APPLICATION MAPS IN PRECISION AGRICULTURE – GRASSLAND PRODUCTION MANAGEMENT IN POLAND

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Abstract: This article discusses the topic of the use of application maps in precision agriculture (PA), particularly in the context of grassland management, which accounts for over 21% of utilised agricultural area (UAA) in Poland. New technological developments in the area of smart agriculture (Precision Agriculture, Agriculture 4.0), in terms of sensor technology and information processing, are creating a wide range of data acquisition opportunities to document biological production processes with both high temporal and spatial resolution. That information can be used to rationalise production processes and reduce trade-offs between different environmental services. The technologies that support this kind of research are analyses using satellite imagery, and map-based applications like the system developed in the GRASSAT project are discussed in detail in this article. The developed application provides farmers with information on events using free data from the Copernicus Programme (Sentinel-1, Sentinel-2, ERA5-Land reanalyses). Remote sensing indices, such as the Normalised Difference Vegetation Index (NDVI), Leaf Area Index (LAI), and fresh biomass production volumes, are calculated to show the condition of the green vegetation in the grassland plots. Meteorological risks, such as field freezing, are also presented. The GRASSAT application is available in both desktop and mobile versions.

Keywords: precision agriculture, maps, application maps, grassland, remote sensing

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Introduction

Precision agriculture (PA) is a comprehensive management system that adapts individual elements of agrotechnology to changing conditions on specific parts of the field, depending on the current state of plant growth and development or soil properties. The necessary data are acquired and processed using highly developed navigation and information technologies. Modern agricultural maps are increasingly developed based on satellite data, supplemented, and validated by field measurements (Ess, Morgan 2003, Rains, Thomas 2009). The rapid development of advanced agriculture is not possible without good field management by the farmer, which is greatly facilitated by dedicated map applications.

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PA maps support many aspects of agricultural production including:
- crop yield forecasts (based on satellite data, drone-acquired data, and meteorological data),
- precision seeding (variable rate system),
- fertilisation (support for mineral, liquid, or sprayer-based fertilisation),
- canopy height adjustment (adjustment of agrotechnical treatments),
- assessment of damage caused by weather phenomena (agricultural drought, floods, and hailstorms).

The above-mentioned aspects are related to the development of Agriculture 4.0, which can be defined as the collection, processing, and use of data to support production management on the farm. PA is referred to by various terms, such as precision farming (PF), site-specific input application (SSA), site-specific agricultural technology, and variable-rate treatment (VRT) (Pedersen, Lind 2017). The broadest related term is smart agriculture, which describes agriculture managed with technology, robotics, and automation. The history of PA began with the introduction of the global positioning system (GPS) in the 1970s. The first yield maps developed using geographic information system (GIS) technology were generated in 1984, and application maps were introduced to agriculture in the early 1990s. An extremely important moment in the development of PA was the use of satellite images to determine crop conditions (1995–98). At the beginning of the 21st century, the first fully automatic agricultural guidance systems were introduced, and a few years later (2008), the use of unmanned aerial vehicles (UAV) began in the development of application maps to support the management of agricultural production (Pedersen, Lind 2017). Technologies currently used in PA are constantly evolving, hooked on issues related to the Internet of Things (IoT), big data analysis, artificial intelligence (AI), and machine learning.

Looking at PA from the side of satellite imagery and GIS technology, there are four areas of application: geographical positioning, information gathering, decision support, and variable-rate treatment (VRT) (Pedersen, Lind 2017). The first area (geographical positioning) allows the management of the movement of agricultural machinery, including the use of Global Navigation Satellite Systems (GNSS)-reference signal, GNSS-receiver on a tractor, tractor computer, or tablet. The 'gathering information' area includes data that can be used in precise farm management, and these include aerial pictures, satellite images, ground-based sensor data, and UAV) data. The next two topics (decision support and VRT) show ways to manage ready-made solutions for managing selected issues, such as fertilisation, yield optimisation, or adjustment to water resources.

The three levels of data are used to properly manage agricultural production: collected *in situ*, aerial level data, and satellite data. Each of these has its advantages and disadvantages, but only using them together can give the most complete picture of the situation in the study by the European Environment Agency (EEA 2023).

Maps

Maps in agriculture

Maps used in agriculture belong to the group of thematic maps (Dent et al. 2009). They inform users about the most important topics related to land cultivation, animal husbandry, agricultural employment, or technologies. Depending on the scale of the map, the subject matter of agricultural maps changes, up to detailed information about individual farms and even sections of them. Maps of agriculture can be divided by the subject matter presented in the following maps (Żyszkowska et al. 2012):
- natural conditions for the development of agriculture (maps of land use, land cover, agrometeorological conditions, and agricultural land classification),
- socio-economic factors of agricultural development (farm structure, agricultural intensity, and agricultural development),
- agricultural land (agricultural land use, agricultural land, and grassland),
- agricultural production (crop production, sowing volumes, harvests, yields, prediction of yields, production, and animal populations),
- general agricultural maps (agricultural commodity, production trends, commodity structure, agricultural productivity, and measures

of the level of development of the local economy),
- agricultural landscape (land use, including types of soil and agricultural complexes),
- fishing (deep sea fishing and inland fishing),
- forestry (forest management and restoration and afforestation of forests),
- hunting (ranges of hunting districts).

