Living lab research project "5G Smart Country" - Use of 5G technology in precision agriculture exemplified by site-specific fertilization

Moid Riaz Bhatti [1], Ali Akyol[1], Henrik Rosigkeit[2], Linda Matzke[2], Isabel Grabenhorst and Jorge Marx Gómez[1]

Abstract: The research project "5G Smart Country" aims at developing ideas for the development and testing of 5G applications for agriculture and forestry under real conditions. Agricultural and forestry data are collected from a wide variety of sources, such as satellites, drones, and robots with special sensors. Artificial intelligence (AI) and data analytics algorithms help make the required decisions, particularly for automatic differentiation between crops and weeds for mechanical weed control, demand-driven fertilization (variable rate application, VRA)—also by means of small-scale application (pointed fertilizing)—automated tracking of wildlife populations, real-time assessment of harvest (smart harvesting), forest inventory maintenance, and targeted logging. Here we present a system architecture and software model for digital crop management and show how multispectral analysis is used to develop vegetation indices to conduct VRA.

Keywords: Living lab, smart farming, BMDV, 5G, site-specific fertilization, VRA, satellite/sentinel, vegetation indices, NDVI, GNDVI, digital plant model, AI.

Addresses Sustainable Development Goal 13: Climate action

1. Introduction

Today's agriculture faces a variety of challenges. The projected increase in population from currently 7.9 to 9.7 billion people in 2050 and the resulting industrialization of cities will continue to reduce the amount of land per capita that can be used for agriculture [Sc21, EH15, Mu21]. The supply of food for the increasing world population is also being constrained by climate change, which is causing a deviation in the optimal temperature and water availability of crops. As a result, yield uncertainties are increasing [EH15]. The spatial heterogeneity of soil properties on agricultural land leads to varying nutrient removal and yields due to the variability of plant development. With the amendment of the Fertilizer Ordinance (Düngeverordnung), the requirements for fertilization have been further tightened [Dü20]. How precision farming with site-specific application/ management (VRA) can be made more efficient with 5G technology is one of the

[1] Oldenburg University, Chair Business Informatics (Very Large Business Applications), Ammerländer Heerstr. 114-118, 26129 Oldenburg, Germany, moid.riaz.bhatti@uni-oldenburg.de https://orcid.org/0000-0002-3426-2960, {ali.akyol, jorge.marx.gomez}@uni-oldenburg.de
[2] Landwirtschaftskammer Niedersachsen, Fachbereich Versuchswesen Pflanze, An der Domäne 1, 38154 Königslutter, Germany, {henrik.rosigkeit, linda.matzke, isabel.grabenhorst}@lwk-niedersachsen.de

questions addressed by the research project "5G Smart Country" funded by the German Federal Ministry of Digital Affairs and Transport (BMDV). In the following work-in-progress paper, an overview of the collaborative project is given based on site-specific Nitrogen (N) fertilization (N-VRA) in winter wheat (*Triticum aestivum* L.). A system architecture for the collection of field data, networking of various machines, and data visualization as well as a software model for digital crop cultivation are presented and the possible scenarios for 5G use in precision farming are explained.

2. Project presentation and work packages

As part of the 5G innovation competition (5G-Innovationswettbewerb), the BMDV is funding cities, regions, and research organizations to develop and test ideas for 5G applications [Bm21]. With prospects of digital transformation of rural areas, the districts of Helmstedt and Wolfenbüttel in Lower Saxony successfully applied to the BMDV for the project "5G Smart Country[3]" [Bm21]. The focus of the project is on testing 5G applications under real agricultural and forestry conditions. The sub-project and the subject of this paper "Smart Farming" has several project partners[4] from science and industry, and six work packages (WP[5]) [Wo21].

