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1 **Revisiting the coupling between NDVI trends and cropland changes in the Sahel drylands: a**
2 **case study in western Niger**

3

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12 **Abstract**

13 The impact of human activities via land use/cover changes on NDVI trends is critical for an
14 improved understanding of satellite-observed changes in vegetation productivity in drylands. The
15 dominance of positive NDVI trends in the Sahel, the so-called re-greening, is sometimes interpreted
16 as a combined effect of an increase in rainfall and cropland expansion or agricultural intensification.
17 Yet, the impact of changes in land use has yet to be thoroughly tested and supported by empirical
18 evidence. At present, no studies have considered the importance of the different seasonal NDVI
19 signals of cropped and fallowed fields when interpreting NDVI trends, as both field types are
20 commonly merged into a single ‘cropland’ class. We make use of the distinctly different phenology
21 of cropped and fallowed fields and use seasonal NDVI curves to separate these two field types. A
22 fuzzy classifier is applied to quantify cropped and fallowed areas in a case study region in the
23 southern Sahel (Fakara, Niger) on a yearly basis between 2000 and 2014. We find that fallowed
24 fields have a consistently higher NDVI than unmanured cropped fields and by using two seasonal
25 NDVI metrics (the amplitude and the decreasing rate) derived from the MODIS time series, a clear
26 separation between classes of fields is achieved ($r = 0.77$). The fuzzy classifier can compute the
27 percentage of a pixel (250 m) under active cultivation, thereby alleviating the problem of small field
28 sizes in the region. We find a predominant decrease in NDVI over the period of analysis associated
29 with an increased area of cropped fields at the expense of fallowed fields. Our findings couple
30 cropping abandonment (more frequent fallow years) with positive NDVI trends and an increase in
31 the percentage of the cropped area (fallow period shortening) with negative trends. These findings
32 profoundly impact our understanding of greening and browning trends in agrarian Sahelian drylands
33 and in other drylands of developing countries characterized by limited use of fertilizers.

34 **Keywords:** NDVI trends, Cropland, Fallowed fields, Phenology, Drylands, Sahel, Niger

35 ***1. Introduction***

36 The Sahel is one of the largest dryland regions in the world and is prone to environmental stress and
37 food shortage due to the combined effects of climatic variations and human pressure on land
38 resources. Changes in the human-environmental system of the Sahel became widely apparent in the
39 wake of the severe droughts that occurred in the 1970s and 1980s and one aspect which has
40 received particular attention was the deterioration and loss of the vegetation cover. However,
41 conflicting characterization and interpretation of those changes in vegetation cover are often
42 reported in the scientific literature (Herrmann & Hutchinson, 2005b). This partly stems from
43 incompatible use of research methods and scales of analysis (Rasmussen et al., 2015) and the
44 relative contributions of different climatic and anthropogenic factors to explain those changes are
45 still debated.

46 Since the early 2000s, several scholars have revealed an ongoing ‘greening’ of most parts of Sahel
47 from an observed positive trend in time series of the Normalized Difference Vegetation Index
48 (NDVI), interpreted as a proxy of vegetation productivity (Anyamba & Tucker, 2005; Fensholt et
49 al., 2012; Olsson, Eklundh, & Ardö, 2005). Change in precipitation has been identified as the major
50 driver of the observed changes in vegetation greenness (Hickler et al., 2005; Huber, Fensholt, &
51 Rasmussen, 2011; Kaspersen, Fensholt, & Huber, 2011). However, the re-greening is not fully
52 explained by climatic factors, but likely influenced by human management of natural resources,
53 which results in an increase of vegetation productivity (Herrmann, Anyamba, & Tucker, 2005a).
54 For a region particularly reliant on rain-fed agriculture, it is vital to understand the coupling
55 between NDVI trends and vegetation changes in the agrarian Sahel. However, conflicting
56 hypotheses have been reported: on the one hand an expansion (into native savanna) and
57 intensification (fertilizer) of cropland cultivation, and on the other hand agricultural land
58 abandonment, caused by, e.g., the civil war in Sudan (Fuller, 1998; Olsson et al., 2005) may both

59 contribute to the observed positive trends. Still at present, little scientific empirical evidence for the
60 link between NDVI trends and cropland changes is provided for drylands in general, and for the
61 Sahel region in particular.

62 Several local scale studies showed a general increase in cropped areas since the 1950s (van Vliet et
63 al., 2013) and in recent years, a few studies have indicated that cropland has a higher annual NDVI
64 than savanna in Sahelian areas, supporting a possible link between cropland expansion/cropping
65 intensification and the observed positive trends in NDVI (Bégué, Vintrou, Ruelland, Claden, &
66 Dessay, 2011; Nutini, Boschetti, Brivio, Bocchi, & Antoninetti, 2013). The linkage between NDVI
67 trends and the role of fallowed fields, as a part of the crop-fallow rotation cycle, should however be
68 taken into account and better studied. In the Sahel, shifting cultivation is the traditional cropping
69 system, by which the fields are cultivated for a given period and then left as fallow for a series of
70 years to restore soil fertility (De Rouw & Rajot, 2004). Fallowed fields are dominated by annual
71 herbaceous plants interspersed with bushes and a sparse tree cover, which is functionally
72 comparable to the vegetation composition of natural savanna. Cropped fields and fallowed fields
73 should have quite different seasonal greenness signals, with the greenness signal of fallowed fields
74 approximating that of savanna. As current classification schemes of the land cover class ‘cropland’
75 encompass fallowed fields in both time and space for the Sahel, there is a need to determine the
76 impact of fallow fields on the NDVI signal and related trends.

77 From the Earth Observation (EO) perspective, a successful differentiation between cropped and
78 fallowed fields is required to improve our understanding of the mechanisms and drivers of observed
79 NDVI trends in relation to changes in the spatio-temporal patterns of crop-fallow rotation due to
80 cropping expansion/abandonment. One of the enduring challenges is the lack of suitable historical
81 Land-Use and Land-Cover Change (LULCC) products documenting the extent of and changes in
82 cropland at the Sahel scale over time (Vintrou et al., 2012). Additionally, fallowed fields have never

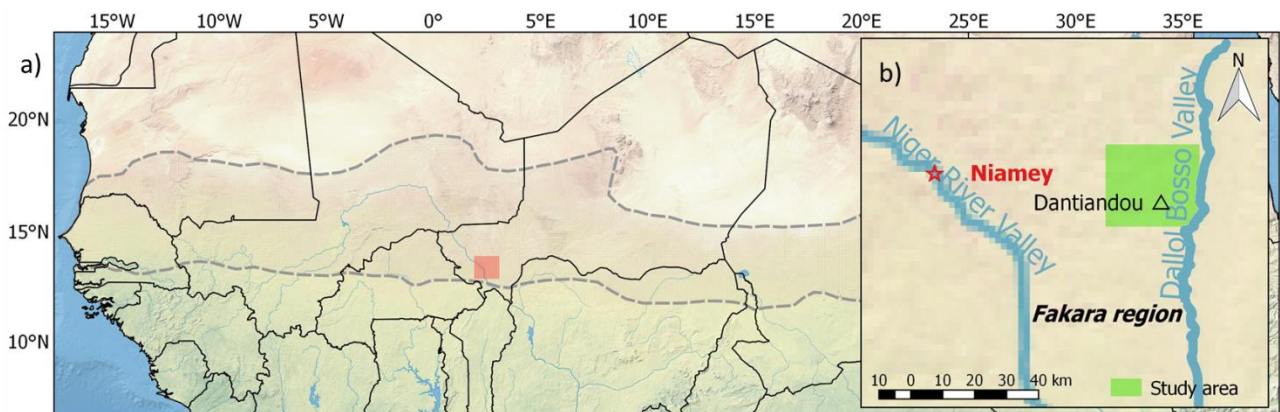
83 been separated from cropland among existing regional and global scale land cover classifications –
84 in higher spatial resolution data such as Landsat (GlobeLand 30) or in relatively low spatial
85 resolution such as SPOT-VGT (e.g., GLC2000: 1 km), MODIS data (e.g., MCD12Q1: 250 m - 1
86 km) and PROBA-V (100 m) (Lambert, Waldner, & Defourny, 2016). However, cropped and
87 fallowed fields have different growing cycles because of the differences in vegetation composition
88 and influences of human management, such as tillage, weeding, and crop harvesting. Differences in
89 growing cycles, such as emergence, growth, maturity, and harvest/senescence, can potentially help
90 to separate cropped and fallowed fields by extracting the unique vegetation phenological signatures
91 using NDVI derived seasonal metrics (Alcantara, Kuemmerle, Prishchepov, & Radeloff, 2012).
92 This approach has been successfully applied in dryland woody cover monitoring (Brandt et al.,
93 2016) and fodder biomass modeling (Diouf et al., 2015).

94 The overall objective of our study is thus to develop an improved basis for understanding the role of
95 changes in areas under cultivation on EO vegetation greening trends in the Sahelian drylands.
96 Specifically, we aim to: (1) Analyze intra-annual seasonal NDVI signatures of the cropped and
97 fallowed fields, (2) separate and map cropped and fallowed fields by image classification using
98 satellite-derived seasonal metrics from time series of MODIS NDVI and fuzzy classification
99 techniques to overcome problems of mixed pixels, and (3) link the NDVI trends to the observed
100 changes in cropped and fallowed fields over an observation period spanning from 2000-2014. To do
101 so, detailed spatio-temporal ground-based knowledge is needed; this study makes use of a unique
102 record of field observations of Sahelian crop-fallow rotation in the Fakara region, western Niger
103 (Hiernaux & Turner, 2002).

