrate Directive to reduce water pollution by nitrates
42 in sensitive zones [3]. Winter soil cover also slows down surface runoff, thus limiting erosion [4].
43 Moreover, it provides an opportunity to increase soil carbon storage [5]. Despite these advantages,
44 the adoption of cover crops is commonly considered to be low to moderate [6].

45 Assessing soil cover by vegetation before spring-sown crops is a necessary step in order to define
46 effective policies to promote the adoption of cover crops. Satellite-based methods offer new
47 possibilities to monitor crop development on a large scale [7], in particular through the computation
48 of the Normalized Difference Vegetation Index (NDVI) from multi-spectral images [8]. This index is
49 especially appropriate for monitoring winter soil cover because, contrary to biomass, soil cover has a
50 linear relationship with NDVI [9]. Several studies have therefore used remote sensing data to evaluate
51 soil cover during winter, as discussed below.

52 Concerning recent trends, winter soil cover before maize increased between 2009 and 2013 in
53 Pennsylvania (USA), likely associated with increased adoption of cover crops [10]. For the same
54 country, but in the Midwest, an increase in winter soil cover for maize and soybean acreage has also
55 been reported, with more than doubling of cover crop acres planted from 2008–2016 [11]. Despite
56 this increase, winter soil cover remained low in this study (less than 10% of maize and soybean acreage
57 in 2016).

58 These studies have also highlighted the influence of soil and climatic conditions on the adoption of
59 cover crops by farmers. Cover crop adoption appeared to be more frequent for low-potential soils [11].
60 In the Netherlands, where cover crops are implemented on nearly all maize fields due to regulatory
61 requirements, a hot and dry summer led to earlier harvest dates, hence earlier sowing dates and
62 greater development of winter cover crops in the eastern part of the country [12]. Regarding the
63 influence of cropping systems, in the USA, it has been shown that cover crops were predominantly
64 grown after silage maize, rather than grain maize, which is harvested later [10]. For the same country,
65 winter soil coverage resulted in a modest yield gain (less than 1%) for the following crop [11].

66 The objective of this study is to provide an estimate of winter soil cover in a large territory (France)
67 prior to the establishment of a spring-sown crop for two years: 2018 and 2019. For each plot reported
68 as seeded with a spring-sown crop, the soil cover rate during the previous winter was estimated from
69 NDVI. The geographical distribution of winter soil cover, as well as the influence of the previous and
70 following crop, is investigated.

71

72 **Methods**

73 *Spatial plot register pre-processing*

74 This study focuses on all plots with spring-sown crops in France, declared within the context of the
75 European Common Agricultural Policy. These plots are mapped in a file known as the Registre
76 Parcellaire Graphique (RPG) in France [13], which covers 99% of the French arable crop area [14]. In
77 this file, a plot corresponds to an area cultivated with one main crop (or a crop mixture) in a given year.
78 Two years of cultivation have been taken into account for the study: 2018 and 2019 harvests. For these
79 two years, plots with spring-sown crops were selected from the plot register. In addition, the previous
80 crops for the year 2018 and 2019 were defined with the 2017 and 2018 register, respectively. A 20m
81 negative buffer was applied to the borders of each plot to avoid edge effects due to sensor resolution
82 or ground geolocation uncertainty.

83

84 *Sentinel-2 images pre-processing*

85 Vegetation monitoring was carried out using Sentinel-2 multispectral images at 10m spatial resolution
86 [15], corrected to surface reflectance using Sen2Cor [16]. For each year, winter soil cover monitoring
87 was carried out for two months (December and January) during the winter before sowing the spring-
88 sown crop. December was chosen as the beginning of the study period to limit the risk of detecting
89 unharvested spring-sown crops on the plots, such as grain maize or sugar beet that can be harvested
90 late in the year. January was chosen as the end of the study period because some spring-sown crops,
91 such as peas, can be sown as early as February. Furthermore, if a cover crop was present on the plot,
92 it must have been already detected in December or January.

93 Two levels of filters were applied to remove invalid observations. First, for the study period, only the
94 least cloudy images (20% threshold) were selected. Then, a second filter at the pixel scale was applied
95 to remove observations identified as clouds, shadows or snow (using the Scene Classification map
96 provided with Sentinel 2 observations).

