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ARTICLE TEMPLATE

A paradigm shift towards decentralized cloud-integrated spatial data infrastructures: Lessons learned and solutions provided for public authorities

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Abstract

Digital transformation is key to turn public authorities into organisations that make decisions based on data-driven insights. Big geodata can enable public authorities to tackle complex sustainability issues. However, the efficient management of large amounts of geodata through implementing viable data infrastructures represents a major challenge for public authorities. In this article, we propose a decentralized, cloud-integrated spatial data infrastructure (SDI) to meet the needs of public authorities mandated to provide data services based on earth observation (EO) imagery. We describe the SDI setup and integration of the EO cloud platform CODE-DE, drawing on the specific SDI implementation at a federal, agricultural authority in Germany. Two practical applications are illustrated, underpinning the added value of a cloud-integrated SDI. We elaborate on lessons learned from SDI implementation by summarizing four key findings that may facilitate effective SDI establishment and use, namely i) the need for an organizational strategy, ii) identifying stakeholders, including their participatory roles, iii) long-term financial and human resource planning, and iv) the implementation of a data governance framework. The SDI proposed, serves as blueprint for public authorities aiding them on their path to become providers of data services, leveraging the potential of big geodata, including EO imagery.

KEYWORDS
Big Data; Cloud computing; CODE-DE, Copernicus; Digitization; Geodata

1. Introduction

The complex challenges of the 21st century urgently require a digital transformation of the public sector (Dunleavy et al. 2005; Ghobakhloo 2020; Mergel et al. 2019). Digi-

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tization in public organisations operating in the agricultural sector, for instance, is key to monitor progress towards Sustainable Development Goals (SDGs, UN 2022) related to food production. Aligning efforts around safeguarding biodiversity and food production, including climate adaptation, mitigation, and food security requires evidence-based decision-making (BMEL 2019; Delgado et al. 2019). Related information is retrieved from large amounts of heterogeneous data being collected, underpinning the need for governmental organizations to invest heavily in capabilities on big data analytics. Geospatial data, including observations and measurements on any spatial scale, play an important role in characterizing historical and current growing conditions on agricultural land (e.g., characteristics of soil, weather, topography, land cover, biophysical conditions). Major challenges on handling big geospatial data include the velocity of data generation and large data volume, both requiring critical changes in data management and analytics (Sudmanns et al. 2020; Hengl et al. 2022). The speed with which data is collected and created often exceeds the ability to integrate it into productive models (Reichstein et al. 2019).

In remote sensing, several advances have opened up the possibility of conducting large-scale, multi-sensor earth observation (EO) missions with unprecedented spectral, spatial and temporal resolution (Justice et al. 1998; Drusch et al. 2012; Wulder et al. 2016; Claverie et al. 2018; Shang and Zhu 2019; Defourny et al. 2019; Hengl et al. 2022). Similar to the American Landsat program (Wulder et al. 2019), the Copernicus program is a long-term EO initiative of the European Commission (Schiavon et al. 2021), operating an increasing number of satellites, called 'Sentinels'. Copernicus aims to supply geo-information products and services based on the use of images from space that will help European institutions and public authorities to fulfill their mandates of safeguarding the population, managing risks, and protecting the environment. Thus, Copernicus Sentinel missions add unique features to our global EO capacity (d'Andrimont et al. 2021). However, with increasing availability of satellite sensors data archives are growing exponentially making access to appropriate Spatial Data Infrastructures (SDI) essential for the EO community (Soille et al. 2018; Wagemann et al. 2021a). The Copernicus program alone generates about 150 TB of data every day (Apicella et al. 2022).

In parallel, the complexity of analysis methods has been growing rapidly in the last decades, driven by the development of various machine learning (ML) algorithms, which can be summarized under the term artificial intelligence (AI) (Maxwell et al. 2018; Hengl et al. 2022). A number of self-learning algorithms have been developed in order to address prevailing challenges in the fields of land use/land cover classification (Li et al. 2014; Yao et al. 2017; Preidl et al. 2020; d'Andrimont et al. 2021), change detection (Liu et al. 2019; You et al. 2020), derivation of various soil and vegetation parameters (Ali et al. 2015), and agricultural statistics (Bahrami et al. 2022) such as crop yield estimation (van Klompenburg et al. 2020; Zhang et al. 2022).

With the onset of the big data era, a paradigm shift has been set into motion, moving data analysis away from centralized in-house solutions towards distributed Spatial Data Infrastructures (SDI) and cloud services (Sudmanns et al. 2020; Wagemann et al. 2021a). Consequently, geodata are no longer downloaded to the local processing computer infrastructure or even single workstations. Instead, algorithms and processing power are brought to the data (Azzari and Lobell 2017), stored in clouds. Big data requires appropriate SDIs for multi-modal and high-dimensional data storage, management and processing that are suitable for effective and high performance tasks such as searching, aggregating, visualizing, and cross-referencing large datasets (Lokers et al. 2016; Kamilaris et al. 2017; Wolfert et al. 2017). This can be achieved by an appropriate

SDI which is defined as technological, semantic, organizational, and legal framework that enables the discovery, sharing, and use of geographic information (Schade et al. 2020). SDI has been subject to continuous development, driven primarily by technological progress, such as (web-)GIS, data portals, API catalogs, cloud computing and storage, open data and ML (Dangermond and Goodchild 2020).

The number of providers offering web-based data storage and catalogs as well as cloud processing power has been increased steeply (see Tab. 1; Schramm et al. 2021). Among those providers are globally operating corporations such as Google (Google Earth Engine (Gorelick et al. 2017)), and Microsoft (Microsoft's Planetary Computer (Luers 2021)). In addition, thematic cloud providers have recently emerged addressing specific user groups. In the field of EO data analytics, these providers include international, publicly funded services such as the European Commission's cloud-based Data and Information Access Services (DIAS; e.g., CreoDIAS, Mundi; Marconcini et al. 2020; European Commission 2022). Numerous initiatives at national and sub-national levels add to the landscape of EO cloud providers, which makes it increasingly difficult to maintain an overview (Hengl et al. 2022). Griffiths (2022) states that, according to the Open Geospatial Consortium (OGC), there are currently at least 78 geo-related cloud platforms in Europe alone. Besides the agony of choice, this wide range of providers poses the risk of fragmenting the heterogeneous landscape of EO cloud services leading to the inefficient use of data and budgets.

Nevertheless, cloud infrastructures are preferable to non-public in-house solutions, in order to avoid spending budgets unnecessarily in the remote sensing community with multiple redundancies (Griffiths 2022). Instead of using the same datasets from different sources, where great efforts must be made for data homogenization it is most efficient to use a centralised (cloud) infrastructure with standardised data products. Griffiths (2022) notes that the constant "reinvention of the wheel" must be stopped and that this burden of data preprocessing could be reduced by simplifying and democratizing processes, increasing collaboration and sharing of data and technologies, and reducing fragmentation and redundancy. Another key development for achieving interoperability of data and infrastructures are standards that are being developed and still need to be developed so that isolated systems can communicate with each other (Schramm et al. 2021), using standardized interfaces such as OGC services (Baumann et al. 2019). This would be enable synergistic workflow development for shared data products preventing duplicated efforts leading to more efficient use of budgets and resources.

In order to support digital transformation processes in Europe, the European Commission has adopted an European Union (EU) wide digital agenda. The framework's goal is to guide measures that ensure interoperability and standards for information technology platforms and data repositories to interact seamlessly (EC 2010). Consequently, governments of EU countries such as Germany have introduced digital agendas at national level to promote digital innovation and economic growth (BMI 2017). In the context of geodata and earth observation, the German government has further developed umbrella strategies setting out objectives on using geoinformation (GDI-DE 2015) and Copernicus data (BMDV 2017). Both strategies elaborate on guidelines for implementing SDIs in public administration and research facilities. These guidelines provide a general outline of how the needs of economic and public sectors could be aligned through access to open (geo)data and services and modern technologies, such as cloud computing and storage to prevent duplicated data production and redundant use of computing resources across individual authorities and organizations.