104 **2. Study area**

105 *2.1 Study area in Fakara, Niger*

106 The study area is the district of Dantiandou, located 80 km east of Niamey, the capital city of Niger
107 (Fig. 1). It is situated in the Fakara region, which lies between the Niger River to the west and the
108 Dallol Bosso valley to the south of the line extending from Niamey to Baleyara (Hiernaux &
109 Ayantunde, 2004). Being part of the central Sahel bio-climatic zone (Hiernaux & Ayantunde, 2004),
110 the climate is typical of the semi-arid monsoonal tropics, with an average annual precipitation of
111 about 500 mm but varying spatially and fluctuating from year to year (Barbé & Lebel, 1997). The
112 rural population has increased steadily in the district since the 1950s, leading to an expansion of
113 cultivated areas (Hiernaux et al., 2009). The crop-fallow rotation practiced to manage soil fertility
114 (Turner & Hiernaux, 2015) is typical for the extensive cropping system in the Sahel. Land use/cover
115 has been extensively studied in the district and monitored annually over 20 years (Cappelaere et al.,
116 2009; Hiernaux et al., 2009).



117
118 **Fig. 1.** a) The location of the Fakara region in Niger (red block) within the Sahelian delineation (dashed lines). b) The
119 study area (green block: latitude North 13.40-13.57, longitude East 2.58-2.82) is located in the Fakara region.

120 *2.2 Phenological characteristics of cropped and fallowed fields*

121 In the Sahel, rainfed crops, dominated by pearl millet and sorghum, are sown with the first rains
122 from late May to late July (Osbaahr, 2001). The main cereal crop is often associated with secondary
123 crops such as cowpea, roselle (*Hibiscus sabdariffa*), and sesame (Ickowicz et al., 2012). Annual

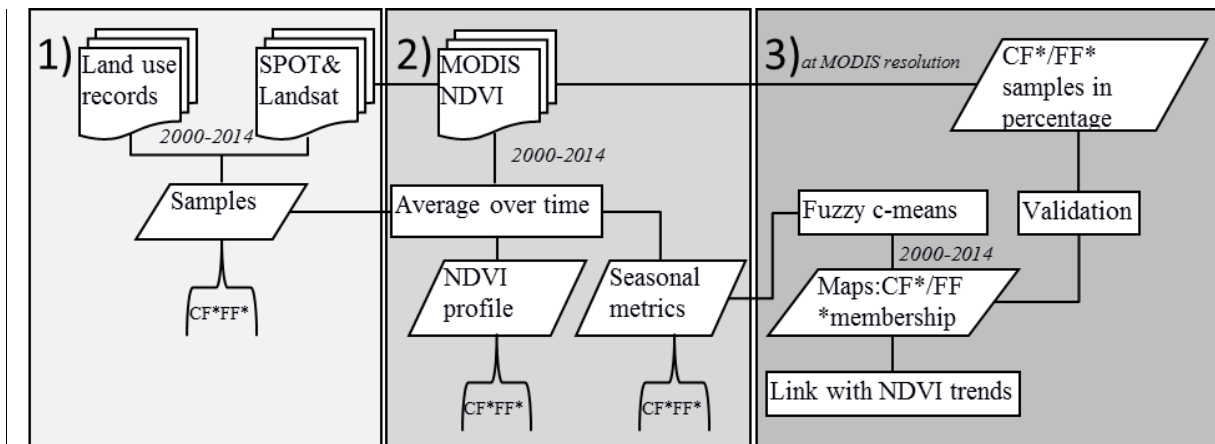
124 herbaceous vegetation, including weeds and crops, germinates within a week. After germination,
125 weeds are suppressed during the early growing season (from two weeks after sowing until late July).
126 Due to the weeding practice, bare soil dominates in cropped fields in the early growing season
127 while herbaceous vegetation continues to grow in fallows and rangelands. By late August and
128 September, green vegetation cover becomes denser in cropped fields because of the rapid growth of
129 the crops. After the crops have matured, the harvest (only the panicles in the case of cereals)
130 normally begins gradually, intensifying from mid-October to late November. The shape of the
131 cropped fields is often irregular and the size of the fields varies from a few tenths of hectares for the
132 manured fields close to villages or camps to a few hectares for the unmanured fields further away
133 from the villages (Minet, 2007).

134 In contrast, fallowed fields are covered by herbaceous vegetation and scattered trees as well as a
135 bush and shrub layer that increases in cover with the age of the fallow (Cisse, Hiernaux, & Diarra,
136 1993). Fallow field vegetation is dominated by annual herbaceous plants (long cycle grasses and
137 short cycle dicotyledons). Both germinate with the first rains and flower from late August to mid-
138 September, driven by the sensitivity to the photoperiod (Penning de Vries & Djitèye, 1982). The
139 herbaceous vegetation wilts soon after seed maturation from mid-September to mid-October.
140 Although the annual herbaceous layer quickly turns into straw, the soil of fallows remains covered
141 with litter for most of the dry season (Bielders, Rajot, & Amadou, 2002). Farmers decide which
142 fields to fallow and for how long by assessing soil fertility, but also by considering the availability
143 of labor for weeding and the accessibility to land for cropping. In Fakara, the landscape was
144 converted from a Sahelian savanna to largely eroded agricultural/agroforestry parkland during the
145 20th century. The native savanna on the cultivable soil, which covered a sizeable portion of the
146 lands in the 1950s, gradually disappeared in the late 1960s (Hiernaux & Ayantunde, 2004). The
147 fields that are not manured are frequently cultivated, typically for five years with alternate years of

148 fallow, typically for three years (Hiernaux & Turner, 2002). There is a transition from fallowed
 149 fields to native Sahelian savanna if a field is left fallow for over 15 years (Hiernaux et al. 2009).

150 **3. Materials and methods**

151 This research is based on data and methods that are sub-divided into three steps (Fig. 2): (1)
 152 Cropped and fallowed fields were sampled using land use/cover records from field observations and
 153 satellite imagery at high spatial resolution (SPOT and Landsat; 10-30 m). (2) The intra-annual
 154 seasonal NDVI signatures (NDVI seasonal metrics) of cropped and fallowed fields were extracted
 155 from MODIS data at a lower spatial resolution (250 m resolution) using the samples generated from
 156 (1). (3) On the basis of the NDVI 250 m resolution seasonal metrics, cropped and fallowed fields
 157 were mapped for each year from 2000 to 2014 using a fuzzy-c means algorithm. Finally, the
 158 dynamics in cropped and fallowed fields were linked to NDVI trends for the study area.



159
 160 **Fig. 2.** Flow chart of the methods applied in this study (CF*FF*: the two field types of cropped and fallowed fields). 1)
 161 Sampling the two field types; 2) temporal profile extraction; 3) mapping the cropped/fallowed fields and analyzing the
 162 relation to NDVI trends.

163 **3.1 Data**

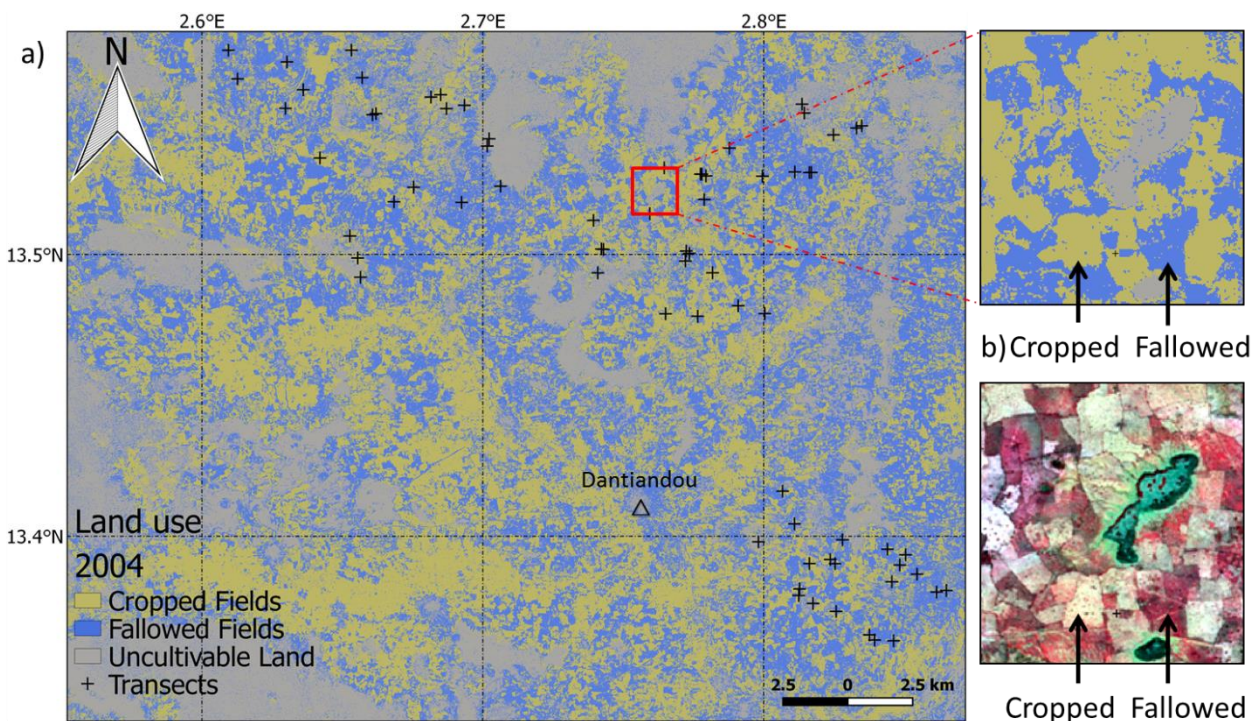
164 **3.1.1 Land use records from field observations**

165 Validation and interpretation of the satellite observed trends are generally limited due to the lack of
166 long-term continuous field measurements (Dardel et al., 2014; Mbow, Fensholt, Nielsen, &
167 Rasmussen, 2014). The long-term monitoring (since 1994) of land use/cover from the Fakara region,
168 available for this study is therefore quite unique for the Sahel (from 1994 to 2006 within the
169 framework of International Livestock Research Institute (ILRI) (Hiernaux & Ayantunde, 2004;
170 Hiernaux et al., 2009) and from 2006 to the present under the AMMA-CATCH observatory
171 activities (African Monsoon Multidisciplinary Analysis-Couplage de l'Atmosphère Tropicale et du
172 Cycle Hydrologique) (Cappelaere et al., 2009; Hiernaux et al., 2009).