97

98 *Definition of the occurrence of vegetative cover for each plot*

99 The spatial average NDVI of each plot that will be sown with a spring-sown crop at the end of the
100 winter was calculated for each satellite acquisition date that was available over the study period.
101 Following this protocol, part of the plots could not be monitored (e.g. 16% of the plots without NDVI
102 extraction in 2019, as shown on **Table 1**) for three main reasons: topological error in the original
103 shapefile delimiting the plots, plot too small after application of the negative buffer or no cloud-free
104 pixel for the period considered. The coverage rate was lower in 2018 than in 2019 because, due to a

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3 105 wetter and cloudier winter [17], fewer satellite images could be exploited. This corresponds to 776,242
4 106 plots monitored in 2018, 907,473 plots in 2019. $NDVI_{Max}$ was then defined as the maximum NDVI value
5 107 among the average NDVI values calculated for each plot for the December-January period. The plot
6 108 was considered covered if $NDVI_{Max}$ exceeded a given threshold. Soil characteristics, such as colour or
7 109 moisture, and crop residues influence NDVI measurements, especially in the early stages of crop
8 110 development, when the soil is still poorly covered [18]. In order to limit these effects, it was therefore
9 111 considered that soil cover had to exceed 50% for a plot to be considered as covered by vegetation.
10 112 Based on the literature [19–26], this corresponds to a threshold NDVI value between 0.45 and 0.59
11 113 (**Table 2**). These two low and high thresholds were used in this study to assess the uncertainty
12 114 associated with the threshold selection.
13 115 Finally, the plot register from the previous year was used to evaluate the effect of the previous crop.
14 116 This association could only be carried out for part of the plots because the borders of some of them
15 117 were modified from one year to the next. Approximately 50% of the plots had both winter NDVI value
16 118 and previous crop information (**Table 1**).
17 119 NDVI calculation was realized through the Google Earth Engine platform [27]. Analysis was conducted
18 120 in R [28] and figures were produced using the package ggplot2 [29].
19 121

122 **Results**

123 *Spatial heterogeneities*

124 For France, global winter soil cover rate before spring-sown crops was estimated between 37% and 48
125 % for 2018 and between 31% and 43% for 2019, depending on the threshold NDVI value for a soil to
126 be considered covered (**Figure 2**). Spatial patterns are relatively similar between the two years studied.
127 Yet, strong disparities are observed between departments. For instance, soil cover rate exceeds 80%
128 for the department of Loire Atlantique (44), in the west of France, while it is close to 10% for the Bas-
129 Rhin department (67), in the east of France. Overall, based on winter $NDVI_{Max}$ values, soils of the
130 western part of the country are frequently covered whereas, in the East, soils are most often left bare
131 before sowing a spring-sown crop (**Figure 3**). The cereal plain around Paris has relatively low $NDVI_{Max}$
132 values, also indicating predominantly bare soils. Like those of the West, the soils of the Massif Central,
133 in the center of the country, are estimated as mostly covered, with the exception of the Puy-de-Dôme
134 department (63).
135

136 *Following spring-sown crop*

137 Cropping systems have an impact on winter soil cover rate. First, the upcoming spring-sown crop has
138 a strong association with winter soil cover. For instance, the results show that plots sown with maize
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3 139 silage are more often covered during the winter than plots sown with sunflowers (**Figure 4**). As shown
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5 140 on this figure, the distribution curve of winter $NDVI_{Max}$ values for maize silage shows a peak close to
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7 141 0.8 for 2019 and slightly higher for 2018. These spectral signatures correspond to well-developed plant
8
9 142 cover. Moreover, depending on the threshold values for a soil to be considered covered, between two-
10
11 143 thirds and three-quarters of the plots could be considered covered prior to the seeding of maize silage.
12
13 144 Conversely, for both years, the distribution curve of winter $NDVI_{Max}$ values for sunflower shows a single
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15 145 peak at 0.2, a value within the range of spectral signatures of bare soils [30]. About a quarter of the
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17 146 plots could be considered covered before sowing this crop. Finally, the winter $NDVI_{Max}$ distribution
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19 147 curve of some crops, such as grain maize, shows two peaks: one at 0.2 and one at 0.8. Such a
20
21 148 distribution illustrates the difference between plots with bare soils during winter and those with
22
23 149 covered soils. For the year 2018, it was estimated that between 30% and 43% of the plots were covered
24
25 150 before sowing grain maize, depending on the threshold $NDVI$ value selected.

151

152 *Previous crop*

153 The previous crop also has an influence on the winter soil cover (**Figure 5**). Surface previously
154 established with temporary grassland, which is cultivated for a maximum of five consecutive years with
155 grass or legumes species, pure or mixed, shows higher winter $NDVI_{Max}$ values than other previous
156 crops, and is thus more likely to be covered during the winter period due to late ploughing of grassland.
157 This may partially explain the high soil cover rates shown for maize silage, as it is the crop that most
158 often follows grassland. But there is also an interaction between the previous and the next crop. For
159 example, a plot cultivated with winter soft wheat is more likely to be covered during the winter when
160 it is followed by corn silage as compared to any other spring crop. In particular, the soil is frequently
161 bare during winter for crop rotations of soft winter wheat followed by beet, or soft winter wheat
162 followed by sunflower, which are common patterns in France.

163 Among cereal crops, winter triticale was the previous crop with the highest winter $NDVI_{Max}$ values. In
164 general, winter soil cover was higher when the previous crop was a winter crop, given that its earlier
165 harvest gave ample time for cover crop growth.

