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Article

Prediction of soil moisture content using unmanned aerial vehicle technology

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Abstract
The application of remote sensing technology is commonly used to predict the soil moisture content of cropland and has become an effective method for smart agriculture. Therefore, this study aims to (i) quantify seasonal variations in soil moisture content at different soil depths during wheat growth stages, (ii) examine the relationships between soil moisture, wheat yield, and UAV-derived vegetation indices, and (iii) evaluate the effectiveness of UAV multispectral data for predicting soil moisture content under semi-arid conditions. We hypothesize that vegetation indices derived from UAV multispectral imagery are significantly correlated with soil moisture content at different soil depths and can be used as indirect predictors of soil moisture. Soil moisture was measured using the gravimetric method, with samples taken at 0-20 cm and 20-40 cm depths from 60 plots in the field at all wheat growth stages. The soil reaction range of the study area varies from 7.3 to 8.0, the soil volume was 1.14 to 1.35 g/cm^3, soil organic carbon was 0.82-2.18%, and total soil nitrogen was 0.9-0.23%. From the results, the air temperature was low; it rained in July of the year between the stem elongation heading stages of wheat. According to the soil sampling, the soil moisture content of the third ten days of July (the early heading stage of wheat) had the highest values (11.7-30.1%), while the soil moisture content had the lowest values (13.53-21.21%) in the sensitive period of wheat from seedling growth to the heading stage. When correlation analysis is performed between soil moisture and wheat yield, the soil moisture in the depth of 0-20 cm has a weakly negative correlation (r = -0.13 (-0.38)), and the soil moisture in the depth of 20-40 cm has a weak to moderate correlation (r = -0.13 (-0.43)). The regression analysis of soil moisture content and vegetation indices calculated by spectral data shows a positive correlation (with an R^2 value of 0.44 at 0-20 cm, $p<0.0001$; an R^2 value of 0.2 at 20-40 cm, $p<0.01$). Using the UAV, the determination coefficient is R^2 = 0.32 at 20-40 cm depth and R^2 = 0.29, $p<0.01$.

Keywords: drone, wheat, yield, vegetation index, growth stage

Introduction

Soil moisture is a key limiting factor for crop production in Mongolia's central agricultural region due to its arid continental climate and uneven precipitation distribution. Soil moisture accumulation is mainly influenced by summer rainfall, particularly in July, and reduced evaporation during August and September, with maximum levels typically observed by the end of September [1]. In Mongolia, insufficient soil moisture in spring often delays seed germination rather than limiting crop development through inadequate heat supply. Small summer precipitation events (0.1-3.0 mm) may not significantly increase soil moisture, but can still influence plant growth [2].

Previous studies have shown that spring residual soil moisture, soil properties, and early-season precipitation can be used to predict crop yields [3]. Soil moisture has been consistently identified as a critical factor affecting grain yield across all agricultural regions of Mongolia [4], although spring moisture levels are frequently inadequate to meet early crop water demands [5].
Earlier research also identified two growth stages during which soil moisture has the greatest influence on grain yield: the germination stage and the tillering stage. Precipitation from late summer to early autumn of the previous year is crucial for successful germination, while rainfall in June plays a decisive role during tillering and stem elongation [4]. These findings highlight the complex interactions between soil moisture dynamics, precipitation timing, and crop development.
Soil moisture content (SMC) is not only essential for crop growth but also plays a critical role in surface water regulation and drought assessment in agricultural systems [6], [7]. Despite extensive research, uncertainties remain regarding the direction and strength of the relationship between soil moisture and wheat yield under varying climatic conditions. Therefore, this study aims to analyze soil moisture dynamics and their relationship with wheat yield in Mongolia’ s central agricultural region, with a particular focus on critical growth stages and implications for soil moisture estimation using remote sensing techniques.

