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Assessment of Agricultural Practices From Sentinel 1 and 2 Images Applied on Rice Fields to Develop a Farm Typology in the Camargue Region

Dominique Courault , Laure Hossard, Fabrice Flamain, Nicolas Baghdadi, and Kamran Irfan

Abstract—In the global change context, an efficient management of the available resources has become one of the most important topics particularly for the sustainable crop development. Many questions concern the evolution of the rice farming systems in Camargue in Southeastern France, which play a crucial role in controlling the soil salinity. Their surface area significantly decreased from 20 000 ha in 2010 to 14 000 ha in 2014. The arrival of the new Sentinel satellites makes it possible to evaluate these crop evolutions. The objectives of this study were to propose operational methodologies to accurately assess the surface areas of the main crops, rice, wheat, and grassland, from classifications based on multispectral data; map agricultural practices (sowing and harvest residue burning); and elaborate a farm typology based on variables computed from remote sensing data to better understand the farming strategies. Dense time series of Sentinel images acquired at high spatial resolution (10 m) were analyzed for 2016 and 2017. A satisfactory accuracy was obtained for land use classification with 88% of correctly classified fields. The accuracy obtained for the estimation of the sowing date varied according to the studied year from 8 to 12 days, and burned areas were correctly identified (80%). The farm typology allowed to cluster farms at the territory level.

Index Terms—Agricultural practices, classification, farm typology, high resolution, remote sensing, rice.

I. INTRODUCTION

IN EUROPE and in many parts of the world, agriculture remains a key component of the social and economic dynamics. However, these last years, many external factors such as climate change, environment protection, and market evolution led to significant changes in the crop systems [1]. Rice cropped in the Rhône Delta area (SE France, 43°36'4.31N—4°33'23.22E) called Camargue region is grown with a quality label (IGP)

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that requires specific monitoring.¹ Despite valorization efforts, rice areas have shown a significant decrease from 20 000 ha in 2010 to only 11 348 ha in 2017 (source CFR, [32]) due to several economic crises, the environmental context, the market, and subsidies cuts [2]. One crucial point for rice monitoring is that it remains difficult to accurately map the main crops and monitor the farm management at regional scale because of the high spatial variability observed [1].

Rice plays a major role in the economic and environmental development of the Camargue region both for the hydrological balance, the maintenance of soils for various crops, and for the biodiversity [2], [27]. The aquifer functioning is strongly influenced by water inflows related to agricultural activities (irrigation and flooded crop). Most farmers cultivate rice crop because the flooded conditions reduce the salinity level and form lands useful for dry cereal crops in rotation and the availability of fresh water is high [2].

A wide variability of agricultural practices is observed in the region, conventional versus organic managements, various sowing dates spreading over more than one month, many cultivars (early, medium, late, long, and round types), great variations in amounts of herbicides and fertilizers used/applied, and in soil preparation (burial or burning of residues after harvest) [2], [28]. Despite the strong incentives offered to farmers to not burn residues, these practices are being continued and there are no maps of burned areas at regional scale [28].

Climatic and soil conditions that influence the various yield components may be either reinforced or counter-balanced through agronomical management including variety choice and technical practices (e.g., sowing date, fertilization, etc. [1]).

Sometimes, small changes in the sowing date according to climatic hazards, variety choice, and soil type may lead to important yield reductions due to cold-induced sterility [3]. Technical practices can be used to avoid, for example, weed competition [1], [28], [29].

A large bibliography proposes different approaches to classify the farms taking into account the cultivated crops, their technical choices, and the available resources (such as water, soil, etc.) [1], [22], [23]. Delmotte *et al.* [1] explain that the farm classification into typologies makes it possible to describe the farm heterogeneity, to propose technical alternatives adapted to the

¹[Online]. Available: <https://www.rizdecamargue.com/section/produits/unequalit%C3%A9-reconnue>

farm particularities, and to evaluate the effectiveness of public policies.

Multiple methodologies can be used to produce farm typologies, depending on the objective and the available data, which often results in different choices of indicators [1], [24]–[26]. Most of the time, large dataset from ground observations or surveys are considered, which are difficult to monitor annually.

Assessing the spatial variability of the agricultural practices through surveys is generally difficult, costly, and time consuming. Up to now, there have been no accurate annual maps of rice crops for the entire Camargue region, quickly available for everybody. The only available information is farmer declarations made through the RPG (graphical parcels recorded each year to receive aids from the Common Agricultural Policy²). These maps are only available the following year, and not all fields are declared (due to changes in farmers' crop planning and to some farmers making no declaration). RPG provides information on the rice areas but not on the technical practices or on the performances of the paddies.

Remote sensing data offer opportunities for land monitoring over space and time with far-reaching socio-economic benefits [4]–[7], [21]. The Sentinel missions from the Copernicus program with their new high-resolution data offer unprecedented possibilities for monitoring these agrosystems [8], [19], [20]. Since the launch of the first Sentinel satellite (2A) in June 2015, the platform THEIA³ provides freely accessible fine resolution images (10 m) every 10 days for the year 2016 and even more frequently (every 5 or 3 days) since March 2017 due to the launch of the second Sentinel satellite (2B). Thanks to the high rate of cloudless days in the Mediterranean region, these data are particularly suitable for crop monitoring in this region.

Sentinel 2 resolution varies from 10 to 60 m in the visible, near infrared (VNIR) and short-wave infrared (SWIR) spectral zones, including 13 spectral channels (see Appendix Table I in supplementary material for more details).

The Sentinel-1 mission comprises a constellation of two polar-orbiting satellites that operate day and night performing C-band synthetic aperture radar imaging, which enables them to acquire imagery regardless of the weather (two polarizations are available (VV and VH) every 6 days at 10 m for spatial resolution). Various studies have shown their potential for crop monitoring in different contexts [19], [20].