However, German public authorities are subject to numerous restrictions and regulations regarding IT security aspects. These regulations lead to severe constraints

Table 1.: Selection of publicly and privately funded cloud providers. Column „geo“ marks providers which are focusing on geodata assessment.

clouds	company/ organisation	funding	scale	geo	website
Google cloud	Google	private	international		cloud.google.com
Google Earth Engine	Google	private	international	x	earthengine.google.com
AWS	Amazon	private	international		aws.amazon.com
Azure	Microsoft	private	international		azure.microsoft.com
Planetary Computer	Microsoft	private	international	x	planetary-computer.microsoft.com
mundialis	mundialis	private	international	x	mundialis.de
Sepal	FAO	public	international	x	sepal.io
openEO	ESA	public	international	x	openeo.cloud
CODE-DE	DLR	public	national	x	code-de.org
EO-Lab	DLR	public	national	x	eo-lab.org
creodias[a]	Creotech Instruments S.A.	public	international	x	creodias.eu
MUNDI[a]	ATOS	public	international	x	mundiweb-services.com
Sobloo[a]	Airbus, Orange	public	international	x	sobloo.eu
ONDA[a]	Serco Italia S.p.A.	public	international	x	onda-dias.eu
WekEo[a]	EUMETSAT, ECMWF	public	international	x	wekeo.eu
Copernicus Data Space Ecosystem	ESA	public	international	x	dataspace.copernicus.eu/

[a] Data and Information Access Services (DIAS) funded by the European Commission copernicus.eu/en/access-data/dias

when working on web-based digital infrastructures and cloud providers. Special criteria must be met for German public authorities in order to use cloud platforms (IT-Rat - CIO Bund 2015): Platforms have to be certified by the Federal Office for Information Security (BSI) and meet cloud platform security standards (BSI for basic protection, ISO 27001 and BSI-C5 standard Cloud Computing Compliance Criteria Catalogue; BSI 2021). Further conditions apply to the geographic location of data stored, especially for data being managed by public authorities, meaning that related data must be stored inside jurisdictional boundaries of a given country. Thus, the operational use of commercial platforms in a federal authority is heavily restricted and in some cases even prohibited. Therefore, alternative solutions need to be found that, on the one hand, take into account legal restrictions and, on the other hand, meet the demands of today's technical and analytical requirements, enabling: (1) the support of data-driven decision making in governmental organizations based on big geodata integrating remote sensing and thematic administrative data, (2) to pursue new opportunities for monitoring and reporting in an administrative context, (3) infrastructure solutions for developing, verifying and delivering tailored thematic services for specific user groups.

This article aims at proposing a viable SDI implementation that meets the needs of public authorities working with geospatial data while complying to IT standards and regulations. In doing so, we use our experience at the Julius Kuehn Institute (JKI, a federal agricultural research institution in Germany) as a real-world example. The article is divided into three parts. The first section introduces the JKI SDI (Sec. 2), illustrating how the cloud platform *Copernicus Data and Exploitation Platform – Germany* (CODE-DE), which is tailored to German authorities and local infrastructure components were included for seamless interactions. Second, agricultural application use cases are presented underlining the added value of proposed SDI for potential end users being federal statistics offices, and sugar beet associations and producers (Sec. 3). The third section addresses challenges that emerged while integrating CODE-DE into an existing public authority's SDI, provides lessons learned, and highlights future plans and vision (Sec. 4). The part on lessons learned aims to help lifting barriers that organisations likely face while implementing their SDI. Lessons learned, thus, focus on (1) an organisational digitization strategy to be developed prior SDI implementation, including the set-up of stakeholder roles and requirements, (2) the need for SDI integration into organisational long term planning and financing, and (3) establishing a holistic data governance system. Concluding remarks are intended to help exploit the full potential of modern digital infrastructures and cloud solutions in the public sector in the future. Although focusing on the public sector in Germany, we believe that organisations such as public authorities in other geographic jurisdictions may benefit equally from our SDI implementation while transitioning towards digital geodata service providers.

2. JKI's Spatial Data Infrastructure (JKI SDI)

To address the given big data challenges and the need to scale computational power in modern EO, a SDI has been developed and implemented at JKI. This SDI integrates both, modern local management systems for spatial data and the cloud platform CODE-DE, that combines large EO volume storage and computing power capacity (Figure 1).

The JKI SDI is one of the digital infrastructures included in the FAIRagro consortium. FAIRagro aims to establish an interoperable and scalable research data in-

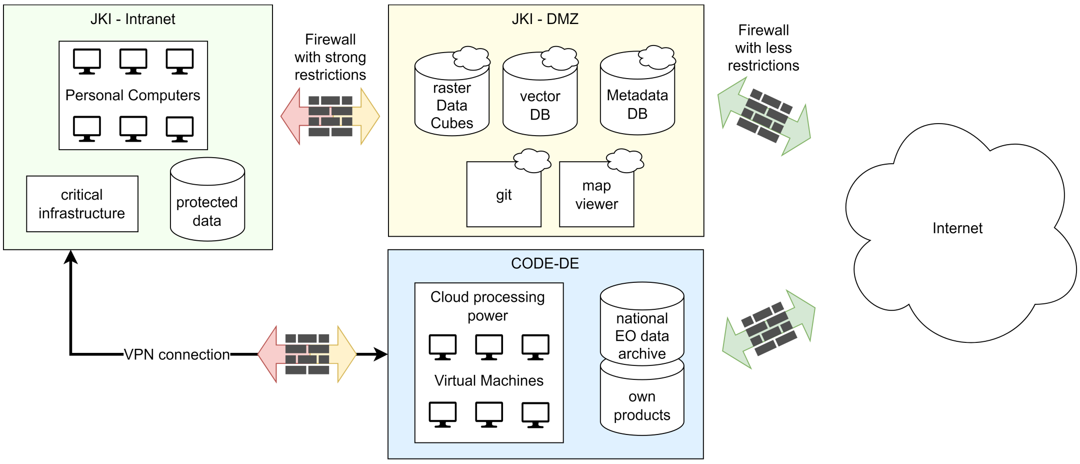

Figure 1.: JKI's Spatial Data Infrastructure

frastructure by connecting different repositories in agrosystem research as part of the nationwide NFDI initiative (National Research Data Infrastructure, Ewert et al. 2021; Kraft et al. 2021; Senft et al. 2022).

The JKI SDI consists of three principle components, which are interoperably connected via standardized interfaces that meet different security requirements: (1) CODE-DE is a cloud platform for German authorities that provides direct access to satellite image data and processing capabilities (Sec. 2.1). (2) The so-called demilitarized zone (DMZ) contains (Geo-)databases for storing vector, raster and metadata as well as software repositories (e.g. Git for code management) and the jKiMap-Viewer (Sec. 2.2). (3) The JKI intranet contains the critical JKI infrastructure and protected data.

2.1. *Cloud provider CODE-DE*

CODE-DE is designed to meet the user needs of German public authorities and is part of the National Geoinformation Strategy (NGIS, GDI-DE 2015; BMI 2021). The platform is an initiative of the German Federal Ministry for Digital and Transport (BMDV, funder), the German Aerospace Center (DLR, project management) and CloudFerro (technical realisation). The project started in March 2016 (Storch et al. 2019) and is in the second phase since April 01, 2020 (Gonzalez and Hoffmann 2020). Main objectives of CODE-DE are improving accessibility and use of Copernicus data, and enabling the implementation of downstream services. By *bringing the user to the data*, processing EO data in the cloud provides great benefits for a large number of CODE-DE users, in terms of available computing power as well as EO data access and storage. Particularly public authorities often lack in-house computing power and storage capacities for big data. The CODE-DE platform complies to IT security standards of ISO 27001 (Basic IT protection) and C5 (Cloud Computing Compliance Criteria Catalogue), certified by the BSI (BSI 2022, 2020). Compliance with IT security standards is a prerequisite for public authorities in order to use EO cloud platforms as part of their own SDI.

CODE-DE is a web-based EO cloud platform rendering multi-mission satellite data highly accessible and usable in a user-friendly fashion. This is achieved by several platform components such as a web-based data viewer, on demand data preprocessing chains, and a scalable, high-performance cloud computation backend (Figure 2). Apart from raw satellite imagery, EO-based analysis-ready data (ARD) products are available, such as monthly composites of Sentinel-1 and 2 imagery, as well as Germany-wide harmonized Sentinel-2 and Landsat data preprocessed using the Framework for Operational Radiometric Correction for Environmental monitoring (FORCE) (Frantz 2019). A full overview of the available data portfolio can be found here CODE-DE (2023b).