Materials and Methods

Experiment sites

Bornuur soum in Tuv province is located in the central agricultural region. The area experiences low precipitation, relatively warm summers, and low air humidity. The long-term average annual precipitation ranges from 160-235 mm, with 85-95% occurring during the warm season. Approximately 80% of this precipitation falls during the growing season, amounting to 150-200 mm annually. The duration of temperatures above +10° C ranges from 100-120 days, with an accumulated active temperature sum of 2066° C. The study site’ s soil reaction ranges from 7.3 to 8.0, with a bulk density of 1.14-1.35 g/cm3, soil organic carbon content of 0.82-2.18%, and total nitrogen content of 0.9-0.23%.

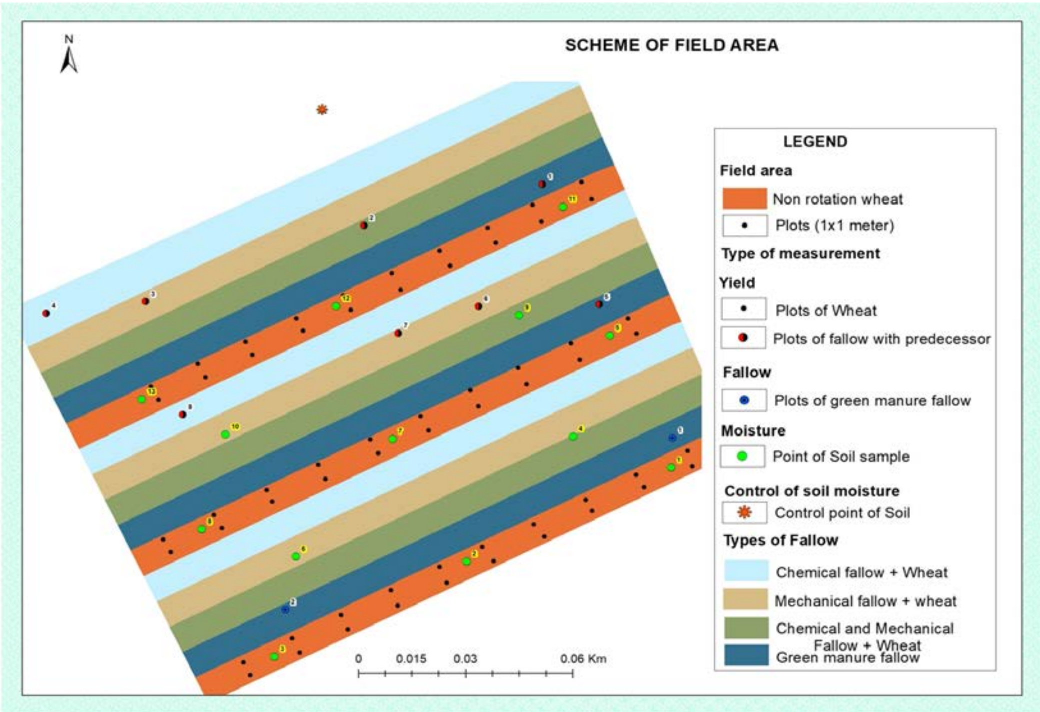

Figure 1. Survey measurement plots

Scheme of Experiment

The field experiment was conducted on three plots of continuous wheat cultivation. Each plot contained 20 measurement quadrats of 1 square meter, totalling 60 quadrats. The wheat variety 'Darkhan-160' was sown on May 20 at a seeding rate of 3.5 million seeds per hectare and harvested on September 20, with a total growing period of 103 days. Soil moisture was determined by the gravimetric method, drying samples at 105° C to measure technical weight. Crop yield was assessed at full maturity by collecting plant samples from each quadrat and converting the estimated yield to hectares. The DJI Phantom 4 RTK Multispectral drone was used for aerial surveys, supplemented by a DJI Mavic 2 Pro drone. These drones captured aerial images along predefined routes, which were validated with ground-truth measurements. The raw aerial data included RGB and Multispectral imagery, processed using Agisoft Metashape Pro (v.1.5.5) for orthophotos and DJI Terra software for spectral index calculations, including NDVI, GNDVI, LCI, OSAVI, and NDRE. The following vegetation indices were calculated from multispectral bands: NDVI = (NIR − Red) / (NIR + Red); GNDVI = (NIR − Green) / (NIR + Green); OSAVI = (1 + 0.16) × (NIR − Red) / (NIR + Red + 0.16); NDRE = (NIR − RedEdge) / (NIR + RedEdge); LCI = (NIR − RedEdge) / (NIR + Red) where NIR, Red, Green, and RedEdge represent reflectance values of corresponding spectral bands.