173 Initially, 48 sites of cropland (24) and fallow and uncultivable rangeland (24) were selected in 1994
174 to study crop-livestock interactions in mixed farming systems within the ILRI framework (Hiernaux
175 & Ayantunde, 2004). Systematic field surveys have been undertaken on an annual basis at the end
176 of growing season (October), providing a continuous data record of land use/cover from 1994 to
177 2015. The land use/cover has been recorded repetitively over the years along transects as cropland,
178 fallow, or uncultivable rangeland. Transects were 100 m long in cropland (cropped fields) and 200
179 m long in fallow fields and uncultivable rangeland; location coordinates were recorded using non-
180 differential GPS. Due to the frequent changes in land use (except three sites of uncultivable
181 rangeland and five sites of manured cropland with no change in land use), the number of monitored
182 sites was extended over time to maintain a balance between on the one hand, the number of
183 cropland sites and on the other, the number of sites of fallow and uncultivable rangeland together.
184 Historical land use/cover of the added sites was filled in on the basis of farmers' recall (Hiernaux et
185 al., 2009). To match the first year of acquisition of MODIS scenes, only land use/cover records
186 collected from 2000 onwards were used in the study, for an updated total number of 72 sites.

187 A mosaic landscape of three land use/cover types can be found in the region (Fig. 3): cropped fields,
188 fallowed fields, and non-cultivable rangeland. The remains of native vegetation consist of 'tiger

189 bush' (D'Herbès, Ambouta, & Peltier, 1997), which grows on the uncroppable ferricrete plateau.
190 The linear thickets of tiger bush and the bare soil impluvium in between them have a distinctive
191 phenology and radiometric signature (Hiernaux & Gérard, 1999). Due to the focus on studying
192 cropped and fallowed fields on sandy cultivable land, the uncultivable rangelands, together with
193 water bodies and villages, were masked out and disregarded from the analysis using a detailed mask
194 based on SPOT data (unpublished) corresponding well to the mask produced by Lambert et al, 2014,
195 based on PROBA-V data.



196
197 **Fig. 3.** a) Land use/cover map showing the location of the 72 transects for the vegetation surveys (Hiernaux et al., 2009).
198 A supervised classification was done using a SPOT 10 m image from September 28, 2004. b) The map insert shows the
199 same SPOT image in a false color composition (patches of bright white and dark red represent cropped and fallowed
200 fields, respectively).

201

202 3.1.2 SPOT and Landsat images

203 Data from the SPOT and Landsat archives were combined to achieve annual coverage of cloud-free
 204 end of growing season images for the study area from 2000 to 2014 (Table 1). As no images of
 205 good quality were available for 2011, this year was omitted from the further analyses. We used
 206 SPOT 4 and 5 multispectral bands with spatial resolutions of 20 m and 10 m, respectively, acquired
 207 from the European Space Agency through Airbus Defence and Space ([http://www.geo-](http://www.geo-airbusds.com/)
 208 [airbusds.com/](http://www.geo-airbusds.com/)). The acquired images were radiometrically corrected and georeferenced to match a
 209 standard map projection (UTM 31/WGS84) based on ground truth points. Systematically corrected
 210 Landsat Surface Reflectance High Level Data Products were ordered from the United States
 211 Geological Survey through EarthExplorer (<http://earthexplorer.usgs.gov/>). For 30 m resolution
 212 Landsat 4-5 Thematic Mapper (TM) or Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data,
 213 surface reflectance data came already pre-processed using the Landsat Ecosystem Disturbance
 214 Adaptive Processing System (LEDAPS), including the atmospheric and geometric correction.

215 **Table 1.** Selected SPOT and Landsat imageries.

Mission	Acquired date	Resolution
Landsat 5	2000.09.24	30 m
Landsat 5	2001.09.11	30 m
SPOT 4	2002.09.28	20 m
SPOT 4	2003.09.26	20 m
SPOT 5	2004.09.28	10 m
SPOT 4	2005.09.28	20 m
SPOT 4	2006.09.23	20 m
SPOT 4	2007.09.27	20 m
SPOT 5	2008.11.20	10 m
SPOT 4	2009.09.08	20 m
SPOT 5	2010.09.21	10 m
SPOT 5	2012.09.08	10 m
Landsat 8	2013.10.06	30 m
Landsat 8	2014.09.23	30 m

216

217 3.1.3 MODIS NDVI data

218 To form a dense time series, a MODIS NDVI time series at 250 m spatial resolution is deemed
219 more appropriate than the higher spatial resolution data such as Landsat and SPOT imagery (≤ 30 m)
220 due to the lack of cloud-free imageries during the short and intermittent rainy/growing season
221 characterizing the Sahel. The newly released MODIS Surface Reflectance product (MOD09Q1)
222 collection 6 from the Terra platform (www.reverb.echo.nasa.gov) was used to derive an NDVI time
223 series at 250 m resolution for 2000 to 2014. MOD09Q1 provides estimates of surface reflectance
224 for two spectral bands (Red band 1: 620-670 nm; NIR band 2: 841-876 nm). The MOD09Q1 8-day
225 product was selected because it contains the best possible level 2 (L2G) daily observations during
226 an eight-day period (Vermote, El Saleous, & Justice, 2002; Gao, Masek, Schwaller, & Hall, 2006),
227 which was found to be optimal for capturing the differences in temporal changes for cropped and
228 fallowed fields.

229 *3.2 Sampling cropped and fallowed fields from SPOT/Landsat data*

230 Using the SPOT/Landsat dataset (Table 1), a method was applied to locate both cropped and
231 fallowed fields covering sufficiently large areas to extract the NDVI signature from 250 m MODIS
232 pixels. (1) Maximum likelihood classification (MLC) was performed on each image (representing
233 individual years) to obtain three classes (cropped fields, fallowed fields, and uncultivable land).
234 This was done using the land use/cover records of the transects (ground observations), which were
235 converted from lines (100 m/200 m) to polygons (200 m \times 100 m/300 m \times 100 m) by buffering 50 m
236 in each direction. (2) Filtering with the majority vote was applied on the classified maps to remove
237 isolated pixels regarded as noise by replacing pixels in clusters of pixels (3 \times 3 pixels) on the basis of
238 the majority of their contiguous neighboring pixels.

239 Cropped and fallowed fields were sampled using an interactive visualization of the classification
240 and SPOT/Landsat image in a false color composition. Given the challenging ground reality of

241 fields, in this way, both field samples and classified maps were evaluated visually using ground
242 truth knowledge (Fig. 3b). For each year, 20 cropped fields and 20 fallowed fields were sampled to
243 meet the requirement that each sample should cover at least one 250 m MODIS pixel.

244 3.3 Extraction of seasonal NDVI signatures for cropped and fallowed fields

245 The NDVI signatures of cropped and fallowed fields for each year were composed of 46 NDVI
246 values (using the 8-day temporal resolution MODIS product), each calculated by averaging the
247 NDVI values of the above mentioned 40 samples of cropped (20) and fallowed fields (20) generated
248 for a given year. The entire study period includes wet and dry years, making single-year seasonal
249 NDVI signatures less representative. To have a robust seasonal NDVI signature, the final NDVI
250 profile for cropped and fallowed fields was generated by averaging the derived seasonal NDVI
251 signatures of the years of the entire study period (Fig.5a).

252 Seasonal metrics were extracted on an annual basis from the MODIS NDVI time series using the
253 Timesat software (<http://web.nateko.lu.se/timesat/timesat.asp>) (Jönsson & Eklundh, 2004), which is
254 a widely-used tool to analyze satellite time series in relation to vegetation phenology (Brandt et al.,
255 2016; Diouf et al., 2015; Fensholt et al., 2015; Olsson et al., 2005; Wang et al., 2015). The seasonal
256 metrics (Table 2) were computed on the basis of the fitted NDVI time series using a Savitsky-Golay
257 filter. The start and end of the season were estimated by setting a user-defined fraction of the
258 seasonal amplitude, based on relevant knowledge of *in situ* seasonality. In this study, the start of the
259 season was set to 20% of the seasonal amplitude to capture the general vegetation growing period
260 (from mid-July to end of October) estimated from field experiences (section 2.2). The end of the
261 season was defined using the criterion of 45% of the seasonal amplitude, approximately
262 corresponding to the end of vegetation growing season, when the senescence of herbaceous

263 vegetation occurs and only woody plants remain green with active photosynthesis (Brandt et al.,
 264 2016).

