# Nationwide demonstration cases of Sentinel-2 satellite exploitation towards early crop area indicator

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## ABSTRACT

Satellite Earth Observation (EO) is a relevant source of transparent, timely and consistent information to monitor crop growth, to provide early area indicator and to stratify the agricultural regions. Thanks to the Copernicus program of the European Union, the satellite EO has recently entered in an operational mode where the data quality, the free and open access and the long-term continuity are major breakthroughs opening the avenue for more ambitious contribution to crop area and production estimate. This is the reason why developing operational agriculture applications from Landsat-8 and Sentinel missions became a strategic target for the remote sensing community, e.g. GEO-Global Agricultural Monitoring Initiative (GEOGLAM) building on GEO’s Agricultural Community of Practice (AG COP) and the Joint Experiment of Crop Assessment and Monitoring (JECAM) supported by the space agencies’ committee (CEOS). In particular, the Sentinel-2 mission was designed to optimize the observation capacity for regional to global agriculture monitoring at field scale in terms of spatial and spectral resolution (10 or 20 meters for targeted spectral bands), revisit frequency (5 days when two satellites in orbit), and coverage (systematic global acquisition). The combination of these features makes them most relevant to deal with a large diversity of agricultural landscapes.

In this context, the European Space Agency launched in 2014 the “Sentinel-2 for Agriculture” (Sen2-Agri) project, which aims at preparing the exploitation of Sentinel-2 data for agriculture monitoring through the development of an open source processing system. Based on key end-users requirements, this is designed to generate four relevant products, i.e. (i) cloud-free surface reflectance composite, (ii) dynamic cropland mask, (iii) cultivated crop type map and area indicator for main crop groups and (iv) vegetation indicators describing the vegetative development of crops. Crop type area indicators will be available after the first half of the season and thus, can serve as early estimate while waiting for the official agricultural statistics. Even if the area estimates accuracy is not yet matching the statistical standards, this product could be highly valuable as complementary geospatial information in a more and more georeferenced world

Thanks to fruitful interactions with key end-users and the network of JECAM sites globally distributed, the first phases of the project completed the product specifications, the algorithms selection, the system design, development and implementation. The third phase is currently dedicated to the demonstration of the Sen2-Agri system in operational conditions at full scale using Sentinel-2 and Landsat-8 data. Nationwide applications are on-going in close interactions with national and international partners, with the additional objective to transfer the system to the end-user's entity. A group of more than 15 champion users are closely engaged in the Sen2-Agri project including international organizations such as FAO, WFP, CGIAR or JRC of the European Commission as well as national mandated institutions in e.g. Mali, South Africa and Sudan. While the system already delivered successful SPOT4 Take 5 and SPOT5 Take 5 results for a dozen of JECAM sites, nationwide demonstration started in 2016 in Mali, Ukraine and South Africa. Five additional local sites were selected in Morocco, Sudan, France, China, and Madagascar covering up to 300 x 300 km in order to further increase the global representativeness of the demonstration findings.

Early results of these on-going demonstration cases are presented, as well as the preliminary lessons learned in the real-life context of the engaged user entities. In particular, the field data campaign, the cultivated area mask and the crop type map are discussed for Ukraine while the other demonstration cases are still going on.

**Keywords:** crop mapping, Sentinel-2 satellite, early estimate of cultivated areas

# 1. Introduction

Since years, satellite Earth Observation (EO) was proved to be a relevant source of comprehensive, timely and spatially consistent reflectance measurement to derive land cover map or even land use map in order to stratify national or regional territory for agricultural sampling. For crop area estimate, stratification allows either to optimize the sampling rate for area estimate and/or to improve the area estimate quality. Mapping crop to derive area estimate was found very challenging for various reasons: (i) classification accuracy hardly reaches the required level to capture the often marginal inter-annual change of the respective crop type areas, (ii) classification precision and accuracy are very dependent to the number and the dates of cloud free image acquisition, (iii) classification results are sometimes biased towards specific crop according to field patterns and pairwise crop spectral signature separability, (iv) statistical system cannot afford to rely on exploratory satellite mission which cannot ensure long-term continuity of observations.