The study employed deep learning-based mathematical modelling to analyze soil moisture and crop yield, comparing results with traditional methods. Correlation analysis was applied to assess the strength and direction of relationships between soil moisture content, vegetation indices, and wheat yield. Regression analysis was further used to evaluate the predictive capability of UAV-derived vegetation indices, using the coefficient of determination (R^2) and significance levels ($p < 0.05$) as performance criteria.

Results

There are two main periods in which the supply of soil moisture affects the grain yield in our country's agricultural centre and steppe areas. Among them: First, when the seeds are planted in the soil, they germinate at the appropriate time, and second, the yield depends greatly on the condition of the grain plant during the most sensitive tillering stage, when it requires water and moisture. It is noted that the June rains play a major role in the stage from tillering to stem elongation [2].

During the 2023 growing season (May-July), air temperature and precipitation patterns deviated markedly from long-term climatic averages in the central agricultural region. Mean daily air temperatures during May and June were 1.6-3.6 ° C lower than the long-term mean, while total precipitation during these months was 10.3-22.3 mm lower than average. In contrast, July experienced exceptionally high precipitation, exceeding the long-term mean by 119 mm, accompanied by relatively cool temperatures during the booting to heading stages of wheat development (Figure 2).

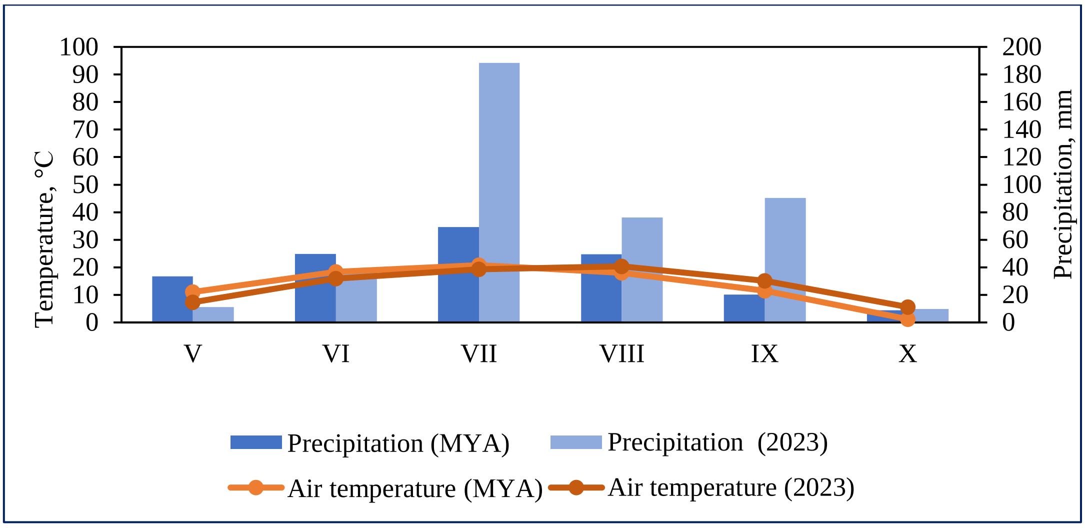

Figure 2. Climate diagram for the 2023 crop growing season

Subsequently, during August‑October, air temperatures were 2.4‑5.4 °C higher than the long-term average, and precipitation exceeded normal values by 0.9‑70.1 mm. These conditions resulted in a warm and humid environment during the grain-filling stage, which is critical for yield formation. Such pronounced intra-seasonal climatic variability strongly influenced soil moisture dynamics and wheat growth processes.