3. Fundamentals of mineral fertilization of winter wheat

Breeding progress, intensification of cultivation strategies, and the use of mineral fertilizers have historically led to an increase in wheat yields. In Germany, the cultivation of winter wheat is particularly widespread [Kr12]. Besides yield increase, N fertilization can also cause leaching of the unused amounts of N with water [Bu15]. With an oversupply of N in the soil due to fertilization and mineralization of the residues of soil organic matter resulting in plant-available forms of ammonium (NH_4^+) and nitrate (NO_3^-), increased losses occur leading to nitrate leaching and ammonia immobilization [Ha14].

To guarantee a fertilization that meets the needs as much as possible, the N available to plants in the soil, N_{min}, is determined as a minimum factor by sampling the sites at the beginning of the vegetation period, and the fertilization strategy is planned in relation to the crop development, e.g., by means of BBCH[6] scale [Fi07]. The first application in spring at the time of plant development at BBCH stages 21-25 has a direct influence on stand density at the time of tillering. At the onset of heading (BBCH 30-32), yield plants

[3] The estimated project duration is 3 years (Nov. 2021 – Nov. 2024); funding amount: 3.9 mill. euros.

[4] Landwirtschaftskammer Niedersachsen, Universität Oldenburg, TU Braunschweig, Julius-Kühn-Institut, Deutsches Zentrum für Luft- und Raumfahrt, Strube D&S GmbH, Rauch Landmaschinenfabrik GmbH, Domäne Schickelsheim, Vodafone GmbH.

[5] WP1: Digitized crop production systems; WP2: Trait recording on individual plants; WP3: Detecting, locating, and regulating weeds; WP4: Recording wildlife populations in agricultural areas; WP5: Pointed fertilizing; WP6: Smart grain harvesting and information gathering.

[6] Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und Chemische Industrie (BBCH)

are differentiated by reducing weak secondary shoots and fixing ear density [Kr12]. Furthermore, N fertilization results in the formation of additional roots on the plant, which promote anchorage in the soil and nutrient uptake on the main shoot [St94]. Optionally, a third application before ear emergence in BBCH-49 is also considered which can be decisive for yield and quality due to its influence on the storage cells in the grain.

3.1 Site-specific fertilization of winter wheat

Increasing N supply to a crop generally leads to a greater crop biomass and hence grain yield, but it can also make the plants susceptible to lodging, which limits yields and quality. Though harvesting of crops with insufficient fertilization increases N use efficiency (NUE)—yield per unit of N available to the crop—it also leads to depletion of soil mineral reserves and deterioration of soil quality [Ha14]. N-VRA considers specific soil conditions of the smaller sections and plant nutritional status resulting in a higher NUE and a lower risk of N leakage into the environment [Me22, Mi20]. An efficient N-VRA in the cultivation of winter wheat brings economic (yield-related) and ecological (regarding substance leaching and emission) advantages [Ra02]. In this context, the heterogeneity of the field is of particular importance. To increase yields, sites with poorer plant development are promoted, especially in the first two fertilizer applications, and those with above-average plant development are fertilized less. This leads to a more homogeneous development of the crop. To maintain the quality of the varieties, high-yielding zones are specifically supplied with sufficient N in the third application, while at the same time sites with a lower crop development are only supplied with a basic amount.

4. Technical concept

The project foresees primarily 5G technology for fast and reliable communication between machines (process control), sensors (data collection), servers (AI/data analytics), and users. The expected data heterogeneity will be served by a data lake.

4.1 System architecture

The project "5G Smart Country" envisages collection of a wide variety of data on winter wheat and sugar beet (*Beta vulgaris* L.). The data will be processed using AI/data analytics and will be displayed as live maps, for instance, for biomass, nutrient quantities, wildlife, stubble, and weed. A possible system architecture is shown as frontend-backend layers [Mo22, FG16] in Fig. 1. The frontend serves as the display layer allowing for userinteraction with the system, and the backend is responsible for data storage and processing.

