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Integrating UAV Multispectral Indices (NDVI) with Yield Data for Optimizing Flax (*Linum usitatissimum* L.) Cultivation

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RESEARCH ARTICLE

Abstract

Flax (*Linum usitatissimum* L.), is a multipurpose crop, grown for fiber, seeds, and oil. This study aims to assess flax growth dynamics and agronomic traits using Normalized Difference Vegetation Index (NDVI) maps generated from multispectral imagery captured by an Unmanned Aerial Vehicle (UAV). Conducted at the Agricultural University of Athens, the field experiment followed a split-plot design with four replicates, encompassing various sowing distances (30 and 40 cm, between rows) and fertilization treatments (urea fertilization, urea with inhibitors, organic fertilizer). NDVI index maps were produced at key growth stages (60, 90, 120, 150, and 179 Days After Sowing) to facilitate comprehensive growth analysis. The findings indicate that while fertilization treatments and sowing densities influenced early growth stages, no significant differences were observed post 90 DAS. NDVI values correlated with agronomic traits, particularly during the early vegetative phase, highlighting the potential of UAV-based NDVI mapping for precise flax cultivation monitoring.

Keywords: Flax (*Linum usitatissimum* L.); NDVI; UAV

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INTRODUCTION

Flax (*Linum usitatissimum* L.), originating from the Mediterranean region and southwestern Asia, is cultivated worldwide encompassing regions such as the Middle East, India, Canada, and numerous European countries (Bilalis et al., 2018). Acknowledged for its multiple purposes, flax mainly produces both fiber and oil. Because of the fiber's quality traits, flax is used in the clothing and textile industries (Vaisey-Genser & Morris, 2003). Flaxseed oil, characterized by its richness in linoleic acid, along with ω-3 and ω-6 fatty acids, is deemed fit for human consumption (Farag et al., 2021; Stavropoulos et al., 2023). Globally, the major producers of flax include Canada, India, Russia, Kazakhstan, and China (FAO, 2023). In Greece, flax is traditionally cultivated as a winter crop. The field of agriculture has seen a substantial increase in the use of remote sensing technologies, particularly for predicting yields and customizing crop management practices (Fountas et al., 2020). This technology, which relies on the reflection of light from plants, facilitates decision-making regarding fertilization, irrigation, and pest management. Remote sensing primarily employs the visible and infrared parts of the electromagnetic spectrum, and is instrumental in generating forecast maps using indices such as the Normalized Difference Vegetation Index (NDVI). NDVI is a widely used index applied in agriculture, environmental science and land classification (Aryal et al., 2022) and it plays a crucial role in detecting changes related to plant size, photosynthetic capacity, chlorophyll content, canopy structure, yield, nutrient deficiencies, and water stress (Papadopoulos et al., 2023).

With the global shift towards precision agriculture practices, there is an increasing interest in understanding the growth dynamics and sustainable field management of flax—a crop cultivated in over 50 countries worldwide. It stands out not only for its economic viability but also for its potential in contributing to climate change mitigation and reducing the environmental impact of agriculture (Stavropoulos et al., 2023). While several studies have utilized remote sensing techniques for various crops, there is limited research focused on the utilization of NDVI maps sourced from UAV multispectral imaging for the assessment of flax performance, particularly in relation to different sowing distances and fertilization treatments. For instance, Kakabouki et al. (2023) delved into how arbuscular mycorrhizal fungi (AMF) inoculation impacts flax growth and yield under varying salinity levels, employing a handheld sensor for NDVI measurements. This method reveals a clear opportunity for our study to further the field, using UAV multispectral imaging for an in-depth analysis across diverse agronomic conditions.
Addressing this gap, the primary aim of this study is to explore the utility of NDVI maps in evaluating flax performance under varied agronomic conditions. By doing so, this research contributes novel insights and offers a unique perspective on sustainable and efficient flax cultivation practices, enhancing the existing body of knowledge in the field.

MATERIALS AND METHODS

A field experiment was conducted at the Agricultural University of Athens (39°59' N, 23°42' E) from November 2022 to May 2023. The soil of the experimental field was clay loam, with a composition of 29.4% clay, 35.1% silt, and 35.5% sand. The pH was 7.39 (1:1 H_2O), total nitrogen (N) was 0.143%, available phosphorus (Olsen P) was 13.6 mg kg^{-1} soil, available potassium (K) was 233 mg kg^{-1} soil, calcium carbonate ($CaCO_3$) was 15.34%, and soil organic matter (SOM) was estimated at 1.67%. In addition, the average temperature and precipitation throughout the experimental period are presented on Figure 1.