265 **Table 2.** Satellite-derived seasonal NDVI metrics used in this study.

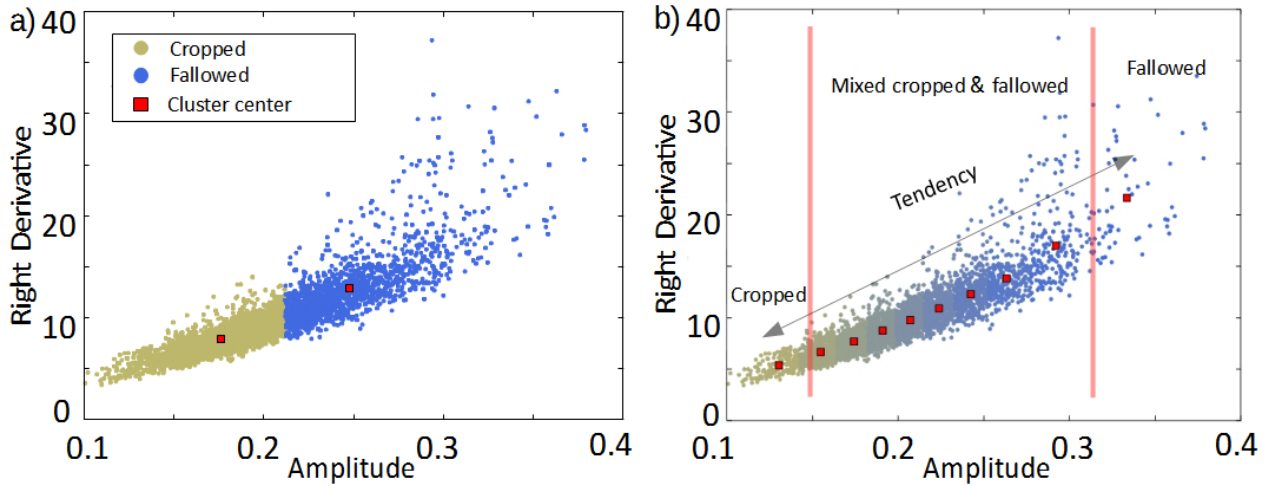
Variable	Definition	Reported Unit
Amplitude	Difference between maximum and base value	NDVI unit
Base value	Mean of minimum NDVI values before sos and after eos	NDVI unit
End of season (eos)	Ending point of the growing season (45% of amplitude)	Day of year
Length of season	Number of days from sos to eos	Number of days
Maximum value	Highest value of a year	NDVI unit
Right derivative	Rate of decrease at the end of the season	NDVI unit/Time unit ⁻³
Small integral	Integral from sos to eos but above base value	NDVI unit
Start of season (sos)	Starting point of the growing season (20% of amplitude)	Day of year

266 *3.4 Cropped and fallowed fields separation from temporal NDVI signatures*

267 Accurate wall-to-wall separation of the ‘cropland’ into cropped and fallowed fields using Timesat-
 268 derived seasonal metrics (see Section 3.3) can be difficult due to the presence of mixed pixels
 269 composed of both cropped and fallowed fields (approximate ≤ 1 ha) at the spatial resolution of
 270 MODIS data (approximate ≥ 6 ha). Also, the development of training sets for supervised image
 271 classifiers without any *a priori* knowledge is another challenging task, as agricultural fields change
 272 dynamically over time from cropped to fallowed fields and back again. Therefore, we applied a
 273 simple and robust unsupervised method for this step, which reports the membership of mixed pixels
 274 to cropped/fallowed fields in a gradation of percentage values and does not require training data
 275 (Ghosh, Mishra, & Ghosh, 2011; Zhang, Du, Li, Fang, & Ling, 2014). The method is an
 276 unsupervised fuzzy c-means (FCM) algorithm (Bezdek, Ehrlich, & Full, 1984), which is a non-
 277 parametric fuzzy clustering (classification) technique appropriate to separate overlapping clusters
 278 (classes) (Mather & Tso, 2016).

279 Upon selection of the desired number of clusters for the FCM algorithm, the belonging of a pixel to
 280 a cluster (membership) is derived through the iterative optimization of an objective function, which

281 calculates the Euclidean distance of each pixel from the center of a given cluster. Without *a priori*
282 training data for the defined clusters, the first iteration starts with an initial guess of the
283 memberships of all pixels and stops when the iteration reaches either the number of times or the
284 accuracy pre-defined by users. The membership value ranges from 0 to 1, indicating the ratio of the
285 class to each of the defined classes (e.g., for two classes of cropped and fallowed fields, a pixel with
286 a membership value of 0.3 for cropped fields will have a membership value of 0.7 for fallowed
287 fields). We used *scikit-fuzzy* (<http://pythonhosted.org/scikit-fuzzy/overview.html>), which is a fuzzy
288 logic toolbox for Python, implemented with an FCM clustering algorithm (Ross, 2004). Following
289 the design of the analysis, the number of clusters (c) should be two (cropped and fallowed fields).
290 However, by including only two clusters, the center of a cluster determined by the unsupervised
291 algorithm will locate in the space of mixed pixels (Fig. 4a) and the algorithm will assign the same
292 membership values to pixels having the same Euclidean distance to the center of cluster. This
293 causes the incorrect clustering of mixed pixels to the endmembers, which represent the pure
294 cropped and pure fallowed fields in a spectral image. To circumvent this, the approach can be
295 optimized in two steps using different settings for the number of clusters (Fig. 4b). Firstly, we
296 applied the FCM algorithm on input images of the selected seasonal metrics to 100 clusters to
297 generate the center of two “pure” clusters of cropped and fallowed fields (endmember sets).
298 Secondly, we re-applied the FCM algorithm to the same input images using the extracted
299 endmember sets to generate the cropped/fallowed field membership maps. Three additional
300 parameters were set: maximum number of iterations (maxiter) = 1000, accuracy (error) = 0.005, and
301 weighting parameter (m) = 2. The weighting parameter is an exponent factor in the algorithm to
302 control the amount of fuzziness in the clustering process; the most widely used values are in the
303 range of 1.25 to 2 (Ross, 2004). The analysis was applied at extent of the detailed mask extent (see
304 section 3.1.1) reported as the study area in Fig.1 b.



305

306 **Fig. 4.** Scatter plots illustrating the locations of unsupervised FCM generated clusters (red squares). Examples of a) 2
 307 clusters and b) 10 clusters using the inputs of amplitude and the right derivative of the year 2004. A larger number of
 308 clusters will facilitate extraction of endmembers for pure cropped and fallowed fields.

309 *3.5 Validation*

310 In several land use/cover mapping studies, the membership value has been used as a proxy for the
 311 fractional coverages of land use/cover classes on the ground (Foody, 2000; Wang, 1990). It is thus
 312 possible to validate the membership of cropped and fallowed fields by comparing with the
 313 corresponding percentage of cropped and fallowed fields estimated by visually identifying and
 314 digitizing the classes using contextual information, such as patterns, texture, and colors from false
 315 color composite Landsat/SPOT imagery. We digitized the fallowed fields in single MODIS 250 m
 316 pixels using the available four years of SPOT 5 imagery (2004, 2008, 2010, and 2012 (Table 1))
 317 (spatial resolution of 10 m). For each of the four years, the size of 50 validation samples,
 318 corresponding to a MODIS pixel size, was randomly generated and the fallowed fields in each
 319 sample were digitized. The proportion of fallowed fields in each 250 m sample was further
 320 calculated by dividing the area of the digitized fallowed fields by the area of one MODIS pixel. The
 321 accuracy of the membership maps was evaluated through the strength (correlation coefficient), the

322 differences (root-mean-square error), and the significance level of linear association between
323 fallowed field membership and the percentage of fallowed fields.