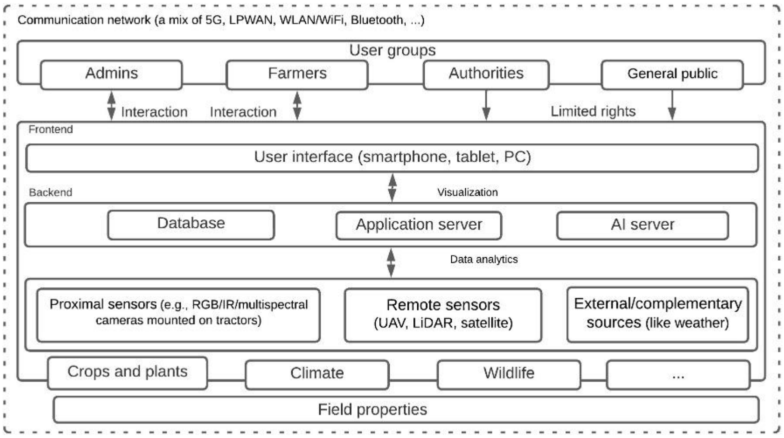

Fig. 1: Possible system architecture [own illustration].

The portal is being designed to be able to manage different individual user groups (farmers, scientists, authorities, public) with a multi-device capable frontend making it operable via different end-devices like smartphone, tablet, and PC. The backend layer collects data from different data sources (from simple proximal sensors to satellites), integrates the measurement data with complementary data (e.g., weather), processes the data set using data analytics/AI algorithms, and provides results such as N availability, biomass, stubble, and wildlife tracking maps.

4.2 Data communication

With higher data transmission speed and connection density, and especially lower latency, 5G technology can create new opportunities for faster and more precise decisions and process control, particularly based on machine-to-machine (M2M) communication [Ha22]. However, data volumes and rates for Internet-of-Things (IoT) sensors in smart farming will not always and everywhere need the highest 5G capabilities, and for such use cases other 'lightweight' technologies would be more optimal. IoT is increasingly using the Low-Power Wide-Area Networks (LPWAN) technology, where we have lower data rates (in the kbit range) than Wireless Local Area Network (WLAN/WiFi), Bluetooth, and cellular technology, but much longer range (10–40 km in rural and 1–5 km in urban areas) and much longer battery life (10+ years) due to low power consumption. An established LPWAN protocol is the Long-Range Wide-Area Network (LoRaWAN), which is built on the Long-Range Modulation (LoRa) technique—a chirped spread spectrum-based communication technique—making the signal transmission robust to channel interference and is, therefore, suitable for long-distance energy-efficient transmissions [CZ20]. The whole communication architecture will be a mix of diverse data transmission rates and corresponding techniques. Some use cases where higher 5G performance would be needed are real-time communication between the agricultural machines (VRA), UAVs (crop analytics), robots (weed detection/elimination, pointed fertilizing, and detection of biotic (such as pest infestation) and abiotic (such as heat) stresses [HH09]) and the servers. Some of the data exchange standards/formats deemed suitable for the communication of geographic data are GeoJSON (encoding and exchange of geospatial data), Shapefiles (distribution of vector/map data), GeoTIFF (raster image file format for satellite and aerial imagery data), LAS (3D LiDAR point cloud data), WMS (display of geospatial data on the Internet), and REST (communication between machines).

4.3 Collection and visualization of field and plant data

The system has different data sources for precision farming with their own requirements for data transmission and algorithms: 1. proximal/near-ground sensors (e.g., RGB/IR cameras mounted on harvesters/tractors); 2. remote sensors (e.g., UAV, LiDAR, satellite) [Ta22]; 3. external sources (e.g., weather). An established technique for soil/land reconnaissance and crop analysis is multispectral analysis, where the reflected light from the object of interest is decomposed into the individual wavelength ranges and analyzed [Cu80]. Multispectral analysis grants conclusions about soil properties and plant health as well as other properties of the crop from the examined areas [Se20]. Based on multispectral analysis, a field can be subdivided into subareas (sections) suitable for VRA.