166 As detailed previously, **Figure 5** confirms that the highest winter $NDVI_{Max}$ values are associated with
167 acreage that will be seeded with maize silage.

168

169 *Interactions between cropping system distribution and spatial heterogeneities of winter soil cover*

170 The distribution of crop rotations across France partially explains the spatial heterogeneities in winter
171 soil cover highlighted in **Figure 3**. Of the four main crop sequences investigated (grain maize followed
172 by grain maize, winter wheat followed by silage maize or grain maize and silage maize followed by
173 silage maize), the period between the harvest of winter wheat and the sowing of maize silage is the

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3 174 one during which the soil is most likely to be covered during winter (**Figure 5**). As this crop sequence
4
5 175 is mainly found in the West of France (**Figure 6**), this may explain the patterns previously observed in
6
7 176 **Figure 3**. However, crop rotation is not sufficient to explain these spatial heterogeneities as different
8
9 177 trends can be observed between departments for the same crop sequence. As shown in **Figure 6**, the
10
11 178 median winter NDVI values between two maize grains are higher in western France, indicating that the
12
13 179 soil is more frequently covered in this region. Similarly, the soil appears to be more frequently covered
14
15 180 in the West between the harvesting of winter wheat and the sowing of grain maize, particularly in
16
17 181 comparison with Central France.

182

183 **Discussion**

184 *Evaluation of winter soil cover before spring-sown crops in France*

185 Areas under spring-sown crops account for slightly more than a quarter of the total arable land in
186 France [31]. It is roughly equivalent to that of winter soft wheat alone, which is the main cereal crop
187 grown in the country [32]. If it is considered that winter-sown crops are sufficiently developed to
188 ensure soil cover, the winter soil cover rate for the total French agricultural area is therefore higher
189 than the figures presented here. Yet, multiple environmental issues are related to the agricultural
190 practices implemented prior to sowing spring crops. On these areas, winter soil cover can both reduce
191 the negative impacts of agricultural systems, for example by limiting soil erosion [33], and improve the
192 services provided by agriculture, such as soil carbon storage [34].

193 Several studies have already assessed winter soil cover before spring-sown crop using satellite imagery
194 on a regional scale [10–12], but this study is the first to propose such an assessment on a national
195 scale. Here, it was estimated for France that between one-third and one-half of the acreage could be
196 considered as covered during the winter preceding the sowing of a spring-sown crop, depending on
197 the year and the NDVI threshold used to consider a plot as covered (**Figure 2**). Winter soil cover was
198 slightly lower in 2019 than in 2018, probably due to a drier autumn [17] which hindered the
199 establishment and development of cover crops. Winter soil cover rate estimated in this study is higher
200 than that estimated for Midwestern United States, where cover crops were detected on 9% of maize
201 and soybean acreage in 2016 [11], but lower than that estimated for Pennsylvania, where 52% to 75%
202 of maize acreage was covered in winter, depending on the county [10].

203 For France, based on a farm structure survey in 2016, it was estimated that before spring-sown crops,
204 about 55% of the soils were covered by cover crops, 21% by crop residues and 24% of the soils were
205 left bare in winter [31]. Crop residues can not be detected with the methodology used in this study,
206 which is based on NDVI monitoring. Furthermore, some plots declared as sown with cover crops may
207 not have sufficient vegetative development to be considered covered with the NDVI thresholds used
208 here, whereas some plots with heavy weed infestation could be considered as covered. Nevertheless,

209 the proportion of cover crops previously reported in the survey mentioned above is relatively similar
210 to the areas estimated to be covered here with reference to the low NDVI threshold (48% in 2018 and
211 43% in 2019).

212 The method proposed in this study, with the calculation for each plot of the maximum NDVI during the
213 winter, is relatively simple. Unlike other methods based on the analysis of vegetation index time series,
214 it does not allow a precise analysis of the agricultural practices, such as the estimation of the sowing
215 date [35], crop identification [36], or the determination of the amount of biomass produced [37].
216 However, these methods may be difficult to apply for monitoring cover crops, which are planted over
217 a short period of time that is generally very cloudy, with few reliable satellite images. Moreover, the
218 method proposed here could easily be applied to other case studies provided that a spatialized plot
219 register is available. Among the potential applications, it could be used to monitor changes in winter
220 soil cover over years or to compare cover crop adoption in different countries for example. Concerning
221 the avenues for improvement, the integration of synthetic aperture radar data such as Sentinel-1 could
222 be relevant for monitoring of winter soil cover, as these data are not sensitive to cloud cover and could
223 be used to identify crops or to monitor agricultural practices [38], especially when combined with
224 multispectral images [39].

225 *Spatial heterogeneities regarding winter soil cover rate before spring-sown crops*

226 There was little difference between the two years studied, but strong spatial heterogeneities in winter
227 soil cover were highlighted in **Figure 2** and **Figure 3**. Based on the results obtained in this study, several
228 factors may explain these heterogeneities.