324 *3.6 Linking cropped and fallowed fields with NDVI trends*

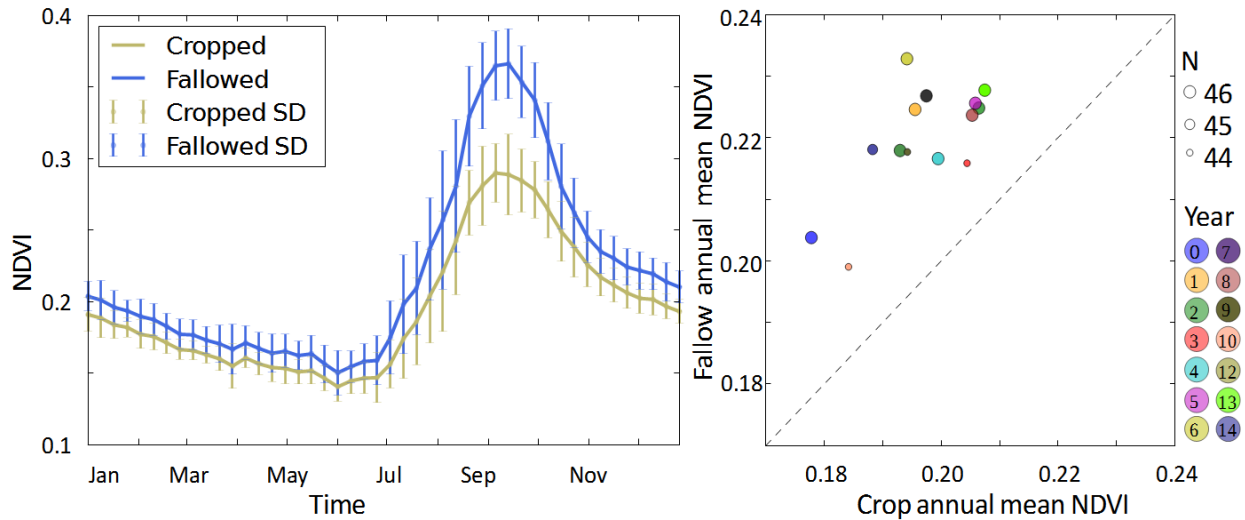
325 To analyze the NDVI trends in relation to land use/cover changes, a time series of annual
326 membership was generated (2000-2014). Temporal trends analysis was applied using a linear
327 regression model to generate the pixel-wise slopes of annual NDVI sum and annual field
328 membership. The slope values were standardized for comparison. Furthermore, the total
329 cropped/fallowed area for each year was calculated by multiplying the cropped/fallowed field
330 membership values with the area of one MODIS pixel and summing the cropped/fallowed field
331 areas of all pixels. The standardized slope, P value, and standard deviation (SD) of the
332 cropped/fallowed area were extracted for further statistical analysis and compared with commonly
333 used time-series NDVI metrics (annual NDVI sum, rainy season NDVI sum (July, August and
334 September), small integral, large integral), and annual rainfall sum (extracted over the Niamey
335 Square Degree from 2000 to 2012 collected by AMMA-CATCH).

336 **4. Results**

337 *4.1 Seasonal NDVI signatures of cropped and fallowed fields*

338 A total area equal to the size of 5,000 MODIS pixels was sampled and averaged for cropped and
339 fallowed fields over the period of study. Over the dry season (November-June), we observed that
340 fallowed fields had a slightly higher NDVI (~0.02) than cropped fields (Fig. 5a). During the rainy
341 season, fallowed fields had a higher maximum NDVI (~0.1) than cropped fields. Also, the NDVI of
342 fallowed fields decreased faster than that of cropped fields after the rainy season. In all years,
343 fallowed fields had a higher annual mean NDVI than cropped fields (Fig. 5b). For 11 out of 15

344 years, all 8-day composite values ($N = 46$) of the averaged fallowed fields NDVI are higher than
 345 cropped fields (for 2003 ($N = 44$), 2010 ($N = 44$), 2012 ($N = 44$) and 2014 ($N = 45$)).

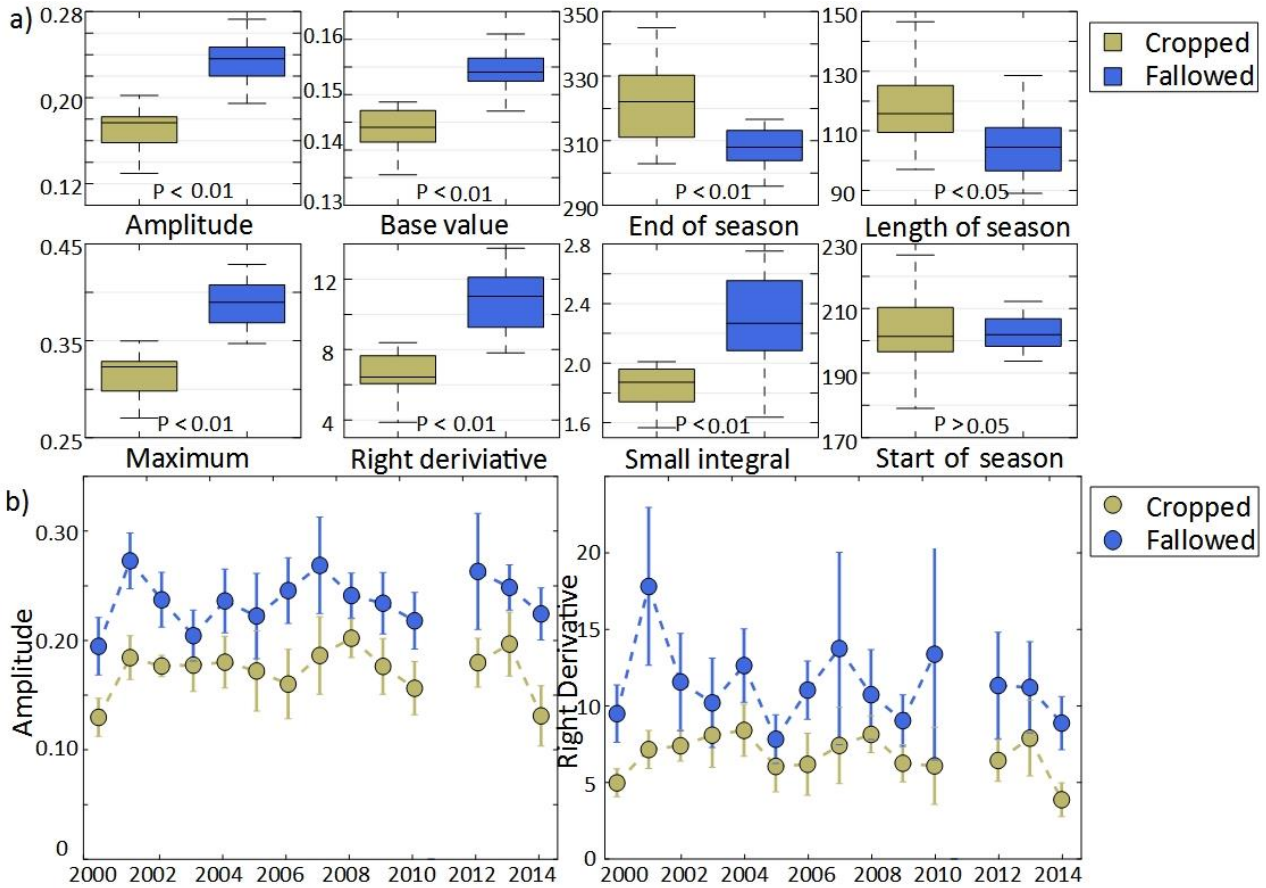


346
 347 **Fig. 5.** a): Intra-annual NDVI profiles averaged for all cropped/fallowed fields between 2000 and 2014. b): Scatter plot
 348 between the annual NDVI average of cropped and fallowed fields. Number (N) of MODIS 8-day composite values (per
 349 year) of higher averaged NDVI of fallowed fields than of cropped fields are indicated by the size of the circles.

350 The fallowed fields were found to have a higher amplitude, base value, maximum, right derivative,
 351 and small integral than cropped fields and the end of season and length of season of cropped fields
 352 are later and longer, respectively, than those of fallowed fields, averaged over all years (Fig. 6a). A
 353 highly significant difference between cropped and fallowed fields was found for all these metrics
 354 ($P < 0.01$), except that the length of season was found to be slightly less separable ($P < 0.05$). No clear
 355 difference was detected for the determination of the start of season ($P > 0.05$).

356 To avoid the problem of model overfitting, only a limited number of metrics were selected as inputs
 357 for final fuzzy c-means clustering. The selection of metrics was based on the significance level (P),
 358 metric robustness, and level of phenology information content. The amplitude (2nd highest P value)
 359 was selected together with the right derivative (4th highest). The selection of amplitude over
 360 maximum (1st) and base value (3rd highest) was deemed appropriate because amplitude combines

361 information on both other metrics. Amplitude and right derivative were found to be significantly
 362 different ($P < 0.01$) between cropped and fallowed fields for each single year (Fig. 6b).