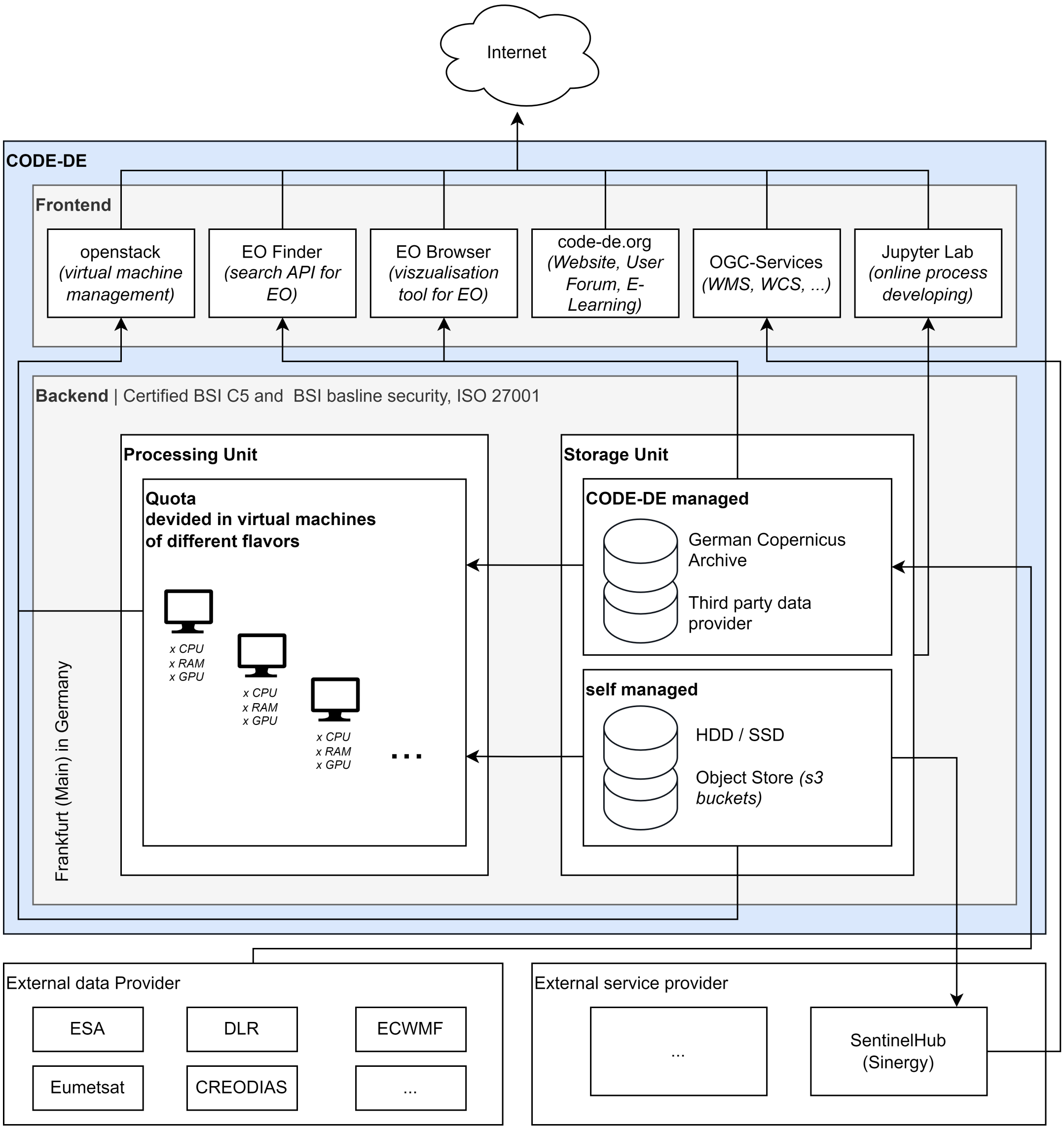

Figure 2.: Schematic structure of the CODE-DE cloud.

2.1.1. *Technical Background of CODE-DE*

All Copernicus data for Germany are stored in a data center located in Frankfurt am Main (Germany). Optionally, Copernicus data and Copernicus Services of global coverage are accessible through the interlinked CreoDIAS data catalog.

The CODE-DE infrastructure (Figure 2) aims at covering the needs of users with varying degrees of remote sensing expertise, ranging from users with little or none experiences to EO experts and programmers. CODE-DE is a hybrid service, built on the open source cloud computing architecture *OpenStack*. This architecture enables the provision of web access to EO data for viewing and downloading, while also offering sandbox capabilities for developing processing and analytical tools based on virtual work environments (virtual machines, VMs). All available services are accessible from the CODE-DE landing page code-de.org.

EO Browser and EO Finder have been set up as simple user-friendly tools. The EO Browser is a visualization tool, where Copernicus data can be searched and displayed. Simple EO data products such as spectral vegetation indices can be calculated and visualized on-the-fly. The EO Finder is used for searching and downloading satellite imagery. Predefined EO processing chains (e.g. radar backscatter data from Sentinel-1 and biophysical plant parameters from Sentinel-2) can be executed through the EO Finder and on-demand processed data products can be downloaded. In addition, rather than working with physical satellite imagery, CODE-DE users have access to the SentinelHub data cubes operated by Sinergise[1], providing OGC web services (Baumann 2021) for Sentinel data (CODE-DE 2023c) enabling data visualisation and further analyses on third party platforms. All three offered services have been specifically designed for enabling novice level users (i.e. users without programming skills) to work with EO data.

In addition, CODE-DE also provides dedicated developing environments for experts and developers who often require extensive processing capabilities for conducting big EO data analytics. A web browser-based Jupyter Lab environment (using Python, R or Julia language) is available enabling rapid prototyping and code-based, automated data processing. German public authorities, as main target group, can apply for a data processing and storage quota (free basic or paid extended quota) to use the full processing capability (Table 2) of CODE-DE utilizing VMs with varying configuration flavours. CODE-DE users may configure their working environments individually, within a given quota. Users have full flexibility to run and maintain their VMs, e.g. by changing volume and object storage or by running multiple instances simultaneously managed through a dashboard (*OpenStack*). Preinstalled images for Linux (Ubuntu and CentOS) or Microsoft Windows operating systems are available on each VM. Users also have access to graphical processing units (GPU) e.g. for applications in deep learning or computer vision. The VMs come in different sizes and flavours, e.g. a most recent OSGeoLife image contains most applications required for geoprocessing. An overview of the available operating systems and flavours (sizes of the virtual machines) can be found here CODE-DE (2023a). Through CODE-DE, each VM has mounted the entire national Copernicus archive (using the simple storage service (S3) protocol, an object storage that provides a web service interface; AWS 2022) to access Sentinel and other EO data (see section 2.1). All VMs are interconnected enabling internal data share and the fusion of computational power. In addition to the above-mentioned data cube functionalities, user-created value-added products can be integrated into the CODE-DE data cubes to access these data with OGC services (Baumann 2021; Bauer-Marschallinger et al. 2019).

The JKI is member of the CODE-DE user advisory board. This advisory board is composed of several federal and state authorities in Germany mandated to use and provide geodata, especially EO data and related services. User experiences are exchanged during biannual board meetings that contribute to the development of CODE-DE by taking stock and adjust, if necessary, according to members' needs.

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[1] https://www.sinergise.com/en/solutions/sentinel-hub

Table 2.: Contingent models of CODE-DE resources for a virtual processing environment. (CPU = number of virtual main processor cores, RAM = main memory, Vol = Volume Storage, IP = number of public floating IPs), T = booking period in months, GPU = AI capability

contingent	CPU	RAM	Vol	Obj	IP	T	GPU
unit		*GB*	*TB*	*TB*			
Basic	4	16	0,5	0,5	1	3	
Standard	8	32	2	1	1	6	
Premium	16	128	4	10	1	6	
Premium Plus	64	512	64	40	1	6	
GPU A6000 Standard	24	118	4	1	1	3	1
GPU A100 Standard	24	118	4	1	1	3	1
GPU A6000 Premium	40	246	8	10	1	3	1
GPU A100 Premium	4	246	8	10	1	3	1

2.1.2. Integration of CODE-DE in JKI's SDI

On CODE-DE platform, the JKI administrates several quotas provided with numerous CPU cores, computer memory, data storage, and GPU capacity. Available resources are allocated over numerous virtual machines and different operators.

The CODE-DE cloud infrastructure is coupled with JKI's in-house geodata infrastructure. The infrastructure itself, is partly integrated in the institute's intranet and partly located in the DMZ (Figure 1). The latter is administrated by the authority's IT service, providing a buffer zone between JKI's protected intranet and the internet. SDI components located inside the DMZ are connected to and used from the intranet, but cannot access other internal sub-networks and components, and vice versa.

Due to strict security standards, a German authority is not allowed to connect to servers on the Internet from the intranet via certain standard protocols and associated ports, e.g. Secure Shell (ssh) with port 22, but this may be necessary in order to be able to work on a cloud-based platform such as CODE-DE. Therefore, CODE-DE is integrated in the JKI SDI using an open source VPN software (openVPN), that can therefore be seen as quasi-part of the JKI's DMZ[2]. By using this technical solution, we can avoid assigning external, i.e. publicly visible, IPs to the virtual machines on the platform. Thus, the numerous machines are only visible in our network and can be used and interconnected with the rest of the JKI SDI without any restrictions (Figure 1).

To access all parts of the JKI SDI, users are connected to virtual machines on CODE-DE, either directly via remote desktop or via tunneled development environments (Visual Studio Code, Jupyter, RStudio Server, ...), which enables the use of modern ML oriented programming languages such as Python and R. The process pipelines are developed and executed directly on the virtual machines. Both the individual CODE-DE components as well as the various JKI-internal software solutions and data stores can be executed together and in parallel.