Soil moisture content exhibited clear temporal variability throughout the wheat growing season and differed substantially between cropland and adjacent pasture land. Across all measurement periods, soil moisture in wheat fields was consistently 4‑8% higher than that observed in pasture land, and in several cases nearly twice as high. This difference can be attributed to variations in soil physical properties, tillage practices, crop water uptake patterns, and moisture accumulation processes associated with cultivated soils. In contrast, pasture vegetation showed greater drought tolerance, lower above-ground biomass, and reduced transpiration rates, contributing to lower soil moisture levels.

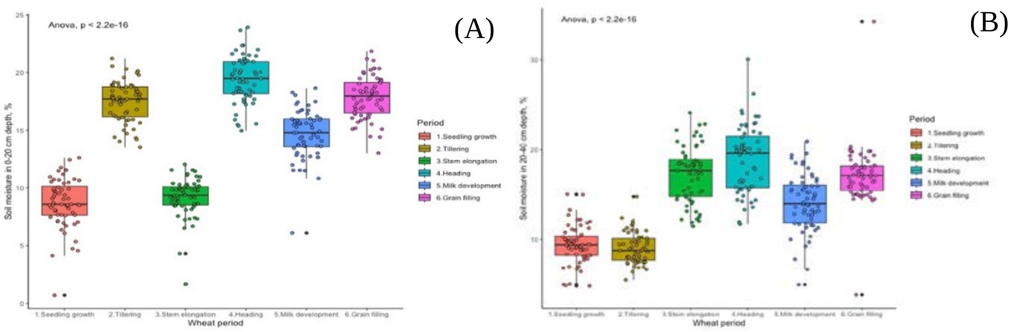

Figure 3. Soil moisture measured at the study site during the wheat growth and development stages, (A) 0-20 cm depth; (B) 20-40 cm depth, %

Measurements indicated that soil moisture content reached its maximum during the late July period, corresponding to the heading stage of wheat, with values ranging from 11.7% to 30.1% (Figure 3). Conversely, the lowest soil moisture values (13.53‑21.21%) were recorded during the tillering to stem elongation stages, which represent the most moisture-sensitive phases of wheat development.

Analysis of long-term precipitation distribution during the wheat growing period revealed that only 7‑8% of total precipitation occurs from sowing to emergence, 20‑24% from emergence to stem elongation, and 22‑26% from stem elongation to heading. A substantial proportion (38‑44%) falls during the flowering to grain-filling stages. This uneven distribution explains the frequent occurrence of moisture deficits during early vegetative stages and excessive moisture during reproductive stages.

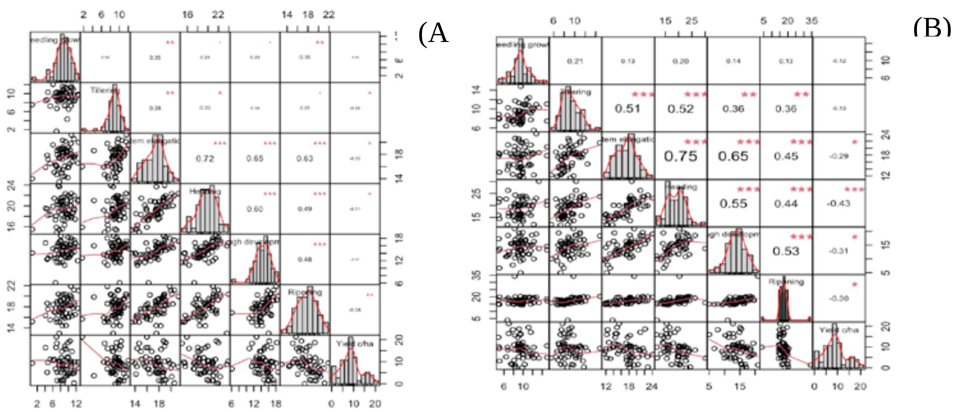

Figure 4. Effect of soil moisture on wheat yield during different growth stages (A) 0-20 cm depth; (B) 20-40 cm depth