The objectives of this study were thus to propose operational methodologies to accurately assess the main crops of the Camargue region, rice, wheat, and grassland in 2016 and 2017 using multispectral data, map some agricultural practices impacting the environment (sowing after flooding and harvest residue burning), and elaborate a farm typology based on variables computed from remote sensing data to better understand the farmer strategies.

The proposed methodology was based on both ground data and remote sensing images to calibrate and validate the developed approaches.

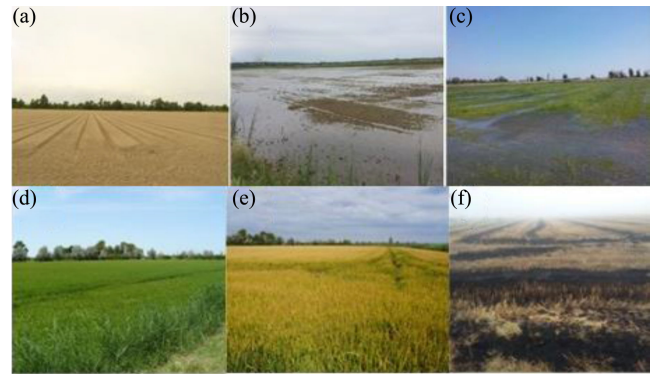


Fig. 1. Photos showing the different states of rice fields in Camargue. (a) Soil preparation, plowing with small channels for irrigation, (b) flooding, (c) emergence, and (d) maturity stages, followed by (e) senescence before the harvest up to the (f) burned residues in October.

II. MATERIAL AND METHODS

A. Study Site

The study area (5 m above sea level on average) is characterized by a large wetland plain of 145 000 ha located between two Rhone branches. 70 000 ha are used for agricultural production with mainly rice (~11 000 ha), wheat (7 130 ha), and grassland (2 320 ha) and the rest is protected for nature conservation (UNESCO reserve since 1977). The climate is characterized by hot summers (varying between 18 and 28 °C during the last 10 years) and mild winters (temperatures rarely drop below 0 °C, maximum can reach up to 14 °C for some years); average air temperatures from May to October ranged between 19 and 22 °C for the period 1991–2018. Precipitations mainly occur in the autumn and winter months (625 mm on average, period 1991–2018). However, a large interannual variation is observed, e.g., 564 mm was observed in 2016 at the Fourques station (43.704N 4.561E) but only 277 mm in 2017. Strong wind (called Mistral) causes significant evapotranspiration up to 1300 mm/year [2].

B. Rice Management in Camargue Region

Cultivated rice in Camargue belongs to the *Oryza japonica* ecotype, which is adapted to large climatic variations from tropical to Mediterranean climates. The rice cycle lasts between 120 and 150 days depending on the variety and the climatic conditions. The minimum temperature for emergence is 12 °C and for flowering 20 °C [2]. Depending on the cultivars' choice (early or late), the soil type (shallow and deep), and the temperature, the sowing dates can extend from mid-April (DOY 105) to end of May (DOY 148).

Water management is an important task all along the cultural cycle, from the sowing to the harvest stages. Small channels are dug in bare fields to better regulate irrigation and drainage [see Fig. 1(a)]. Most farmers sow 4–5 days after flooding [see Fig. 1(b)].

Management of the water level and the water temperature are also essential factors for seedling emergence and weed control

²[Online]. Available: <http://professionnels.ign.fr/rpg>

³[Online]. Available: <https://www.theia-land.fr/>

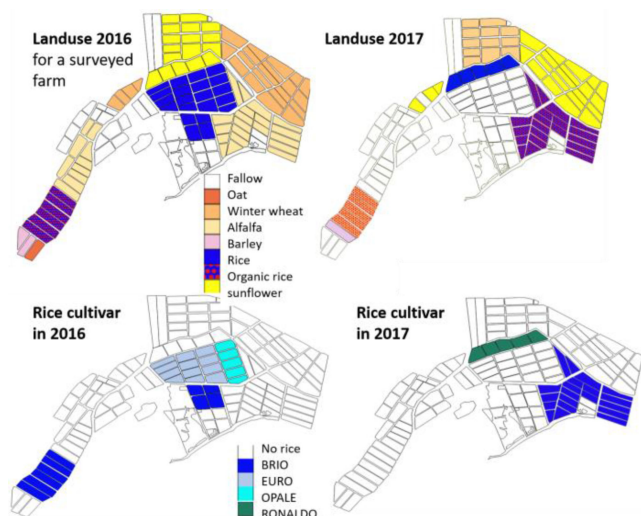


Fig. 2. Land use and rice cultivars from surveys obtained for a typical farm of Camargue.

[2], [3]. The water level (succession of drying up and delivery of water varying between 15 and 30 cm) is regulated according to the climate and cultural interventions. For example, rice farmers apply an average of two weeding operations, during which they decrease the water level. Then, the farmers try to keep a constant level of water for thermal regulation. During the growing period, nitrogen fertilizer can be applied 2 to 3 times (average 150 kg N/ha). Harvest usually starts in mid-September (DOY 258) and continues until the end of October (DOY 288). The grain must have a humidity of less than 22% to be harvested.

Stubble management varies between farms. Some bury the stubbles and plow the soil immediately after to sow a new crop, while others prefer to burn rice straw residues [see Fig. 1(f)], even though this last practice is less recommended because of the negative impact on the environment [1]. During winter, some rice fields are left fallow (sometimes for grazing) or planted with alfalfa to bring nitrogen to the soil.