To carry out VRA, a preliminary analysis of several factors is conducted, e.g., plant condition and soil nutrient content. Such an analysis can hardly be done manually on even moderately large farms. For this purpose, multispectral sensors mounted on satellites, UAV, or ground-based equipment are generally used. From multispectral data, various vegetation indices (VI) can be calculated by using ratios, differences, ratios of differences and sums, or by forming linear combinations of spectral band data. VIs enhance the vegetation signal, while minimizing the effect of solar irradiance and soil background [JH91], and can be integrated into GIS maps for site-specific analysis, processing, and yield forecasting [Di16, PG21]. One prominent example of VIs is the Normalized Difference Vegetation Index (NDVI) which uses the fact that a healthy plant absorbs most of the incident visible wavelengths (particularly the red (R) ones) while transmitting or reflecting most of the falling near-infrared (NIR) wavelengths. NDVI is calculated as the normalized difference of the spectral reflectance in the R and NIR regions (NDVI=(NIR–R)/(NIR+R)) [Ro73, JH91]. NDVI values for vegetative areas vary between 0 and 1. They increase towards 1 with an increase in the soil cover by the growing plants, their Leaf Area Index (LAI), chlorophyll content, and plant N-nutritional status [VSB19].

An example of NDVI maps is shown in Fig. 2, where Sentinel-2 satellite images [SDH] of a winter wheat field in March and April were used to calculate NDVI on a 10 m grid (QGIS, version 3.16.14). The field can thus be divided into small sections that can be viewed and managed individually. With sufficiently high-resolution multispectral data, it is even possible to view the individual plants in row crops. The storage and processing of the site-specific data and the required fertilization process control decision mechanisms are part of the digital plant cultivation model which is described in the following section.

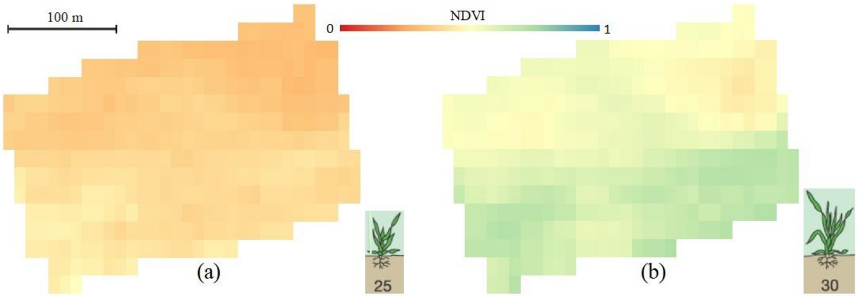

Fig. 2: NDVI maps of a winter wheat field in different plant growth stages (Sentinel-2 L2A data with 0% cloud cover; NDVI scale: 0: hardly any; 1: good vegetation). (a) BBCH-25: tillering, (b) BBCH-30: just before the second fertilizer application with the beginning of the stem and the first internode elongation. Cartoons: the plants in their corresponding phenological stages [Br15].

4.4 Software model for digital plant cultivation

The digital plant cultivation system is based on the object-oriented software design methodology (OO) [BJR07] in the form of classes. Fig. 3 shows a Unified Modeling Language (UML) class diagram [Fo04]. The main classes are Environment, Soil, Seed, Fertilizer (field/site-specific, i.e., uniform/VRA), Plant, and Wheat. The classes contain agricultural parameters as fields and methods for data retrieval, processing, and process control, respectively. The basic idea behind the software model is explained below.

The Environment class hosts environmentally relevant information such as temperature and relative humidity. Current as well as historical environmental data serve as a basis for agricultural planning and process control. The Soil class models the physical and chemical properties of the soil where crops are planted. The soil type is derived from the composition of sand, clay, and silt [US99]. Other important parameters include pH, soil salinity, and nutrients in the soil. Seed quality significantly affects plant stand, crop quantity and quality, and is modeled by the Seed class, which collects data on seed quality (seed purity) and seeding parameters (seeding depth, rate…) that enable plant growth and yield prediction. The fact that different phenological stages in plant growth have their own needs for nutrients is considered by the Plant class which models plant phenology with data on initial parameters (plant type/position, soil salinity), vegetation parameters (vegetation stage (VS), transpiration rate), morphological parameters (LAI), and vegetation indices (VI), e.g., NDVI or the GNDVI [Gi96] which is computed similarly to the NDVI, but the green (G) band is used instead of the R band (GNDVI=(NIR–G)/(NIR+G)). GNDVI is more sensitive to chlorophyll concentration in a wide range of chlorophyll variations than the 'red' NDVI allowing more precise estimation of pigment concentration and is linearly correlated with LAI and biomass [Gi96, Hu08]. Using this set of data, the Plant class provides an objective basis for yield prediction. The characteristics of the produce depend on the plant type and the Wheat class models this with data on physical properties (hectoliter weight, foreign matter, falling number...)