2.2. *JKI's demilitarized zone*

A key component of the JKI-DMZ is the JKI Data Cube using rasdaman (business) as management system (rasdaman 2023). The high-performance raster data management

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[2] A more detailed description can be found in the CODE-DE forum (code-de.org/de/forum/).

system contains geodata time series, which are managed locally and made analysis-ready via OGC-compliant web services (Web Mapping Services and Web Coverage Services). This includes, for example, meteorological time series provided by the German weather service (DWD„Deutscher Wetterdienst“) and phenological time series (Kaspar et al. 2019; Möller et al. 2020).

In addition to the JKI Data Cube, vector data, e.g. data from ATKIS (German Authority Topographic-Cartographic Information System; Jaeger 2003) or IACS (Integrated Administration and Control System; European Commission 2020), are stored and processed in PosgreSQL and Oracle databases and are available inside the DMZ.

We have also set up an INSPIRE-compliant (Ogryzek et al. 2020) metadata system, in which all geodata are documented in such a way, that JKI staff can find the data internally and integrate them into their processing chains. The metadatabase can be used externally to share data products and results with research partners, authorities and other third parties. The metadatabase uses the open source software GeoNode (GeoNode 2023). GeoNode derives metadata from the JKI Data Cube and vector data bases using an open source GeoNode extension. Data sharing can be done via OGC services and download links.

We use the WebGIS framework jKi-mapviewer (JKI 2023) to share geodata and scientific models internally and with third parties in a user friendly fashion. The framework is an in-house software development following a modular and service-oriented design approach. All applications and tools meet specific user requirements, which assist geodata to be analysed, visualised, searched, selected and downloaded in an intuitive way.

3. SDI application: Agricultural use cases for federal authorities

3.1. *Analysis-ready Sentinel-2 data*

3.1.0.1. Motivation. A total of 30 PB geodata are currently available on CODE-DE, of which 1.5 PB of national data (primarily Sentinel-1 to 5) are stored in a German data center in Frankfurt am Main (CODE-DE 2022). For Sentinel-2 (Drusch et al. 2012), there are different preprocessing levels. The most complete archive covers level 1C and level 2A data, provided by ESA in the SAFE folder structure (ESA 2021). However, EO users cannot analyse this data without conducting prior processing steps. This circumstance has multiple reasons such as different spatial resolution of individually stored spectral bands, the overlapping between single image tiles, clouds still being present in the imagery covering earth's surface underneath, and various geodetic projections (corresponding to different UTM zones). To avoid further preprocessing for EO users, multi-temporal Sentinel-2 images were transformed into analysis-ready data (ARD), called *S2_ GermanyGrid*, covering entire Germany from 2015 to date, aiming to lower barriers to the use of Sentinel-2 imagery.

3.1.0.2. Approach. Preprocessing of Sentinel-2 level 2A imagery was performed using the CODE-DE platform applying a grid over Germany consisting of 4212 10 × 10 km non-overlapping square tiles (see grid in Figure 3b - 3d). For each tile, raster datasets containing 10 cloud masked spectral bands (Blue, Green, Red, RedEdge1, RedEdge2, RedEdge3, NIR[3] 10 m, NIR 20 m, SWIR[4] 1, SWIR 2) have been created

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[3] Near Infrared

[4] Shortwave Infrared

(for more information about spectral bands of Sentinel-2 see Drusch et al. 2012). The scene classification layer from ESA's atmospheric correction approach was used as a masking basis for pixels affected by clouds, snow, and others (Main-Knorn et al. 2017). All bands are spatially resampled to 10 m ground sampling distance (GSD) and reprojected to one single coordinate reference system[5]. Satellite observations covered by 100 % cloud coverage were discarded. The *S2_ GermanyGrid* is located on S3 buckets enabling fast data access and cross-SDI availability.

3.2. *Large-scale extraction of production-related dates in sugarbeet cultivation*

3.2.0.1. Motivation. Sugar producers acquire sugar beets from very large areas and countless individual farmers. These farmers are actively supported, by industrial partners for optimizing crop yields both qualitatively and quantitatively. This is done on the basis of various field-specific data, such as nutrient supply, sample-based crop quality ratings during growing seasons, and harvested volumes. Using modern technologies, it is possible to optimize cultivation, logistics and production towards more sustainable sugar beet production. It is therefore important for sugar producers to monitor the development of sugar beet stands supporting timely decision-making on crop disease and damage management, optimal nutrient supply taking into account site-specific characteristics, and logistics management supplying the processing factories aligned to demand dynamics. Remote sensing could play a significant role in this process, by providing high-resolution information about vegetation stands in terms of temporal, spatial, and spectral resolutions. Particularly, Sentinel-2 imagery is suitable for this purpose, due to ESA's open data policy and a long-term operational perspective for the Copernicus program.

3.2.0.2. Approach. In the BeetScan project, production-related phenologcial events in sugar beet cultivation were determined using remote sensing data (Figure 3; Beyer et al. 2022). To extract the dates of tillage, closed vegetation stands and harvest at agricultural parcel level, Sentinel-2 based features have been generated and correlated with interpolated phenological phase entry dates using the CODE-DE platform. Based on reported reference data from different farmers, an optimization procedure has been developed to evaluate tuning parameters for interpolation and selection of Sentinel-2 feature time series as well as optimal time windows for detection of production-related events (Figure 3a).

For each parcel, Sentinel-2 reflectance information was obtained covering entire growing seasons using the *S2-Germany Grid* ARD. This reflectance information was then used to compute time series of $SAVI$[6], a vegetation index indicating plant vitality and growth status (Huete 1988). Invalid $SAVI$ values, often caused by remaining cloud fragments not detected during cloud masking, were removed from time series using the BISE index (VIOVY et al. 1992). An interpolation of daily values was performed to impute time series data gaps. Corresponding phenological phase entry dates were subsequently retrieved from PHASE data (Gerstmann et al. 2016; Möller et al. 2020) interrogating the JKI Data Cube through WCS queries using parcels' centroid coordinates. Extracted PHASE entry dates were used further to define narrow time windows in which the final dates should be found. For this purpose, the time windows deter-

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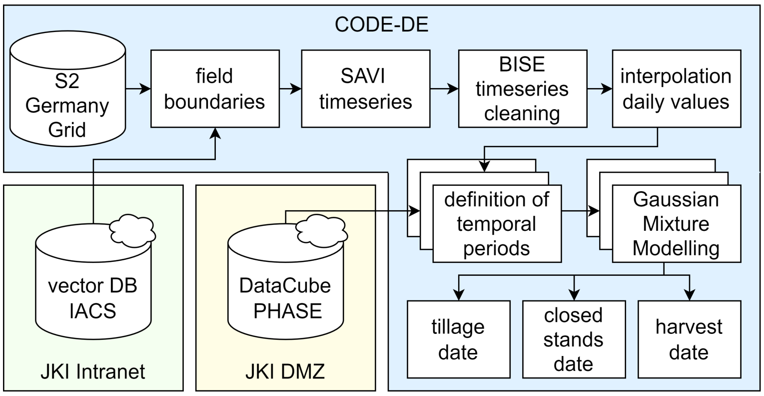
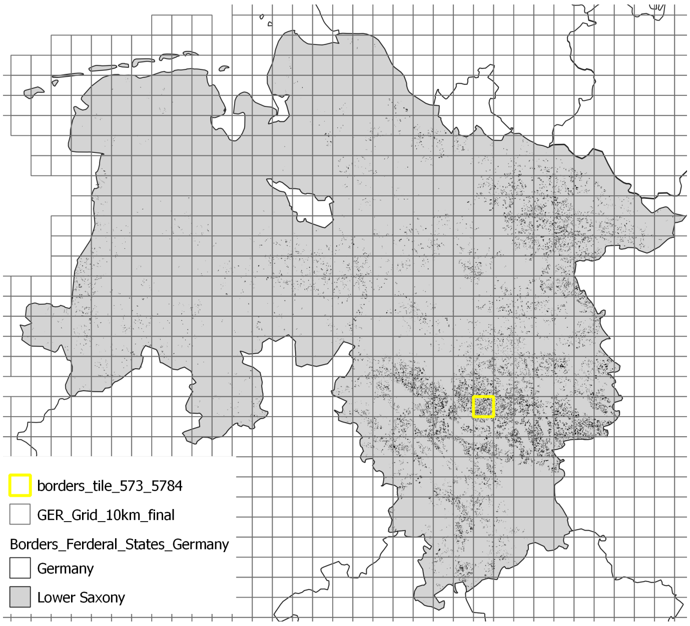
[5] `https://epsg.io/32632` (last access: 2022-11-10)