An example of a study that deals extensively with agricultural issues in Poland is 'Atlas of Agriculture of Poland' prepared by the Department of Rural Geography and Local Development of the Institute of Geography and Spatial Management of the Polish Academy of Sciences (Bański 2010, Fig.1). This Atlas comprehensively discusses agricultural issues ranging from the role of agriculture in the Polish economy through agricultural land use, plant cultivation, and agricultural production to science, education, and agricultural service. However, it is a small-scale study, although the authors indicate that it deals with the local, regional, and national scale.

According to The Atlas of Agriculture of Poland, grasslands in Poland cover approximately 21% of all utilised agricultural areas (UAA). In 2004, the grassland area was 2,390,000 ha and the pasture was 975,000 ha. Currently, these values are similar, with an increase in the share of meadows in the UAA (Łączyński 2020). In comparison with the status of grasslands in 1990, the share of permanent meadows in UAA increased by around 40%, but the percentage of permanent pastures in UAA has fallen by almost 70% (Goliński, Golińska 2019). The widest areas of grassland are in the regions where the quality of the agricultural production area is low. Meadows are concentrated along the valleys of major rivers and mid-field depressions, in the mountains and wetlands. Pastures are mainly found in the north-eastern part of the country, in the Carpathians and their foothills, and in the Sudeten Mountains. The characteristic of Poland's surface features means that 90% of grasslands are covered by lowland meadows. They comprise dry-ground meadows, flooded meadows, boggy meadows, and post-boggy meadows (Goliński, Golińska 2019).

Studies like the aforementioned atlas, however, are not sufficient at the scale of a single field and will not be useful in the management of individual farms. Small-scale maps can only inform about general trends, the main directions of regional development, and the main agricultural problems. In this case, a small one on a larger scale comes with help. Maps in agriculture at larger scales were initially developed, among other things, to collect information on soils and their agricultural suitability. In the 1950s–60s, the development of soil-agricultural maps began in Poland, intended mainly for farmers, producers, and organisers of agricultural production (Witek

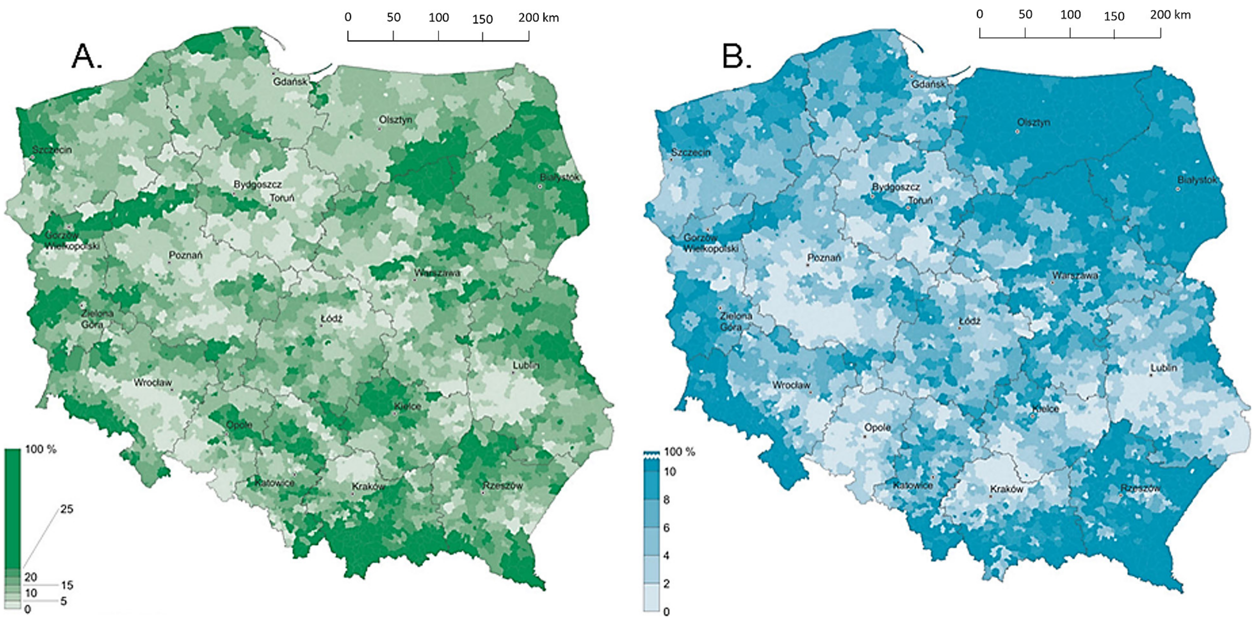

Fig. 1. A – Share of meadows in the total area of agricultural lands, 2005; B – Share of pastures in the total area of agricultural lands, 2005. Maps from: Atlas of Agriculture of Poland (Bański 2010).