[St17]. Fertilizer application is modeled by the Fertilization class. VRA is controlled according to the VSs and VIs which are determined from the sensor data and allow yield forecasting which is integrated in the Wheat class [HH09, JC19, Le86].

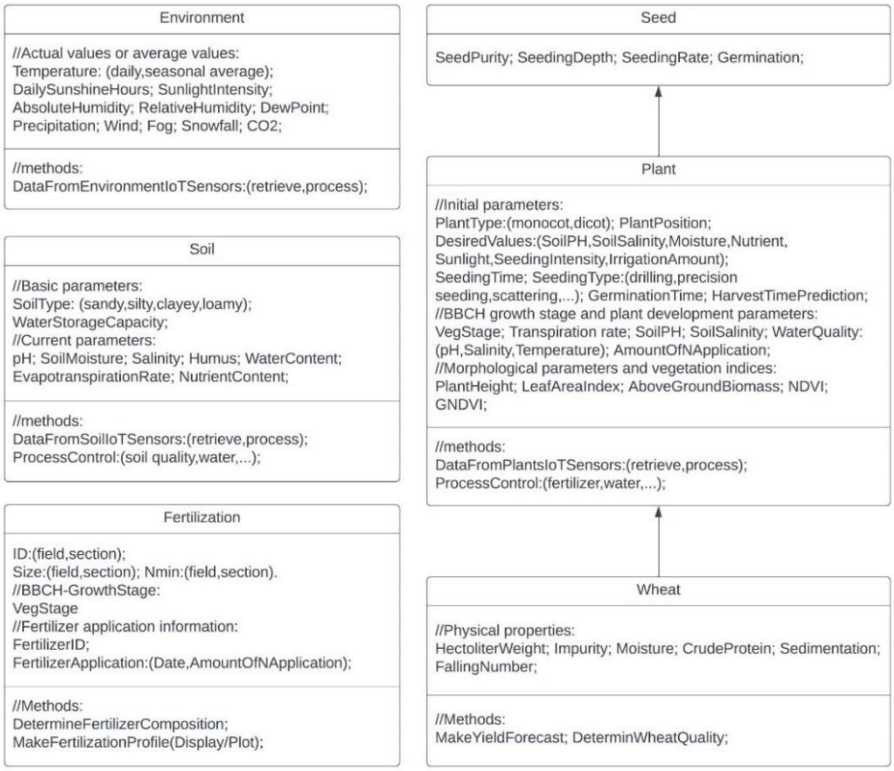

Fig. 3: UML class diagram for the digital plant cultivation system. The arrows show OO inheritance relationship between the classes [Fo04], e.g., wheat plant is a special plant and therefore the class wheat inherits data and methods from the class plant and extends this with its own specific features.

Based on this georeferenced data, AI and statistics are used to gain insights and control processes such as trajectory generation for UAV flights for VRA and waypoint map for robot control for mechanical weed elimination or microdosing. Phenotypic measurement data are documented and processed in a standardized manner according to the Crop Ontology Model (COM) [Pi22]. Here, a variable is defined as a combination of three quantities: Trait (what is being studied: e.g., plant height), Method (how is the measurement made: e.g., measurement, calculation), and Scale (how is the measurement represented: qualitative or quantitative (unit)). In summary, 1 variable = {1 trait, 1 method, 1 scale}. A variable name is constructed like this: Trait_Method_Unit. Tab. 1 illustrates this with an example data set from the COM:

Variable name	Trait name	Trait abb.	Method name	Method explanation	Unit
PH_M_cm	Plant height	PH	PH measurement	The distance from the ground to the top of the plant measured with a ruler	cm
GY_Calc_gm2	Dehulled grain yield	GY	GY computation	Measured on harvested and dehulled grain. Divide weight by plot area.	g/m²

Tab.1: A data set from the COM.