More recently, satellite remote sensing is also used to empirically estimate the yield wherever the field size is compatible with the spatial resolution of existing satellite time series.

With the Sentinel-1a satellite in orbit since April 2014, the Copernicus program of the European Commission started to launch a fleet of EO satellites, which change completely the game for agriculture remote sensing. Unlike many other EO satellites, the Copernicus space segment is designed as an operational service providing consistent data quality, open and free access and long-term continuity (more than 20 years). For instance, Sentinel-1a and -1b, already both in orbit, carry exactly the same instruments providing complementarity but more importantly redundancy. Recurrent satellites for each of the Sentinels are in preparation and will be ensuring long-term continuity. While Sentinel-1 SAR instruments operate in the microwave domain to observe through the clouds, Sentinel-2 satellites capitalize on the heritage of Landsat and SPOT experiences to provide the first non-commercial EO system really designed for agriculture remote sensing. Combining visible and near-infrared bands with red-edge bands allows capturing most of the key vegetation properties while three other specific spectral bands support a better atmospheric correction (figure 1). The 10-day revisit cycle with a 10 – 20 m resolution and a wide swath of 290 km make it capable to acquire observation time series over large areas while capturing the field level. These features allow addressing a lot of the diversity of the agricultural landscapes. Launched in June 2016, Sentinel-2a will be complemented by Sentinel-2b scheduled for early 2017 to enhance the revisit cycle to 5 days. This is expected to provide dense time series adapted to temporal crop dynamics in most cropland regions. Some areas cloudy during the growing season would require even a more frequent observation capacities or the complementarity of SAR system not affected by cloud coverage like Sentinel-1. The Copernicus fleet also includes several additional satellites such as Sentinel-3 providing 300 m daily observation once both will be operating. Last but not least, the global systematic acquisition of Sentinel-2 and the open and free access license policy clearly open the door for more ambitious contribution of satellite remote sensing to agriculture assessment.

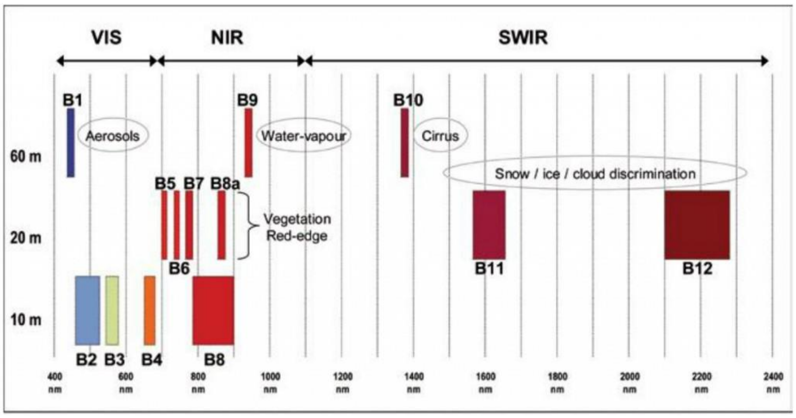


**Figure 1:** *Sentinel-2 spectral bands distribution (source: ESA).*

In this evolving environment, developing operational agriculture applications from Landsat-8 and Sentinel missions became a strategic target for the remote sensing community. Building on GEO's Agricultural Community of Practice (AG COP), the Joint Experiment of Crop Assessment and Monitoring (JECAM) and the Geo-Global Agricultural Monitoring Initiative (GEOGLAM) both supported by the space agencies' committee (CEOS) are instrumental to develop best practices and speed up the operational adoption of state-of-the-art remote sensing methods.

In this context, the European Space Agency launched in 2014 the "Sentinel-2 for Agriculture" (Sen2-Agri) project, which aims at preparing the exploitation of Sentinel-2 data for agriculture monitoring through the development of an open source processing system. Based on key end-users requirements, this is designed to generate four relevant products, i.e. (i) cloud-free surface reflectance composite, (ii) dynamic cropland mask, (iii) cultivated crop type map and area indicator for main crop groups and (iv) vegetation indicators describing the vegetative development of crops. Crop type area indicators will be available after the first half of the season and thus, can serve as early estimate while waiting for the official agricultural statistics. Even if the area estimates accuracy is not yet matching the statistical standards, this product could be highly valuable as complementary geospatial information in a more and more georeferenced world.