C. Ground Observations

Seven large farms and 830 fields were monitored during 2016 and 2017 by INRAE teams. These farms were chosen to represent the soil, and technical practices variability encountered in the Camargue region. We selected farmers according to the contacts given by the UMR Innovation of Montpellier that conducted studies for many years in this sector [2]. Detailed surveys on the main agricultural managements were made with farmers to know the rice variety, the sowing and harvest dates, their residue management, and their yields. All these data were processed with QGIS software (version 3.6.3) in order to spatialize the main practices (see Fig. 2). Statistical analyses were performed to extract the average farming practices. Fig. 2 shows an example of cultivars for the two studied years for a typical farm doing crop rotation. The farmer has cultivated wheat and sunflower in 2017 instead of rice. Other fields were flooded for rice to avoid the salinity issues.

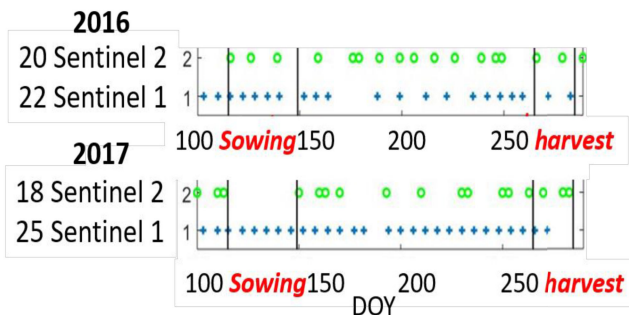


Fig. 3. Different acquisition dates of images used in this study.

Specific observations have been done after the rice harvest in 2017 at different dates in October and November to identify burning residues. 160 points have been scored. These observations have been added to the surveys conducted among the aforementioned farmers (a detailed description of agricultural practices for every field).

D. Sentinel Data Selection

In 2016 and 2017, 38 cloud free Sentinel 2 images (20 in 2016 and 18 in 2017 acquired from DOY 100 to DOY 290) were selected and downloaded from the THEIA platform at level 2 (georeferenced in UTM projection and corrected from atmospheric effects according to the MAJA chain.⁴

Sentinel 1 data have been also downloaded from the ESA platform⁵ according to processing described in [11]. Fig. 3 shows the different acquisition dates of the used satellites. Sentinel images were chosen between March and October. All images allow to monitor the main growth stages of the rice from the emergence, tillering, panicle development, and maturity. In 2017, the spring was cloudier than in 2016, impacting the number of Sentinel 2 images available for this period.

E. Land Use Classification

In the first step, a supervised classification (support vector machine (SVM), see Appendix 2 in supplementary material for the detailed parameters) was computed using the ENVI software (ESRI version 5. www.exelvis.com). The observation dataset was split according to the expert knowledge of the region and to avoid spatial autocorrelation between samples, into two parts, one for the training, and the second for validation. Each dataset has been analyzed to cover the spatial variability of the main crop classes on the whole Camargue territory. 150 points have been used for calibration with multispectral images acquired at various dates. The reflectance of the spectral bands 2-3-4-8 were chosen for their high spatial resolution (10 m), 7 dates (1 per month from March to October) were selected. The validation was done with both an independent dataset of 200 points and the RPG data (declarations made each year by the farmers). The

⁴[Online]. Available: [described in http://www.cesbio.ups-tlse.fr/multitemp/](http://www.cesbio.ups-tlse.fr/multitemp/)

⁵[Online]. Available: <https://scihub.copernicus.eu/dhus/#/home>

training dataset was chosen in order to cover the main crops encountered in the study site. The rice areas covered 800 ha for the learning dataset and 900 ha for the validation dataset (the selected fields were distributed in order to cover the spatial variability of practices and soils). Accuracy was evaluated by computing the confusion matrix and the kappa index.

F. Methods for Mapping Agricultural Practices

From the previous land use classification obtained for each studied year (raster files), a shapefile was built with the ENVI software to obtain the boundaries of all the fields of the Camargue area (using the function “classification to vector”). As the vectorization sometimes did not match the real field boundaries, the RPG shapefile⁶ corresponding to the fields declared by the farmers to receive subsidies has been used to merge information related to field boundaries (using Qgis functions “table joins”). To avoid the edge effect for field boundaries, a buffering of 3 m was considered between the fields. All information from our surveys have been added in the final table describing all the fields.

Then, different spectral indices (NDVI, LSWI, and SAVI detailed in [13]) were computed for each rice field considering mean values of reflectance of Sentinel 2 VNIR and SWIR bands [12], [13], or reflectivity (ratio between the two bands VH/VV as described in [8], [11], and [19]). The different dates were stacked using Envi Software. The shapefile containing all the field boundaries was then overlaid with the raster images of spectral indices for each Sentinel 2 date in order to compute mean and standard values for each rice field. This was done using QGIS3.6.3 software and zonal stats functions developed with R software. Finally, excel files (or tables) containing the mean value have been analyzed. The temporal profiles of these spectral indices or of the ratio VH/VV were analyzed in regards to the technical practices (sowing date) performed at field scale provided by the surveyed farmers. We had 120 observations for the sowing date. Classical statistical analyses were computed: correlation coefficients, root mean square error (RMSE), and bias as indicators to define of the most pertinent indices and the accuracy of the chosen method.

For 2016, as 20 cloud-free Sentinel 2 data were available, the minimum value of NDVI followed by an NDVI increase during at least one month provided the best correlation with the observed sowing date obtained from farm surveys. The developed algorithm detected all minimum values and checked if for the following dates, an increase of NDVI is observed for at least one month corresponding to the main growth period for the rice from emergence to the tillering and panicle development. This last condition is important to avoid the selection of minimum values corresponding sometimes to a false sowing practiced by some farmers to remove weeds.