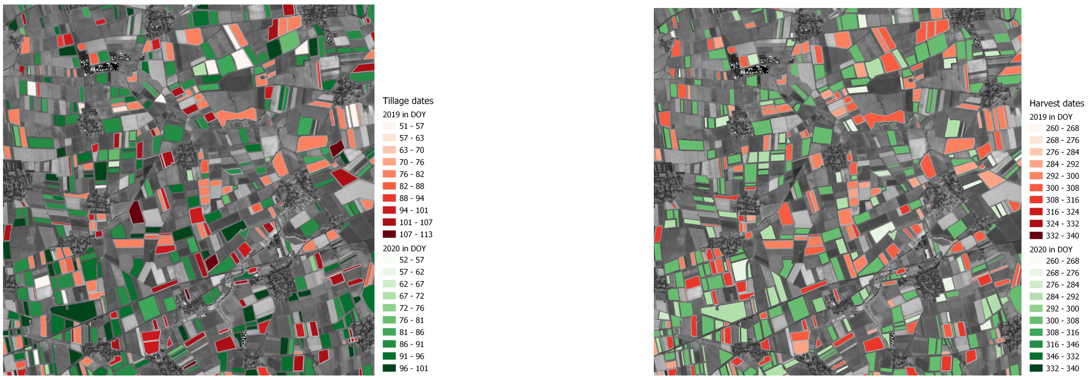
[6] soil-adjusted vegetation index



(a) BeetScan workflow



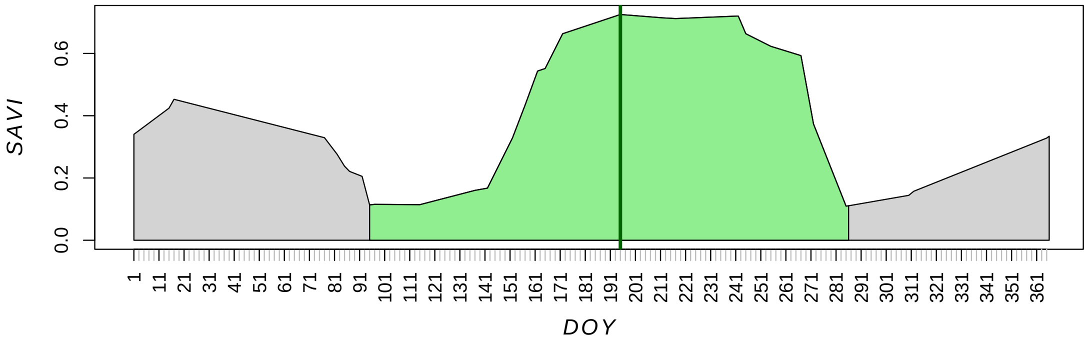
(b) Germany Grid tiles for Lower Saxony with tile ID 573_5784 (yellow)



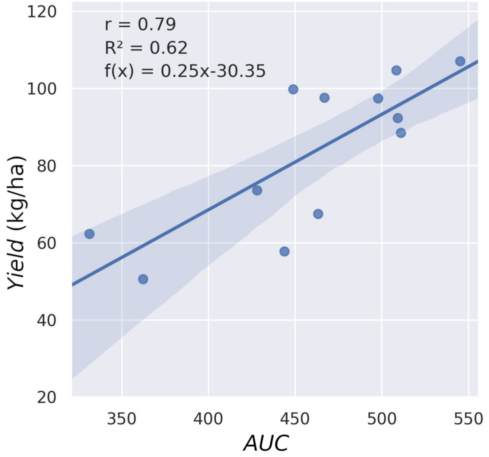
(c) Predicted tillage events within the area of tile ID 573-5784 for the years 2019 and 2020.

(d) Predicted harvest events within the area of tile ID 573-5784 for the years 2019 and 2020.

Figure 3.: Workflow and results of detection of phenological events on the example of sugar beet in Lower Saxony for the years 2019 and 2020.



(a) Field-specific *SAVI* time series, phenological events and corresponding *Area Under Curve* (AUC)



(b) Yield estimation based on relations AUC

Figure 4.: Parcel-specific statistical yield estimation on the example of sugar beet in Lower Saxony for the years 2019 and 2020.

mined from the optimization were used in the first step, which can be further optimized iteratively in the course of the calculation. A clustering procedure was applied to daily *SAVI* values for the defined time windows using a Gaussian Mixture Modelling algorithm (Fraley and Raftery 2002, 2007; Scrucca et al. 2016).

As a result, each parcel is characterized by *SAVI* time series and corresponding phenological events. In Figure 3, the tillage (3c) and harvest (3d) dates are mapped for 2019 and 2020 using a tile from the *S2_GermanyGrid* (tile ID 573_5784). The area under the curve bounded by sowing and harvest dates was calculated to estimate sugar beet yields (Perich et al. 2023). Estimated yields were compared against measured yields from 2019 and 2020 Figure 4. This parcel level procedure has been scaled-up and parallelized on the CODE-DE platform in order to process 10,103 sugar beet fields in 2019 and 16,804 fields in 2020 (Figure 3b).

3.3. *Scalable crop yield estimation supporting official agricultural statistics*

3.3.0.1. Motivation. The German Federal Statistical Office (DESTATIS) is a governmental organisation mandated to provide national agricultural statistics such as regular reports of area-based statistics for major crops being cultivated in Germany, including their productivity at various spatial scales, ranging from district to national level.

These reports are released sub-annually and annually, fed with data collected through on-farm measurements and survey-based campaigns coordinated by 16 State Offices for Statistics, being the counterparts of DESTATIS at federal state level.

Recurrent obligations to collect data from a significant amount of farms result from running these campaigns every year, translating into substantial resource and budget needs. In addition, existing data collection approaches may become a burden for farmers participating in these activities during periods that are already marked as busy in their schedules, e.g. during harvest seasons. Recently, it has also been more difficult to attract new farmers for voluntary reporting activities and to retain on-boarded farmers as part of an active reporting network (DESTATIS 2022).

Before mentioned points corroborate the need to explore the potential of scalable approaches that are capable to support yield reporting at national scale by integrating EO data into crop yield modelling. Thus, JKI and DESTATIS joined forces to launch a series of projects named 'SatAgrarStat' and 'SatAgrarStat_PLUS', involving several state offices for statistics and about 100 voluntary farmers providing parcel level farm management and crop productivity information (DESTATIS 2019). These projects aimed at shedding light on the potential to support official crop yield reporting by developing a data-driven yield estimation approach. Such an approach may reduce resource needs and costs of data collection campaigns, and alleviate the burden of farmers by drawing from the following benefits:

- Advanced and transparent monitoring capabilities of EO satellites such as ESA's Sentinel-2 mission. Multi-spectral imagery obtained from Sentinel-2 covers large swaths of area. Each scene has a spatial dimension of 100 km x 100 km. Spectral bands relevant for vegetation monitoring feature spatial resolutions of 10 – 20 m. Due to rather short revisiting intervals of 4 - 5 days, high density time series of vegetation signals can be derived from Sentinel-2 images.
- An integrated EO platform, providing high computational performance and the capacity to process and store large amounts of satellite data in order to scale yield estimation models covering larger administrative regions up to the national level.
- Integrated service delivery, to disseminate value-added data products such as estimated crop yields, building on web service standards.

Currently, our model-based approach is capable of estimating crop yields for agricultural parcels that are cultivated under four major crops i.e. winter wheat, winter barley, winter rapeseed, and summer barley. Crop yields are estimated by deploying ML models fueled with multi-temporal and static model features. Related data represent a number of key factors that either indicate plant growth and health through biophysical plant parameters such as leaf area index (LAI) and above ground dry biomass (DM) or limit crop yields through meteorological and soil conditions (He et al. 2020; Dhillon et al. 2020; Whetton et al. 2021).

3.3.0.2. Approach. The following steps describe the general work flow (Figure 5).

Multi-spectral ARD is queried from the *S2_GermanyGrid* enabling the inference of biophysical parameters (LAI and DM) across Germany by using a crop-specific spectral library, following the methodology of Gerighausen et al. (2016). Related imagery is retrieved from the grid by querying areas of interest using parcel geometries obtained from various project related data collection campaigns and IACS available

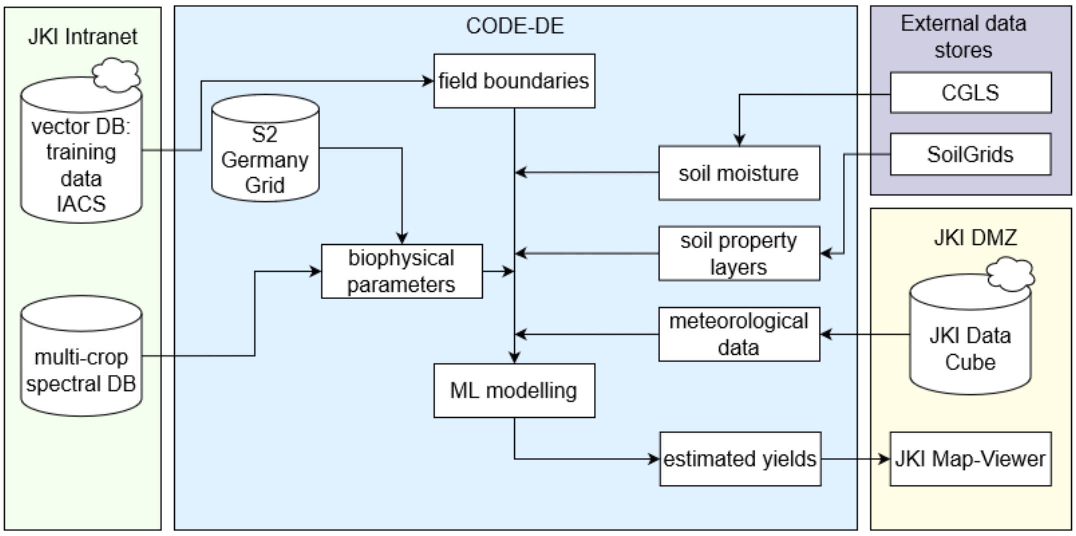


Figure 5.: Yield estimation at scale: Fueling crop-specific yield models with EO, meteorological, and soils data, using the cloud computing platform CODE-DE

through data portals of various federal states.