1973). These maps were produced for the whole country at a scale of 1:5000, and for selected areas, more detailed studies were produced at a scale of 1:1000 or even 1:500. The soil-agricultural map made it possible to manage agricultural land to a certain extent as it contained information not only on soil type but also on agricultural characteristics and suitability for farming.

Application maps

The soil-agricultural maps are not accurate enough for PA. In the context of this issue, much more detailed application maps are used, i.e., large-scale thematic maps placed in apps (on tablets and phones) to manage work in, for example, a grassland plot. Application maps are mostly a form of visualisation of elaborate systems developed based on satellite data, aerial data, and *in situ* measurements.

This section will discuss the agricultural production management systems available on the Polish market that use application maps. An overview of the available solutions was necessary during the GRASSAT project, and through this, the most important functionalities and satellite indicators were identified to be included in the application under development.

The satellite indicators measure environmental conditions (e.g., vegetation condition, drought, freezing, or flood risks) in continuous time and space (Dąbrowska-Zielińska et al. 2015). Currently, available free-of-charge satellite data allow measurements with an accuracy of up to 10 m (e.g., based on Sentinel-1 and Sentinel-2 data). Timescale availability is also important – from 1 day (e.g., Sentinel-3, 100 m resolution) to several (e.g., Sentinel-1 and 2).

The following vegetation and environmental satellite indicators are important from the perspective of managing agricultural production in grassland plots:
– Normalised Difference Vegetation Index (NDVI) – an index that determines the condition of vegetation (Tucker 1979) and normalises green leaf scattering in near infra-red wavelengths with chlorophyll absorption in red wavelengths,
– Normalised Difference Infrared Index (NDII) – this index detects canopy water content (Hard-

Table 1. Selected mapping applications to support agricultural production management.

	365FarmNet	SatAgro	OneSoil yield	EOSDA crop monitoring
Access	10 days demo then paid	Free demo then paid	Free demo then paid	Free demo then paid
Language	PL, DE, EN, FR	PL, UK, ES, EN, DE, CS	PL, ES, CS, RU, FR, PT, DE, HU, UK	ES, RU, FR, PT, UK
Background maps, satellite data	Google Maps and satellite images from NASA, Sentinel-2	Satellite images (Sentinel-2, PlanetScope, Landsat8, MODIS), maps (OSM, Google)	Google Maps and satellite images from NASA	Sentinel-2, PlanetScope, EOS SAT-1
Cultivation/ breeding	Any kind of cultivation (without details for grasslands)/ breeding	Any kind of cultivation/breeding	Any kind of cultivation/breeding	Any kind of cultivation/ breeding
Field options	Vegetation, crop condition, fertilisation, sowing, crop protection, harvest, weather	Crop condition, weather (IMGW), soil tests, sowing, harvesting, fertilisation, other biochemicals, alarms	Field, crop rotation, notes, fields by season, sowing, harvesting, crop classifications, weather	Vegetation, crop condition, weather, crop classification, tracking, soil moisture analytics, yield prediction, soil organic carbon, crop rotation, sowing, harvesting, notifications, irrigation
Satellite indicators	NDVI (Sentinel-2)	NDVI (Sentinel-2, PlanetScope), GDD	Maps with indicators in the paid version (for advisors, farmers, soil testing companies), for example, NDVI	NDVI, NDRE, MSAVI, RECI, NDMI
Additional options	Yes, it can be added (vehicle)	Yes, e.g., profitability	Yes, e.g., file converters	Yes, e.g., API access to satellite data

isky et al. 1983) and was investigated for monitoring drought conditions (Móricz et al. 2018),
– Leaf Area Index (LAI) – this index is a dimensionless index measuring the one-sided green leaf area over a unit of land (Yan et al. 2019), and the article will discuss both LAI from field measurements and the product using data from the Sentinel-2 satellite,
– Normalised Difference Moisture Index (NDMI) – a normalised index that uses infrared data to display moisture conditions (Ochtyra et al. 2020),
– Normalised Difference Red Edge Vegetation Index (NDRE) – an index that is typically used to monitor crops that have reached the maturity stage (Evangelides, Nobajas 2020),
– Modified Soil-Adjusted Vegetation Index (MSAVI) – this vegetation index is designated to mitigate soil effects; it is applied when NDVI cannot provide accurate values, particularly, with a high percentage of bare soil, scarce vegetation, or low chlorophyll content in plants (Chehbouni et al. 1994),
– Red-Edge Chlorophyll Vegetation Index (RECI) – an index that reacts to the amount of chlorophyll in the leaves to which nitrogen is supplied (Li et al. 2014),
– Growing degree day (GDD) – this is used to estimate the growth and development of certain crops and pests during the growing season (McMaster, Wilhelm 1997).

The review of available mapping applications to support on-farm agricultural production management was intended to indicate how useful the available solutions are for grassland management, rather than cereal or root crops. In this case, it is important, among other things, to be able to mark in the application such actions on the field as cutting (performed three times on grassland plots in Poland). It was also checked which satellite data were used by the solution authors to generate satellite indicators, and which indicators were based on satellite data. A comparison of four popular applications on the Polish market (365FarmNet, SatAgro, OneSoil Yield, and EOSDA Crop Monitoring) is presented in Table 1. Among the features compared were general application features (access, language, and additional options), data issues and processing capabilities (background maps, satellite data, and satellite indicators), agricultural issues (cultivation/breeding), and field/production management (field options).