229 First of all, the results of this study showed that crop rotation has a strong influence on winter soil
230 cover. Previous crops such as winter triticale or winter wheat had a higher winter soil cover than some
231 spring crops such as sugar beet or soybean (**Figure 5**) which, harvested later, leave less time for the
232 establishment of cover crops. Thus the greater occurrence of the crop sequence of winter wheat
233 followed by silage maize in western France partly explains the greater winter soil cover in this region
234 (**Figure 6**). However, as different trends can be observed between departments for the same crop
235 sequence, other factors than crop rotation must therefore be considered to explain the adoption of
236 winter cover crops.

237 Secondly, the pedoclimatic conditions may influence the development of plant cover. Cover crops are
238 better suited to warm regions with abundant precipitation [4], which is the case of Western France,
239 that is characterized by an oceanic climate, with mild winters and high annual rainfall. This region had
240 indeed the highest soil cover rates of the country (**Figure 3**). In the east of France, the continental
241 climate can hinder the adoption of cover crops, as cooler soil temperature under crop residues may
242 retard the growth of the next crop in a cold climate. In the south of France, with a Mediterranean
243 climate and low rainfall, water used by cover crops can have a negative impact on the yields of the

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3 244 following crops. In addition, under these climates, the droughts which can occur during the sowing of
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5 245 cover crops, is a barrier to the success of these crops. A study based on French case studies has shown
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7 246 that the number of consecutive days without significant water input after sowing is the most significant
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9 247 variable to predict cover crop emergence [40].

10 248 Thirdly, the agricultural production of each territory can also influence winter soil cover rate. Here, it
11
12 249 has been shown that crops most frequently related to livestock production, such as temporary
13
14 250 grassland or maize silage, are more likely to be associated with winter cover soils (**Figure 4**). Potential
15
16 251 nutrient excesses resulting from manure application could explain the high winter soil cover in some
17
18 252 livestock regions such as western France [3]. Higher winter soil cover in livestock regions may also be
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20 253 partially explained by the use of cover crops to produce additional fodder resources in livestock
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22 254 systems, as previously highlighted in the literature [41]. Here, grasslands alternating with spring-sown
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24 255 crops have also been pointed out as another way to provide winter soil cover in mixed crop-livestock
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26 256 systems, due to their late destruction date. Agricultural systems combining livestock and crop
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28 257 productions may provide multiple benefits, such as improving nutrient cycling [42]. These mixed
29
30 258 systems can also provide alternatives to cover crops for winter soil cover, by fostering the integration
31
32 259 of grasslands into crop rotations, as a primary crop or as an intermediate crop between two primary
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34 260 crops.

35 261 Further work is needed to test the hypotheses formulated here. For example, since the type of
36
37 262 agricultural production (i.e. crop or livestock) seems to influence the adoption of cover crops, it would
38
39 263 be interesting to allocate each of the plots monitored in this study to the farm to which it belongs in
40
41 264 order to study the effect of farm structure on winter soil cover. This could be achieved through the
42
43 265 unique identifier that characterizes each plot in the register, provided that confidentiality can be
44
45 266 waived for such a study. In addition, the influence of weather data and soil types on winter soil cover
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47 267 has not been fully investigated here but, thanks to the data sets that are now available for France, it
48
49 268 could also be possible to characterise the pedoclimatic factors of each plot. The work initiated in this
50
51 269 study can therefore be further extended to better understand the drivers of winter soil cover before
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53 270 spring-sown crops.

54 271

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45 378

379 **Tables**380 **Table 1** Summary of data extraction for the ten main spring-sown crops cultivated in France

Crop	Total acreage (kha)		NDVI extraction (% of total acreage)		NDVI extraction and information about previous crop (% of total acreage)	
	2018	2019	2018	2019	2018	2019
Grain maize	1536	1620	67%	83%	43%	54%
Silage maize	1274	1286	76%	79%	47%	49%
Sunflower	548	593	60%	94%	39%	65%
Sugar beet	496	455	70%	91%	35%	46%
Spring barley	481	634	54%	80%	32%	51%
Soybean	154	162	62%	87%	38%	55%
Spring pea	103	108	59%	91%	32%	56%
Sorghum	61	83	66%	95%	39%	64%
Lentil	37	37	22%	100%	38%	70%
Spring oat	31	37	65%	84%	39%	49%
Total	4721	5015	67%	84%	41%	53%

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383 **Table 2** *Estimation of soil cover rate from NDVI*

