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Assessing the Cost-Effectiveness of Using Remotely Sensed Data in Agriculture for Sustainable Land Management

Marzhan A. Sadenova*, Nail A. Beisekenov, Zhakhangir B. Anuarbek, Turezhan B. Anuarbekov, Erbolat T. Ualiyev, Natalya A. Kulenova

Priority Department Centre «Veritas» D. Serikbayev East Kazakhstan technical university, 19 Serikbayev str. 070000, Ust-Kamenogorsk, Kazakhstan
MSadenova@ektu.kz

Satellite imagery has revolutionised sustainable land management and crop yield forecasting. This article presents the results of the effective use of precision farming practices based on Remote Sensing (RS) data on the example of sunflower crops in 2 soil and climatic zones of Kazakhstan. Calculation of the correlation coefficient of the sunflower crop remote sensing data for further optimisation and increase of the resolution of the information of the space images was done. Through testing the classification of macronutrients in the soil (nitrogen, phosphorus, potassium, humus) using remote sensing data, this study examined two distinct soil and climate zones in Kazakhstan. The findings revealed that the integration of macroelement results in the soil, vegetation index of plant growth and development (NDVI) from the Sentinel-2 L2A satellite, Geographic Information Systems (GIS) data, and mathematical modeling leads to a 25 % reduction in fertilizer consumption. Additionally, it enhances the precision of yield forecasts by 92 %. The novelty of this study lies in the effective use of remote sensing data and precision farming techniques to optimize fertilizer consumption and sunflower yield forecasting, which can contribute to sustainable land management and increase farmers' profits.

1. Introduction

Agricultural production is one of the most important activities in Kazakhstan. The use of Earth Remote Sensing (ERS) technology allows the monitoring of crop conditions. Crop monitoring in crop production using remote sensing has become an important research and application in modern agriculture. In recent years, with the development of remote sensing technology, high-resolution images of fields have constantly been emerging. They open up many new possibilities for modernising agriculture. One of the most important tasks of agricultural land monitoring is to assess the condition of fields and crops on them, to track the dynamics of various indicators, etc. Monitoring is part of Precision Farming (TP) technology. A farmer needs good statistics to understand the situation in his fields. Maps of the state of a particular farm's fields, based on visual and multispectral images, provide information for decision-making and management of the farm as a whole. The ability of remote sensing to monitor Earth systems at different spatial and temporal scales makes it suitable for global environmental, ecological, and socio-economic issues. Remote Sensing (RS) can provide a synoptic overview of spatial information at local, regional, and global scales, which facilitates rapid decision-making and action (Lanya et al., 2019). As information can be obtained directly from remote sensing, it is the main imaging technology used for data collection in hard-to-reach and remote locations. Several benchmark studies on the role of remote sensing in sustainable development have been conducted, covering various sub-themes in the areas of environmental assessment, natural hazards, and socio-economic development.
The work of Sadenova et al. (2022a) proposed approximation of dynamic curves corresponding to the values of seven-day composite NDVI (Normalized Difference Vegetation Index) indices using Gaussian function and Levenberg-Marquardt algorithm, the value of average absolute forecast error depending on the forecast week was from 0.67 to 10.7 %/y in the period estimated, which is an acceptable accuracy for seasonal forecasts.Thus, it was found that image extraction from satellite data by processing according to special algorithms in selected spectral ranges allows studying plant productivity, biomass, photosynthesis intensity, and other parameters.

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Joiner et al. (2018) developed a global vegetation index that can be used to monitor dynamic plant growth behaviour. Ye and Kuang (2022), among others, evaluated the effect of zoning on vegetation indices and temperature in urban ecosystems using RS, while Sun et al. (2022) mapped water resources in flatland and hilly and mountainous areas using RS as the main data source. Assessing the cost-effectiveness of using remote sensing data in agriculture has been a subject of research interest for many years.

Past studies have demonstrated the potential of RS data in agriculture, such as the ability to predict crop yields and identify macronutrients in soils. However, there are still research gaps, especially in terms of determining the most cost-effective methods of collecting and processing remotely sensed data.

In the last three decades, RS has been increasingly used to assess sustainable development efforts. Advances in remote sensing technology and the availability of large amounts of data have led to significant improvements in data analysis, especially when combined with Geographic Information System (GIS) and Machine Learning (ML) algorithms. ML techniques such as Convolutional Neural Network (CNN), Random Forest (RF) and Support Vector Machines (SVM) have been used for analysing ERS data for environmental assessment and socio-economic development monitoring since the early 1990s (Sadenova et al., 2022b). These algorithms will likely play a crucial role in maximising the benefits of geospatial data. Due to the scarcity of imagery with an accurate spatial and temporal resolution, these methods have not always been effective and accurate when used to monitor sustainable development efforts. Ongoing research is aimed at developing new algorithms and models for remote sensing data processing and analysis. This research is aimed at improving the accuracy and speed of data processing and at developing new applications of remote sensing data in agriculture.