From the perspective of the GRASSAT project (*Tools for information to farmers on grassland yields under stressed conditions to support management practices*), the most interesting applications were SatAgro and EOSDA Crop Monitoring. Only these two applications rely on more than one satellite data set (Sentinel-2, PlanetScope, Landsat 8, MODIS, and EOSAT-1) and a wider range of satellite indicators. In addition to the standard calculated NDVI, the two aforementioned applications provide options for calculating: GDD, NDRE, MSAVI, RECI, and NDMI. These applications allow the user to enter the most information about the field.

The review of the applications revealed that they focus on the management of cereal and root crops and are not dedicated to grassland. Also, it was not noticed that they specify such events as freezing, which is a problem in grasslands, especially in northern Poland (Goliński et al. 2018). The available applications are based on NDVI, an indicator that is not the best in determining biomass production but is more useful in determining the condition of the vegetation (Bajocco et al. 2022). In the case of grassland plots, it works well in determining when a cut has occurred. These considerations of available map applications indicated the way for the authors to develop an application to support grassland management in Poland at the individual field level. The data sets used and approaches are discussed in later sections of the article.

Data and methodology

In situ data

In situ data were collected in two voivodeships of Poland (Wielkopolskie PL41 and Podlaskie PL184, Fig. 2.) from 46 grassland plots. Several *in situ* measurement instruments were used:
– LAI-2200C Plant Canopy Analyser – LAI,
– AccuPAR – fraction of Absorbed Photosynthetically Active Radiation (fAPAR),
– SPAD – Chlorophyll Content Index (CCI),
– TRIME-PICO 64 – soil moisture,

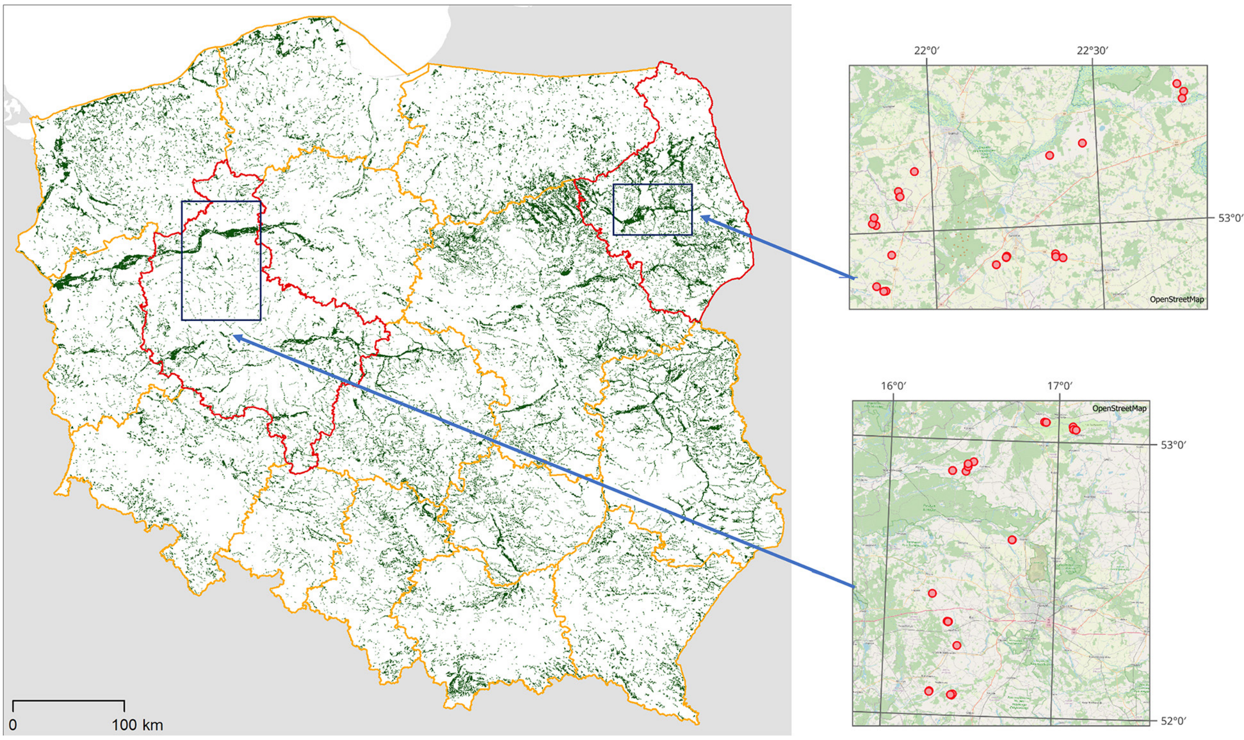

Fig. 2. Poland – in situ data collection sites used to validate satellite data.

