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Assessments on the impact of high-resolution-sensor pixel sizes for common agricultural policy and smart farming services in European regions

Jonas Meier[a,*], Wolfram Mauser[a], Tobias Hank[a], Heike Bach[b]

[a] Dept. of Geography, Ludwig-Maximilians-Universität Munich, Germany
[b] VISTA GmbH – Remote Sensing Applications in Geosciences Munich, Germany

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ABSTRACT

High-resolution (5–50 m) remote sensing satellite sensors provide a reliable, free and open data infrastructure for public and private agriculture and land use services. The further market penetration of these services critically depends on the fraction of agricultural fields and area that the services can cover. EU's Common Agricultural Policy (CAP) and smart farming services require a minimum of spectrally pure measurements per agricultural field. The impact of pixel size on the coverage of agriculture is studied in this paper considering present free and open optical sensors (Sentinel-2 and LANDSAT). It further studies the implications of the selection of spatial resolution of planned extensions of these sensors, i.e. the next generation of Sentinel-2, as well as Copernicus's hyperspectral CHIME and thermal LSTM future candidate missions.

The paper analyzes the 2018 vector boundaries and crop types of 3.6 million agricultural fields in the German States of Bavaria and Lower Saxony and the Netherlands. The fields were rasterized using Sentinel-2 flight geometry and a pixel spacing of 5, 10, 20, 30 and 50 m. The study specifically considered: (1) fields with no pure pixel inside where no CAP services can be provided and (2) fields with less than 50 pure pixels inside, which is estimated to be the critical number for site-specific smart farming. The percentage of agricultural fields and agricultural area was determined for the main crop types. It shows, that with 10 m pixel spacing 2–4% and 20 m pixel spacing 12–22% of the agricultural fields in the study area do not contain a single pure spectral sample (Sentinel-2 case). This fraction decreases to 1–3% at 5 m spacing and increases to 25–40% for 30 m (LANDSAT and CHIME) and 50–70% for 50 m (LSTM) spacing. The percentage of fields with less than 50 pure pixels is 20–50% at 10 m and 70–85% at 20 m spacing (Sentinel-2). This fraction decreases to 5–12% for 5 m spacing and reaches the level of 92–97% for 30 m (LANDSAT) and 99% for 50 m spacing (LSTM). Our analysis shows, that with a pixel spacing of 5 m the Sentinel-2-based site-specific smart farming services could increase their potential customer base from ~50% to ~90% of the agricultural fields and could potentially cover 99% of the regions' agricultural area. A 20 m pixel spacing would increase the agriculture area from 23% to 56% in the Central and Western European study regions on which the Copernicus hyperspectral candidate mission CHIME is capable to measure pure and full spectra for highly advanced future site-specific management services. LSTM would also profit from a spatial resolution of 30 m, which would raise coverage of the agricultural area in Central Europe with pure thermal measurements from 3% at 50 m to 23% at 30 m.

1. Introduction

Approximately 12% of the global land surface is managed farmland (grassland and cropland) and subject to high temporal dynamics through annual, inter-annual and perennial variations in crop type and areal extent (Faostat, 2019). Managed farmland, contrary to unmanaged nature, is spatially organized as fields. Field size varies considerably depending on the level of mechanization of agriculture and on the economic, cultural and geographic background (Lesiv et al., 2019; Fritz et al., 2015; Graesser and Ramankutty, 2017). In general, crop management actions like plowing, seeding, fertilizing and harvesting are practiced on an agricultural management unit, which we denote a field. A so-defined field is independent of a cadastral property unit. In Central and Western Europe each field in general carries one crop at a time and is managed by one farmer. Using the information contained in spectral measurements of agricultural fields e.g. through the Copernicus Sentinel-2 satellites, to improve farm management is among the most promising and economically as well as environmentally important

* Corresponding author.
E-mail address: jonas.meier@lmu.de (J. Meier).

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applications of land surface remote sensing. Time series of satellite images at a spatial resolution, which enables to recover information of and within a field, allow monitoring important crop parameters like crop type, plant growth and health, phenology and yield formation. In-field, site-specific agricultural management in the context of smart farming promises large commercial and environmental benefits by improving resource efficiency and minimizing environmental impacts (Wolfert et al., 2017; Walter et al., 2017).

The practical usefulness on remotes sensing data for digital services for agriculture depends on its spatial, spectral and temporal resolution (Hank et al., 2018). This paper focuses on the assessment of the role of pixel spacing for the coverage of agricultural fields and area with special emphasis on high-resolution 5–50 m Earth observation sensors. We chose this resolution segment for our study in favor of the available ultra-high resolution of 0.5–5 m because it provides a reliable, free and open public data infrastructure, which will emerge into the future with candidate satellites for a hyperspectral and thermal coverage of the Earth surface. Pixel spacing of remote sensing data results from a trade-off between a number of system parameters. Among those are, most importantly, the spatial resolution of the instrument expressed by the modulation transfer function (MTF) of the optical system, the sensor (sensitivity, signal-to-noise ratio (SNR), spectral resolution) and the electronics, the on-board storage capacity and/or the transmission bandwidth in combination with the chosen orbit and revisit time. Pixel spacing can also be chosen during the processing of raw sensor data into the defined final data-products. Pixel spacing determines the data quality (SNR), the data volume and handling costs and the loss or gain of valuable information on agricultural fields and their spatial heterogeneity. Therefore, being aware of the difference of concepts of pixel spacing and spatial resolution, in the following text we assume that pixel spacing of a real world space borne sensor closely resembles its spatial resolution, which is also the well-introduced term in almost all documentations of Earth observation sensors. Therefore, we further use the term spatial resolution synonymously with pixel spacing. Decreasing spatial resolution increases the fraction of mixed pixels in a field and below a certain ratio of a field to pixel size, no pure pixel can be identified. At least one pure spectral measurement should be available to determine crop type, which is a monitoring requirement of the EU's Common Agricultural Policy (CAP) , from a time series of spectral measurements (Skogstad and Verdun, 2009; European Commission, 2019). The ability to resolve in-field heterogeneity of crop growth is the prerequisite for satellite-based remote sensing to contribute to site-specific field management in the context of smart farming. Site specific smart farming uses understanding of in-field spatial heterogeneity of crop growth conditions (e.g. soil fertility, ground water level, relief and its influence on erodability and climate) and their influence on crop growth and yield in combination with advanced farming machinery to optimize resource use (fertilizer, pesticides, irrigation water) and minimize cost and environmental impacts. Site specific smart farming usually divides a field into management zones for which different management options are chosen. Different strategies are available to optimize results. They range from gradually intensifying to extensifying the less fertile parts of a field depending on situation and aim. For the management options to be successful the spatial resolution should of the spectral samples should be at a fraction of the sizes of the considered agricultural field to be able to fully quantify the in-field heterogeneity.

Current generation Sentinel-2 delivers multispectral images in 13 bands with a spatial resolution of 10 m in the VIS/NIR bands, 20 m in the NIR/SWIR bands and 60 m in the atmosphere bands (ESA, 2015). For next-generation Sentinel-2 satellites, an increase in spatial resolution of the VIS to SWIR bands to 5–10 m is considered (European Commission, 2016). In addition, ESA currently conducts Phase A/B1 studies on the candidate Copernicus Hyperspectral Imaging Mission (CHIME) (Nieke and Rast, 2018) and the Land Surface Temperature Mission (LSTM) (Koetz et al., 2018). Here mission requirements regarding spatial resolution between 20 and 30 m for CHIME and between 30 and 50 m for LSTM are discussed.