Thanks to fruitful interactions with key end-users and the network of JECAM sites globally distributed, the first phases of the project completed the product specifications, the algorithms selection, the system design, development and implementation. The third phase is currently dedicated to the demonstration of the Sen2-Agri system in operational conditions at full scale using Sentinel-2 and Landsat-8 data. Nationwide applications are on-going in close interactions with national and international partners, with the additional objective to transfer the system to the end-user's entity. A group of more than 15 champion users are closely engaged in the Sen2-Agri project including international organizations such as FAO, WFP, CGIAR or JRC of the European Commission as well as national mandated institutions in e.g. Mali, South Africa and Sudan. The system already delivered successful SPOT4 Take 5 and SPOT5 Take 5 results for a dozen of JECAM sites.

## 2. Objectives

This demonstration study aims to assess the performances of the Sen2-Agri system to deliver in a timely manner the cropland and area indicator for the main crops at national level. This pre-operational system designed as a generic open source software relies on near real time acquisition of Sentinel-2a and Landsat-8 imagery. The crop type mapping also requires timely in situ data collection while cropland mapping can run either from in situ data or only from existing land cover map. A crop type area indicator corresponds to unqualified crop area estimate and is obtained by pixel counting corrected for possible bias as assessed by a confusion matrix.

These nationwide applications respectively in Ukraine, Mali and South Africa are planned in close collaboration with national partners, with the additional objective to transfer the system to the national entity. This is the reason why the Sen2-Agri system is operated in a centralized way on one hand and in parallel at national level closely engaging and empowering the national stakeholders. National stakeholder's workshops are organized to provide insights from a user's perspective as well as to assess the quality and the relevance of the delivered information. Five additional local sites were selected in Morocco, Sudan, France, China, and Madagascar covering up to 300 x 300 km in order to further increase the global representativeness of the demonstration findings.

The objective of this paper is to report the preliminary outputs of the Sen2-Agri system, mainly illustrated through the Ukraine demonstration case, and to discuss the first lessons learnt.

## 3. Methods

Being part of the ESA Data User Element programme, the product to deliver by the Sen2-Agri system was entirely driven by a user-oriented approach in order to address concrete user needs and requirements. A suite of four core products was defined as top priority and are delivered automatically along the growing season by the system which was designed to take advantage of the near-real time imagery acquired by Sentinel-2 satellites as well as Landsat-8. Before the launch of the satellites, systematic benchmarking of state-of-art methods led to develop specific processing chain for each product (Bontemps et al., 2016). Only the cropland mask and the crop type mapping are presented in this paper.

The dynamic cropland mask delivered several times during agricultural seasons consists of a binary map at 10-meter spatial resolution separating annual cropland areas from other areas. Cropland is defined according to the JECAM guidelines (JECAM, 2014) as follows: “the annual cropland from a remote sensing perspective is a piece of land of a minimum 0.25 ha (minimum width of 30 m) that is sowed/planted and harvestable at least once within the 12 months after the sowing/planting date. The annual cropland produces an herbaceous cover and is sometimes combined with some tree or woody vegetation”. There are three known exceptions to this definition. The first concerns the sugarcane plantation and cassava crop, which are included in the cropland class, although they have a longer vegetation cycle and are not planted yearly. Second, taken individually, small plots, such as legumes, do not meet the minimum size criteria of the cropland definition. However, when considered as a continuous heterogeneous field, they should be included in the cropland. The third case is the greenhouse crops that cannot be monitored by remote sensing and are thus excluded from the definition. This definition discards perennial crops and fallow, as they are less important to monitor from an annual perspective.

The mask is delivered for the first time after 6 months of data acquisition and is then updated monthly. The season start date is a parameter defined a priori by the user. From one year of data acquisition, the production is based on a 12-month moving window. The regular update is expected to lead to an accuracy progressively increasing along the growing season. The processing chains producing the cropland mask are respectively described by Matton et al. (2015) and Valero et al. (2016) whether in situ data are available or not.