Today, remote sensing can be seen as a scientific tool that has been applied in almost all areas of earth and environmental science. Given the importance of sustainable development in the 21st century, the purpose of this study is to assess the advantages and limitations of using remote sensing data in agriculture and to identify ways to optimise the use of this technology for sustainable land management. Firstly, it was decided to determine the correlation of UAV data with oilseed-based remote sensing data to optimise further and increase the resolution of the space imagery information. Second, to develop and evaluate the forecasting of yield based on remote sensing data. Thirdly, to develop and test solutions for classifying soil macroelements content (nitrogen, phosphorus, potassium, humus) using RS data.

2. Materials and methods

The experimental polygons are located in the east of Kazakhstan and cover two areas; the area of the two polygons is 267 ha. According to soil taxonomy, the dominant soil unit for polygon N1 (82.3432 °E and 50.0404 °N) is the chernozem soil type, and for polygon N2 (77.1423 °E and 51.5830 °N), the chestnut soil type. Every year, about 400 mm of precipitation falls in the east of Kazakhstan. The wettest months are from May to September. The region is characterised by a sharply continental climate. Temperatures rise to 45 °C in summer and drop to - 40 °C in winter. The geographical location of the two polygons is shown in Figure 1.

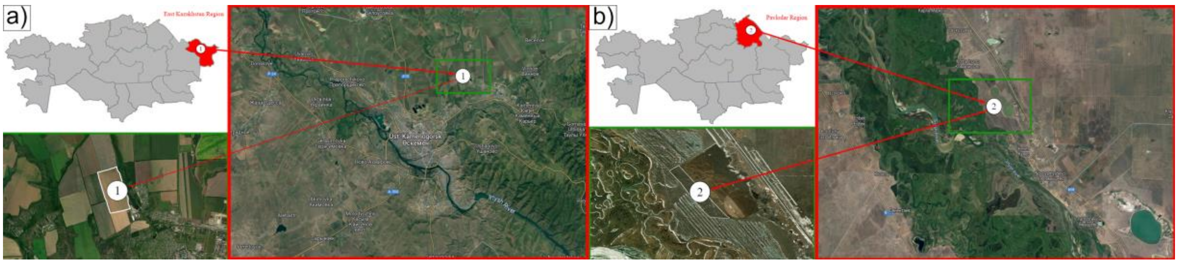

Figure 1: Geographical location of study polygons N1 (a) and N2 (b)

Remote sensing data for the experimental polygons were obtained using the EO Browser platform, Sentinel-2 L2A spacecraft. The NDVI was calculated using the web-based index calculation tool provided by EO Browser (Sadenova et al., 2022c). NDVI is obtained by calculating the normalized difference between near-infrared and red light reflected from vegetation using the equation (NIR - Red) / (NIR + Red), where higher values indicate denser and healthier vegetation. Sentinel-2 L2A images were used due to the high resolution of 10 m and frequent updates every 3-5 days. In this study, satellite images of the experimental polygons for the growing season from May to September 2022 were used. Based on the ERS data obtained, satellite imagery for August 2022 was processed using the method presented by the authors (Stow et al., 2019). The experimental aerial work was performed using senseFly eBee X UAV (manufactured by senseFly, Switzerland) for similar dates. The licensed software Pix4DFields 2.3.1 (license number: b5fade56) was used to process the acquired images.

Sadenova et al. (2022d) methodology was used to classify macronutrients in soil based on RS data. Sixteen-day composite images with 250 m resolution from Sentinel-2 satellite were used as remote sensing data. Agrochemical indicators on the experimental plot were assessed using spectral indices: NDVI - vegetative plant development; NDWI - normalized difference water index; SWIR - short-wave infrared range; MSAVI - modified soil vegetation index; RECI - chlorophyll index; and the altitude map. The main idea of the methodology is an original approach to analyse agrochemical elements from remotely sensed land data using Sentinel-2 multispectral imagery using the CNN Eq.(1).

$$f(p, min, max) = \frac{p - min}{max - min} \tag{1}$$

where f is the normalisation function; p is the value of the spectral index (space image); min – minimum pixel value of 0; max - maximum pixel value of 255. The input layer takes into account the two-dimensional image topology and consists of several maps (matrices), consisting of 3 maps, where each map corresponds to an image with a specific channel (red, blue, and green). The input data for each specific pixel value is normalised to a range of 0 to 1. The determination of crop yield was based on the analysis of the dynamics of spectral parameters of growth and development determined by multispectral satellite images. The space radiometer (ASTER) V3 was used to construct the height maps of the experimental polygons, and the maps were constructed in the SAGA GIS software.