For 2017, as there were not sufficient Sentinel 2 data for the sowing period due to clouds and rain in spring, Sentinel 1 data have been used. The microwave signal presents a high sensitivity for the soil water content and roughness but is also

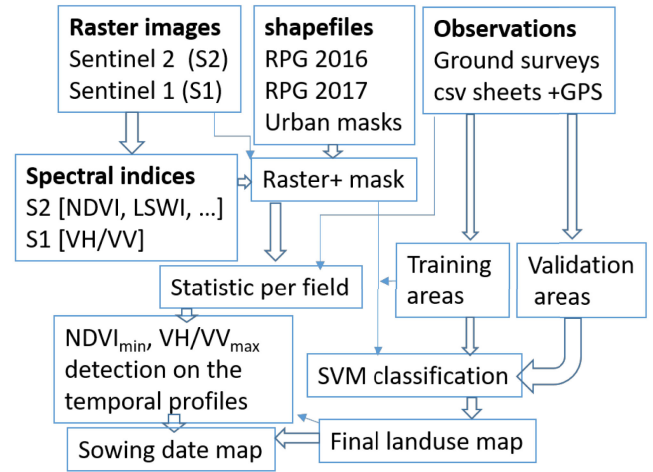


Fig. 4. Main steps for the land use classifications and the maps of the sowing dates combining ground observations and Sentinel images.

influenced by vegetation density [30]. The temporal profiles of the ratio VH/VV has been chosen since the authors in [8] and [30] have shown their interesting potentialities for the phenology monitoring of various crops. We noticed that the plots had higher values of VH/VV few days before the sowing date. This maximum was related to rice flooding, which in most cases takes place 4 to 5 days before sowing. We have, therefore, developed an algorithm described later (written in MATLAB, version 2017b, composed of different steps) using a first function that automatically detected the date of the maximum VH/VV ratio from the temporal profiles in the period from 15/04 to 10/06. A file with the dates obtained for each field is stored. The second step consists in subtracting 4 days to this file to estimate the final sowing dates. One hundred twenty plots were used to evaluate this method.

These methods have been applied by an automatic process from MATLAB functions developed by our team and applied at regional scale for more than 3300 rice fields and validated considering 120 ground plots.

Fig. 4 summarizes the main processing stages to obtain land use and sowing date maps.

G. Assessment of the Burned Rice Residues From Sentinel 2 Images

Some papers have proposed automatic methods to map fires and burned areas, but most of them are based on the use of the thermal spectral range [16], [17] only available at low spatial resolution (1 km with MODIS). This resolution is not suitable for our studied area, where the field size is generally small (<2 ha). Yadav *et al.* [18] have shown that optical range can give also high performances for estimating burning areas. We analyzed the comparison of the spectral profiles from the visible to the middle infrared bands for 2 rice fields with and without burned residues, and observed significant differences particularly in the 11 and 12 Sentinel 2 bands (centered at 1610 and 2190 nm, respectively, Fig. 5). A supervised classification (SVM) has then been proposed based on the following spectral bands: B8A, 11,

⁶[Online]. Available: Downloaded from <http://professionnels.ign.fr/rpg>

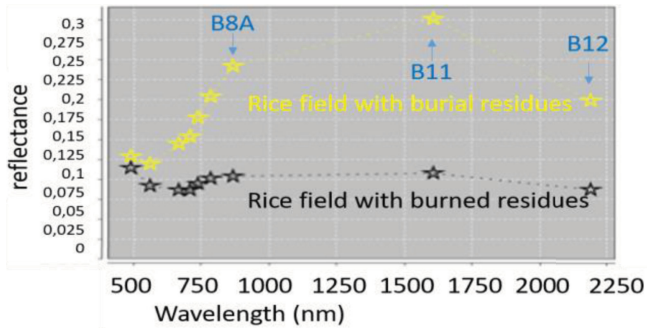


Fig. 5. Spectral profiles of two rice fields with different postharvest residue management.

and 12 spectral bands (see Table I in Appendix in supplementary material), and ground observation points for the training dataset. The resulting map has been vectorized and combined with the parcel map. A threshold has been defined to consider a burned area: if more 50% of pixels of a field are burned, the entire field was considered in the same burned class. The validation has been performed at farm scale from ground surveys (140 points).

H. Methodology to Develop a Farm Typology

The last stage consisted of aggregating all information computed at field scale to the farm scale. A shapefile provided by the UMR innovation containing the farm identification has been used. There were 275 farms for the entire Camargue area. A joint with QGIS software has been made to relate each field extracted from the previous land use maps obtained for each year to a farm identifier. Each farm consisted in numerous fields, for which land use of 2016 and 2017 were informed. Based on this information, we used R (version 4.0.0., [31]) to calculate the yearly total areas for each crop (rice, wheat, grassland, and “others”) and each farm. We then expressed these variables as percentages per year and farm. Each farm was thus characterized by a unique set of eight variables, summing to 200% [2 years \times 100%, 100% being the sum of the yearly four land uses (Appendix 3 in supplementary material)]. This land use share at the farm scale is considered as a pertinent variable to classify the different farms encountered in the Camargue region, as already observed by [1] and [2]. Indeed, farmers carry out rotation between wheat and rice to avoid soil salinity, depending on soil type. Soil type is a major factor determining yield [2], [3]. The main soil types correlate with small variations in the topography. There are hydromorphic shallow soils and deeper soils with a higher sand content. The salinity concerns more shallow soils. On these soils, it is necessary to cultivate rice more frequently to decrease the soil salinity. The agricultural practices of farmers are driven by the environmental constraints, which can be inferred from their main crops. In this study, the objective was to use variables easily available and obtainable every year, without requiring ground surveys that are often costly and time consuming.