The cultivated crop type map is a map of the main crop types (or crop groups) for the whole country at 10-meter spatial resolution. It builds upon the cropland mask to process the time series only over the cropland areas. The main crop types are defined as (i) those covering a minimum area of 5% of the annual cropland area and (ii) whose cumulated area represent more than 75% of the annual cropland area. A maximum of 5 crop types are considered by country in the demonstration. In an operational context, the user can map the crop types he wants, providing that he collects the corresponding in situ data. The crop type map is delivered twice during the growing season with user-defined season start and end dates. The first map is produced after six months of data acquisition, with a legend that might be slightly different from the final one depending on what can be discriminated during the early stages of the season (e.g., summer vs. winter crops, irrigated vs. rain fed fields, etc.). Its accuracy may be variable but is intended to provide the best current information critically needed for crop monitoring systems. The second map comes at the end of the growing season and is expected to have much higher accuracy. The product allows deriving an early crop area indicator, which consists of the proportion of each crop type reported on the map within a 1 km² pixel. In the case of significant bias, the proportions will be corrected using the information provided by the confusion matrix of the crop type map. The area indicator can also be delivered at the most convenient aggregation level from the user point of view, i.e. administrative or census entity.

Aiming at developing an operational processing system globally relevant and coping with the large diversity of agro systems is not straightforward (Bontemps et al., 2016). It raises several challenges. From the remote sensing point of view, being relevant over the whole range of agricultural systems require to deal adequately with the global diversity of surface reflectance values to extract meaningful land cover information. Furthermore, the local heterogeneity of the agricultural practices (rotations, unusual crops, grassland edges, etc.) and the agro-meteorological variability will prevent the use of expected trajectories for crop discrimination and will require methodologies able to account for specific local conditions.

As described in Bontemps et al. (2016), products relevance does not only depend on their accuracy but also on their timeliness. Indeed, the value of most agricultural information rapidly decreases over time, as the seasonal production cycle leads to a sequence of critical dates for information delivery. The challenge is to provide the capacity to handle rapidly the processing of whole country, with the associated large volumes of data and products. The demonstration study also addresses challenges from the methodological, digital and organizational points of view. Indeed, most operational monitoring systems rely on proxies and qualitative indicators based on medium to coarse spatial resolution sensors. While the potential of high spatial resolution imagery is widely recognized, most of the research activities in this area currently rely on one site, one crop and one sensor. Supporting the development of operational agriculture monitoring methods based on high resolution images will first require collecting both EO and in situ data coming for the same season. Second, enough in situ data are to be acquired over each country to allow both algorithm calibration and independent validation of each product.

Three national demonstration cases (table 1) have been selected according to criteria including the representativeness of the selected countries with regard to a large demonstration ambition. These concerned the type of agricultural systems to monitor (e.g. crop type diversity, spatial heterogeneity, croplands fragmentation and field size distribution) and the agro-climatic conditions defining the actual availability of valid cloud free observation at the critical periods of the growing season.

**Table 1:** *Summary of national demonstration cases.*

| Country (study area) | Main characteristics | Main crops and calendar | National Stakeholders |
|---|---|---|---|
| Mali (447 948 km²) | ➢ Northern hemisphere<br>➢ Sudano-sahelian climate<br>➢ Field size: 1–5 ha | ➢ Millet, Sorghum, Rice, Maize, Cotton<br>➢ From June to October with field preparation in March/April; | ➢ ICRISAT<br>➢ Ministry of Agriculture : IER and Cellule Planification et Statistiques |
| Ukraine (576 604 km²) | ➢ Northern hemisphere<br>➢ Humid continental climate, with snow cover in February and March<br>➢ Field size: 30–250 ha | ➢ Wheat, sunflower, maize, barley, soybean<br>➢ From September to July and from April to October | ➢ Space Research Institute of National Academy of Science<br>➢ National agro-meteorological service (Ministry of Emergency) |
| South Africa (619 606 km²) | ➢ Southern hemisphere<br>➢ Sub-humid to semi-arid climate<br>➢ Field size: 40 ha | ➢ Maize, wheat, sunflower, soybean<br>➢ Major season from December to June; from April to November | ➢ Agriculture Research Council (ARC) |

## 4. Results

While the Sen2-Agri system is currently running at national scale for Ukraine, Mali and South Africa, the performances are here illustrated from the preliminary results obtained in Ukraine.