3. Results and discussion

Agrochemical soil parameters are an important characteristic of differentiated fertilisation. If one fertiliser rate is used in a field, some areas may have an excess of nutrients and others a deficit. Differentiated fertilisation takes into account the heterogeneity of the soil and selects the exact fertilisation rates for all areas of the field. According to the results of agrochemical analysis on the selected soils, all four elements: exchangeable potassium, mobile phosphorus, humus, and total nitrogen, showed an excessive content of substances in the soil relative to the norm. Cartograms based on the actual agrochemical data obtained from soil sampling are shown in Figure 2I.a - I.d. Figure 2II.a - II.d shows maps based on ERS data calculated and presented based on Sentinel-2 L2A satellite image processing. The colour gradation from light blue to dark green in the analysed maps reflects the quantitative content of one or another agrochemical indicator.

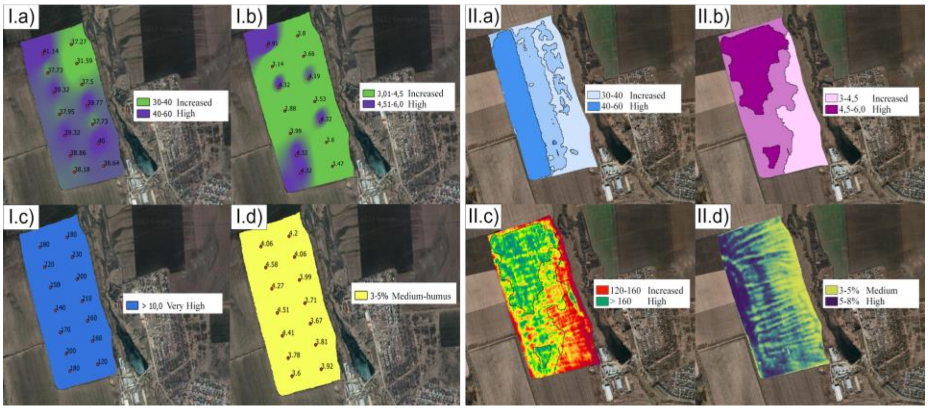

Figure 2: Cartograms based on the results of: agrochemical analysis (I.a - I.d), RS data (II.a - II.d), experimental site N1: a) K20 (mg / 100 g soil); b) P2O5 (mg / 100 g soil); c) total nitrogen content; d) soil humus composition %

It was found that by processing satellite images of the fields in selected spectral areas, it is possible to estimate plant productivity, biomass value, photosynthesis intensity, and other parameters with a high degree of reliability. The mean total error (calculated as mean absolute error) between remote sensing data and the actual analysis of soil samples for phosphorus, potassium, and nitrogen content was processed mathematically using a statistical data set. This analysis was carried out for a certain period and the results showed that the mean absolute error ranged from 24 % to 36 %. Using RS and CNN data, the spring wheat yield forecast has been calculated in the soil and climatic zone of East Kazakhstan. The results obtained by the predictive model are close to the actual yield results of the previous year (error less than 9 %), indicating the relationship between yield and agrochemical analysis of soil.

Soil curvature, or topography, can have a significant impact on crop yields. Changes in soil depth, texture, moisture, and nutrient availability in different parts of the field due to topography can affect crop growth and development. For example, in areas with steep slopes, the soil may be shallower and contain less water and nutrients, resulting in lower crop yields. On the other hand, waterlogging and soil erosion can occur in low-lying areas, which can also lead to lower yields. Fertilisers should be applied according to the topography to ensure optimum crop growth and yields. Applying fertiliser evenly across the field can lead to over-fertilisation in some areas and under-fertilisation in others. This can lead to nutrient imbalances, reduced crop quality and yields, as well as an increased risk of nutrient runoff into water bodies. By considering the topography of the field, fertilisers can be applied in such a way that crops receive the necessary nutrients for optimum growth while reducing the risk of nutrient loss and environmental damage. For this reason, it was decided to construct an altitude map based on data from the spaceborne radiometer (ASTER) V3, in the SAGA GIS software of the study site N1, shown in Figure 3.