Market penetration of Copernicus based remote sensing services in a region is limited by spatial resolution. Copernicus-based agricultural services are usually contracted on a field basis and paid per hectare. Empirical evidence on these real-world limits of different high-resolution sensors must therefore determine both all agricultural fields and the complete agricultural area affected by mixed pixels with varying spatial resolutions. This assessment is not straight forward. It has to take into account the field size distribution, the ratio of the field to pixel size as well as the shape of the fields. EU's "Land Parcel Identification System" (LPIS) as part of the "Integrated Administration- and Control System" (IACS) is the basis for EU-subsidies to farmers. Farmers annually report the crop type of all their subsidized agricultural fields. IACS-LPIS therefore contains all fields for which satellite-based services can potentially be offered to support CAP and site-specific smart farming. IACS-LPIS data of selected regions in Central and Western Europe is used in our study reported as agricultural parcels, containing field boundaries of single fields and their cultivated crops per year. We have chosen Central and Western Europe test regions because they are among the most productive agricultural areas on the globe, have a diverse agricultural structure and because their agricultural services, which depend on EU's Copernicus Sentinel data, dynamically emerge.

This paper evaluates the impact of spatial resolutions ranging from 5 m (possibly improved future Sentinel-2), 10 m (current Sentinel-2, VIS-NIR), 20 m (current Sentinel-2 NIR-SWIR and upper CHIME specification), 30 m (LANDSAT, lower CHIME and upper LSTM specification) and 50 m (lower LSTM specification) on the coverage of agricultural fields for digital agriculture services in Central and Western Europe. We use as indicators the fraction of fields and the affected area in the selected Central and Western European study areas, which at a selected spatial resolution (1) have to be excluded from any remote sensing based agricultural services and (2) have to be excluded from in-field heterogeneity analysis due to a lack of pure pixels. The study covers three European regions: The German Free State of Bavaria and State of Lower Saxony in Central Europe and the Netherlands in Western Europe. The three regions represent different cultivated landscapes from large agricultural operations to small family owned part-time farms and therefore covers a large portion of the variety of Central and Western Europe's agriculture. Rather than using simulated field boundaries, the use of real-world field boundaries is needed to obtain unbiased and objective assessment results because of the complexities in field shapes, proportions of various shapes and sizes, adjacent fields' neighboring topology, and disturbances in field regularities caused by land surface features such as streams (Graesser and Ramankutty, 2017; Yan and Roy, 2014; Schmidt et al., 2016).

To our knowledge, this is the first time that field-wise agricultural coverage by different spatial resolutions of remote sensing instruments is investigated on a complete set of real-world subsidized fields for application in EU's common agricultural policy (CAP) as well as in site-specific farming in three Central European regions. To create these new scientific results, the paper relies on state-of-art geo-statistical methods. The challenge of aggregating spatial data into defined boundaries is well known and discussed since years under the "modifiable areal unit problem" (Gehlke and Biehl, 1934; Openshaw and Tylor, 1979; Openshaw, 1984). The problem also affects satellite images when the spectral reflectance measured in a pixel is composed of objects with different spectral properties (mixed pixel) (Löw and Duveiller, 2014). Several studies addressed the influence of spatial resolution on land use classifications derived from remote sensing data (Fisher et al., 2018; Pax-Lenney and Woodcock, 1997) or on estimated biophysical parameters like leaf nitrogen concentration (Zhou et al., 2018) or leaf area indices (Sprintsin et al., 2007). To find the most suitable spatial resolution these studies suggest to consider the local conditions, the topic of the research or service question and costs when choosing the appropriate spatial resolution (Atkinson, 1997).

2. Materials and methods

The study is based on data from the EU's "Integrated Administration- and Control System" (IACS). One element of the IACS is called the "Land Parcel Identification System" (LPIS), containing all agricultural plots in EU countries as georeferenced vector field boundaries together with information on cultivated crops. LPIS provides the field information in different types as "Agricultural parcel" (AP), "Farmer block" (FB), Physical block" (PB) and "Cadastral parcel" (CP) (Grandgirad and Zielinski, 2008). The following analysis is based on the LPIS type "Agricultural parcel", which means "a continuous area of land, declared by one farmer, which does not cover more than one single crop group […]. Member states may lay down additional criteria for further delimitation of an agricultural parcel." (European Union, 2013). The three regions provide crop specific data for each field. Since the European agrarian subsidies are based on this data and because field boundaries, as well as crops, are changing by growing season, the data is updated annually and carefully checked by regional agricultural authorities. We use 2018 data for this study because the data is available as "Agricultural parcels" for all three selected regions. They describe a field with one crop, which is independent on the cadastral situation. The regions 1) State of Lower Saxony (LS) (Lower Saxony Ministry of Food Agriculture and Consumer Protection, 2018), 2) Free State of Bavaria (BY) (Bavarian Bureau for Agriculture, 2018) in Germany and 3) the Netherlands (NL) (Ministerie van Economische Zaken - Rijksdienst voor Ondernemend Nederland) were selected (Fig. 1) based on (1) availability of data (IACS-LPIS-data usually is not publically available, in our case data from Netherlands (Basisregistratie Gewaspercelen BRP") and Lower Saxony ("Schlaege 2018") is publically available) and (2) a broad range for Central and Western European farming systems. The three study areas are similar in size (NL: 42,508 km^2, LS: 47,614 km^2, BY: 70,550 km^2, see Table 1) and fraction of agricultural land. Agriculture land use in the three selected regions is dominated by grassland and staple crops like maize, wheat, barley etc. as well as potatoes (see Fig. 2). The IACS-LPIS data contains more than 200 crop types. For a better comparison the crop types are aggregated to crop groups (see Fig. 2).

Table 1
Sizes of the land area, agriculture area and number and average sizes of fields in the analyzed regions derived from EU–IACS-LPIS data.

	Bavaria	Lower Saxony	Netherlands
Land Area Size	7.055 Mio. ha	4.761 Mio. ha	4.250 Mio. ha
Agriculture Area	3.173 Mio. ha	2.595 Mio. ha	1.880 Mio. ha
% Agricultural Area	44.97%	54.51%	44.24%
Number of Fields	1.9 Mio.	0.9 Mio.	0.7 Mio.
Ø Field Size	1.6 ha	2.8 ha	2.4 ha

Table 1 shows statistics of the IACS-LPIS data sets of the three study regions. Bavaria and the Netherlands have similar shares of agricultural land whereas in Lower Saxony the share of agricultural land is largest with more than 54%. With 1.6 ha the average field size is smallest in Bavaria pointing at a large share of small farms managed part-time as well as the influence of topography, which limits field sizes in some parts of the State. In Lower Saxony, the average field size is largest (2.8 ha) which is a consequence of larger commercial farms. Average field size in the Netherlands (2.4 ha) is between Bavaria and Lower Saxony.