- Plate Meter EC20 and cutting, height, fresh and dry matter sward – biomass,
- ASDpec4 Hi-Res – spectral responses,
- EVEREST AGRI-THERM II – radiation temperature.

The data were collected in a database, each point being defined by coordinates from the GPS. This allowed the field measurements to be related to the satellite data used in the GRASSAT application. The satellite data were validated with field measurements (Dąbrowska-Zielińska et al. 2021), for example, the field measurement of dry biomass was used to validate the fresh biomass model developed as part of the project.

Satellite data and models

To develop the GRASSAT application, free Copernicus satellite data from the Sentinel-1 and Sentinel-2 satellites were used. The data from the Sentinel-1 radar satellite (10 m resolution) were applied to determine soil moisture variation. The already existing soil-moisture model developed at IGiK was calibrated using a set of *in situ* measurements (Dąbrowska-Zielińska et al. 2018). For other calculations (including NDVI, normalised difference water index [NDWI], NDII, LAI freezing, and biomass measurements), data and products from the Sentinel-2 optical satellite (10 m resolution) were used. In computing ground freezing, hourly ERA5-Land reanalysis data on temperature and snow cover were used (9 km resolution).

Vegetation condition – NDVI

Vegetation condition based on the NDVI index. The use of Sentinel-2 optical satellite data (processing level: L2A) from the Copernicus Open Access service.

$$NDVI = (NIR - RED) / (NIR + RED) \quad (1)$$

where:
- NIR – near infrared channel,
- RED – red channel.

The formula for calculating the NDVI based on Sentinel-2 data:

$$NDVI = (B8 - B4) / (B8 + B4) \quad (2)$$

where:
- B8 – NIR channel 8 (842 nm),
- B4 – red channel 4 (665 nm).

The GRASSAT application displays the NDVI for each Sentinel-2 overflight over a user-defined area (field coverage), counting of accumulated

NDVI (sum of positive NDVI values from a user-defined period) and counting of anomalies (deviations from the average NDVI value of the previous year).

Number of days per year at risk of frost – ERA5-Land

Climatological reanalysis data can be downloaded from the Copernicus Climate Data Store website (C3S 2024a) via the Application Program Interface (API). The ERA5-Land hourly data product from 1950 to the present (C3S 2024b) was used for the analyses: data on air temperature (2 m temperature) and snow depth (Snow Depth) allowed counting the number of days in a particular winter that a field was at risk of frost. In the 'Snow Depth' product, snow thickness is expressed in meters (m), while the '2m temperature' is measured in Kelvin (K), which is converted to Celsius (°C) using the formula $t = T - 273.15$ [°C]. The hourly data product was then standardised for the whole day. For temperature, it is the daily minimum temperature and snow thickness is the daily average thickness. The analyses for a particular winter extend from 1 November to 31 March. Finally, the number of days in the field with a risk of freezing was counted. The condition defined the danger of freezing: IF snow depth ≤0.001 m AND temperature ≥0°C.

The water standing in – NDWI

The water standing in is calculated based on the NDWI index. The use of Sentinel-2 optical satellite data (processing level: L2A) accessed from the Copernicus Data Space Ecosystem. The project uses the NDWI formula, which relates to monitoring changes related to the water content in water bodies, using green and NIR wavelengths, as defined by McFeeters (1996):

$$\mathrm{NDWI} = (\mathrm{GREEN} - \mathrm{NIR}) \;/\; (\mathrm{GREEN} + \mathrm{NIR}) \qquad (3)$$

where NIR – near-infrared channel.

The formula for calculating the NDWI index from Sentinel-2 data:

$$\mathrm{NDWI} = (\mathrm{B3} - \mathrm{B8}) \;/\; (\mathrm{B3} + \mathrm{B8}) \qquad (4)$$

where:
- B3 – green channel 3 (560 nm),
- B8 – NIR channel 8 (842 nm).

NDWI values above 0 represent standing water.

Plant water stress – NDII

Plant water stress was calculated using the NDII index. The optical Sentinel-2 satellite data (processing level: L2A), obtained from the Copernicus Data Space Ecosystem, were used to calculate NDII:

$$\mathrm{NDII} = (\mathrm{NIR} - \mathrm{SWIR}) \;/\; (\mathrm{NIR} + \mathrm{SWIR}) \qquad (5)$$

where:
- NIR – near infrared channel,
- SWIR – short wave infrared RGB composite.

The formula for calculating the NDII index from Sentinel-2 data:

$$\mathrm{NDII} = (\mathrm{B8} - \mathrm{B11}) \;/\; (\mathrm{B8} + \mathrm{B11}) \qquad (6)$$

where:
- B8 – NIR channel 8 (842 nm),
- B11 – SWIR 1 (1610 nm).

The GRASSAT application displays the most up-to-date humidity status – from the last Sentinel-2 flight.