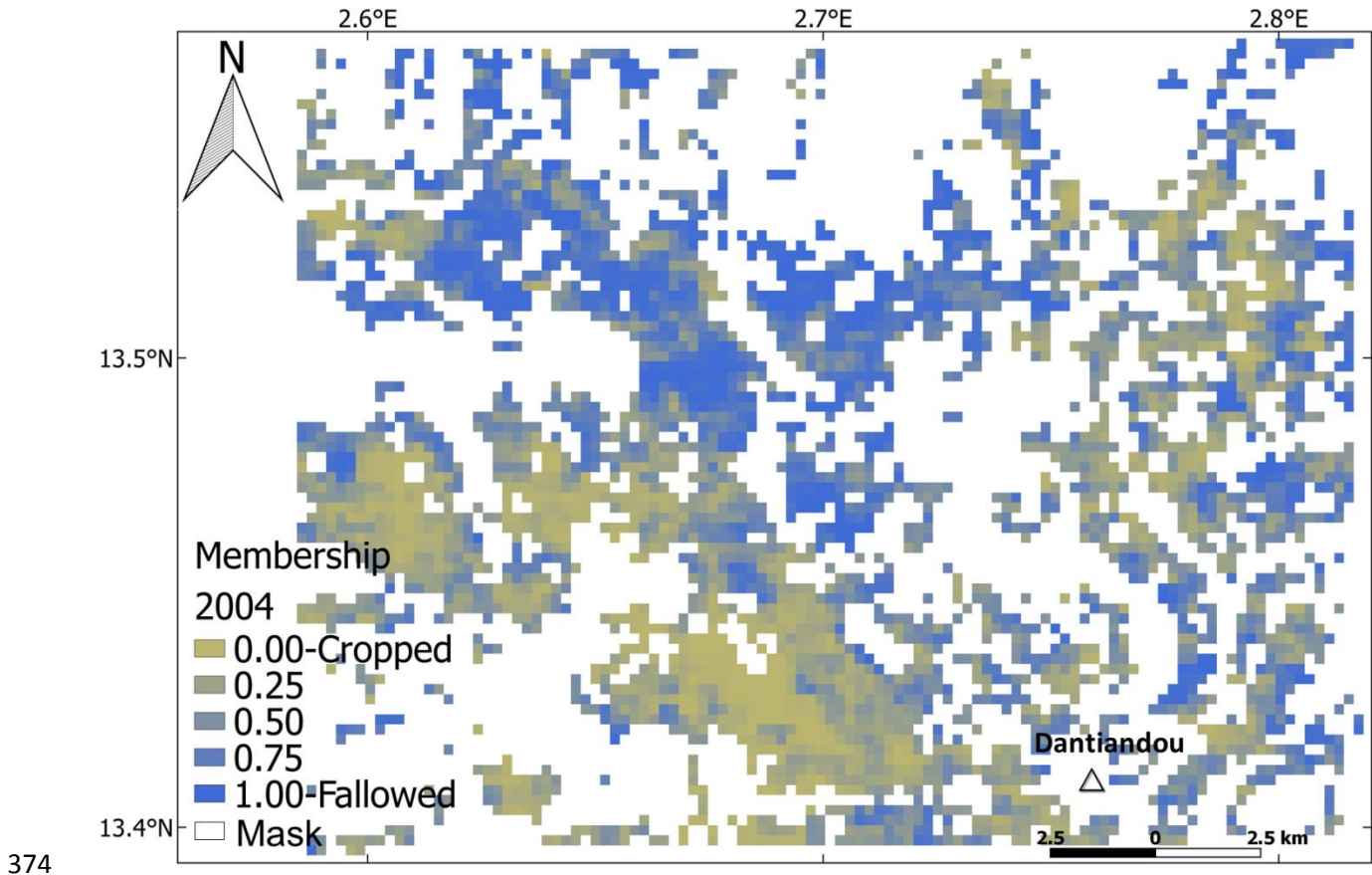


363
 364
 365 **Fig. 6.** a) Box plots comparing NDVI metrics for cropped and fallowed fields averaged over the period of analysis
 366 (2000-2014). b) Plots showing the yearly difference of amplitude (left) and right derivative (right) between cropped and
 367 fallowed fields. The standard deviations shown correspond to the variability between samples.

368 *4.2 Separation between cropped and fallowed fields*

369 The fuzzy classifier (Fig.7) captures very well the spatial distribution shown in Figure 3
 370 (classification based on SPOT 10 m, 2004). Higher concentrations of MODIS pixels with a high
 371 fallow membership (blue) are found in the northern part of the study area and higher concentrations

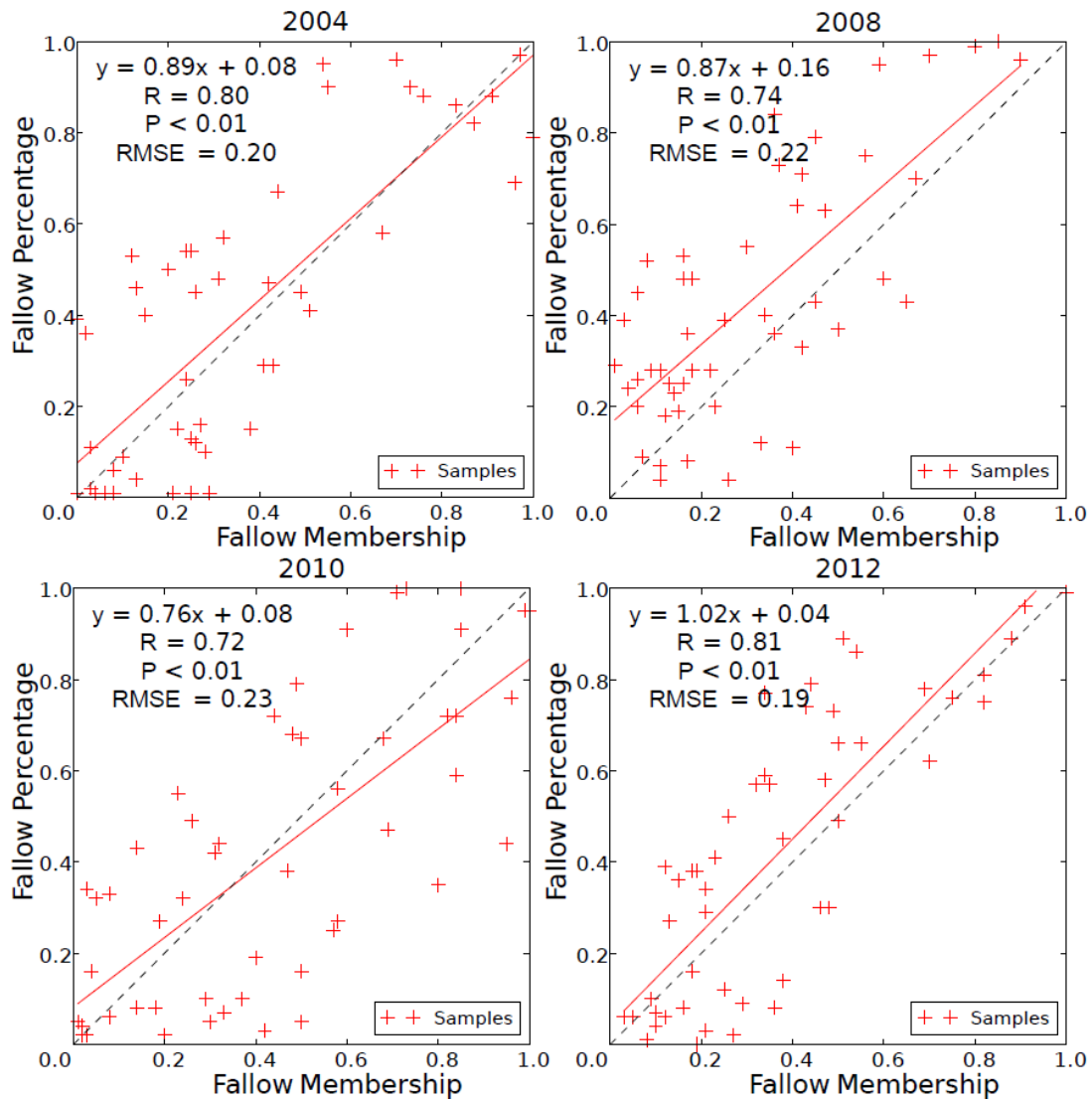
372 of pixels characterized by a high crop membership can be observed in the southwestern part of the
373 region (Fig. 7).



375 **Fig. 7.** Cropped/fallowed field membership map of 2004 using MODIS 250 m resolution seasonal NDVI metrics inputs
376 (amplitude and right derivative).

377 4.3 Validation results

378 The correlation coefficients (R) between FCM membership and fallow percentage range from 0.72
379 to 0.81 ($p < 0.01$) for the four validated years, indicating an overall good fit (Fig. 8). The error rates
380 for predictions (RMSE) are low, ranging from 19% to 23%. An underestimation of the fallowed
381 field percentage is observed for 2008 and 2012. The fallowed field percentages of 2004 and 2010
382 were slightly underestimated for MODIS pixel size samples with a larger percentage of cropped
383 area and overestimated for the samples with a larger percentage of fallowed area.