## 4.1 In situ data collection

The purpose of in situ data collection within the season is twofold in the context of Sen2-Agri: for the calibration to support the training of EO data processors (Sentinel-2, Landsat 8) and for the validation to assess the quality of the Sen2-Agri products. The validation sampling is spatially independent of the calibration samples. It will allow assessing the map accuracy by compiling a confusion matrix and deriving various accuracy metrics (Overall Accuracy, Precision, Recall, and F-Score) in order to document the quality of the Sen2-Agri products.

The objective of the calibration or training sampling is to cover the diversity of situations existing at national level in order to represent the range of possible signatures for croplands versus non croplands and for the five main crop types. In addition, discriminating and mapping these crops required also to collect data about the other crops. The samples are really targeted to establish all the links between a given target of interest and the range of its features used for classification (i.e. Sen2-Agri processors). Various types of sampling seem appropriate as long as it is fairly well distributed across the territory and containing enough information for each targeted class. In order to cover the diversity or gradient observed over large areas, it is recommended to stratify the croplands according to the interaction between agrosystem type – crop distribution – cropping calendar – biophysical context.

For each sampled parcel, the crop type must be identified from ground observation during the on-going growing season. As adopted by the JECAM network, a comprehensive ‘windshield survey’ along the main and secondary roads is found very efficient for in situ data collection for calibration purpose. A particular attention is required to reduce the bias related to the road proximity by getting off road regularly. For the calibration of the cropland mask, two options can be considered to sample non-agricultural land cover. If up-to-date very high resolution imagery is available from Google Earth or Bing geoportal for a large part of the area of interest, a systematic random sampling is proposed to collect by photo-interpretation a sufficient number of non-agricultural land cover types. Alternatively, the non-cropland samples can be selected during the crop type validation sampling by windshield survey along the same roads. The figure 2 reports the sample distribution of the nationwide field campaign completed in July 2016 by the field team of the Space Research Institute (NAS, Ukraine). In Ukraine, an agro-ecological zoning strongly correlated to crop distribution delineates four very distinct strata, which are classically use for agriculture reporting.