Biomass – LAI

The amount of fresh (wet) biomass was calculated based on the product LAI (10 m resolution) from Copernicus Land Monitoring Service (CLMS). LAI is not directly accessible from remote sensing observations due to the possible heterogeneity in leaf distribution within the canopy volume. LAI data from CLMS have been modelled with a neural network approach using images from Sentinel-2 (HR-VPP Biopar VI NeuralNet module). During GRASSAT Project, the data were downloaded from the WEkEO service (WEkEO 2024). Fresh (wet) biomass was calculated by cutting. For the development of the fresh biomass model, the CLMS LAI data were validated with *in situ* LAI data (Dąbrowska-Zielińska et al. 2024). The following formula for calculating wet (fresh) biomass was used in the project (Dąbrowska-Zielińska et al. 2024):

$$\mathrm{BW} = \exp(a \times \log\mathrm{LAI} + b) \times \exp(\mathrm{Res}) \qquad (7)$$

where:
- BW – wet (fresh) biomass,

– a, b – parameters dependent on cut,
– exp(Res) – a multiplicative error for which the expected value is equal to 1.

Relationship models were developed as a result of the GRASSAT project to predict grassland fresh (wet) biomass yield with an R^2 accuracy of 0.72 for the first cut, 0.81 for the second cut, and 0.91 for the third cut. For farmers, efficient management and monitoring of grassland throughout the growing season are possible by using biomass model within GRASSAT application (Dąbrowska-Zielińska et al. 2024). The nature of the relationship between BW and LAI is non-linear. LAI appears in a power with an exponent >1, depending on the section. It is the highest for the first cut.

Results – GRASSAT application

Infrastructure

Both a desktop and mobile application have been developed as part of the GRASSAT project. Within the application, farmers can monitor (Fig. 3):
– the condition of the vegetation in the grassland plots (data for a given year, the previous year, and a comparison of years, possibility to observe grass damage),
– the amount of biomass production in the field and its variation within the field (use of an algorithm to predict biomass based on LAI and NDII),
– soil moisture conditions (standing water in the field),
– thermal conditions – identifying days with a possible danger of ground freezing (winter stress),

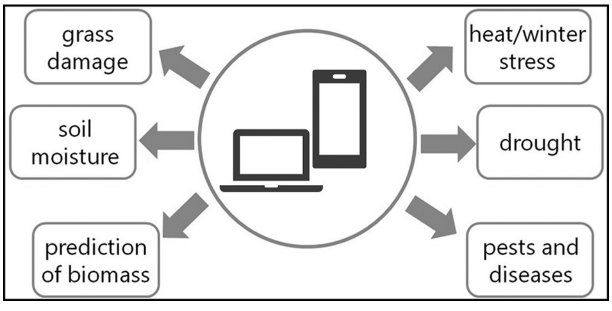

Fig. 3. Main themes that can be monitored with the GRASSAT application.

– amount of fertilisation, the occurrence of pests, and diseases in the field (adding events to the field, option from the application user side).

Various open-source technologies were used to develop the GRASSAT application. For data processing, the Python 3.8 language was adopted. Access to APIs for data access and analysis (e.g., WEkEO) was made possible using the .net programming platform (NET Framework). Satellite (raster) data, *in situ* measurements, and other spatial data were collected in PostgreSQL 12 with PostGIS 3.4 and published using Geoserver 2.25.0. Web framework was developed in Angular – an open framework and platform for creating Single Page Applications (SPAs). A diagram of the development of the GRASSAT application is included in Figure 4.

To download satellite images, the application uses the external SkyWatch service. To retrieve such data, the application performs the following sequence of operations via the API:
– creation of a *pipeline* based on the given geometry and the passed date range for which data are to be returned,
– querying the status of the *pipeline* until all images are ready for download,
– downloading all the requested images based on the data returned in the previous point.

For downloading the LAI product (product from Copernicus Land Monitoring Service), the application uses the API of the WEkEO service, the European Copernicus Data and Information Access Services reference service for environmental data, virtual processing environments, and skilled user support (WEkEO 2024). The procedure, in this case, is more complex:
– creation of a *job* based on the passed *bbox* for the field and dates for which the data are to be returned and the product of interest to the application – in this case LAI,
– querying the status of the *job* – for the *job*, the API returns a list of possible products to be ordered,
– the application orders all available products indicated by the *job*,
– the application retrieves the status of each order,
– when all orders are ready, the application downloads the ordered products.