Subsequently, multivariate analysis techniques [principal component analysis (PCA) and ascendant hierarchical classification (AHC)] have been used (summarized in Fig. 6) to identify clusters of farms. First, PCA was used to visualize

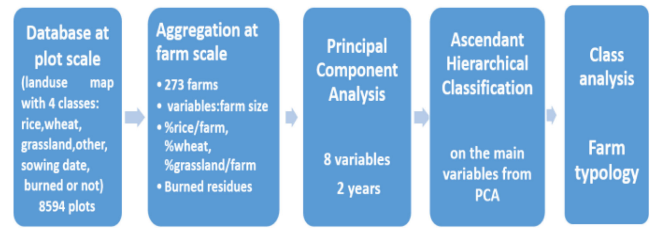


Fig. 6. Main steps to develop a farm typology from remote sensing data.

TABLE I
CONFUSION MATRIX OBTAINED FROM THE LAND USE CLASSIFICATION
COMPUTED FROM SENTINEL 2 IMAGES (USER A: USER ACCURACY)

Validation classification	rice	wheat	Grass land	Other crops	Total (user a)
Rice	68	0	1	3	72 (92%)
Wheat	0	44	2	8	54 (82%)
Grassland	1	1	24	2	28 (86%)
Other crops	0	5	0	41	46 (89%)
Total (producer accuracy)	69 (99%)	50 (88%)	27 (89%)	54 (76%)	200 (88%)

TABLE II
RESULTS (IN HA) OBTAINED FROM THE SUPERVISED CLASSIFICATIONS
COMPARED TO RPG DATABASE

Crop	2016 (S2)	2017 (S2)	RPG 2016
Rice	11331	10291	11355
Wheat	7132	6213	7370
Grassland	2320	2572	1743

relationships between variables, and decrease the complexity of the dataset. Based on PCA results, we then applied AHC. In AHC, the number of clusters had to be set by the user. This number is chosen by analyzing a dendrogram performed on PCA data. The final number of clusters is validated by looking at clusters’ statistics (dominant classes, significancy) to verify that clusters are different and meaningful. We used the PCA and HCPC functions of the R package FactoMineR [15], with Euclidean distances and Ward method to build the clusters (AHC, function HCPC).

The main variables derived from remote sensing data were considered.

III. RESULTS

A. Accuracy of Land Use Classification

Considering independent observations, supervised classifications estimated 88% of crops (rice, wheat, and grassland) correctly. Table I shows the confusion matrix obtained taking into account the validation dataset described in Section II-D and Table II displays the areas in hectare for the three main crops compared to another dataset, RPG for 2016. Not all fields are declared on the latter database, but more fields were

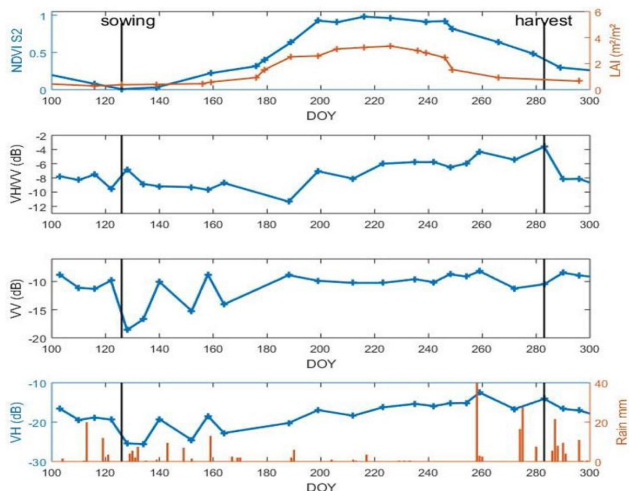


Fig. 7. Temporal spectral profiles obtained from Sentinel 1 and 2 data for a rice plot, in 2016.

included than in our own observations (more than 11 032 plots were considered). The performances were very good for rice (99.8% correct compared to RPG) and wheat (96.8%). The grassland class appeared to be overestimated from the Sentinel 2 data compared to the farm declaration. It is important to note here that there are different types of grasslands in Camargue area. On the one hand, there are large natural grasslands used for pasture that are sometimes not declared by farmers, and on the other hand, irrigated grasslands harvested for the production of hay. Thus, this class is difficult to evaluate accurately based on ground truth. As this study focused mainly on rice cropping systems, the classifications obtained for the two years were considered as sufficiently precise for the successive work.

B. Mapping of Technical Practices

Our ground surveys have shown that the earliest sowing started in mid-April, and the latest started in beginning of June in 2016 and 2017. Most farmers mechanically sowed five days after flooding. Very few sowed before flooding in dry conditions. In the latter case, the grain density was generally lower and the flooding occurred when roots were developed.

The analysis of the temporal profiles of the spectral indices computed from Sentinel 1 and 2 allowed identifying clearly the sowing date for most rice plots (see Fig. 7). In 2016, the minimum of NDVI has been chosen because of the highest statistical score to detect the sowing dates (RMSE of 8 days). In 2017, as not sufficient Sentinel 2 data were acquired because of high frequency of clouds during the sowing period, the maximum of the ratio VH/VV Sentinel 1 data to which 5 days are added has given the best performances compared to the observations (RMSE 11 days).

The map of the sowing date computed for 2016 is displayed in Fig. 8, which allowed to analyze the spatial variability of the agricultural practices at the territory level. Thus, it appeared that some farmers located mostly in the Southeastern part of



Fig. 8. Map of the sowing date obtained from NDVI minimum, in 2016.