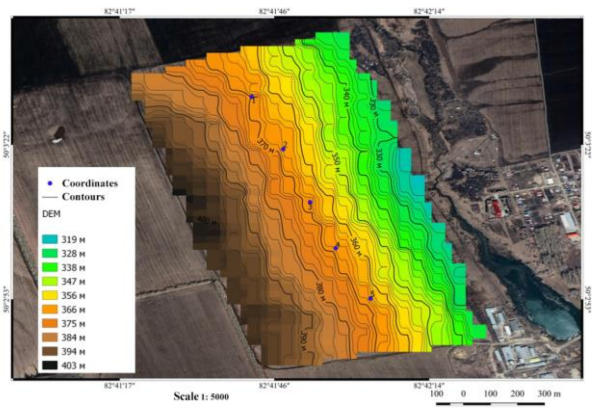

Figure 3: Steep slopes map of polygon N1 (spaceborne radiometer image ASTER V3)

Figure 3 illustrates the topography of the polygon, which had a curvature of more than 60 m. Based on this information, the fertiliser rate was adjusted to the topography of the field to ensure an even and optimal distribution of nutrients. In particular, fertiliser was applied to the top of the field in accordance with the standard rates, while the bottom of the field received 25 % less fertiliser based on our recommendations. This adjustment was designed to compensate for the negative effects of soil flushing due to rainfall. Similar procedures were applied to polygon N2.

Figures 4a, 4b show NDVI values calculated based on Sentinel-2 L2A satellite imagery processing from EO Browser open-access platform. The effectiveness of the developed approach for moderate resolution image refinement from UAV images was carried out on the example of sunflower. It was found that for the first polygon N1 for 25.08.2022, the mean value of NDVI index for satellite images was 0.64-0.73 (Figure 4a), the mean value of NDVI index for the second polygon N2 for 23.08.2022, was 0.27 - 0.48 (Figure 4b).

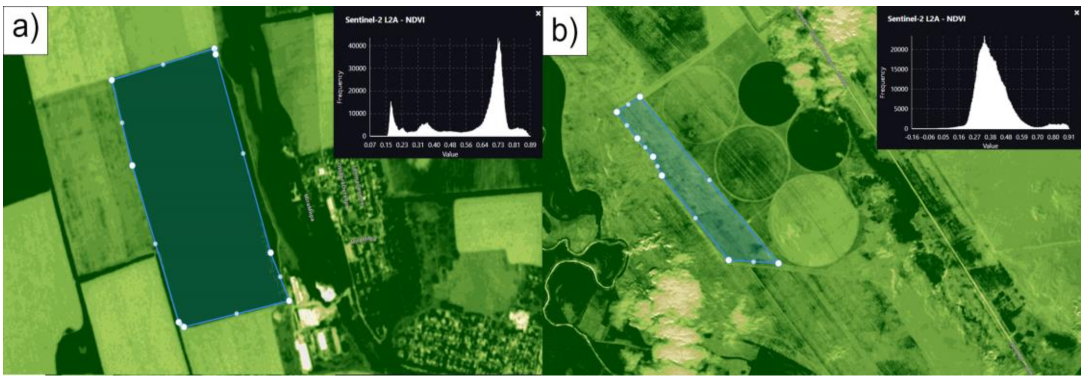

Figure 4: NDVI index calculation map for polygon N1 (a: 25.08.2022), N2 (b: 23.08.2022) from Sentinel data

Figure 5 shows the results of aerial survey data processing performed by senseFly eBee X UAV on the same dates as the satellite imagery. According to the results of UAV data processing average NDVI index value for the first polygon was: 0.67 (Figure 5a); for the second polygon was: 0.37 (Figure 5b). according to the dates of satellite images.

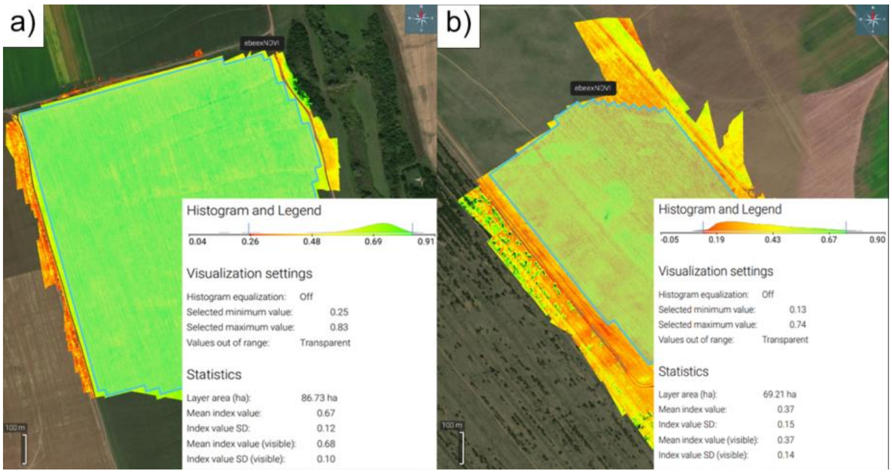

Figure 5: NDVI index calculation map of polygon N1 (a: 25.08.2022), N2 (b: 23.08.2022) from UAV images