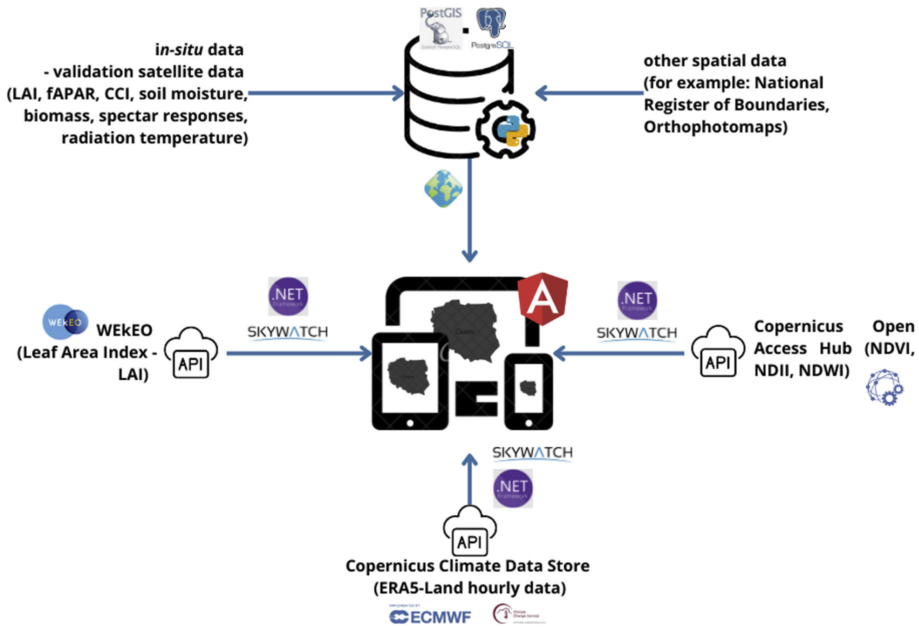

Fig. 4. Diagram of proceedings in the development of the GRASSAT application.

Maps and functions of the GRASSAT application

A user defines his grassland plots via a web interface (desktop or mobile version – Fig. 5). Subsequently, the grassland plots are analysed by a process running in the background, which first retrieves the source data from external services and then, generates products for indicated grassland plots such as NDVI, NDII, LAI, and biomass. In addition, the user can keep a log of field activity, so, it is possible to add information about harvest, fertilising, and soil sampling results.

The condition of the vegetation in grassland is calculated using the data from the Sentinel-2 optical satellite with 10 m resolution (based on the NDVI). The data are provided for a given year (Fig. 6. – the year 2023), the previous year, and a comparison of a given year with the previous year. For each field, the date of the available satellite image is given. The greener the colour of the field, the better condition the vegetation is in. In case of missing data (cloud cover, inability to

Fig. 5. An example view of a grassland plot in the GRASSAT application.

access optical data from the Sentinel-2 satellite), the area is marked in grey.

The application mostly used ordinal colour scales and not referring to satellite indicator values directly. The application of such a colour scale is related to the fact that the users (farmers) do not have extensive knowledge of the interpretation of vegetation satellite indicators. An example of an ordinal colour scale is presented in Figure 6.

The fresh biomass calculation is based on the Sentinel-2 LAI and NDII products. The darker the green colour on the map, the greater the weight of the predicted fresh biomass production on the grassland plots (Fig. 7). Information on predicted fresh biomass is given in t ha^{-1}. This provides an estimate of the total biomass grown on the grassland plots.

The water standing in the grassland plots is calculated based on the NDWI. The GRASSAT

Fig. 6. An example view of a field with vegetation condition information in the GRASSAT application. Possibility to compare the condition of grassland plots for the current and previous year.

Fig. 7. The weight of the predicted fresh biomass production on the grassland plots on the GRASSAT application.

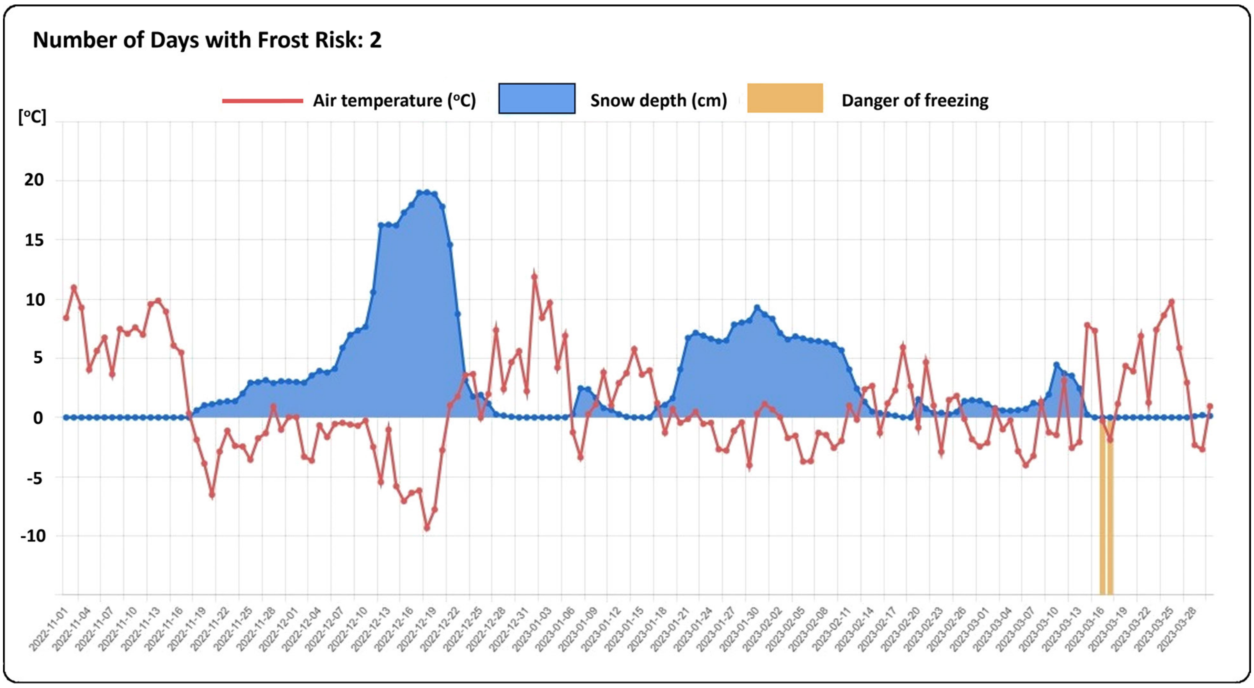

Fig. 8. Diagram showing the dangers of freezing in the grassland plot available in application.

application displays the current water level in the field – from the last Sentinel-2 flight.