2.1. Analysis approach

The vector field boundaries from the IACS-LPIS data sets were rasterized at 5, 10, 20, 30 and 50 m resolutions using the Sentinel-2 pixel locations and geometry. The conversion into pixel-based raster dataset

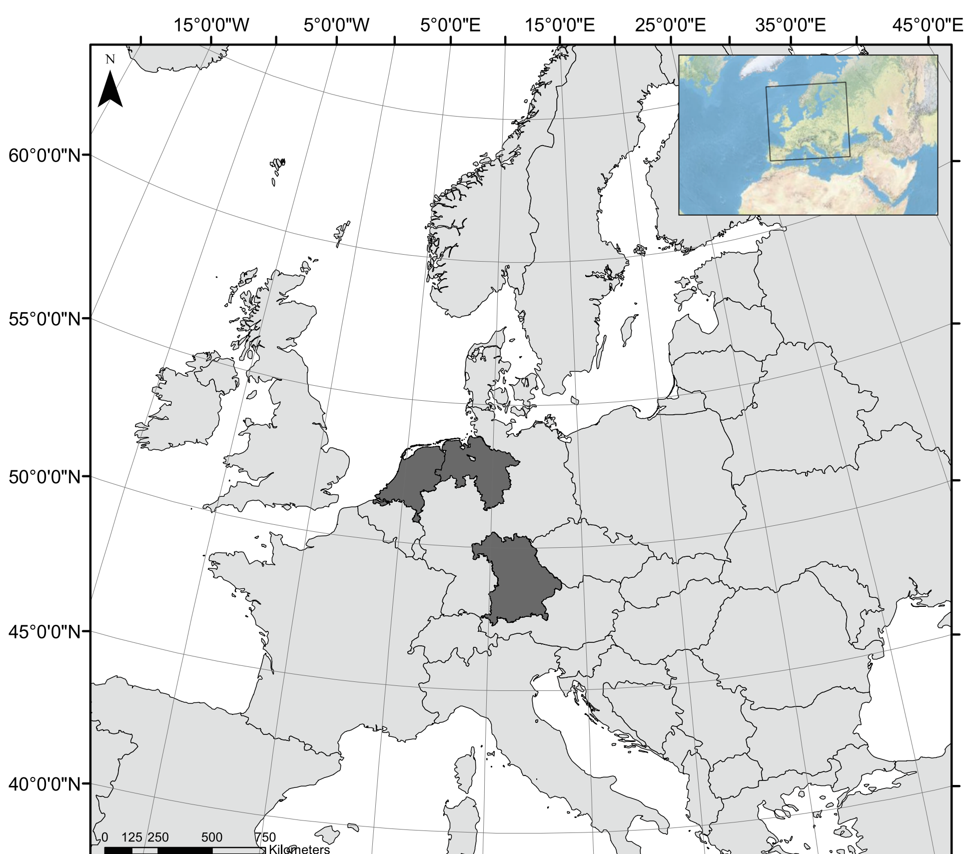

Fig. 1. Location of the three study regions in Central Europe in dark grey.

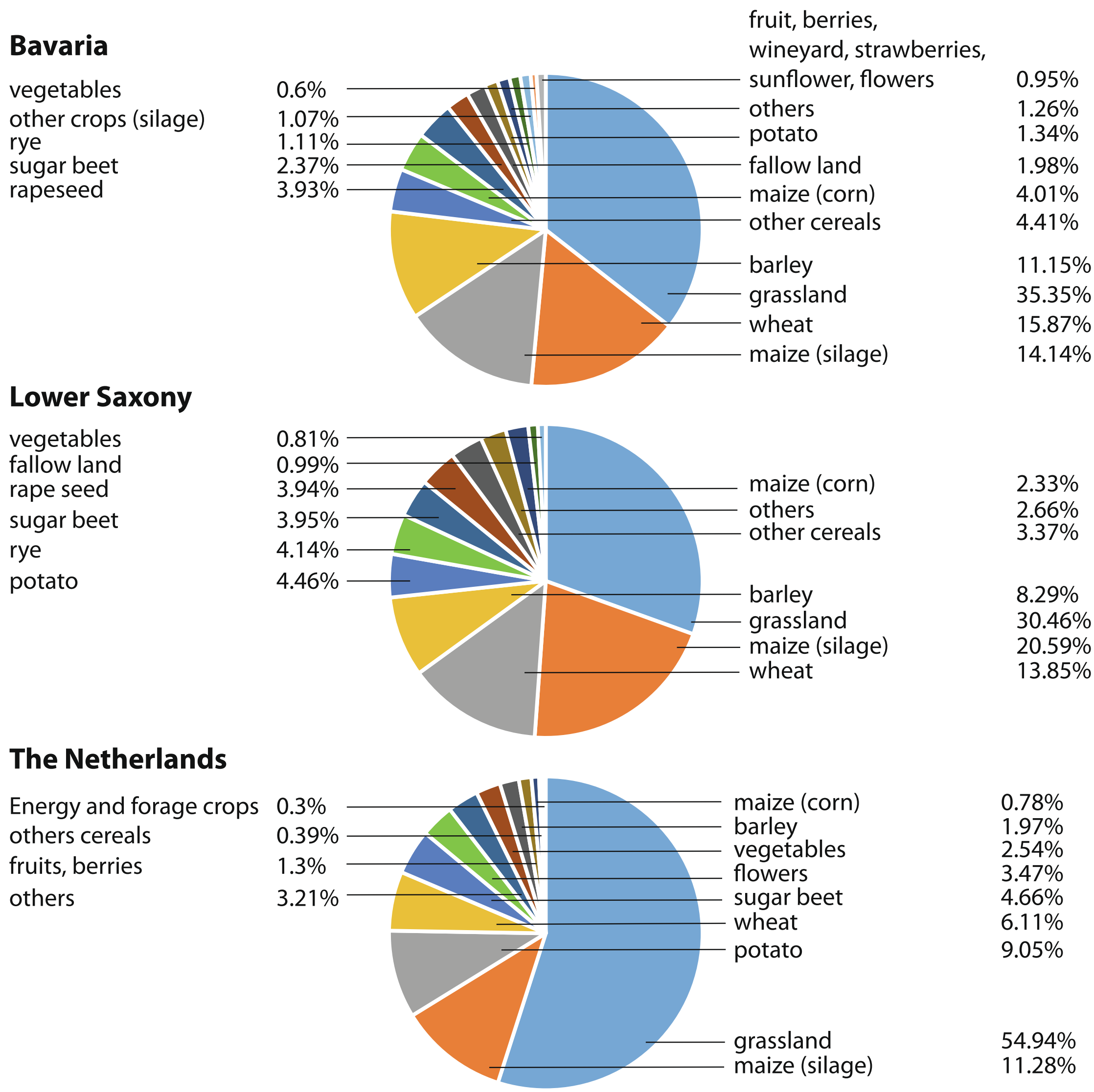

Fig. 2. Crop composition in the three study regions Bavaria, Lower Saxony, and the Netherlands in 2018 (Source: EU-IACS-LPIS).

is carried out using a modified Bresenham's line algorithm (Bresenham, 1965), which assumes the pixel center to be the valid pixel coordinate. This approach tends to increase the rasterized fields beyond the vector field boundaries by maximum half of the chosen resolution. The protrusion of the pixels beyond the field boundaries consequently leads to pixels containing a mix of the spectral reflection of the field crops and their surrounding area. To ensure pure agriculture pixels the vector field boundaries are shrunk before rasterization by half the size of the spatial resolution. Assuming square pixels, the reduction value is calculated via Eq. (1), which is based on the Pythagorean theorem:

$$\text{reduction value} = \sqrt{2 * \left(\frac{\text{resolution}}{2}\right)^2} \tag{1}$$

Fig. 3 shows an exemplary result of shrinking vector field boundaries to ensure that only pixels are rasterized, which completely lie within the vector field boundaries. The shrinking of the fields changes the shape of the original field boundary polygons and may lead to new island polygons. Small fields collapse depending on size and shape and do not include a valid pixel.