Gridded meteorological time series data daily temperature, precipitation, and global radiation are obtained by interrogating JKI's Data Cube using standardized web service requests. This data is provided daily by the DWD (DWD Climate Data Center (CDC) 2018) at a spatial resolution of 1 km. Additional gridded, soil-related data such as a multi-temporal soil moisture product with a spatial resolution of 1 km and various geospatial layers on physio-chemical soil properties at a spatial resolution of 250 m are derived from external data portals such as the Copernicus Global Land Service (CGLS) and SoilGrids 2.0 operated by the International Soil Reference and Information Centre (ISRIC) (Bauer-Marschallinger et al. 2019; Hengl et al. 2017; Poggio et al. 2021).

Biophysical parameters, meteorological and soil related datasets are processed and aggregated for obtained parcel geometries. Multi-temporal model features cover a period from March to July, a period where large parts of vegetation growth and grain or pod production takes place. Crop specific regression models are created in an automated fashion using Python scripts, making use of parallel computing capabilities on CODE-DE. By utilizing an ensemble of state of the art ML techniques, a series of models are calibrated, tuned and validated using high quality yield data for available parcel geometries. Subsequently, trained ML models are used to estimate crop yields for several tens of thousands of IACS parcels covering large proportions of overall cultivation areas for each of the four crops in Germany. In principle, estimated yields can be visualized in any mapping environment employing web services (e.g. WMS or WCS) available on CODE-DE, either at parcel level (limitations apply due to confidentiality constraints) or further aggregated using vector data on administrative boundaries such as districts or federal states (Figure 6).

Post-processing includes the conversion of gridded model outputs into cloud optimized GeoTIFFs (COGs). This rather new raster data format is tailored towards web service applications. COGs[7] have the advantage of (1) internal tilling, allowing for a more flexible and faster visualization based on actual user demand, (2) providing

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[7] cogeo.org/in-depth.html

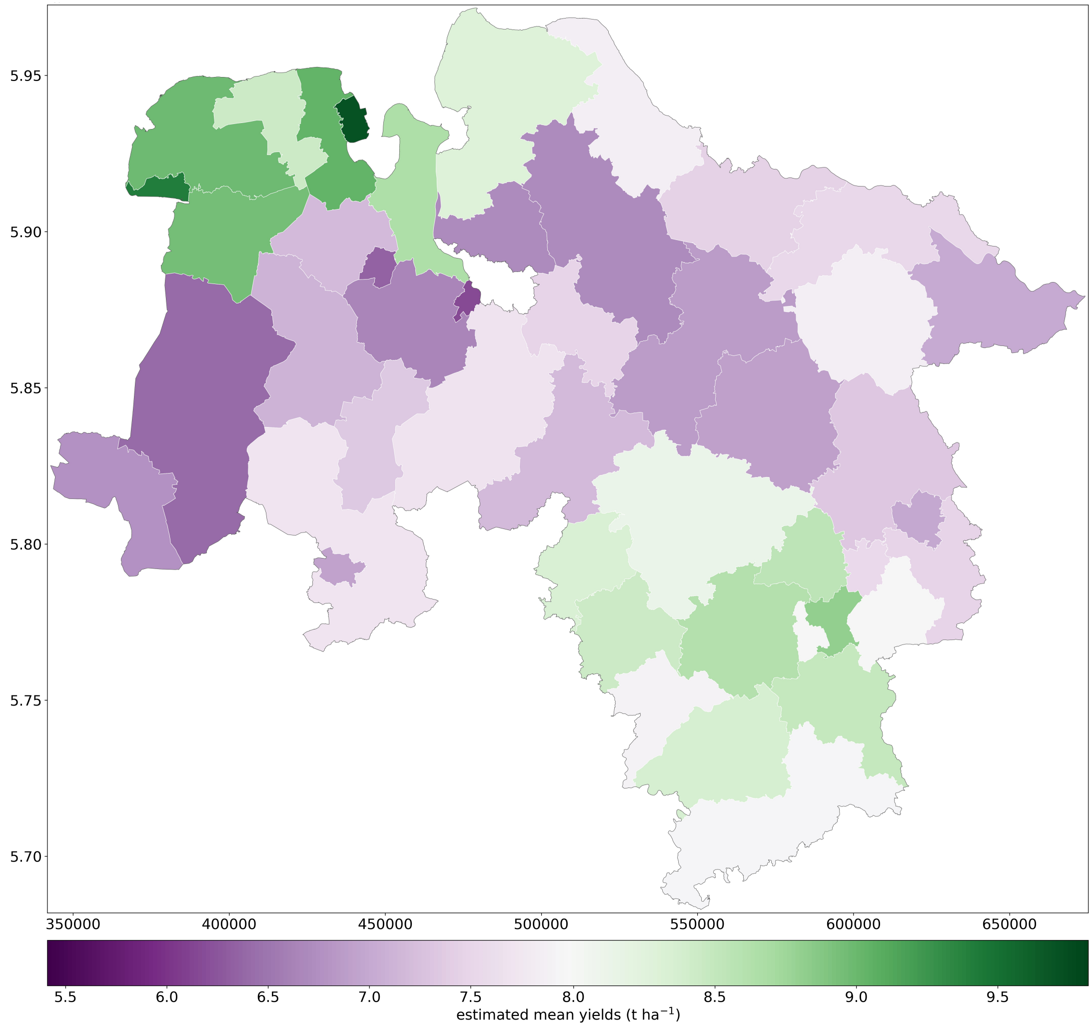

Figure 6.: Example results showing estimated winter wheat yields for 2020, aggregated at district level and mapped for the German federal state Lower Saxony.

overviews based on downsampled views on the actual data accounting for different zoom levels, and (3) applying compression, rendering data transfer highly efficient. A web client interface based on the jKi-mapviewer (JKI 2023) has been prototyped as part of the SatAgrarStat projects providing project partners access to value-added products such as annual crop yield maps.

4. Discussion — Challenges of integrating an EO cloud platform into the SDI of a public authority

4.1. *SDI Usage in public authorities*

The integration of external cloud platforms into in-house SDIs allows incorporating large data storage, processing, and computation capacities. Following the new 'algorithms-to-data' paradigm, complex analyses of big (geo)data become feasible for public authorities that are often rather resource constrained. Using cloud resources prevents duplicating required infrastructure components and data storage. A cloud integrated SDI reduces, thus, the risk to inflate budgetary needs of public authorities to acquire technical and human resources individually for setting up and maintaining an in-house infrastructure for big data storage and computation. During integration, care must be taken to ensure that the interfaces between the cloud components and the authorities' hard- and software tools are standardized so that cloud providers can also be substituted if necessary. When choosing a suitable cloud provider, public authorities should take into account a number of aspects such as IT security and legal compliance, data sovereignty, location of data storage, availability of customer support, transparent cost structure, orchestration as well as customization (Rouse 2022). At JKI, we chose CODE-DE as a EO cloud provider for several reasons, e.g. certificated platform and location of the data center. Besides that, we required access to Copernicus data for Germany and the necessary computing power both located in the same cloud environment. This avoids duplicating the big data Copernicus archive, which no longer occupies the JKI's in-house data infrastructure as the processing capacity in the data center is used directly in the same location where the data are located.

CODE-DE has been integrated into our existing JKI SDI, enabling:

- access to satellite data from Copernicus multi-mission image repositories, updated in real time throughout Germany,
- the development of processing and analysis algorithms using CODE-DE's sandbox capabilities,
- the customization and scaling of processing chains and modelling algorithms using CODE-DE's cloud computing resources,
- the distribution of value-added products using standardized web service functions.