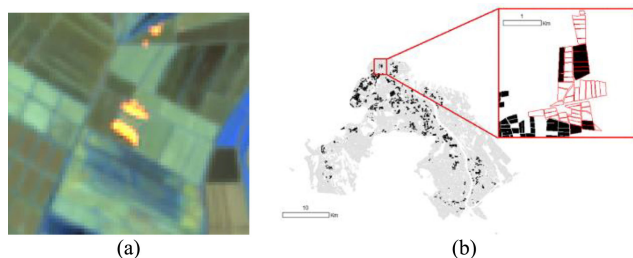


Fig. 9 (a) Colored composite of spectral bands 8 A, 11, and 12 with fire well identified in orange. (b) Map of the burned rice areas in 2017 obtained from the supervised classification with a zoom on a farm (in black rice fields with burned residues).

Camargue preferred to sow rice later in 2016 (DOY 149) than the majority of farmers who have sown rice rather average around the DOY 126 (6 May). The late sowing date observed in the South may be adapted to the soil types in this part of Camargue. Indeed, they are often exposed to high salinity, leading farmers to wait longer to have the most favorable conditions for the crop, with higher temperature conditions and less rain for a better growth of rice. In contrary, the early sowing dates often corresponded to dry sowing conditions located mainly in the Northern part of Camargue with shallows and sandy soils more favorable for rice implantation.

Fig. 9 shows the colored composite based on the spectral bands B 12 (coded in red), B11 (in green), and B8A (in blue) on October 15, 2017. The fires can be clearly identified. The supervised classification performed using these spectral bands gave an accuracy of 80% of burned areas correctly classified fields.

In total, 5 907 ha (57% of rice surface area) were burned in 2017, despite the strong negative impact on environment [14]. This practice is prohibited at European level, but Camargue farmers have obtained derogation each year. Farmers seem to continue to prefer this practice rather than burying crop residues. Burning represents less work and is less costly, but the loss of organic matter is greater, as straw is not naturally degraded [1], [2].

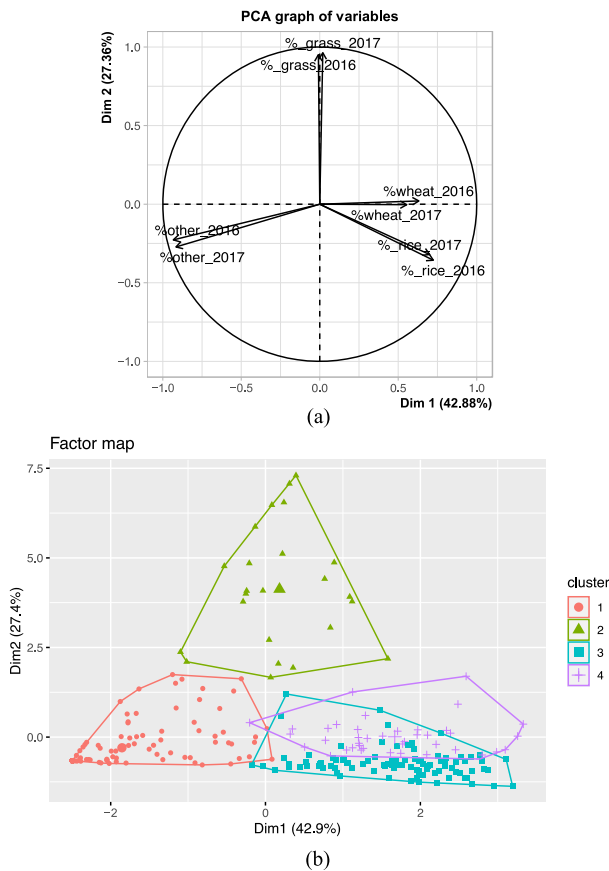


Fig. 10. Results of (a) PCA and (b) AHC considering all farms characterized by their areas in rice, wheat, and grasslands computed from Land use maps obtained from Sentinel 2 images. In (b), clusters 3 and 4 overlap, but are differentiated on the further dimensions (see inertia in Appendix 4 in supplementary material). Cluster 1 gathers 119 farms, cluster 2 gathers 24, cluster 3 gathers 89, and cluster 4 gathers 41.

C. Farm Typology

A first analysis on the database (excluding remote sensing information) showed that among the 273 studied farms, 58 covered more than 250 ha each, the majority (79%) had areas inferior to 250 ha.

When remote sensing information was added, we observed 11 farms that had more than 80% of rice crops, 50% (136 farms) cultivated between 10 and 50% of rice.

In 2016, there were 174 rice farms with 11 248 ha of rice (63%). The largest farm covered 783 ha. There were 11 farms with more than 80% rice, 50% of the farms dedicated between 10% and 50% of their land to rice cultivation.

In 2017, there were 167 rice farms (61%), with 10 140 ha of rice. Of these farms, the one with the largest area of cultivated rice covered an area of 513 ha. There are 12 farms (3%) that have more than 80% rice and 50% of the farms have dedicated between 10% and 50% of their area to rice growing.

In summary, the changes between the years 2016 and 2017 were minimal for the main farm characteristics.