Fig. 4 shows the resulting difference between rasterization using the classical Bresenham's line algorithm based on the original polygons (center approach) and on the shrunken field boundaries (pure-pixel approach) where the whole pixels' area is located inside the vector field boundaries.

3. Results

The rasterization is carried out for each of the 3.5 million 2018 IACS-LPIS fields in the study regions and each selected spatial resolution of 5, 10, 20, 30 and 50 m pixel size. It results in five raster-data sets containing the spectrally pure pixels in each agricultural field at five different spatial resolutions. The number of pure pixels per field serves as parameter for the suitability of the selected spatial resolution to analyze crop type and in-field heterogeneities in the context of site-specific smart farming.

Fig. 5 shows an example cut-out of the rasterized pixels at the selected spatial resolutions. The lowest level in Fig. 5 shows the spatial resolution of 5 m (green) with reducing resolution to 10 m (blue), 20 m (orange) and 30 m (black) and 50 m (purple) in the following layers. The expected change in pixel size and pixel pattern can be seen in Fig. 5 as well as a considerable increase of white area not covered with pure pixels and some fields, which completely lose their pixels with decreasing spatial resolution. The approach clearly reduces the sampled

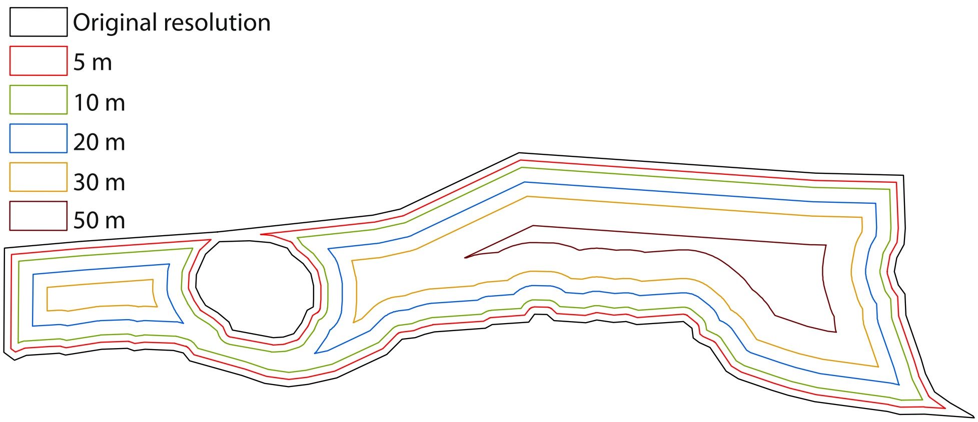

Fig. 3. Exemplary polygon to demonstrate the shrinking of the field boundaries to ensure that only pixels, which are completely within the vector field boundaries are rasterized. The figure shows the original shape of the field in black and the shrunken field boundaries depending on the spatial resolution. At 50 m raster resolution the polygon left from the gap disappears by the approach.

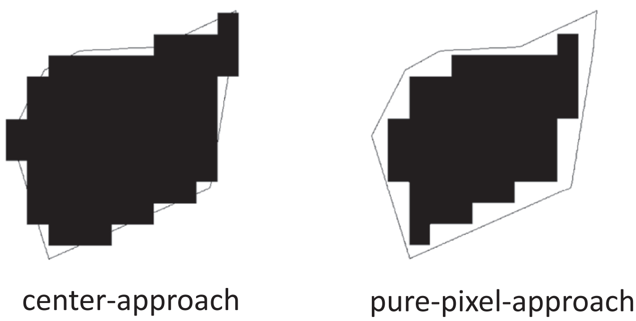

Fig. 4. Center-approach vs. pure-pixel-approach: Center-approach burns the pixel if the center of the pixel is inside the polygon and thereby increases the size of the field. The pure-pixel-approach burns the pixel only where the pixel is completely inside the field boundaries. This method results in "pure-field-pixel" but leads to a loss of covered field area.

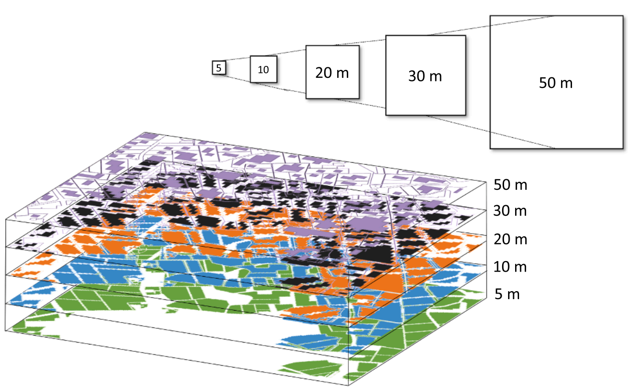

Fig. 5. Exemplarily the change of the field sizes and shapes at different spatial resolutions: 5 m (green), 10 m (blue), 20 m (orange), 30 m (black) and 50 m (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

area in a region because it eliminates all mixed pixels. The reduction of the total sampled agricultural area mainly depends on the field size distribution and the field shape.

Farmers manage fields. Of central importance are therefore (1) the number and total area of fields that are either not covered at all by a pure spectral measurement and (2) the number and total area of fields that contain less than a minimum number of pure pixels. As a consequence, spectral analysis is of limited use to determine crop type in case 1 or in-field spatial heterogeneity in case 2. Consequently, these fields are assumed to be lost to the respective scientific analysis and/or commercial service. Case 1 fields will further be denoted 'lost fields'. Case 2 is not straight forward and requires a threshold number of pixels below which field spatial heterogeneity cannot be determined in a meaningful way for site-specific smart farming. To our knowledge no literature-based general agreement exists on the number of pure samples in a field, which are required to enable site-specific smart farming as defined above. The number depends on the heterogeneity of the considered field as well as on the farming machinery used and management action applied (fertilization, plant protection, irrigation). Practical experience suggests that a minimum of 50 pure pixels per field is desired to determine a spatial distribution of crop growth conditions on which in-field site-specific management actions can be based in a meaningful way and so was selected for this assessment. This is based on the assumption that fields are divided into zones with similar growing conditions and management actions are defined for each zone. We assume that a meaningful division of a field is made up of at least three zones. In order to cluster three different zones in a field with any statistical significance a minimum sample size of 15–20 samples per zone is necessary. This results in a minimum number of ~50 pure spectral samples per field to develop site-specific smart farming services. Fields with an insufficient number of pure pixels for site-specific farming will further be denoted 'no site-specific farming'. Analysis based on thresholds of 1, 10, 20, 30 and 100 pixels are provided in the supplement (S8).

Fig. 6 shows the fractional histograms of pure pixels per field for the three test regions and the selected resolutions of 5, 10, 20, 30 and 50 m. The zero pixels per field column (blue) in the histograms represent the percentage of lost fields, the red line marks the threshold of 50 pure pixels below which a field is denoted 'no site-specific farming'.

Fig. 6 clearly shows the changing shape of the histograms with decreasing spatial resolution. At a resolution of 5 m the percentage of lost fields is small (< 3%) and the increasing pure pixel number classes tend to be equally populated for all three test regions. Percentages of lost fields sharply increase and the population of the classes becomes more right-skewed with decreasing resolution along the lines of the histogram matrix.