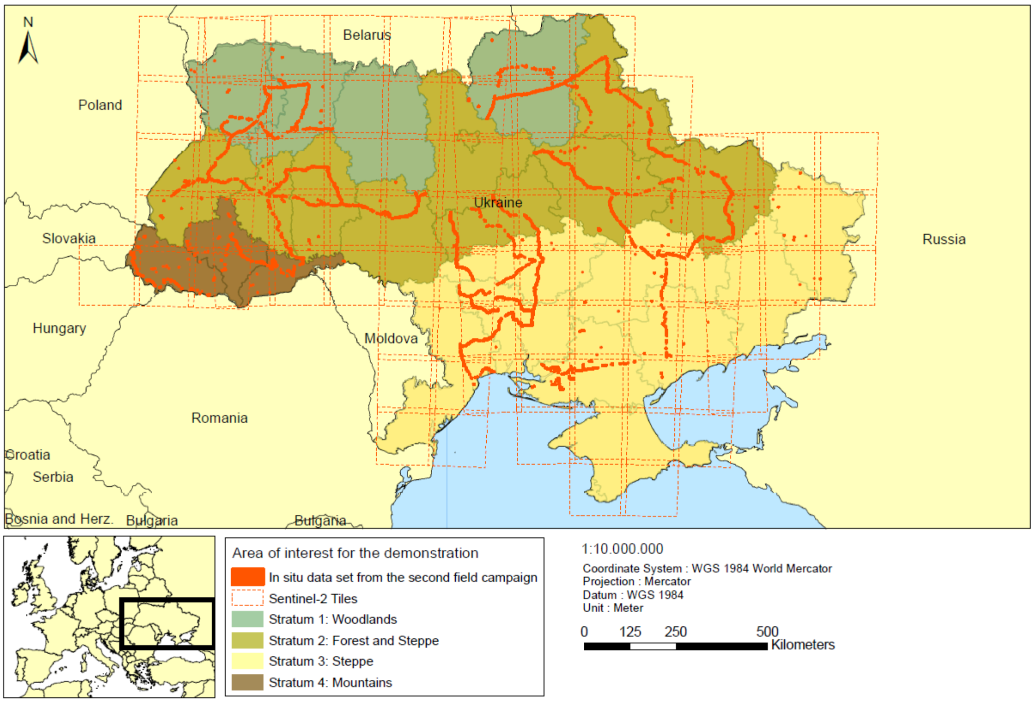


**Figure 2:** *Agro-ecological zoning of Ukraine used to stratify the Sentinel-2 time series processing and windshield sampling across the country for calibration purpose.*

## 4.2 Sentinel-2 data observation

Each Sentinel-2a acquisition has been processed from the 1st April to the 9th September 2016 in order to accumulate cloud free surface reflectance along the growing season. Using the MACCS module (Hagolle et al., 2010, Hagolle et al. 2015) included in the Sen2-Agri, a spatio-temporal cloud screening allows to detect the clouds and the associated shadows. The figure 3 shows the number of cloud free observation available over the 2016 growing season for each pixel of 10 m, highlighting the orbit overlap (in green).

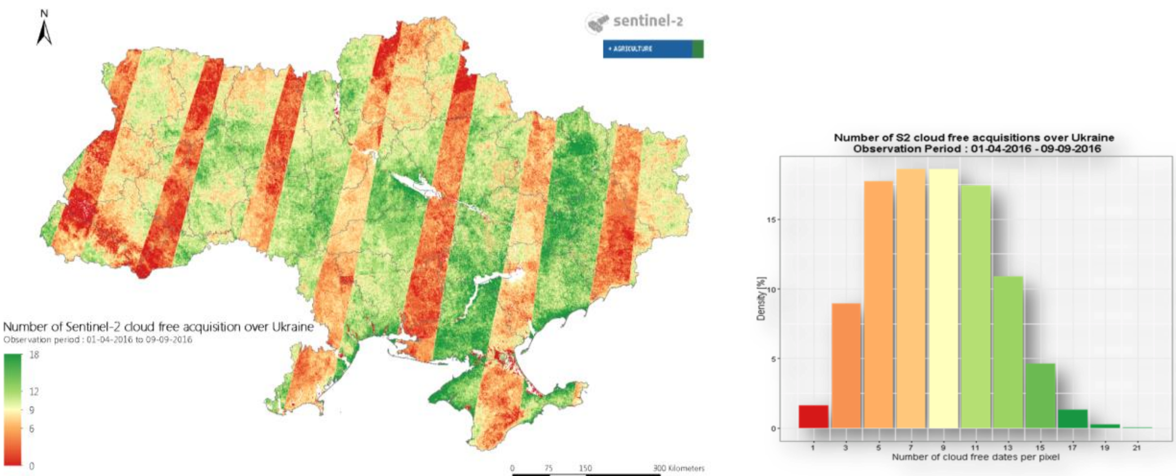


**Figure 3:** *Number of cloud free observation provided by Sentinel-2a over Ukraine during the 2016 growing season.*

4.3 Production and validation of crop mask

Once the field data quality controlled, they must be uploaded into the Sen2-Agri system to produce the crop mask and the crop type map. The figure 4 corresponds to a single tile (100 x 100 km) of the Ukraine territory to highlight the spatial details of the Sentinel-2 images acquired on 17 July 2016 and the associated in situ data.

The full time series of all Sentinel-2 observation acquired from April to September 2016 over the whole of Ukraine (more than 1,5 Tb of compressed input data) was automatically processed to surface reflectance (6 Tb of processed surface reflectance data). Thanks to the upload of the in situ data, the time series was then classified to derive the crop mask at 10 m resolution by early October for the on-going growing season over a national territory of more than 600,000 sq km. The figure 5 displays samples of this unique result of 10 m crop mask. This early estimate of the 2016 cultivated area can be compared with the available early statistics for 2016 compiled from the sowing area declaration by the farmers aggregated at oblast level.