The GRASSAT application provides the opportunity to monitor meteorological conditions in the grassland plots in the context of frost. Based on ERA5-Land reanalysis, it is possible to indicate the days when the temperature was below zero without snow cover. The user gets such information as a graph (Fig. 8.). The red colour represents the temperature (°C), the blue – the thickness of the snow cover, and the orange – the risk of frost. In addition, that information is displayed above the graph (number of days per month).

For each field, it is possible to upload information on field activity. As part of this functionality, the user can provide, for example, information about the date, amount, and type of fertilisation, cutting date information as well as information from soil sampling.

Conclusions

Constant changes in climatic conditions, increased stress from human activities, and inadequate management contribute to both a decline in grassland productivity and habitat quality. To properly manage grasslands and mitigate or avoid stress, accurate information on grass growth conditions is needed. The provision of this type of information is made possible through the use of applications containing geo-referenced data, including satellite imagery. Contemporary, satellite data allows monitoring of grasslands with both high temporal and spatial resolution. As opposed to traditional *in situ* surveys, remote sensing technology has an overall advantage in terms of convenience, efficiency, and cost-effectiveness, especially over large areas (Wang et al. 2022).

The application of satellite data for grassland monitoring in Poland has not previously been a popular topic on the world stage. It is noticeable that in the literature review on this issue (Reinermann et al. 2020), no article related to the Polish area was selected. During this review, 253 articles were analysed, which focussed on investigated grassland production (70%), dealing solely with management and use intensities (18%), and had more than one of these topics (12%). The most popular journals were the International Journal of Remote Sensing (35 studies), Remote Sensing (30 studies), Remote Sensing of Environment (21 studies), and Ecological Indicators (16). For that reason, addressing the topic of the use of application maps in grassland management in Poland appears to be a very important issue.

There are more than a dozen of PA applications on the market for farmers. Most of them are cloud-based tools that facilitate the tracking and handling of data, including georeferenced data. They help users obtain data on crop conditions from planting to harvest. The soil conditions and terrain are also monitored for each specific location in the field. For the most part, these applications are not dedicated to grasslands, which is what sets the GRASSAT application discussed in this article apart.

The GRASSAT system, in the form of desktop and mobile applications, provides a complementary tool for grassland production management, mainly for medium and large farms. Combining the efficiency of the application with the support of external advisors is key to improving grassland production management.

Compared to other applications (Table 1), the novelty of the methodology used in the GRASSAT application is the use of the LAI in biomass modelling, which allows a more accurate determination of grassland biomass than using the NDVI.

According to Wang et al. (2022), during the review of the literature on grassland monitoring, many research works have focussed on radiative transfer models using both ground-based and satellite imagery. Some examples include the adoption of the PROSAIL model and estimation of LAI on grazed grassland (Punalekar et al. 2018) or development a soil-canopy observation model of photosynthesis and energy fluxes (SCOPE), which is a combination of a radiative transfer model and soil-plant-atmosphere transfer models, and introduced several constraints into the model for different parameter estimates using ground photos (Pacheco-Labrador et al. 2019). In comparing the biomass model and the application developed in the GRASSAT project, it should be noted that the model is adapted to the cut. In Poland, there are mostly three cuts (between June and September). For other LAI-based biomass models, there are often no such divisions.

The GRASSAT application, developed as part of the project *Tools for information to farmers on grassland yields under stressed conditions to support management practices*, can be used by both individual users (individual growers) and groups of growers, scientific institutes (i.e., IUNG – Institute of Soil Science and Plant Cultivation), or state agricultural development and support institutions (i.e., KOWR – National Agricultural Support Centre or Agricultural Advisory Centres).

Author's contribution

Conceptualisation – A.M., K.D.-Z.; data curation – K.W., A.M., M.W-.J.; formal analysis – K.W., M.W-J., A.M; funding acquisition – K.D.-Z., P.G., M.W-J.; investigation – M.W-J., K.W., D.Z.; methodology – K.D.-Z., P.G., project administration – K.D.-Z., P.G.; resources – M.W.-J., K.W., A.M; software – M.W.-J.; supervision – K.D.-Z., P.G.; validation – K.W., M.W.-J., A.M.., D.Z.; visualisation – K.W., A.M., M.W.-J.; roles/writing – original draft – A.M., M.W.-J., K.W.; writing - review & editing – K.D.-Z., A.M., P.G, D.Z.

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