Fig. 10(a) shows the results obtained from the principal component analysis. The first two PCA axes represent a large part of the variability in the dataset (70.2% of the variance) with,

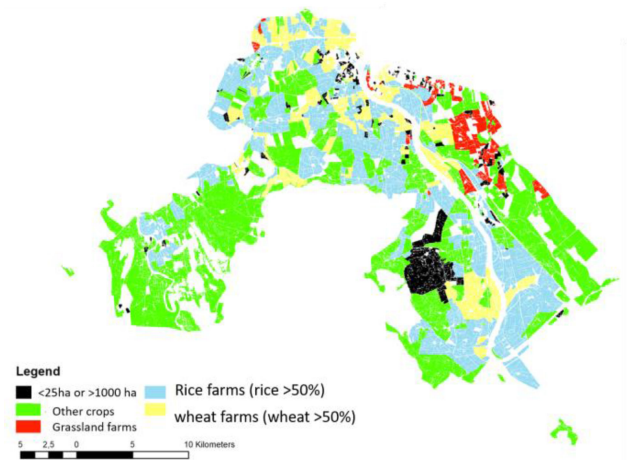


Fig. 11. Map of the farm typology in the Camargue region obtained from the AHC method (other crops correspond to crops that are not rice, wheat, and grassland, this class can include natural surfaces such swamps, forests, and saline areas).

respectively, 42.8% for the first axis and 27.3% for the second axis. Based on the analysis of the dendrogram performed on PCA results (Appendix 4 in supplementary material), we chose to derive four clusters [see Fig. 10(b)]. These clusters grouped between 24 and 119 farms [see Fig. 10(b)]. The first cluster (in red) gathered farms largely dominated (>86% on average by land uses other than the three dominant classes (i.e., rice, wheat, and grassland). Natural surfaces, pasture, swamps, forests, or crops with small areas such as vegetables and sunflower can be found in this cluster. The second cluster (in green) was dominated by grasslands (>57% in both year) and showed about 24% of “other” class in both years. The third cluster (in blue) was dominated by rice in both years (>52%), together with 24–28% of wheat (Appendix 4 in supplementary material). The fourth cluster (in magenta) was dominated by wheat (>53% in both years), also growing a significant part of “other” class (23–30% in 2017 and 2016, respectively). All statistics are presented in Appendix 5 in supplementary material.

Fig. 11 shows the map of the farm typologies obtained for the studied years.

Most of farms that cover large areas of grasslands were found in the North-Eastern part of the Camargue region. In contrast, rice and cereal farms could be found in the central and Southern parts.

Each group has been analyzed according to the crop management (information from surveyed farms) and compared with the classification proposed by Delmotte *et al.* [1] in 2007. 43% of farms classified in 2007 that cultivated mostly rice crops have changed their crop management and diversified their agrosystems up to 2016 and 2017. The cluster grouping farms with a high percentage of grasslands, corresponding to breeders has not changed substantially since 2007.

IV. DISCUSSION AND CONCLUSION

This study has proposed operational methods based on the use of new remote sensing data acquired at high spatial and

temporal resolution (Sentinel 1 and 2 images) to first classify rice cropping systems of the Camargue region, map the sowing dates and the burned areas, and develop a farm typology to classify the main crop practices at the territory level. The results have shown that a satisfactory accuracy is obtained for land use maps (88% of correctly classified fields) using multispectral data acquired at different dates. We proposed simplified approaches to detect the sowing dates and the burned areas that are easy to implement at large scale. For these two agricultural practices, it is necessary to have cloudless Sentinel 2 images at crucial periods at high temporal frequency. If there are too many clouds in spring, the use of the ratio VH/VV extracted from Sentinel 1 data can be used to estimate the sowing date (the precision obtained was lower compared to the sowing dates obtained from Sentinel 2 (12 days against 8 days with Sentinel 2)). Nevertheless, this information still remains very useful for crop modeling and to assess the management variability at regional scale since no dataset exist on these variables yet.

These different variables computed from Sentinel data can be used to characterize farms at regional level using multivariable statistical techniques. Up to now, such typologies used only data from surveys, costly, and time consuming. The innovative approach is to use remote sensing data and methods easy to implement. This first dataset can be increased by adding other variables. Other information could be added to improve this typology, particularly, soil characteristics, topography, but also information on farming practices that could be gathered based on remote sensing data, e.g., cultivar precocity, water management, soil management, yield, etc. Considering a large set of remote-sensing-derived variables could be of high value for those typologies, as they would allow to consider spatially variable practices over time. No census of such detailed information is currently available at field and farm scale, and their acquisition requires time-consuming farm surveys, which cannot be repeated frequently and rarely includes all farms. The type of analyses presented here offers thus a unique opportunity to study the trajectory of the different farms, to observe, e.g., how cluster evolve both in direction and intensity (e.g., dominance of crops).

Capturing agricultural heterogeneity thanks to high resolution satellites by investigating farm typologies is key to design sustainable policies and to better understand the farmer strategy according to the various environmental contexts, global change, and the market evolution.

In the context of limited information, this study has shown that the use of high-resolution remote sensing data is beneficial for rice monitoring.