Correlation analysis revealed a predominantly negative relationship between soil moisture content and wheat yield, particularly during the heading stage (Figure 4). Soil moisture at a depth of 0‑20 cm showed a weak negative correlation with yield ($r = -0.13$ to -0.38), while moisture at 20‑40 cm depth exhibited a weak to moderate negative correlation ($r = -0.13$ to -0.43). Notably, soil moisture measured during the heading stage demonstrated the strongest negative association with yield ($r = -0.31$ to -0.43).

These results indicate that excessive soil moisture during reproductive stages can adversely affect yield formation. High moisture levels during heading are likely to reduce soil aeration, impair root respiration, and increase the incidence of fungal and bacterial diseases, thereby limiting effective grain filling. In contrast, wheat yield showed the strongest positive dependence on soil moisture at a depth of approximately 50 cm during the second ten-day period of June, highlighting the importance of adequate subsoil moisture during the tillering and stem elongation stages.

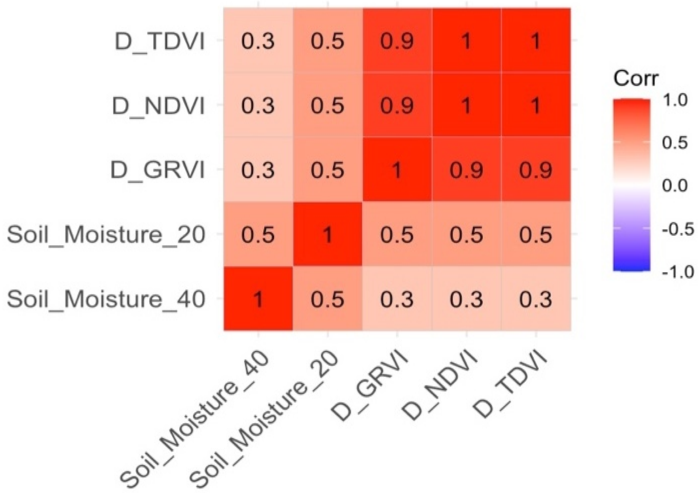

Figure 5. Correlation of soil moisture content and vegetation indices

Regression analysis demonstrated statistically significant positive relationships between soil moisture content and UAV-derived vegetation indices (Figure 5). At the 0‑20 cm soil depth, vegetation indices explained up to 44% of the variation in soil moisture ($R^2 = 0.44$, $p < 0.0001$). At the 20‑40 cm depth, the explanatory power was lower but still significant ($R^2 = 0.20$, $p < 0.01$).

UAV-based predictive models yielded coefficients of determination ranging from $R^2 = 0.29$ to 0.32 ($p < 0.01$), indicating moderate predictive capability under field conditions. Although these relationships were influenced by spatial heterogeneity, soil properties, and crop management practices, the results confirm that multispectral UAV data can serve as effective indirect indicators of soil moisture dynamics at different soil depths.

Discussion

The results of this study indicate a negative correlation between soil moisture content and wheat yield, particularly during the heading stage. Although soil moisture is generally considered beneficial for crop growth, excessive or poorly timed moisture can negatively affect wheat development under the climatic conditions of Mongolia's central agricultural region. High soil moisture during the heading stage may reduce soil aeration, limit root respiration, and increase disease pressure, ultimately constraining grain filling and yield formation despite adequate water availability [4], [8].

In addition, periods of high soil moisture are often associated with increased cloud cover and lower solar radiation, which can reduce photosynthetic efficiency during critical reproductive stages. These conditions may explain why higher soil moisture does not necessarily translate into higher yields in this region. Similar results have been reported in semi-arid agroecosystems, where excessive moisture during sensitive growth stages negatively affected wheat productivity.