384

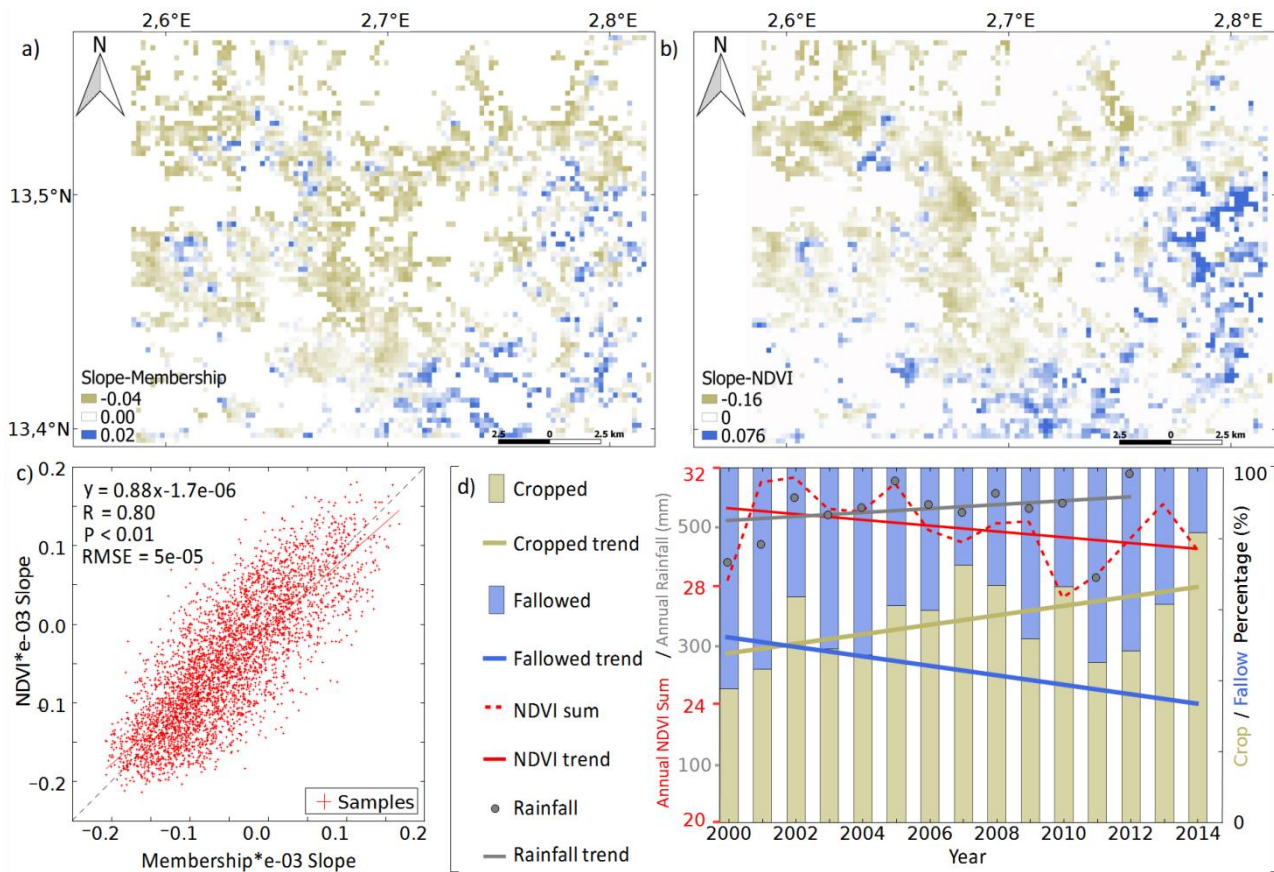
385 **Fig.8.** Linear regression between FCM membership and fallow percentage (derived from digitalizing SPOT 10 m
 386 imageries), plotted for four years (2004, 2008, 2010, and 2012).

387 *4.4 Trend analysis*

388 Negative trends in cropped/fallowed field membership are observed in the northern and central part
 389 of the study area (Fig. 9a), indicating an increase in the area of cropped fields from 2000 to 2014.
 390 Positive trends, associated with an increase in the fallowed area over time, are mostly seen in the
 391 southeastern part of the region. Compared with the slope map of annually summed NDVI (Fig. 9b),
 392 both the negative and positive trends of NDVI display a similar spatial pattern to cropped/fallowed

393 field membership. The slopes of NDVI and cropped/fallowed field membership are highly
394 correlated, with a correlation coefficient (R) of 0.8 ($p < 0.01$) (Fig 9c).

395 The overall trend in NDVI for the Fakara study area is negative for all summed NDVI metrics
396 commonly used for trend analysis in the period 2000-2014 (Fig. 9d and Table 3). No trends are
397 found to be significantly negative, which is primarily due to the exceptionally low NDVI values for
398 the first year of analysis (2000) caused by low rainfall (Hiernaux et al., 2009). The trend of the
399 annual NDVI sum (slope = -0.083; $P = 0.19$) is stronger and more significant than that of the small
400 integral (slope = -0.057; $P = 0.38$). Starting the analysis in 2001 (excluding the abnormally dry year
401 of 2000) would cause the negative trend of the annual NDVI sum to be highly significant (slope = -
402 0.150; $P = 0.014$) (Table 3). In contrast, there is a significant positive trend in the total cropped area
403 ($p < 0.1$) and a corresponding decrease in total fallowed area. As no significant trend in annual
404 rainfall was observed over the 15 years studied, it is unlikely that rainfall is responsible for the
405 negative NDVI trend, pointing towards changes in the cropped area as a main driver for the
406 observed trend. Although the timing and frequency of rainfall can have a significant impact on
407 vegetation productivity, it is beyond the scope of analysis in the current study.



408

409 **Fig. 9.** a) Slope values from linear regression trend analysis of cropped/fallowed field membership maps (2000-2014).
 410 Positive slope values mean a direction of change towards more fallows, b) slope values from the linear regression trend
 411 analysis of MODIS annual NDVI sum (2000-2014), c) scatter plot showing the relation between slope values of
 412 cropped/fallowed field membership and annual NDVI sum, and d) bar plot showing the percentage of cropped and
 413 fallowed areas in the Fakara study area. Linear trends are shown for cropped fields, fallowed fields, annual NDVI, and
 414 rainfall sum.

415 **Table 3.** Standardized coefficients of linear regression analysis (2000-2014).

Variables	Cropped/Fallowed		NDVI metrics				Rainfall	
	fields	fields	Annual sum		Small integral	Large integral	JAS sum	annual sum
			2000-2014	2001-2014				
Slope	0.113	-0.113	-0.083	-0.150	-0.057	-0.042	-0.047	0.068
P value	0.065	0.065	0.192	0.014*	0.380	0.522	0.472	0.403
SD	0.056	0.056	0.060	0.052	0.062	0.063	0.063	0.078

416 * Significant at $p < 0.05$

417

418 **5. Discussion**

419 This study has demonstrated that cropped and fallowed fields are characterized by different
420 seasonal NDVI metrics, which has important implications for the interpretation of greening and
421 browning trends in the Sahel based on satellite time series (Dardel et al., 2014; Kaptué, Prihodko, &
422 Hanan, 2015). Cropped fields have been shown to have a significantly lower summed NDVI than
423 fallowed fields for the study area, and if cropped and fallowed fields are merged into one land
424 use/cover class, the corresponding NDVI trends must be interpreted with caution.

425 *5.1 Linking changes in cropped and fallowed field areas to NDVI trends*

426 For the study area in Fakara, an overall negative NDVI trend was observed in the period 2000-2014,
427 and at the same time we also observed an increase in cropped areas. Although this is in line with
428 Dardel et al. 2014, who related the negative NDVI trend in Fakara to a decrease in field measured
429 herbaceous mass (1994-2011), the period of analysis is different, and Dardel et al. 2014 did not find
430 a negative trend for herbaceous mass between 2000 and 2011. Furthermore, no trend in rainfall was
431 observed for the time period analyzed here, which is in line with Dardel et al. 2014 and Hiernaux et
432 al. 2016, making changes in water availability very unlikely as an explanation for the decreasing
433 NDVI (a strong coupling between integrated NDVI and rainfall is normally observed in the Sahel
434 (Fensholt et al., 2013; Huber et al., 2011). This points towards land use and management as
435 explanations for the decrease in NDVI, and here we document an increase in per pixel cropped area
436 percentages. Given the fact that all arable land was under human management in the Fakara region
437 prior to 2000, it can be assumed that the observed change in the percentage of cropped area is
438 caused by a change in the crop-fallow cycle towards less fallowed and more cropped fields during
439 the period studied.

440 Although no greening was observed in our study area, these findings should be considered in the
441 greening Sahel debate. Apart from the well-known influence from changes in rainfall (Dardel et al.,
442 2014), there are two different interpretations of the causes of a positive NDVI trend in cropland
443 areas: (1) an intensification due to increased use of fertilizers (usually organic manure on staple
444 crops) (Hiernaux, Dardel, Kergoat, & Mougín, 2016), and (2) a change in the crop-fallow cycle of a
445 given area with more frequent fallow years or even the complete abandonment of the cropped fields
446 for several years. This second cause, supported by the current findings, might lead to a rethinking of
447 several assumptions about the re-greening of the Sahel. It suggests that, in some places, the Sahel
448 greening might not be caused by an increased agricultural productivity (Bégué et al., 2011), but
449 rather by an abandonment of the fields, i.e., a decrease in agricultural activities. The abandonment
450 could be caused by declining soil fertility (paradoxically leading to an increased NDVI, as savanna
451 vegetation takes over fallowed fields), or by a diversification of livelihoods of the local people (the
452 prolonged droughts in the 1970s and 1980s and the following dry period made cultivation a highly
453 uncertain income, and some people abandoned their fields and sought alternative livelihood
454 strategies (Brandt, Romankiewicz, Spiekermann, & Samimi, 2014; Rasmussen & Reenberg, 2012;
455 Romankiewicz, Doevenspeck, Brandt, & Samimi, 2016)). Rainfall in the Sahel has increased during
456 recent years, but inter and intra-annual variability has increased as well (Sanogo et al., 2015), and
457 many farmers are reluctant to take this risk or have generated a different income (Romankiewicz et
458 al., 2016). Even though fields might be abandoned or rarely used, this is likely to be missed in
459 traditional classifications based on Landsat-like spatial resolution, which merges cropped and
460 fallowed fields. Alternatively, it may be detected as an increase in NDVI and interpreted as an
461 increase in agricultural productivity. Since lands that are being left for fallow over long time periods
462 (around 15 years) tend to have vegetation similar to natural savanna, also the conversion from

463 savanna to (cultivated) cropland might impact NDVI trends in a way comparable to our case study
464 area (i.e. a negative NDVI trend).