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REFERENCES

- [1] S. Delmotte *et al.*, "On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate," *Eur. J. Agronomy*, vol. 35, pp. 223–236, Nov. 2011.
- [2] J.-C. Mouret and B. Leclerc, *Le Riz et la Camargue: Vers Des Agroécosystèmes Durables*, M. Jean-Claude Mouret and Bernadette Leclerc, Eds. BP 87999 21079 Dijon cedex France: Educagri, 2018, pp. 17–480.
- [3] R. Confalonieri *et al.*, "Evaluation of parameterization strategies for rice modelling," *Spanish J. Agricultural Res.*, vol. 7, no. 3, pp. 680–686, 2009.
- [4] M. F. McCabe *et al.*, "Advances in the remote sensing of terrestrial evaporation," *Remote Sens.*, vol. 11, 2019.
- [5] X. W. Wang and H. J. Xie, "A review on applications of remote sensing and geographic information systems (GIS) in water resources and flood risk management," *Water*, vol. 10, no. 5, pp. 1–8, 2018.
- [6] A. Begue *et al.*, "Remote sensing and cropping practices: A review," *Remote Sens.*, vol. 10, no. 1, pp. 1–32, 2018.
- [7] J. Inglada *et al.*, "Assessment of an operational system for crop type map production using high temporal and spatial resolution satellite optical imagery," *Remote Sens.*, vol. 7, no. 9, pp. 12356–12379, 2015.
- [8] A. Veloso *et al.*, "Understanding the temporal behavior of crops using Sentinel-1 and Sentinel-2-like data for agricultural applications," *Remote Sens. Environ.*, vol. 199, pp. 415–426, Sep. 2017.
- [9] F. Ruget *et al.*, "Parametrization of crop model using a regional agronomical database: Rice in Camargue with STICS," in *Proc. Int. Crop Model. Symp.*, 2016, pp. 272–273. [Online]. Available: <https://hal.archives-ouvertes.fr/hal-01602215>
- [10] S. Delmotte *et al.*, "From stakeholders narratives to modelling plausible future agricultural systems. Integrated assessment of scenarios for Camargue, Southern France," *Eur. J. Agronomy*, vol. 82, pp. 292–307, 2017.
- [11] E. Ndikumana *et al.*, "Estimation of rice height and biomass using multi-temporal SAR Sentinel-1 for Camargue, southern France," *Remote Sens.*, vol. 10, pp. 1–18, 2018.
- [12] M. Boschetti *et al.*, "Multi-year monitoring of rice crop phenology through time series analysis of MODIS images," *Int. J. Remote Sens.*, vol. 30, pp. 4643–4662, 2009.
- [13] M. K. Mosleh *et al.*, "Application of remote sensors in mapping rice area and forecasting its production: A review," *Sensors*, vol. 15, pp. 769–791, 2015.
- [14] A. Niang *et al.*, "A cost-benefit analysis of rice field winter flooding for conservation purposes in Camargue, Southern France," *Agriculture Ecosyst. Environ.*, vol. 231, pp. 193–205, 2016.
- [15] S. Le *et al.*, "FactoMineR: An R package for multivariate analysis," *J. Statistical Softw.*, vol. 25, no. 1, pp. 1–18, 2008. [Online]. Available: <http://factominer.free.fr/>
- [16] L. Giglio *et al.*, "The collection 6 MODIS active fire detection algorithm and fire products," *Remote Sens. Environ.*, vol. 178, pp. 31–41, 2016.
- [17] J. L. McCarty *et al.*, "Agricultural burning in the southeastern United States detected by MODIS," *Remote Sens. Environ.*, vol. 108, pp. 151–162, 2007.
- [18] M. Yadav *et al.*, "Estimation of wheat/rice residue burning areas in major districts of Haryana, India, using remote sensing data," *J. Indian Soc. Remote Sens.* vol. 42, pp. 343–352, 2014.
- [19] S. Ferrant *et al.*, "Detection of irrigated crops from Sentinel-1 and Sentinel-2 data to estimate seasonal groundwater use in south India," *Remote Sens.*, vol. 9, pp. 1–21, 2017.
- [20] K. Clauss *et al.*, "Estimating rice production in the Mekong Delta, Vietnam, utilizing time series of Sentinel-1 SAR data," *Int. J. Appl. Earth Observ. Geoinf.*, vol. 73, pp. 574–585, 2018.
- [21] D. Courault *et al.*, "Contribution of remote sensing for crop and water monitoring," in *Land Surface Remote Sensing in Agriculture and Forest*, N. Baghdadi and M. Zribi, Eds. London, U.K.: ISTE press-Elsevier, 2016, pp. 113–177.
- [22] A. M. Stuart *et al.*, "Yield gaps in rice-based farming systems: Insights from local studies and prospects for future analysis," *Field Crops Res.*, vol. 194, pp. 43–56, 2016.
- [23] T. Lebacqz *et al.*, "Sustainability indicators for livestock farming. A review," *Agronomy Sustain. Develop.* vol. 33, pp. 311–327, 2013.
- [24] P. Tittonell, "Livelihood strategies, resilience and transformability in African agroecosystems," *Agricultural Syst.*, vol. 126, pp. 3–14, 2014.
- [25] G. C. Pacini *et al.*, "Combining multi-dimensional scaling and cluster analysis to describe the diversity of rural households," *Exp. Agriculture*, vol. 50, pp. 376–397, 2014.

- [26] J. Cortez-Arriola *et al.*, “Leverages for on-farm innovation from farm typologies? An illustration for family-based dairy farms in north-west Michoacán, Mexico,” *Agricultural Syst.*, vol. 135, pp. 66–76, 2015.
- [27] V. Longoni, “Rice fields and waterbirds in the Mediterranean region and the Middle East,” *Waterbirds*, vol. 33, pp. 83–96, 2010.
- [28] A. Niang *et al.*, “A cost-benefit analysis of rice field winter flooding for conservation purposes in Camargue, Southern France,” *Agriculture Ecosyst. Environ.*, vol. 231, pp. 193–205, 2016.
- [29] C. A. Pernollet *et al.*, “Seed density and waterfowl use of rice fields in Camargue, France,” *J. Wildlife Manage.*, vol. 81, pp. 96–111, 2017.
- [30] A. Nasrallah *et al.*, “Sentinel-1 data for winter wheat phenology monitoring and mapping,” *Remote Sens.*, vol. 11, pp. 1–29, 2019.
- [31] *R: A Language and Environment for Statistical Computing*, R Development Core Team, R Foundation for Statistical Computing, Vienne, Austria, 2015. [Online]. Available: <https://www.R-project.org>
- [32] CFR, *Bulletins Annuels, Bilans de Campagnes, Essais Variétaux*, 2017, pp. 1–26. [Online]. Available: http://centrefrancaisduriz.fr/bilans_de_campagne-43.html



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