Entire workflows, including data preprocessing, modelling and post-processing, are consistently implemented using Python or R programming languages. The development of new or adapting existing analytical approaches benefit from the use of open source developing environments that provide web-based, open source notebook interfaces (Jupyter, R markdown). These web-based coding interfaces are highly suitable for rapid prototyping of new model versions and corresponding documentation.

External data, e.g. meteorological datasets needed for crop yield modelling or phenological data to extract production-related dates in sugar beet cultivation, are ingested into CODE-DE working environments by using the web services provided in the JKI

Data Cube (see section 3). Value-added data products on biophysical parameters, i.e. gridded *LAI* and *DM* datasets, and estimated crop yields are post-processed and disseminated by making use of web services available on CODE-DE. These technologies enable potential service delivery models such as *data-as-service* through web services for related governmental organisations. Presented use cases illustrate example applications potentially addressing a wider range of agricultural themes and target groups. The latter include federal and state statistical offices and farmers, producers of agricultural commodities and food.

4.2. *Lessons learned – JKIs SDI*

This article addresses the transformation of a centralized local SDI into a decentralized i.e. distributed SDI within a public authority, characterized by the following features:

- cloud integration to link centralized, highly accessible big data storage archives and dedicated data processing capacity,
- modern local SDI components, allowing to store and to use sensitive data,
- modular (open source) SDI design, enabling replacement of obsolete components with new components based on emerging technologies in the future,
- consistent use of FAIR metadata (Wilkinson et al. 2016) throughout the data lifecycle, including data provenance and quality information,
- use of standards for API (e.g., OGC) and data formats to enable interoperability along the entire value chain (from data provenance to evaluation of the actual data products).

The presented SDI can be seen as the result of a bottom-up approach in which requirements and interests of different departments and responsibilities have been balanced in an iterative process. The complexity of the problems to be solved required the establishment of agile communication structures (Tyagi et al. 2022).

During the transformation process away from a data-centric localized computing infrastructure towards a digital authority with decentralised, interconnected SDI (Sudmanns et al. 2020), several issues have emerged that are specific to public authorities:

Digitization strategy An organisation that aims to build its capacity to efficiently process and analyse big (geo)data needs a soundly planned and maintained SDI. SDI design and implementation should be guided by an organisational strategy. Such strategy provides the framework that aligns the related organisational efforts towards a common goal by involving internal and external stakeholders from the beginning.

IT security requirements Federal authorities have specific security requirements that must be assessed, implemented and managed by their IT departments. Here, key friction points arise between the needs of SDI users and in-house IT security administration.

Long-term planning In order to provide products and services generated by using a cloud-integrated SDI reliably, all SDI components must be financed in such a way that personnel, licensing and maintenance are guaranteed long term.

Data governance Defining data ownership and rules for storing, using, and sharing data are key requirements for organisations moving forward on their path towards digital authorities. The use of agricultural data collected by or from farmers is a complex topic due to legal constraints such as individual privacy rights, confidentiality and data protection laws. Fragmented and conflicting data policies at federal and national levels further impede the use and exchange of agricultural data (e.g. IACS data). Hence, a holistic data governance model clearly setting the roles, responsibilities, and guidelines along the entire value chain of data collection, production, use, and dissemination should be conceptualised and implemented as part of the SDI development.

4.2.1. Digitization strategy, stakeholders and security representatives

Individual authorities should develop their digitization strategies aligned to overarching frameworks (e.g. digital agendas, geoinformation strategies) formulating specific goals and describing concrete implementation steps to achieve those goals. Strategy development must involve relevant stakeholder groups from the beginning. On this basis, processes can then be initiated at respective management levels. Following combined top-down and bottom-up processes, particular needs and requirements for modern infrastructures and their components are defined by developers and users. However, framework conditions must be formulated by strategic decision makers within the authorities, taking thematic goals into account. This creates a common strategic understanding among all stakeholders, on the basis of which the way can be paved for concrete implementation of the required technology.

In Germany, national strategies, like NGIS or National Copernicus Strategy (BMDV 2017), were initiated by the federal government. However, the stimulation and implementation of these guidelines often does not seem to arrive at all levels of government or in all individual authorities while the implementation if applied often happens very slowly. Thus, the authorities' organisational strategy must take into account all stakeholders so that everyone involved has some sort of road map on how to act in the context of SDI development, maintenance and usage.

According to Soille et al. (2018); Echterhoff et al. (2021); Schramm et al. (2021) three stakeholder groups are identified having different roles in and requirements for a cloud-integrated SDI: (1) the data and cloud or platform providers (e.g. CODE-DE), (2) the intermediate users or data producers (e.g. JKI), and (3) the end users (e.g., organisations that utilize data products as part of their mandates). From the authorities' perspective, the IT security representatives and IT service are another stakeholder group that has significant weight in the choice of providers and future use of SDI, which was not yet considered in current literature. Table 3 summarizes the perspectives of stakeholder groups on their roles and requirements and related issues in establishing SDIs in public authorities.

Table 3.: Stakeholder group perspectives regarding their roles and requirements as well as related issues in establishing SDIs in public authorities.

STAKEHOLDER GROUP	ROLE	REQUIREMENTS	ISSUES	SOLUTIONS
INTERMEDIATE USERS	- Data producers (such as the JKI) who use the SDI to develop processing chains and offer value-added products. - They form the bridge between cloud (data) providers and end users who further use the products.	- They need free access to input data for the execution of process chains and the processing capacities for the application of diverse methods of modern data analysis, including a barrier-free possibility to test new technologies and software and to transfer them into operational use.	- Free access to modern and innovative systems of big data analytics, process improvement through ML algorithms and decentralized use of cloud providers is limited or prohibited due to security restrictions. - Although strategies have been created to initialize the digitization process of the public sector at European level (European Commission 2021), and at national level in Germany (GDI-DE 2015; BMI 2021) providing umbrella frameworks for spatial data infrastructures, concrete implementation plans and guidance at organisation level are often lacking.	- Agile cross-thematic working groups develop multi-hierarchical public authority strategies empowering all stakeholders involved to drive forward digitization and decentralization. - Personnel will be trained in new technologies. - Qualified personnel are educated, trained or hired.
END USERS	- Authorities such as government, public facilities, private sector and citizens who further utilize value-added products to serve their fields of activity.	- Data products, provided by intermediate users, should be accessible in a user friendly way, must be retrievable and usable in the long term and (if necessary) with consistent regularity, must have been subject to a robust validation process ensuring maximum trustworthiness. - The vulnerability to cyber attacks must be minimized as much as possible in order to protect data from being compromised and misused.	- (Geo)Data are often not collected, processed, and stored in a standardized format. - The way in which data are accessed is regulated differently. - As a consequence, especially SDIs of state authorities are characterized by a high degree of storing data and processing.	- Uniform standards for data ingestion, interoperability, dissemination, storage, and accessibility will be established (Kraft et al. 2021). - Publicly funded geospatial (meta)data must be provided through web services.
IT SERVICE AND SECURITY REPRESENTATIVES	- Ensuring that internal network resources are secure reducing the risk of compromising the organisational IT infrastructure and data.	- In addition to the installation of new and proven hardware and software technology, IT services in public authorities are obliged to assess security risks of potential hardware and software components to be acquired, taking into account current national and European legislation (European Parliament 2019; BMJ 2021).	- The lack of certification and legal policy is one of main reasons why cloud-based infrastructures are still not being used (Wagemann et al. 2021b). - Despite the existing high level of CODE-DE IT security certification, the German IT Security Act requires that the security officers of each authority must review and permit the cloud infrastructure as well as software which interacts with the Internet. - Strict data security requirements and the protection of in-house critical infrastructure usually take priority over the needs and requirements of the intermediate users, which often results in a decision to reject novel systems.	- Decision support and regulations for the use of cloud platforms are established. - Working groups of (public) cloud providers and agencies with specific security requirements have to be established. - Sustainable financial and personnel resources must be ensured to develop, maintain and expand SDIs.
CLOUD PROVIDER	- Web-based providers of geospatial data, computational capacity, or both.	- Cloud providers (CPs) invest in IT infrastructure available in secure data centers. - In return, users such as public authorities must accept a service level agreement (SLA) and liability for the use of related resources. Generally, a CP is an IT company that provides customers with on-demand computing resources through the internet. CPs are often categorized by the type of resource they provide: (1) Software as a service (SaaS) – provides customers software apps that are accessed through a web browser or application program interface (API). (2) Infrastructure as a service (IaaS) – provides customers with access to APIs and other resources that facilitate the creation of a virtual data center capable of supporting workloads across multi-cloud environments. (3) Platform as a service (PaaS) – extends the capabilities of IaaS and SaaS by giving customers access to software tools and compilers that support building and hosting cloud applications.		