In addition to the results for the 'no site-specific farming' case results for fields with 1, 10, 20, 30 and 100 pure pixels are provided in the supplement (S8) together with the numerical values of the histograms (S5-S7). This enables further analysis with additional threshold values. The results show that the monotonously increasing fraction of fields that are lost to site-specific smart farming does not provide any intrinsic indicator for an optimum number of pure samples per field. Table 2 shows the percentage of 'lost fields' and 'no site-specific farming' fields and the related agricultural area in the three test regions as a function of spatial resolution.

As can be expected, Fig. 6 and Table 2A show, that the percentage of 'lost fields' and 'no site-specific farming' fields both increase with decreasing spatial resolution. Table 2A shows, that in all test regions only

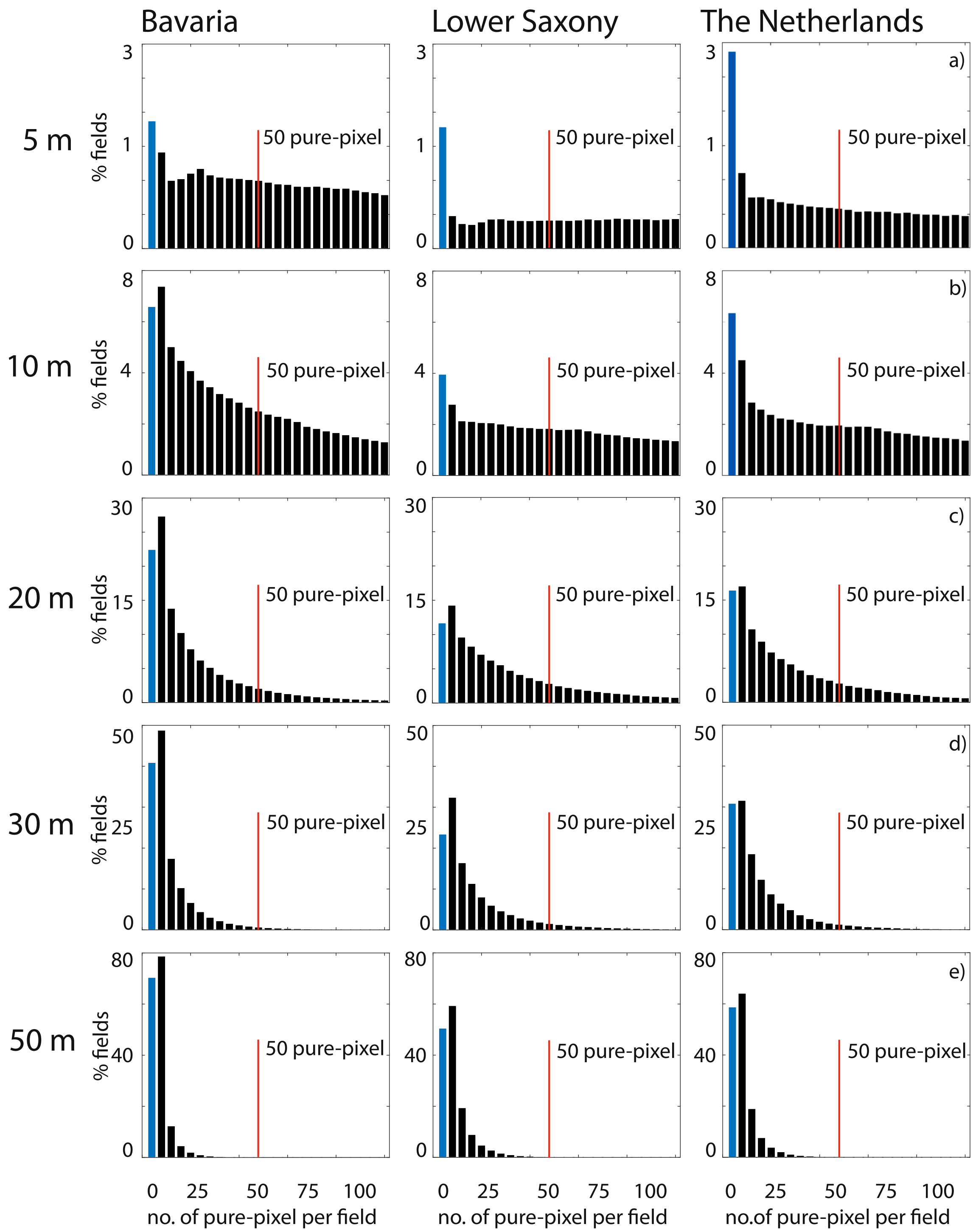

Fig. 6. Fractional histograms of the number of pure pixels per agricultural field for the three test regions Bavaria, Lower Saxony and the Netherlands (columns) and the selected rasterization resolutions of 5, 10, 20, 30 and 50 m (lines).

2–3% of all fields are lost to spectral analysis at a spatial resolution of 5 m. This percentage roughly doubles to around 5% at the 10 m resolution of the contemporary Sentinel-2 VIS-NIR bands. It further increases to 10–20% for the 20 m Sentinel-2 NIR-SWIR bands and the upper resolution of CHIME. 25–40% of all fields in the test regions are lost to a spectral analysis on at least one pure pixel at a spatial resolution of 30 m, which is today's LANDSAT, the lower proposed CHIME and upper proposed LSTM resolution. At LSTM's lower proposed resolution of 50 m, 50–70% are lost. The loss of fields with at least one pure pixel is largest in Bavaria with its compartmentalized agriculture and less severe in Lower Saxony with its large commercial farms. In the Netherlands, the effect lies between the two extremes.

Table 2A also shows the analysis of the percentages of fields that fall in the 'no site-specific farming' category. The general tendency is similar to the 'lost' fields although the level of rejection is considerably higher. 5–12% of the agricultural fields fall into the 'no site-specific farming' category at a spatial resolution of 5 m. This percentage increases to 22–50% at the current Sentinel-2 VIS-NIR spatial resolution of 10 m, further increases to a stunning 70–85% at the current Sentinel-2 NIR-SWIR and upper CHIME spatial resolution of 20 m. It reaches

Table 2
Percentage of (A) 'lost fields' (with no pure pixel inside) and 'no site-specific farming' fields (<50 pure pixels inside) and percentage of (B) agricultural area connected to the 'lost fields' and 'no site-specific farming' fields in (A) for each test region and selected spatial resolution.

A	Bavaria:		Lower Saxony:		Netherlands:	
	% lost fields (no pure pixel inside)	% no site-specific farming fields (< = 50 pure pixels inside)	% lost fields (no pure pixel inside)	% no site-specific farming fields (< = 50 pure pixels inside)	% lost fields (no pure pixel inside)	% no site-specific farming fields (< = 50 pure pixels inside)
5 m	1.69%	12.17%	1.78%	5.72%	2.87%	9.54%
10 m	6.41%	49.79%	3.96%	23.14%	6.36%	28.84%
20 m	22.27%	86.40%	11.67%	69.65%	16.43%	75.27%
30 m	40.73%	97.72%	23.40%	91.51%	30.86%	94.42%
50 m	70.22%	99.93%	50.52%	99.57%	58.76%	99.74%

B	Bavaria:		Lower Saxony:		Netherlands:	
	% area lost fields (no pure pixel inside)	% area no site-specific farming fields (< = 50 pure pixels inside)	% area lost fields (no pure pixel inside)	% area no site-specific farming fields (< = 50 pure pixels inside)	% area lost fields (no pure pixel inside)	% area no site-specific farming fields (< = 50 pure pixels inside)
5 m	0.08%	0.98%	0.12%	0.37%	0.21%	0.63%
10 m	0.49%	10.53%	0.29%	3.74%	0.51%	4.95%
20 m	3.58%	55.43%	1.58%	33.52%	2.34%	39.82%
30 m	10.82%	85.86%	4.86%	68.56%	7.61%	75.20%
50 m	33.91%	98.76%	18.88%	96.34%	25.35%	96.17%

92–98% for the current LANDSAT and discussed lower CHIME and upper LSTM resolution of 30 m and 99% for the discussed lower LSTM resolution of 50 m.