5. Conclusion

In this paper we have presented the BMDV project "5G Smart Country". The objective is to develop and implement new concepts for 5G-based precision farming, particularly plant analytics and intelligent process control aimed at increasing agricultural efficiency by increasing yields while optimizing resource use and complying with fertilizer, pesticide, and climate-oriented environmental regulations. The planned key milestones include 5G-based fertilization (VRA, pointed), machine/software-based detection of crop stresses, automated initiation of actions, e.g., robotic weed detection and elimination, and wildlife tracking. In the end, a web-based software system/app will be available to farmers, scientists, authorities, and the public, providing information vital for smart farming (weather, field heterogeneity, plant growth, N demand/uptake, weeds, biomass, yield forecast, stubble...) in the form of maps, tables, and files.

6. Outlook

The software model for digital crop cultivation will be further developed to include additional components in the farming processes as well as communication with sensors and machines and implemented in a programming language. Furthermore, a data visualization app with weather, wildlife, stubble and weed maps as well as a satellite data processing pipeline for the study of crop development and determination of VIs for VRA and yield forecasting will be developed.

Acknowledgement

The authors thank the BMDV for funding this research project (grant number: 45FGU117)

Bibliography

[Bm21] 5G-Innovationsprogram.www.bmvi.de/DE/Themen/Digitales/Mobilfunk/5G-Innovations programm/5g-innovationsprogramm.html, last access: 20.05.2022.

[BJR07] Booch, G.; Jacobson, I.; Rumbaugh, J.: Object-Oriented Analysis and Design with Applications. 3rd ed., Pearson Education, MA, 2007.

[Br15] Brockerhoff, H.: Entwicklungsstadien im Getreide, LWK-NRW, 2015.

[Bu15] Bull, I. et al.: Qualitätsdüngung zu Winterweizen: in Mitteilungen der Landesforschungsanstalt für Landw. und Fischerei: Heft 55, 2015.

[Cu80] Curran, P.: Multispectral remote sensing of vegetation amount. Progress in Physical Geography 4(3), pp. 315-341, 1980.

[CZ20] Chaudhari, B.S.; Zennaro, M.: LPWAN Technologies for IoT and M2M Applications. Academic Press, CA, 2020.

[Di16] Diepenbrock, W.; Ellmer, F.; Leon, J.: Ackerbau, Pflanzenbau und Pflanzenzüchtung. Verlag Eugen Ulmer, 4th ed., 2016.

[Dü20] Bundesanstalt für Landwirtschaft und Ernährung. Düngeverordnung (DüV), 2020.

[EH15] Ehrlich, P.; Harte, J.: Opinion: To feed the world in 2050 will require a global revolution. Proc. Natl. Acad. Sci. USA, 112(48), pp. 14743–14744, 2015.

[Fi07] Finck, A.: Pflanzenernährung und Düngung in Stichworten, 6th ed., Borntraeger, 2007.

[FG16] Foster, E.C.; Godbole, S.: Database Systems: A Pragmatic Approach. 2nd ed., Apress, Berkeley, CA, 2016.

[Fo04] Fowler, M.: UML Distilled: A Brief Guide to the Standard Object Modeling Language. 3rd ed., Pearson Education, MA, 2004.

[Gi96] Gitelson, A.A. et al.: Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sensing of Environment, 58(3), pp. 289-298, 1996.

[Ha14] Hawkesford, M.: Reducing the reliance on nitrogen fertilizer for wheat production, Journal of Cereal Science, 59(3), pp. 276–283, 2014.