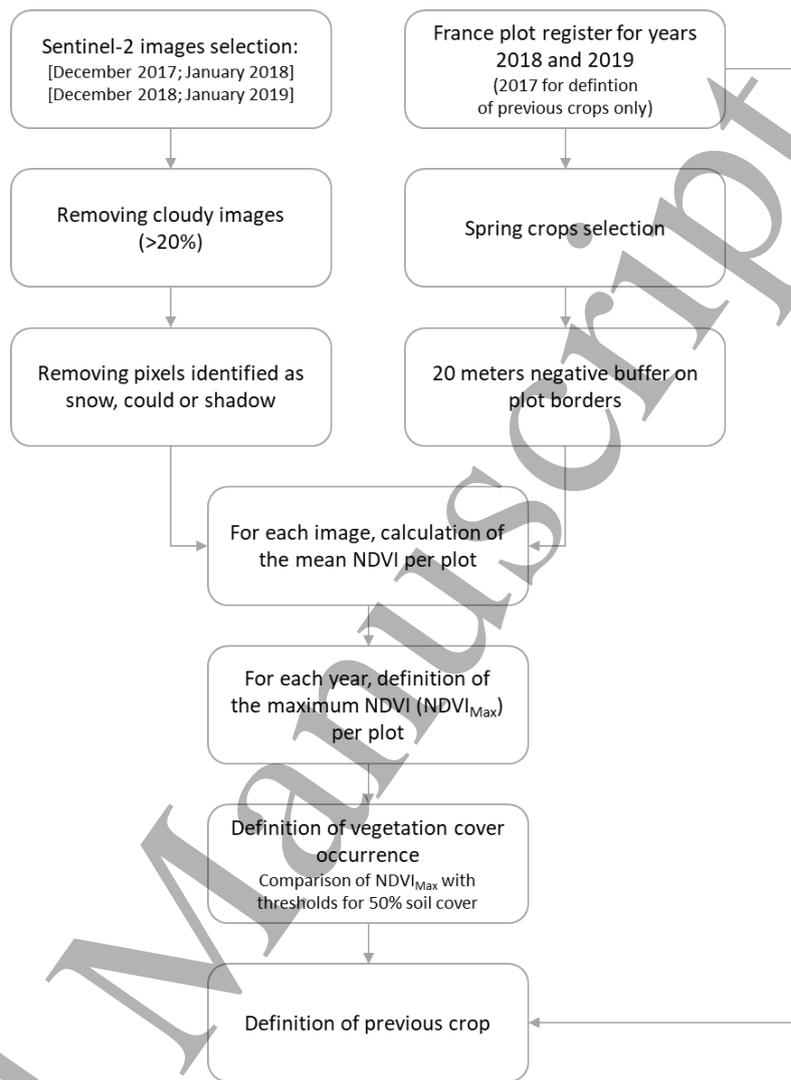
Authors	Year	Crop	Country	NDVI value for 50% soil cover with vegetation	Date source for NDVI calculation
de la Casa et al.	2018	Soybean	Argentina	0.45	Landsat satellite images
Er-Raki et al.	2007	Wheat	Morocco	0.54	CROPSCAN field sensor
Imukova et al.	2015	Multiple crops	Germany	0.57	RapidEye satellite images
Jimenez-Munoz et al.	2009	Multiple crops	Spain	0.53	PROBA/CHRIS satellite images
Johnson and Trout	2012	Multiple crops	USA	0.54	Landsat satellite images
Lopez-Urrea et al.	2009	Wheat	Spain	0.55	GER3700 field sensor
Prabhakara et al.	2015	Multiple crops	USA	0.56	CROPSCAN field sensor
Trout et al.	2008	Multiple crops	USA	0.59	TetraCam field sensor

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387 **Figures**

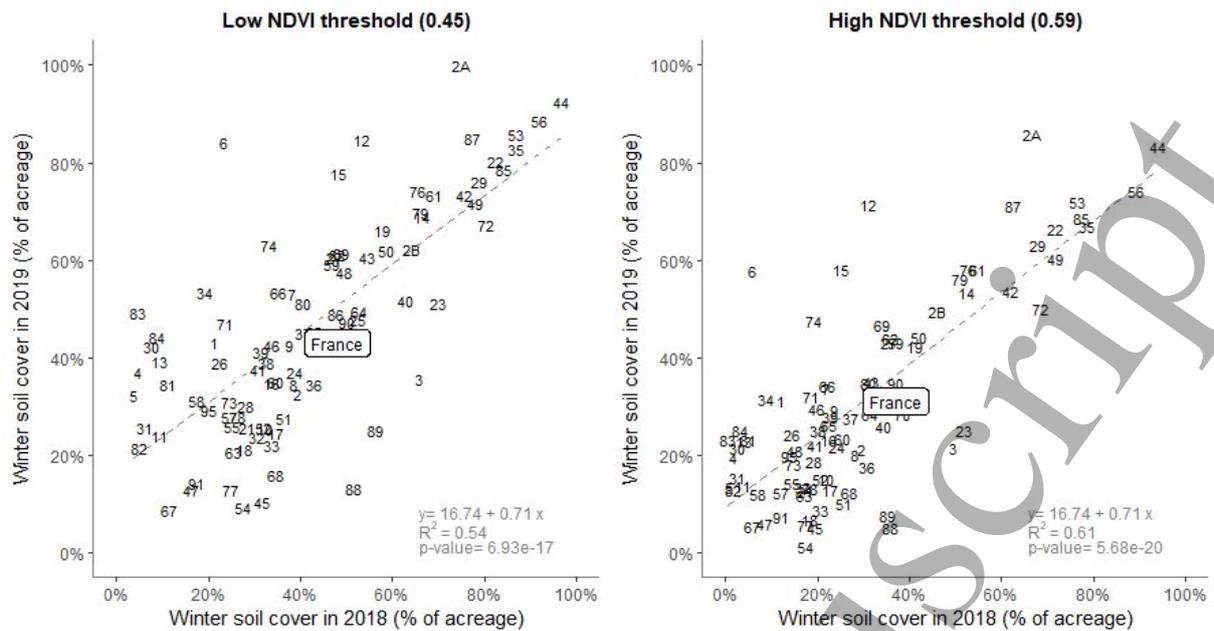
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390 **Figure 1** Workflow to set the maximum value of NDVI ($NDVI_{Max}$) for each plot