465 *5.2 Applicability of results at the Sahel scale?*

466 To further relate the current results to the re-greening of the Sahel, an extrapolation of our method
467 to Sahel scale is required, which poses a number of challenges. Firstly, natural resource
468 management is not uniform, and the method should be robust toward different land use practices.
469 Secondly, the vegetation is adapted to the decreasing mean rainfall gradient from South to North
470 (approximately 1 mm/km). Although rainfed cropping is only marginally practiced in the northern
471 zones of the Sahel, it would be wise to study the cropped/fallowed differences for each rainfall zone
472 separately. Thirdly, a frequently updated pre-classification could be necessary to separate non-
473 arable land from potentially cropped areas to be analyzed for changes in cropped/fallowed spatio-
474 temporal patterns. Reliable classifications across the Sahel have been deficient, but recently, a few
475 promising approaches on cropland classifications have emerged (Lambert et al., 2016), which might
476 be used to overcome this issue. However, these are snapshots in time, and without proper field data,
477 which are usually scarce and not publicly available, and/or reliable and detailed classifications
478 covering several years, validation and calibration is not possible. Finally, manured cropped fields
479 that are sown more densely and grow more rapidly are likely to be characterized by different NDVI
480 seasonal metrics (being more similar to fallowed fields) than unmanured cropped fields. As
481 manured fields are usually located around villages, we masked these areas by using a buffer of 500
482 m around settlements, but this might be challenging at Sahel scale.

483 *5.3 Methodological limitations*

484 The method presented includes several assumptions/uncertainties, which also must be taken into
485 account when applying the method at larger spatial scales and/or using it to interpret NDVI trends.

486 The fuzzy classification method was used to estimate the percentage of a field that is
487 cropped/fallowed on an annual basis. However, strictly speaking, the method predicts the
488 probability of a pixel belonging to either the crop or the fallow endmember class. While several
489 studies have interpreted this as equivalent to percentage (Foody, 2000; Wang, 1990), it is not
490 exactly the same unless no untrained classes are included in the analysis (Foody, 2000). Even
491 though cropped/fallowed fields are the only two classes considered in the analysis, some uncertainty
492 remains when applying FCM to coarser resolution imagery, which might still include untrained
493 classes at the sub-pixel level. To improve the method, a higher spatial resolution would be
494 advantageous, which is, however, currently not available at this temporal frequency over a longer
495 time period. PROBA-V provides a resolution of 100 m (Lambert et al., 2016) but it is not yet
496 available for multiple years, and the lower temporal frequency, as compared to MODIS, reduces the
497 chance of having cloud-free images.

498 Disturbances by clouds have also been shown to influence the current MODIS based analysis of
499 seasonal NDVI metrics. The start of the growing season metric (SOS), which is a period with
500 persistent cloud cover in the Sahel (Fensholt et al., 2011), has been of limited use for our analysis,
501 despite the expectation of a distinct difference between the green-up of crops and the herbaceous
502 stratum of rangelands and fallows (due to the weeding of cropped fields). This is in line with Diouf
503 et al. 2016, who did not find any significant relationship between a satellite-based metric of SOS
504 and rangeland field data from Senegal. A newer MODIS retrieving algorithm termed MAIAC
505 (Multi-Angle Implementation of Atmospheric Correction) can deliver more cloud-free images as
506 compared to the standard MODIS processing (Bi et al., 2016; Lyapustin et al., 2012) and this might
507 enable the implementation of additional seasonal NDVI metrics to improve the separability of land
508 use/cover classes in future studies.

509 Another variable influencing seasonal NDVI metrics in general, and the SOS metric in particular, is
510 the woody vegetation, as leaves of several Sahelian woody species sprout before the wet season
511 starts and the herbaceous vegetation and crops germinate (Brandt et al., 2016). Here, we observed a
512 constant gap between cropped and fallowed fields (Fig. 5a), which might be caused by differences
513 in woody vegetation cover. Whereas most shrubs are annually coppiced in fields prior to cultivation,
514 they are left to grow in fallowed fields, leading to a higher shrub/woody plant cover. In recent years,
515 though, there have been great efforts in the Sahel to leave more trees on agricultural land
516 (agroforestry parklands) (Bayala, Sanou, Teklehaimanot, Kalinganire, & Ouédraogo, 2014), likely
517 to influence the NDVI signals of cropped fields in a different way than is observed in the Fakara
518 region (very limited agroforestry). Potential effects of Parklands on seasonal metrics should be
519 analyzed further if applying the current method at the Sahel scale. Finally, the abundance of big
520 trees in the cropped fields in proximity to the villages impacts the NDVI signal significantly.

521 **6. Conclusion**

522 Existing land use/cover studies commonly merge cropped and fallowed fields into one class of
523 cropland/agriculture and different hypotheses have been brought forward when interpreting the
524 relation between positive NDVI trends and changes in areas under cultivation. For a case study area
525 in the southern Sahel (Fakara region, Niger) we have developed a classification approach to
526 separate cropped from fallowed fields based on the different phenological characteristics of the
527 vegetation as monitored by MODIS 250 m resolution data. Fallowed fields generally have a higher
528 NDVI and a more rapid decreasing rate (after the wet season) than unmanured cropped fields and
529 these differences in phenology were used to separate the seasonal signals of cropped and fallowed
530 fields. A fuzzy classifier (unsupervised fuzzy c-means (FCM) algorithm) was used to quantify the
531 percentage of cropped/fallowed fields for the period 2000 to 2014 on an annual scale. We observed
532 a trend toward an increase in the percentage of cropped area and a decrease in fallowed fields,

533 which can be interpreted as a shortening of the fallow period for this region, and at the same time,
534 we observed a generally negative NDVI trend that was not explained by changes in rainfall over the
535 period of analysis. In contrast to other hypotheses about re-greening being driven by an increase in
536 organic fertilizers, we have shown here that an increasing NDVI trend might be linked to an
537 increase in fallowed fields, caused by more frequent fallow years or land abandonment. If this result
538 can be projected to larger areas, this has significant implications for our understanding and
539 interpretation of greening and browning trends in relation to EO based monitoring of ecosystem
540 services and land degradation in the arable lands of Sahel. The MODIS based development of the
541 classification of the percentage of cropped/fallowed fields builds on their differences in seasonal
542 metrics using an unsupervised algorithm and thereby might be applicable at the Sahel scale,
543 although there are scale-dependent challenges to overcome in relation to differences in land use
544 practices and annual rainfall. To further test the importance of land abandonment and intensification
545 (both from usage of manure and from shortening fallow periods) for the observed trends in NDVI at
546 the Sahel scale, the applicability of this phenology driven classification approach must be studied at
547 larger scales involving a wider range of climatic conditions and human livelihood strategies.

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734 *List of Figure Captions*

735 **Fig. 1.** a) The location of the Fakara region in Niger (red block) within the Sahelian delineation (dashed lines). b) The
736 study area (green block: latitude North $13^{\circ}23'54''$ - $13^{\circ} 33' 57''$, longitude East $2^{\circ}35'3''$ - $2^{\circ}49'8''$) is located in the
737 Fakara region.

738 **Fig. 2.** Flow chart of the methods applied in this study (CF*FF*: the two field types of cropped and fallowed fields). 1)
739 Sampling the two field types; 2) temporal profile extraction; 3) mapping the cropped/fallowed fields and analyzing the
740 relation to NDVI trends.

741 **Fig. 3.** a) Land use/cover map showing the location of the 72 transects for the vegetation surveys (Hiernaux et al., 2009).
742 A supervised classification was done using a SPOT 10 m image from September 28, 2004. b) The map insert shows the
743 same SPOT image in a false color composition (patches of bright white and dark red represent cropped and fallowed
744 fields, respectively).

745 **Fig. 4.** Scatter plots illustrating the locations of unsupervised FCM generated clusters (red squares). Examples of a) 2
746 clusters and b) 10 clusters using the inputs of amplitude and the right derivative of the year 2004. A larger number of
747 clusters will facilitate extraction of endmembers for pure cropped and fallowed fields.

748 **Fig. 5.** a): Intra-annual NDVI profiles averaged for all cropped/fallowed fields between 2000 and 2014. b): Scatter plot
749 between the annual NDVI average of cropped and fallowed fields. Number (N) of MODIS 8-day composite values (per
750 year) of higher averaged NDVI of fallowed fields than of cropped fields are indicated by the size of the circles.

751 **Fig. 6.** a) Box plots comparing NDVI metrics for cropped and fallowed fields averaged over the period of analysis
752 (2000-2014). b) Plots showing the yearly difference of amplitude (left) and right derivative (right) between cropped and
753 fallowed fields. The standard deviations shown correspond to the variability between samples.

754 **Fig. 7.** Cropped/fallowed field membership map of 2004 using MODIS 250 m resolution seasonal NDVI metrics inputs
755 (amplitude and right derivative).

756 **Fig.8.** Linear regression between FCM membership and fallow percentage (derived from digitalizing SPOT 10 m
757 imageries), plotted for four years (2004, 2008, 2010, and 2012).

758 **Fig. 9.** a) Slope values from linear regression trend analysis of cropped/fallowed field membership maps (2000-2014).
759 Positive slope values mean a direction of change towards more fallows, b) slope values from the linear regression trend
760 analysis of MODIS annual NDVI sum (2000-2014), c) scatter plot showing the relation between slope values of
761 cropped/fallowed field membership and annual NDVI sum, and d) bar plot showing the percentage of cropped and
762 fallowed areas in the Fakara study area. Linear trends are shown for cropped fields, fallowed fields, annual NDVI, and
763 rainfall sum.