[Ha22] Hassan, M.: Wireless and Mobile Networking. CRC Press, FL, 2022.

[HH09] Hopkins, W.G.; Hüner, N.P.A.: Introduction to Plant Physiology. 4th ed., John Wiley & Sons, Inc, NJ, 2009.

[Hu08] Hunt, E.R. et al.: Acquisition of NIR-green-blue digital photographs from unmanned aircraft for crop monitoring. Remote Sensing, 2(1), pp. 290-305, 2010.

[JC19] Jose, S.; Clennet, C.: Trees, Leaves, Flowers & Seeds. A Visual Encyclopedia of the

Plant Kingdom. DK Publishing, NY, 2019.

[JH91] Jackson, R.D.; Heute, A.R.: Interpreting vegetation indices. Preventive Veterinary Medicine, 11(3-4), pp. 185-200, 1991.

[Kr12] Kropf, U.: Getreide-Guide, Top agrar Ratgeber, 2012.

[Le86] Leonard, D.: Soils, Crops, and Fertilizer Use: A Field Manual for Development Workers. 4th ed., Peace Corps, 1986.

[Me22] Mezera, J. et al.: Comparison of Proximal and Remote Sensing for the Diagnosis of Crop Status in Site-Specific Crop Management. Sensors, 22(1), p. 19, 2022.

[Mi20] Mittermayer, M. et al.: Erfassung der räumlichen Variabilität von Boden- & Pflanzenparametern: Grdl. für die teilflächenspezif. N-Bilanzierung. LNI, GI, Bonn, 181, 2020.

[Mo22] MongoDB: What is the MEAN Stack? Introduction & Examples, www.mongodb.com/mean-stack, last access: 05.05.2022.

[Mu21] Mugiyo, H. et al.: Evaluation of Land Suitability Methods with Reference to Neglected and Underutilized Crop Species: A Scoping Review. Land, 10(2), p. 125, 2021.

[PG21] Panek, E.; Gozdowski, D.: Relationship between MODIS Derived NDVI and Yield of Cereals for Selected European Countries. Agronomy, 11(2), p. 340, 2021.

[Pi22] Pietragalla J. et al.: Guidelines for creating crop-specific ontologies to annotate phenotypic data, Alliance Bioversity International-CIAT, version 2.1, 2022.

[Ra02] Raun, W. et al.: Improving N Use Efficiency in Cereal Grain Production with Optical Sensing and VRA. Agronomy Journal, 94(4), 815, 2002.

[Ro73] Rouse Jr, J. W. et al.: Monitoring vegetation systems in the Great Plains with ERTS. 3rd Earth Resources Techn. Satellite-1 Symp., Washington, D.C., 351, pp. 309-317, 1973.

[Sc21] Scholik, N.: Limit. Ein Essay zur Lage der Weltbevölkerung. Teil 1: Grenzen und Herausforderungen. Z. Außen Sicherheitspolit., 14, pp. 189–212, 2021.

[SDH] Scientific Data Hub, ESA, https://scihub.copernicus.eu/dhus/#/home.

[Se20] Segarra, J. et al.: Remote Sensing for Precision Agriculture: Sentinel-2 Improved Features & Applications. Agronomy 10, p. 641, 2020.

[St17] Steber, C.M.: Avoiding problems in wheat with low Falling Numbers. Crops & Soils 50.2, pp. 22-25, 2017.

[Ta22] Tao, H. et al.: Proximal and remote sensing in plant phenomics: 20 years of progress, challenges and perspectives. Plant Communications, 3, p. 100344, 2022.

[US99] U.S. Department of Agriculture, Natural Resources Conservation Service.: Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Handbook 43, 2nd ed., 1999.

[VSB19] Vizzari, M.; Santaga, F.; Benincasa, P.: Sentinel 2-based N VRT fertilization in wheat: Comparison btw traditional & simple precision practices. Agronomy, 9(6), p. 278, 2019.

[Wo21] Lk Wolfenbüttel: Forschungsantrag "5G Smart Country", 2021.