Table 2B shows the percentage area represented by the lost fields of Table 2A. In general, the fraction of the area is lower than the fraction of fields because small fields tend to get lost first. At the resolution of 10 m, the fields that are lost because they do not contain a single pure pixel is ~1% of the total agricultural area in all three regions. The lost area increases to 1–3% at 20 m, 5–10% at 30 m and to 19–34% at 50 m resolution.

The analysis of the agricultural area assumed lost for site-specific smart farming (<50 pure pixels inside) shows a different perspective. Here at 5 m resolution, the lost area is below 1%. This value increases to 4–10% at 10 m resolution. 20 and 30 m resolution show a strong increase of lost area to 33–55% (20 m) and 68–86% (30 m) respectively. At 50 m resolution, 96–99% of the area is lost to smart farming, which makes a resolution of 50 m unsuitable for site-specific farming services in the selected test regions in Western and Central Europe.

Field sizes and shapes may vary considerably depending on land use and crop selection. Specialty crops like wine, hops and vegetables, etc. tend to be cultivated on smaller fields with more intensive management and higher revenues per hectare. Staple crops like maize, cereals as well as potatoes and sugar beet, etc. tend to be cultivated on larger fields with more mechanization and smaller revenues per hectare. We therefore analyze the resolution dependent fraction of 'lost' and 'no site-specific farming' fields for the major agricultural crops in the selected regions. We exemplary present the results for Bavaria since it is the most compartmentalized of the chosen regions and may therefore serve as a lower baseline for estimating the potentials of different resolutions for high- resolution remote sensing based agriculture services (crop specific analyses of the Netherlands and Lower Saxony are attached in the supplement). Fig. 7a and b show the percentage of 'lost fields' and 'no site-specific farming' fields in Bavaria for different crop types as a function of spatial resolution.

In Fig. 7a and b, the position of the crop categories is ordered by the respective percent loss of fields. The colors of the bars represent different spatial resolutions. Fig. 7 shows that different crops are unequally affected by the reduction in the spatial resolution regarding the percentage of (a) lost fields as well as (b) no site-specific farming fields. Two categories can be distinguished. First staple crops like cereals and maize as well as sugar beet, which generally populate the left side of the graphs. They show relatively small percentages of both 'lost' and 'no site-specific farming' fields. Second specialty crops like wine, flowers fruits and vegetables, with higher percentages of 'lost' and 'no site-specific farming' fields, which tend to populate the right side of the graphs. Fig. 7 clearly shows that the current Sentinel-2 configuration allows field-based crop type identification for more than 90% of the staple crops in Central Europe. For about 20–40% of specialty crops, no identification is possible because of small field sizes. On the other hand, the 20 m NIR-SWIR spectral information of Sentinel-2 is insufficient to determine heterogeneity for site-specific agricultural services on approx. 60–80% of Central European fields (Fig. 7b). Specifically, for staple crops, the percentage of 'no site-specific farming' fields decrease considerably when moving to 10 and decisively when moving to 5 m spatial resolution.

Fig. 8a and b show the corresponding crop-specific agricultural area affected by the choice of resolution. Again, similar to the results show in Table 2B, Fig. 8a shows that the fractional agricultural area related to the lost fields is smaller than the fractional number of lost fields for all categories. Fig. 8 also confirms the distinction between crop categories found in Fig. 7: areal loss in staple crops is smaller for coarser resolutions than for specialty crops like wine, hops, vegetables, flowers or fruits.

Fig. 8b shows the lost area of the 'no site-specific farming fields' (<50 pure pixels). The results show that the 10 m resolution of the current Sentinel-2 fleet is able to cover about 80% of the crops area, the fraction of the specialty crops is lower, the fraction of the lost area of the staple crops lies under 10%. Decrease of spatial resolution of 20 m increases loss to about 40% at staple crops and a decrease to 30 m increases losses to 80%. At the spatial resolution of 50 m nearly no field of any crop is suitable for agricultural remote sensing services based on pure pixels.

Table 3 summarizes the three test regions to one overview result, which includes all three Central and Western European study regions. Columns 2 and 3 show the resulting fraction of fields, column 4 and 5 the fraction of agricultural area affected by the selected spatial resolution. Table 3 clearly shows that with a resolution of 5 m 90% and more fields and more than 99% of the agricultural area can be accessed with high-resolution satellite remote sensing systems even for sophisticated agricultural services. Current Sentinel-2 due to its limited spatial resolution cannot cover roughly half of the Western and Central European study sites' agricultural fields or a quarter of their agricultural area with site-specific smart farming services. At the spatial resolution of 30 m or even of 50 m, more than 90% of the fields and roughly 85%