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394 **Figure 2** Estimation of the winter land cover rate by French department for the years 2018 and 2019,
 395 according to the NDVI threshold chosen to consider a soil as covered. Numbers represent the codes of
 396 the different departments. "France" label represents the estimate for mainland France.

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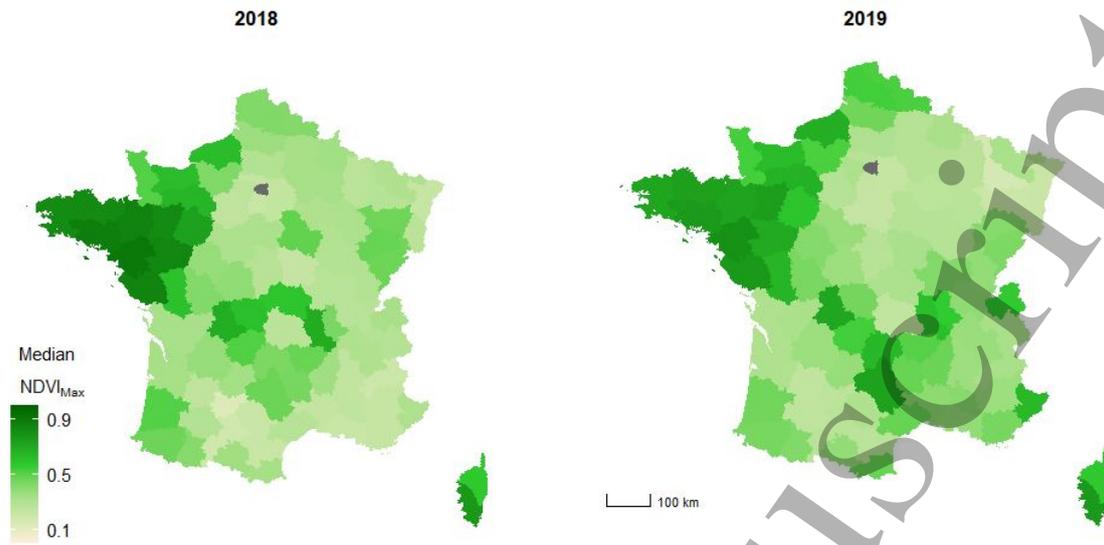
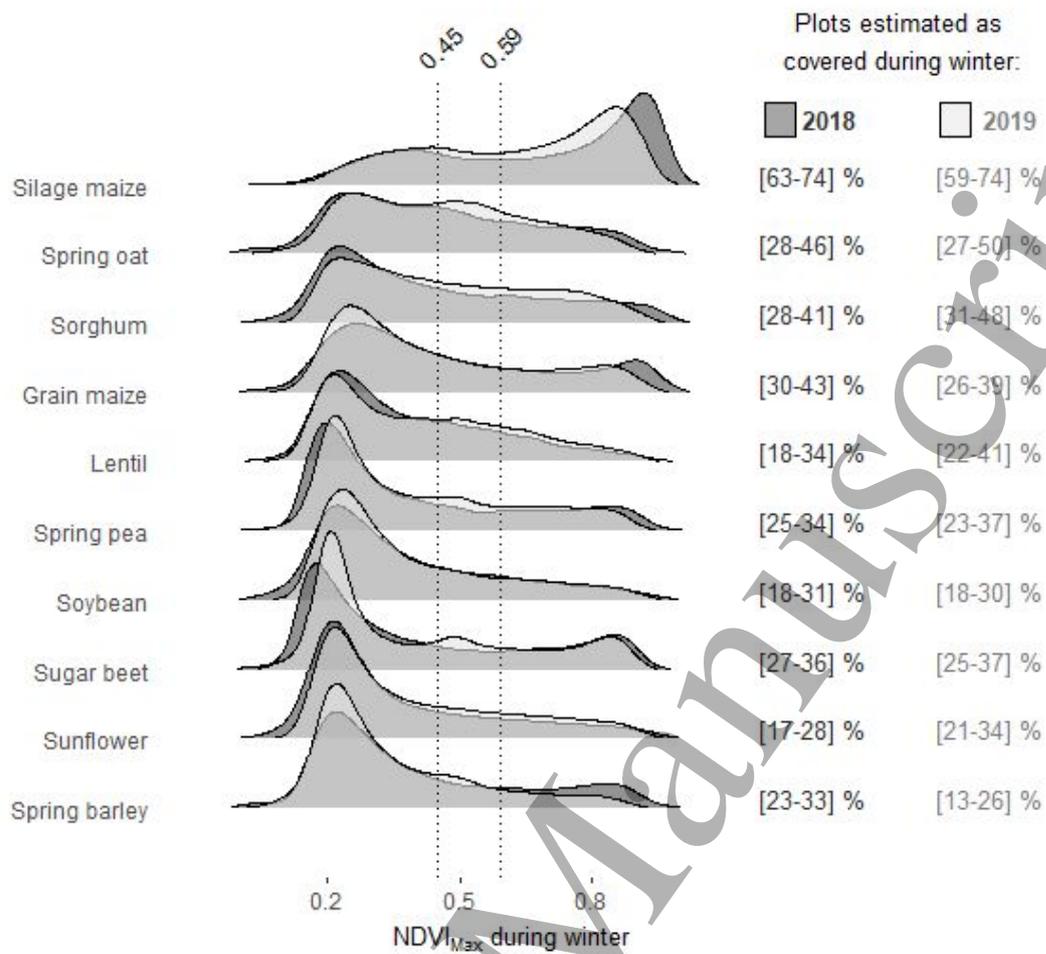
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Figure 3 Map of median winter NDVI_{Max} preceding spring-sown crops by French department (all spring-sown crops combined). The department in grey corresponds to the Paris area, where no crops are grown.