The analysis of UAV data and satellite images resulted in calculation of r-Pearson correlation coefficient, which was 0.9424, which is a high modulus. The effectiveness of the proposed approach for moderate resolution image refinement from UAV images was implemented in the TensorFlow environment and trained on satellite data and UAV data obtained in 2022. This methodology was used to develop and test the yield forecasting module by increasing the accuracy of the vegetation indices, which managed to improve the forecasting accuracy to 92 %. The coefficient of determination (R^2) was used to assess the validity and analyse the accuracy of the developed model in this study. The coefficient algorithm (R^2) reflects the degree of linear relationship between observed and predicted sunflower yields Eq.(2).

$$R^2 = \frac{(\sum_{i=1}^{n}(O_i - \bar{O})\,(F_i - \bar{F}))^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(F_i - \bar{F})^2} \tag{2}$$

The application of the developed method to the sunflower grain crop resulted in an average absolute error of 0.32 to 6.4 %/y in the simulated period. The developed yield determination algorithm showed a reasonably good accuracy of up to 92 %. The result was evaluated using matrix estimation based on the algorithm of the determination coefficient method R^2.

It should be noted that the high value of the NDVI index in the N1 polygon during the indicated vegetation period indicates a good level of plant growth and development and proper organisation of agronomic measures. Low values of the NDVI index on the second polygon N2 at this stage indicate the need for a prompt intervention to help the plant by feeding, organising irrigation and/or other agronomic measures. By implementing the recommended corrective agronomic practices in polygon N2, negative developments were avoided. The visualised actual sunflower yield of the two N1 and N2 polygons is shown in Figure 6.

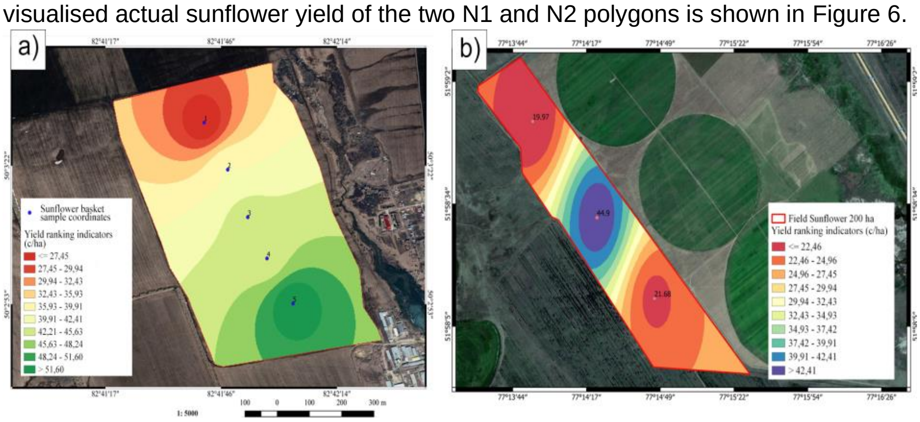

Figure 6: Visualisation map of sunflower actual yield distribution: a) Polygon N1; b) Polygon N2

4. Conclusions

The TensorFlow-based satellite image refinement and resolution enhancement system used by the authors, using information from high resolution multispectral UAV images and multispectral satellite images, demonstrated its validity. The calculated correlation coefficient, r-Pearson, was 0.9424, which is a high modulus. The calculated correlation coefficient was used for the yield prediction module and contributed to a 92 % increase in yield prediction accuracy. As a result of the study, the developed sunflower yield prediction technique showed a mean absolute error of 0.32 to 6.4 %/y in the simulated period using a machine learning algorithm calculation: the coefficient of determination R^2. Refined NDVI satellite maps obtained at different periods during the growing season of sunflower, as shown by correlation analysis, describe crop conditions better compared to the raw data. It is shown that spatial data from remote sensing and other sources can be integrated using GIS along with other spatial integration tools not only for crop monitoring but can also be used for the analysis of global ecological processes and changes. It has been found that the economic effect of the implementation of the results obtained is a 25 % reduction in fertiliser consumption. In addition, the obtained results provide timely information on the quality condition of agricultural land, which serves as the basis for its rational and efficient use.

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