The quality of the crop mask displayed on figure 4 is assessed by the set of accuracy metrics already mentioned. It is clear that the accuracy varies spatially according the fragmentation of the landscape, the crop diversity, the density of field data and, last but not least, as long there is only one Sentinel-2 in orbit (till 2017), the frequency of cloud free images along the season. Fortunately, these characteristics can be easily documented and therefore the area estimate uncertainty can be predicted.

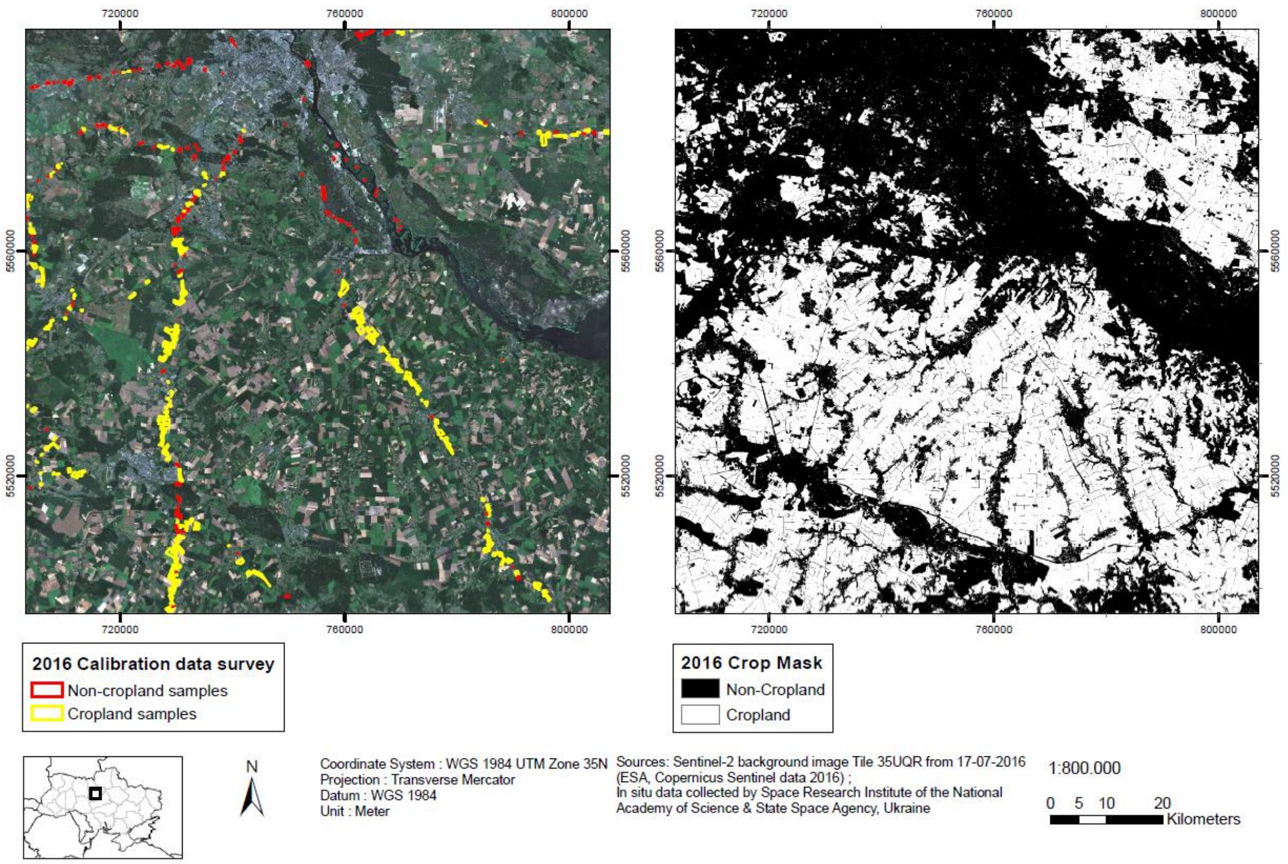


**Figure 4:** *Sentinel-2 10-m color composite acquired on 17 July 2016 over the South of Kyivs'ka oblast (on the left) overlaid by the field data used to produce the 2016 crop mask for the corresponding area (on the right side).*

4.4 Production of crop type map

Using the same in situ data, the Sen2-Agri system can also deliver a mid-season crop groups map and a more detailed crop type map by the end of the growing season. Zooms on the outputs obtained are displayed at figure 5. First, a map discriminating winter crops versus summer crops was produced while at the end of the season a more precise map of the different main crop types will be produced. Please note that the season was not over at the time of writing and the crop type map illustrated at the figure 4 is only an intermediary product.