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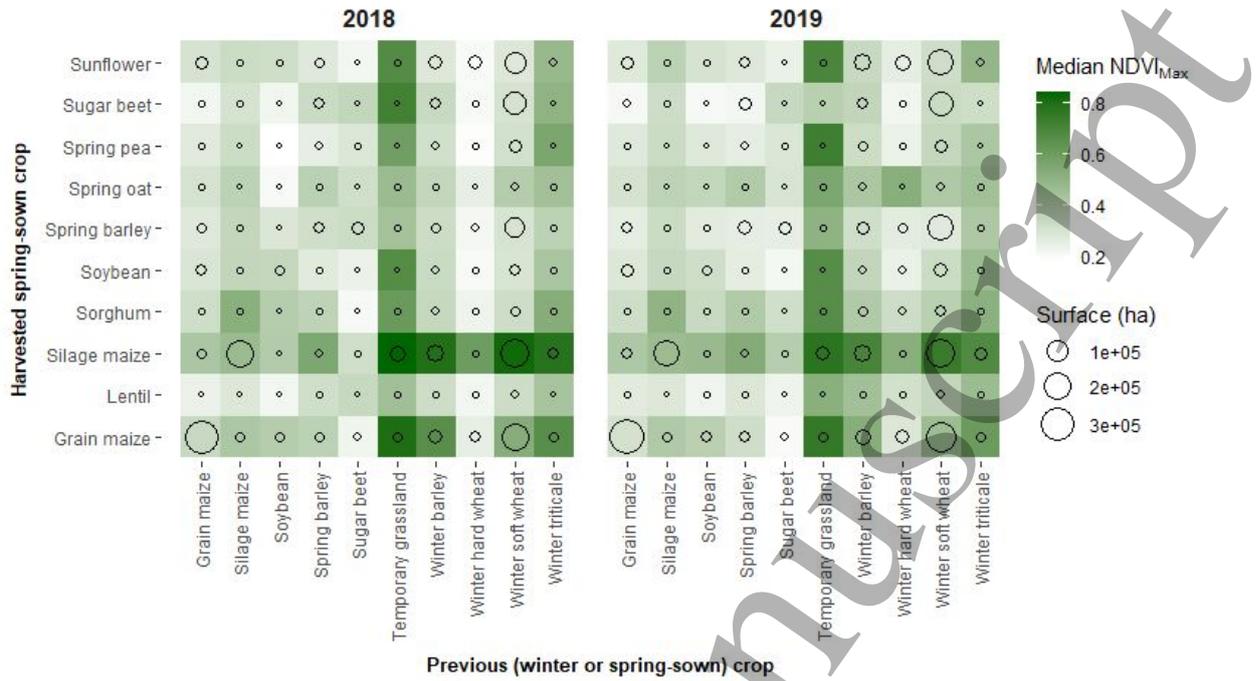
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407 **Figure 4** Distribution curves of winter $NDVI_{Max}$ by plot depending on the crops sown the following spring
 408 for years 2018 (dark colored) and 2019 (light colored). The estimate of the percentage of plots with
 409 winter soil coverage is given according to two NDVI thresholds for a plot to be considered covered (0.45
 410 and 0.59).