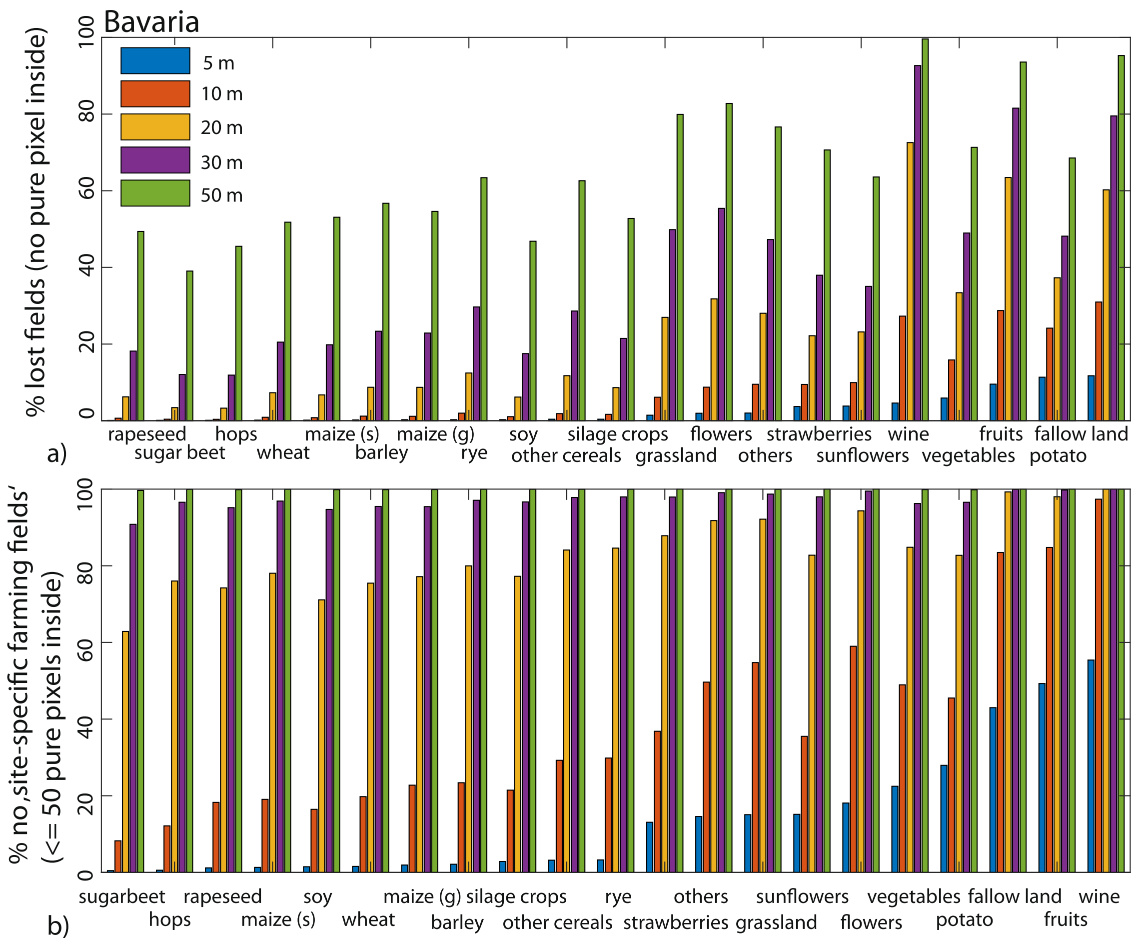

Fig. 7. Percentage of (a) 'lost fields' and (b) 'no site-specific farming' fields of different crop types in Bavaria for the selected rasterization resolutions of 5, 10, 20, 30 and 50 m. Maize (s) = silage maize, maize (g) = maize grain, silage crops = silage crops without maize.

of the area are lost to site-specific smart farming services. Nevertheless, it should be stated that the fraction of fields and related area on which time series of images can be used to identify crops on one pure pixel is much larger making resolutions of 30 m and above much more suitable for EU-CAP monitoring purposes.

4. Discussion

The impact of pixel spacing / spatial resolution of existing and anticipated space borne sensors on the potential coverage of agriculture with EU's Common Agricultural Policy (CAP) and site specific smart farming related remote sensing services was analyzed in a real-world scenario. We used the 2018 vector field boundaries and crop types of 3.5 million fields (management units) in the German States of Bavaria and Lower Saxony and the Netherlands. We determined, for spatial resolutions of 5, 10, 20, 30 and 50 m, the fraction of fields with (1) no pure pixel and (2) less than 50 pure pixels. We assume case 1 fields excluded from CAP-related and case 2 fields excluded from site-specific smart farming remote sensing services. The composition of the analyzed fields is representative for large parts of Western and Central Europe's agriculture. Nevertheless, we want to point out that there are regions within EU with smaller (e.g. Romania, Southern Poland, northwest Spain) and larger (e.g. Hungary, Czech Republic, South Spain, East Germany) average field sizes (Kuemmerle et al., 2013).

The spatial resolution range from 5 to 50 m represents the global present and future land surface Earth Observation free and open data infrastructure. It covers both existing systems like Sentinel-2 and LANDSAT and anticipated systems like the future generation Sentinel-2 as well as the Copernicus hyperspectral CHIME and thermal LSTM candidate missions. Their data will operationally be available with dense temporal coverage for a foreseeable future and therefore is ideally suited to develop the science behind operational agricultural services for public and private users. Ultra-high resolution space borne sensors, which offer data at spatial resolutions of the order of 1 m on a commercial basis currently lack the long term operational commitment as well as the combined spectral and temporal coverage to base e.g. site-specific smart services on their data. A spatial resolution of the order of 1 m is also an order of magnitude larger than the swath width of the usual agricultural machinery, which is 10 m. Sensors, which offer this resolution therefore often over perform when it comes to site-specific smart farming services.

The analysis of the loss of coverage of agricultural fields and their related area with spatial resolution was carried out for the major staple and specialty crops on all agricultural fields in the selected regions subsidized by EU. This gives insight into the relation of crop-specific analyses, which are important because from an application point of view it makes a difference whether fields with highly-valued crops (e.g. specialty crops like wine, hops, vegetables) or lower-valued staple crops (e.g. maize, cereals) and potato are lost. The first category produces more revenue per hectare and therefore tends to be managed more intensively. In this category, the overall economic impact of improvements of crop management (water saving in irrigation, more efficient fertilization, early detection of pests, etc.) with agricultural remote sensing services is potentially higher. On the other hand, staple crops generally cover much larger areas and therefore, potentially, site-specific agricultural management based on agricultural services can improve efficiency and achieve positive environmental impact on much larger areas.

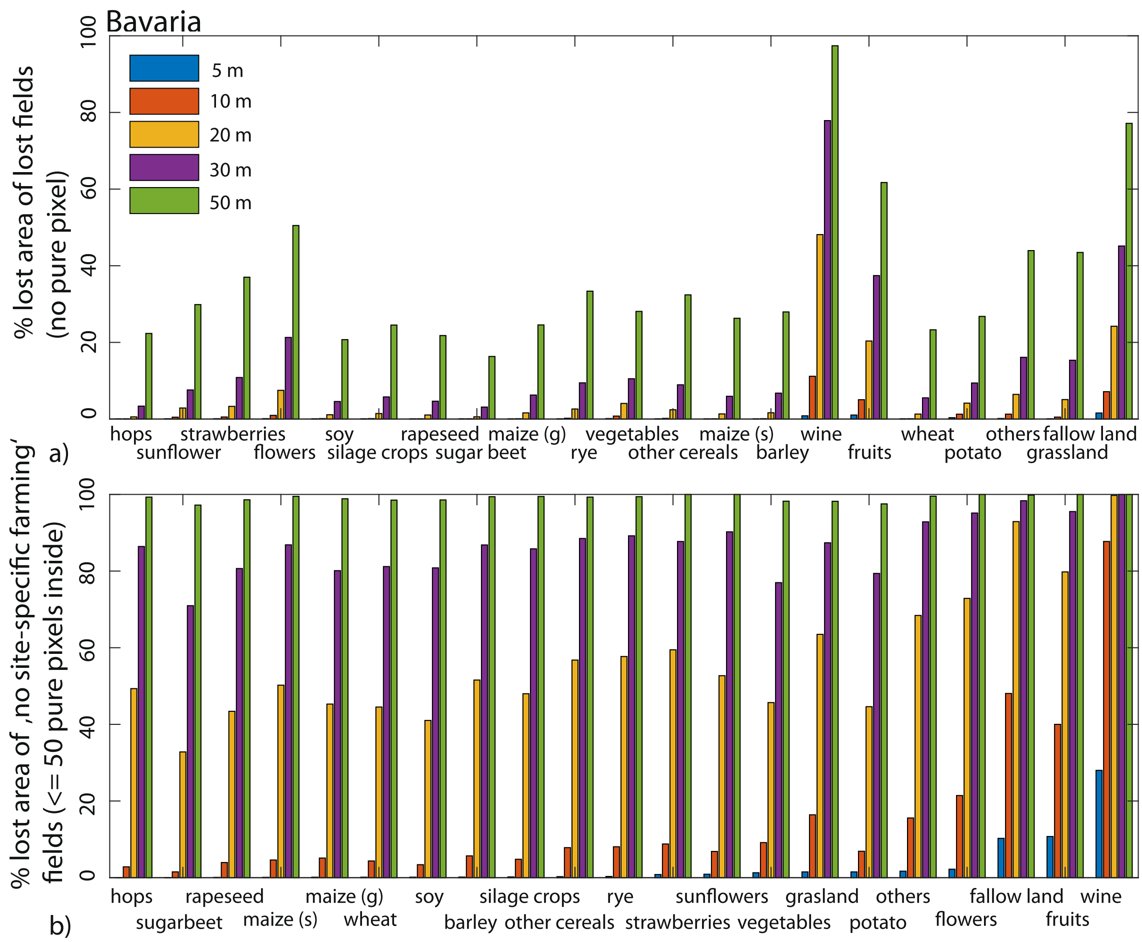

Fig. 8. Percentage of (a) 'area of lost fields' and (b) 'area of no site-specific farming' fields of different crop types in Bavaria for the selected rasterization resolutions of 5, 10, 20, 30 and 50 m. Maize(s) = silage maize, maize(g) = maize grain, silage crops = silage crops without maize.