Previous studies conducted in Mongolia have shown that satellite-derived soil moisture products, particularly those combining SMAP and MODIS data, exhibit statistically significant relationships with in situ soil moisture measurements and interannual crop yield variability, supporting the reliability of remote sensing-based soil moisture monitoring under continental semi-arid climatic conditions [9].

The findings are consistent with recent international studies using UAV-based and hyperspectral remote sensing approaches for soil moisture estimation in semi-arid agricultural landscapes. These studies have reported moderate relationships between vegetation indices and soil moisture due to spatial heterogeneity, crop management practices, and climatic variability. In this study, the optimal soil moisture content estimation model demonstrated strong performance, with coefficients of determination (R^2) of 0.912 and 0.792 for the modelling and validation datasets, respectively. Corresponding RMSE values were 0.005 and 0.004, while mean relative errors (MRE) were 2.390% and 2.380% [10].

Furthermore, land suitability and agricultural assessment studies in Mongolia have emphasized that soil moisture, together with climate and soil characteristics, represents a key limiting factor for sustainable crop production, underscoring the importance of integrated moisture management in regions exposed to high climatic variability and land degradation risks[11].

These results demonstrate the potential of hyperspectral remote sensing techniques for estimating soil moisture content at different crop growth stages and for improving the understanding of soil moisture-yield relationships. Furthermore, the findings highlight the importance of considering both the timing and distribution of soil moisture when evaluating its effects on crop yield. Future research should focus on integrating soil, climate, and management factors to improve soil moisture estimation models and to support adaptive moisture management strategies under changing climatic conditions [11].

Conclusions

This study investigated seasonal soil moisture dynamics, their relationship with wheat yield, and the potential of UAV-derived multispectral data for soil moisture estimation in the semi-arid conditions of Mongolia's central agricultural region. The results demonstrate that soil moisture availability and its temporal distribution play a decisive role in wheat growth and yield formation.

Soil moisture content was lowest (13.53-21.21%) during the critical tillering to stem elongation stages, indicating a moisture deficit that can constrain vegetative growth and yield potential. In contrast, soil moisture reached its maximum during the heading stage due to excessive July precipitation. Correlation analysis revealed a weak to moderate negative relationship between soil moisture and wheat yield ($r = -0.13$ to -0.43), particularly during the heading stage, suggesting that excessive moisture during reproductive growth can adversely affect yield formation. This negative effect is likely associated with reduced soil aeration, impaired root respiration, and increased disease incidence under humid conditions.

Regression analysis showed statistically significant positive relationships between soil moisture content and UAV-derived vegetation indices. Vegetation indices explained up to 44% of soil moisture variability at the 0-20 cm depth ($R^2 = 0.44$, $p < 0.0001$) and 20% at the 20-40 cm depth ($R^2 = 0.20$, $p < 0.01$). UAV-based predictive models achieved moderate accuracy, with coefficients of determination ranging from $R^2 = 0.29$ to 0.32 ($p < 0.01$), confirming the feasibility of using UAV multispectral imagery as an indirect tool for soil moisture estimation.

Overall, the findings highlight that not only the amount but also the timing of soil moisture is critical for wheat productivity in semi-arid environments. UAV-based multispectral remote sensing provides a practical and efficient approach for monitoring soil moisture dynamics and supporting precision water management. These results contribute to improved understanding of soil moisture-yield relationships and offer valuable guidance for adaptive agricultural management under increasing climatic variability in Mongolia.

Conflict of Interests:

The authors declare no conflict of interests.

Author's contribution

Sh.T., E.Z., M.I., B.B., Kh.M., E.J., and A.D. conceived and planned the experiments. Sh.T., A.D., and E.Z. carried out the experiments. B.B. and E.Z. contributed to the interpretation of the results. A.D. and Sh.T.took the lead in writing the manuscript. All authors contributed to the final manuscript and approved the submitted version.

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