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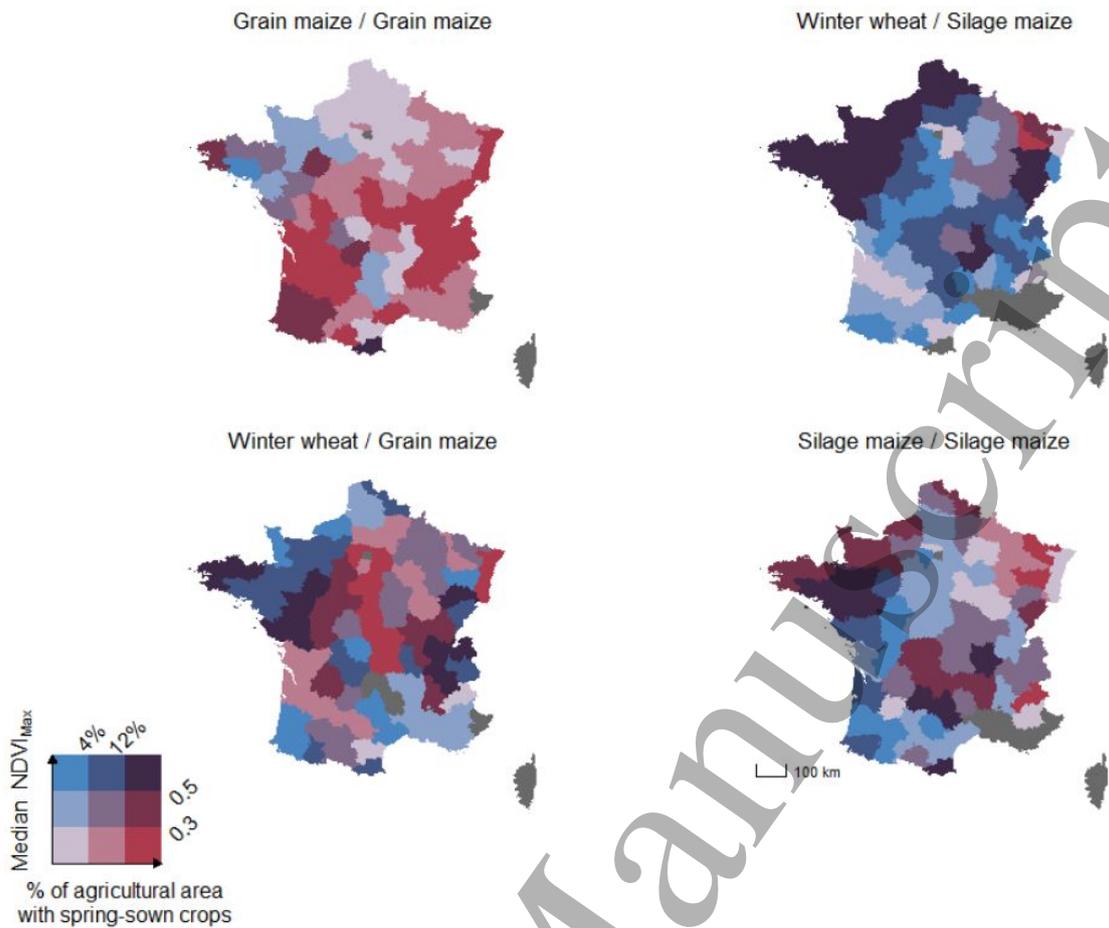
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415 **Figure 5** Median winter NDVI_{Max} by previously harvested crop (in column) and next spring seeded crop
 416 (in row) for the years 2018 and 2019. The color intensity represents the NDVI_{Max} value, the shape size
 417 represents the scale of each crop succession (in hectares).

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420 **Figure 6** Maps of median winter $NDVI_{Max}$ values and percentage of area occupied by each crop rotation
 421 for the four main crop sequences ending with a spring-sown crops (Grain maize followed by grain
 422 maize, winter wheat followed by silage maize or grain maize and silage maize followed by silage maize).
 423 Percentage of area occupied by each sequence is calculated from the total area of spring-sown crops
 424 with information about preceding crop (Table 1). Classes in the legend correspond to the one-third and
 425 two-third quantiles of the variables. Values are calculated for both study years (2018 and 2019)
 426 together. For the departments coloured in grey, the corresponding crop sequence was not present in
 427 the dataset