4.2.2. Long-term planning

The current project status of CODE-DE guarantees platform operation until September 2024. In contrast to commercial actors, especially in the technological sector, public sector organisations rely heavily on long term planning, ensuring certainty, to deliver on their principal mandates. This has advantages such as planning security, but also contradicts the current funding model of CODE-DE. Based on our experience in the CODE-DE User Advisory Board and Copernicus events (e.g. BMDV 2022), the uncertain long-term perspective of CODE-DE is one of multiple reasons why the public sector is reluctant to commit to a permanent use (among others like security issues, high technical barriers to entry or unwillingness to change running systems, Wagemann et al. 2021a). In order to lift this adoption barrier, CODE-DE needs a guaranteed long term operational status through viable funding mechanism and tender model.

Replacing CODE-DE hypothetically with commercial cloud providers, such as Microsoft, Google or AWS would bear both advantages and disadvantages. Such companies, for instance, have high innovation potential and ensure a high level of scalability through massive utilization of computational and data storage resources. However, commercial providers act in competitive market environments, leading to fluctuating pricing policies and bearing the risk to exit markets in which case the delivery of cloud services could simply discontinue. In addition, companies' data policies are usually not in compliance with the high regulatory requirements (i.e. certain IT certifications) of German public institutions.

A purely publicly-funded governmental cloud initiative would have the advantages of being independent with a long-term, cost-effective, and fail-safe perspective. However, this approach runs the risk of lacking the necessary flexibility due to regulatory inertia and low scalability.

A compromise would be a public-private partnership. In such a partnership, the advantages of public funding and the innovation potential of commercial entities result in the long term operation of a scalable and elastic cloud computation platform. This is in part already the case with CODE-DE. The CODE-DE project is publicly funded by the German Federal Ministry for Transport Digital and Transport (BMDV). The German Aerospace Center (DLR) coordinates the project. DLR contracted the company CloudFerro to manage computing capacity and cloud resources. Commitment to finance CODE-DE permanently is required, which would help turning the EO cloud platform into a trusted long-term partner for public authorities.

4.2.3. Data governance

Data Governance is a system of decision rights and accountabilities for information-related processes, executed according to agreed-upon models which describe who can take what actions using certain information, by defining time, circumstance, and methodological contexts (The Data Governance Institute 2015; Alhassan et al. 2016). It refers to setting the roles, responsibilities around data related processes, agreed by involved stakeholders. Design and implementation of a data governance framework that incorporates data handling on cloud platforms is pivotal to manage data effectively as part of a cloud integrated SDI (Al-Ruithe et al. 2019). Principles such as FAIR (Wilkinson et al. 2016) and TRUST (Lin et al. 2020) should guide data governance for organisations to provide trustworthy data that is accessible, interoperable, and actionable by focusing on users' needs and requirements (Lin et al. 2020).

At the JKI, five interest groups were set up to establish a geodata governance system: the institute's security officer, the data protection officers, the data center administrators, the research data management team, and the spatial data users. Together, these stakeholders developed a roadmap for the management of geodata at the institute. The interest groups are organized in two main communication groups, which are connected by common members:

- A SDI and geodata project group, consisting of research and IT management, is clarifying overarching structural, financing, strategic, network and security issues. Regular meetings at management level serve as a form of communication, with agile working expert groups addressing specific issues.
- A geodata network group aims at exchanging technical and thematic aspects on issues related to the management, access and analysis of geodata at JKI. In contrast to the SDI project group, the access is not restricted and open to interested technical and scientific staff. In addition, the group provides a forum to help identify and solve issues related to SDI.

4.3. *Future plans and vision*

New technologies and software solutions are constantly emerging, which need to be tested and evaluated to determine if they could be a useful addition to a public authority's SDI. However, this flexibility is often difficult to align with the modus operandi of public authorities, especially in terms of regulatory constraints and organisational inertia limiting adoption rates that match technology advances.

Moving foreword, we like to highlight a few organisational and technological aspects that aid in turning the SDI ecosystem of a public authority into a future proof architecture:

First, well trained personnel must be available to test emerging new technologies and expand the SDI as needed, guaranteeing effective management and maintenance of the SDI ecosystem holistically. To achieve this, certain team roles and responsibilities are standard in commercial companies and must also find their way into government agencies. Central roles for the maintenance and development of the cloud component of the SDI are (Bigelow 2021):

- the cloud architect: knowledge and expertise of cloud applications, resources, services and operations,
- the cloud engineer: responsible for cloud implementation, monitoring and maintenance,
- the software developer: expert programmers, testers and communicators,
- the cloud security specialist: responsible for security in the cloud
- the cloud compliance specialist: understands and monitors cloud compliance certifications and confer with legal staff and
- the analyst: gathers metrics and works to ensure workload capacity and performance remain within acceptable parameters.

Second, a digital authority requires capacity building around more agile modes of working and management to keep pace with rapid technology developments. Roles such as scrum masters and product owners are usually aligned horizontally across existing organisational structures enabling teams to collaborate more agile and product oriented through direct interactions and improved communication. A tailored education curriculum could provide required know-how by offering related seminars to relevant staff (DESTATIS 2019).

Third, there is great potential to scale CODE-DE further. The DLR has launched another national data platform, namely EO-Lab (BMWK 2023, funded by the Federal

Ministry for Economic Affairs and Climate Action), designed to be a twin of CODE-DE focusing on the scientific community and EO data licensed for scientific use while giving acccess to the CODE-DE data and services. Technical interoperability between these two platforms will help create synergies through more direct collaboration between scientific communities and public authorities in a way that scientific research (e.g., developing and testing pilot projects) feeds into concrete use cases set by public authorities based on their needs.

Fourth, other national and supranational cloud platforms have been created or are in the process of being created in other EU countries, from which our own SDI could benefit in the future (Schramm et al. 2021; Griffiths 2022). Examples include the Euro Data Cube (EDC 2023), OpenGeoHub Foundation (Open Geo Hub 2023), Cube4All (Baumann 2023), the openEO platform (ESA 2023), and the openEO API (openEO 2023). In particular, the openEO API is an initiative that could contribute greatly in the future to SDI developers and operators, and ultimately to decision makers and policy makers at EU level. openEO is developing an API to connect R, Python, and JavaScript clients in a simple and uniform way to large EO cloud backends, which already include the European DIAS platforms, such as CreoDIAS. With the help of this API, workflows developed for Germany could be scaled to continental level to perform EU-wide monitoring tasks. Processing chains developed on other platforms could be applied at German federal level vice versa (Bigelow 2021). Platform interoperability, API and data standards may enable the emergence of a federated (EU wide) SDI ecosystem, interconnecting data cubes of multiple existing EO cloud platforms (Sudmanns et al. 2022). These federations would greatly improve the accessibility of numerous data products that exist on each of those individual platforms. That would ultimately lead to compliance with data governance principles (FAIR, TRUST, CARE), translating into benefits for science and society at large.

5. Conclusions

In this article, we propose a SDI solution for public authorities that are on their journey to become users and providers of EO and geospatial data and data products, by describing the technical components of a cloud-integrated SDI and by highlighting two use cases. Despite high IT security regulations, we found a solution to integrate a EO cloud environment into the IT ecosystem of our authority enabling us to fully utilize the platform to perform big geodata analytics. Moreover, we elaborate on our experiences regarding the challenges we have faced during SDI implementation and provide lessons learned. The organisational transformation towards a digital and future-oriented authority is a complex process often entailing a number of barriers. We believe the following points are key to overcome those barriers:

- On our journey to implement a cloud-integrated SDI, needs and requirements have been predominantly formulated bottom-up by SDI developers and users. Although individual umbrella strategies at German governmental level do exist (i.e. NGIS, national Copernicus strategy), development and implementation of a cloud-integrated **SDI at organisational level requires a strategy**, specialised human resources and capabilities on how to leverage modern technologies for public authorities. Particular procurement procedures, existing IT security standards and regulations in public authorities may render the mere adoption of commercially developed products and services (i.e. software or cloud platforms) unfeasible.

- **All stakeholders**, yet especially government IT services responsible for security, must be included in the process of SDI development and implementation, right from the beginning. Due to the long-term nature and complexity of structural changes within public agencies, the monetary costs emanating from introducing and using new technologies should be made transparent early enough and require **budgetary planning at organisational level**. This applies above all to the human resources needed and the long-term allocation of financial funding required to develop, implement and manage cloud-integrated SDIs.
- A final point that will have a decisive influence on the **use of geodata** in the future is the question of their provenance, access, rights of use, lifespan and licensing. This implies that geodata products developed through public financing should be subject to opendata policies, comply with data protection standards, and has to be findable and usable long term.

The digitization of public authorities is a complex and long term process. However, for public authorities to fulfil their mandates, it is absolutely key to tackle challenges of the 21st century by profiting on opportunities that result from cloud computing, big geodata analytics, and AI. Thus, the SDI solution proposed could serve as blueprint for public authorities on how to utilize a hybrid ecosystem consisting of various modern geodata management systems located on premise and an EO cloud computation platform under given regulatory constraints.

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