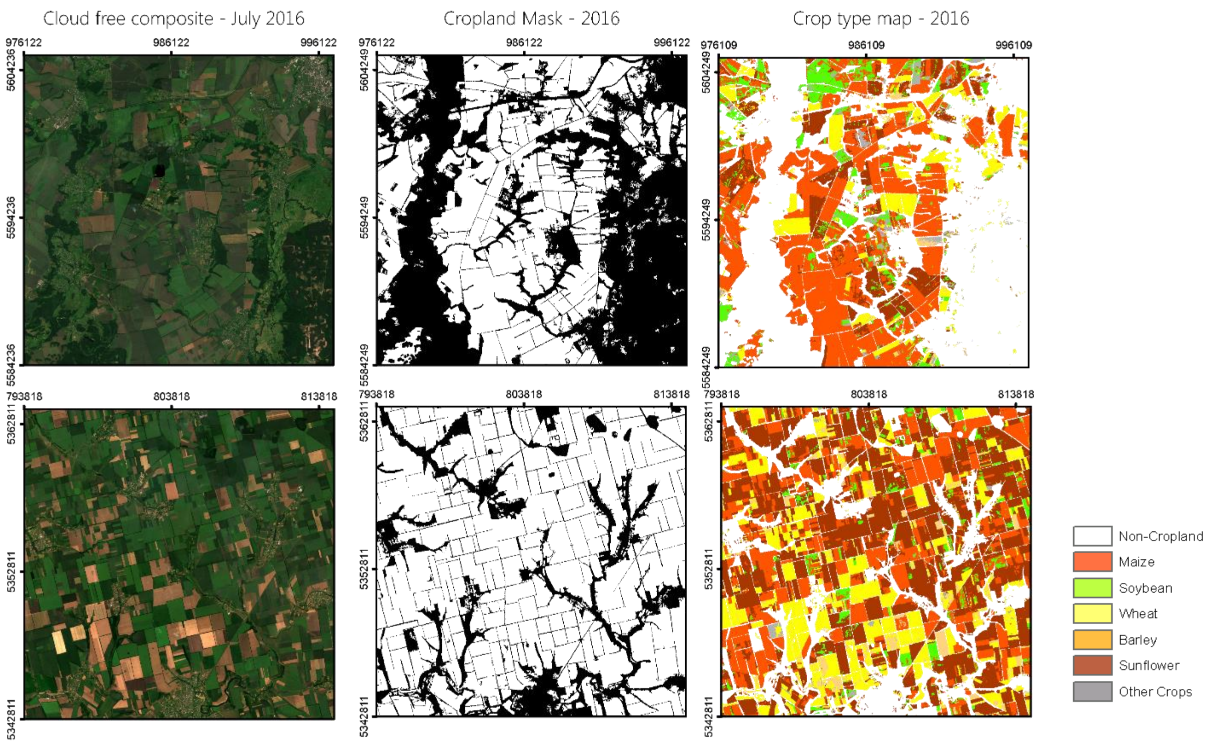


**Figure 5:** *Details of the 2016 cropland and main crop types map for two zoom in Ukraine.*

## 5. Perspective

The on-going demonstration of the Sen2-Agri highlights the significant impact of the availability of the Sentinel-2 time series on the capacity to deliver along the season various products including crop mask and crop type maps. The accuracy obtained for some of these products indicates that the early area estimate can be derived and be relevant as a complementary information to the official agricultural statistics. By the end of the growing season in the various demonstration countries, the final nationwide maps and derived area estimate will be available and compared with the existing official statistics. In addition, a user-oriented assessment, involving the national stakeholders such as the Ministry of Agrarian Policy and Food of Ukraine, will be reported in order to assess the Sentinel-2 demonstration products utility and benefit and the possible improvements.

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