Table 3
Percentage of 'lost fields' (with no pure pixel inside) and 'no site-specific farming' fields (<50 pure pixels inside) for all regions analyzed.

	All regions:			
	% lost fields (no pure pixel inside)	% no site-specific farming fields (< = 50 pure pixels inside)	% area lost fields (no pure pixel inside)	% area no site-specific farming fields (< = 50 pure pixels inside)
5 m	1.79%	10.02%	0.13%	0.69%
10 m	5.79%	37.75%	0.43%	6.85%
20 m	18.40%	79.89%	2.60%	44.16%
30 m	34.34%	95.48%	8.01%	77.37%
50 m	62.90%	99.80%	26.70%	97.30%

We found, as can be expected, a strong decrease of loss of coverage of fields and the related area with increasing spatial resolution. Since there are more small fields than large fields, the decrease in loss of coverage is more pronounced for the number of fields than for their related area. At the lowest resolution of 50 m ~ 60% of the fields and 25% of the agricultural area do not contain a single pure pixel. This resolution also does not allow to derive site-specific smart farming services in all three test regions. The situation becomes slightly less serious with the current LANDSAT and lower CHIME and upper LSTM candidate Missions' resolution of 30 m. The fraction of analyzed fields, which do not contain a single pure spectral measurement, decreases to from ~60 to 35% with 8% of the area lost. With the spatial resolution of today's Sentinel-2 sensors still a notable fraction of 18% (at 20 m) and 6% (at 10 m) of the fields and 2.6% (at 20 m) and 0.4% (at 10 m) of the related agricultural area are still too small to contain at least a single pure pixel. As a conclusion, with the spatial resolution of current Sentinel-2-time series reliable quantitative image analysis like crop type specification to serve EU's CAP is not possible for roughly every 5th analyzed field. An increase of spatial resolution to 5 m would in turn allow finding at least one pure pixel in almost all analyzed fields.

Since the criterion for a field to be accessible for site-specific smart farming services was defined to be at least 50 pure pixels it can generally be expected that both a larger fraction of fields and a larger area is lost for site-specific smart farming services. With resolutions of 30 m and below only the 5% largest fields, which cover 20% of the area, are accessible for these services. This, together with the low temporal revisit frequency explains why LANDSAT data is not suitable for developing smart farming services for the analyzed fields. Sophisticated site-specific agricultural services like the provision of spatial chlorophyll distributions within a field go beyond simple computation of NDVI. They rely on the complete set of all Sentinel-2′s 10 and 20 m resolution VIS-SWIR bands. They depend on some sort of resolution merge between 10 m VIS/NIR bands and 20 m NIR/SWIR bands which inevitably degrades the spatial resolution of the merged pixels to somewhere between 10 and 20 m. At the 20 m resolution the fraction of fields, which are potentially accessible with site specific smart farming services is 20% and the covered area is 66%. On the other hand, a spatial resolution of equal or better than 10 m completely changes the situation. Site-specific smart farming services can then potentially be made available ~2/3rd of the analyzed fields and for more than 93% of the related agricultural area. Most importantly, at this resolution staple crops in the selected European regions would almost completely be covered.

Finally, with a resolution of 5 m 90% of the analyzed fields, which cover more than 99% of the agricultural area in the selected regions contain more than 50 pure pixels and are therefore accessible for site-specific smart farming services. A major part of the specialty crops would then also be covered. With a spatial resolution of 5 m in all bands and the current spectral coverage and revisit time a future 2nd generation Sentinel-2 would allow developing site-specific smart farming services for almost all farmers in the selected European study regions. It would make next Sentinel-2 s the information backbone necessary for smart farming to completely cover Europe's agriculture and to realize the environmental and commercial benefits, that potentially go along with it.

CHIME in its upper resolution of 20 m would enable to use high-valued, pure and complete spectral information to develop new sophisticated Copernicus based agricultural services, that go far beyond current smart farming approaches, on 1/3rd of all fields and 55% of the agricultural area in the selected European study regions. These numbers are reduced to well below 10% of fields and 23% of the area when choosing CHIME's lower resolution of 30 m which is equivalent to that of the existing and upcoming hyperspectral missions PRISMA (Labate et al., 2009) and EnMAP (Guanter et al., 2015). Although the pivotal role that CHIME will potentially play for developing advanced next-generation site-specific agricultural services is not questioned by this choice in resolution, an increase beyond the spatial resolution of existing and upcoming hyperspectral missions would be a decisive difference for both science and application and an important success-factor for CHIME. It strongly enlarges both the number of accessible crops and fields and as a result accelerates the transition towards next-generation site-specific farming. LSTM in its upper resolution of 30 m has the same coverage in terms of fields and area than CHIME's lower resolution. Implementing LSTM's lower resolution of 50 m would increase the fractions of fields and covered area for which no sufficient unmixed thermal information on in-field heterogeneity can be measured for the analyzed fields to 58–70% and 99% respectively. That means that only a few very large fields would be accessible.

5. Conclusion

Any increase in spatial resolution extends both the customer base and the accessible acreage for Copernicus-based CAP as well as site-specific agricultural services in Central Europe. The effect is most pronounced between a resolution of 20 and 5 m for the number of fields because it allows tapping into a large number of specialty fields. The increase in covered acreage is most pronounced between 20 and 10 m because it allows extending services to cover almost all non-specialty crop fields in Central Europe. This is an essential step in commercial terms because it would provide small farmers with the information to catch up in raising the efficiency of fertilizer, pesticide and irrigation water use. It also touches social aspects in providing to a large base of small part-time Central European farmers the basic information needed for fully digitized farm management, which eases their documentary and bureaucratic burdens thereby supporting them in their struggle to survive and to play a positive role in protecting rural lifestyles. The benefit of a resolution increase of Sentinel-2 for central European agriculture applications goes far beyond economic and social terms. It also is an essential step in environmental terms because it provides a cost-efficient path to site-specific, optimized fertilizer application on many small fields, which currently contribute strongly to Central Europe's groundwater resources.

The current Sentinel-2 workhorses have already proven the usefulness and cost-effectiveness for site-specific agricultural services in Central Europe (Bach et al., 2018). The results of the study clearly show the added value in terms of coverage of an increase in spatial resolution from today's effective 10–20 m to ideally 5 m for all spectral bands on a future Sentinel-2 follow-up.

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CRediT authorship contribution statement

Jonas Meier: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Wolfram Mauser:** Conceptualization, Methodology, Writing - original draft, Resources, Supervision, Project administration, Funding acquisition. **Tobias Hank:** Conceptualization, Writing - review & editing, Supervision. **Heike Bach:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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