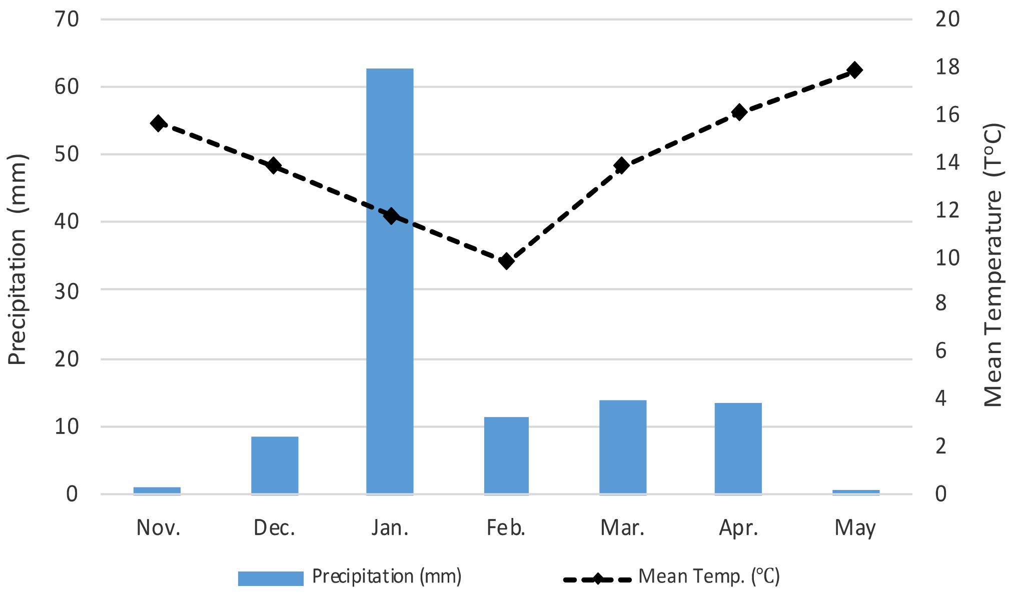


Figure 1. Weather data for experimental location during the experimental period (November 2022 – May 2023).

The experiment was set up on an area of 837 m^2 according to the split-plot design following the guidelines of Kowalski et al. (2002), with four replicates, two main plots (sowing distance 30 [D1] and 40 [D2] cm, between rows) and four sub-plots (urea fertilization [U], urea with nitrification and urease inhibitors [I], organic fertilizer [O] and control [C]). The total applied fertilizer dose for urea fertilizers with and without inhibitors was 100 kg N ha-1. The type of urea fertilizer was 46-0-0. The nitrification inhibitor was N-((3(5)-methyl-1H-pyrazol-1-yl) methyl) acetamide (MPA; 0.07%) and the urease inhibitor was N-(2-Nitrophenyl) phosphoric triamide (2-NPT; 0.035%) for the fertilizer with urea with double inhibitors (46-0-0). The fertilizers were broadcasted at a rate of 300 kg N ha^{-1} and incorporated to the soil prior to the sowing. Main plot size was 84 m^2 and sub–plot size was 21 m^2. Sowing distance within row was 3 cm. Sowing took place on 14th November 2022. Flax seeds (*Linum usitatissimum* L. cv. Everest) were sown by hand at a depth of 2–3 cm. During the experiment, weeds were removed by hand and hoeing, when it was necessary. Harvest took place on 12th May 2023. The experiment duration was 179 Days. An UAV, equipped with a multispectral camera, was employed to generate NDVI index maps, capturing key measurements at 60, 90, 120, 150, and 179 Days After Sowing (DAS) following the method previously described by Papadopoulos et al. (2023). The experimental data were subjected to statistical analysis according to the split-plot design. The statistical analysis was performed with SigmaPlot 12 statistical software (Systat Software Inc., San Jose, CA, USA). The differences between means were compared using Tukey's test. All comparisons were made at the 5% level of significance.

RESULTS AND DISCUSSIONS

Based on the results of the present study the NDVI values Figure 2, did not note any statistically significant differences after 90 DAS. Fertilization significantly affected the NDVI values. In particular, C reported the lowest NDVI values both during 60 and 90 DAS. Inductively, in D1 60 DAS NDVI values observed in C were 6, 2 and 8 % lower compared to the respective values reported in U, I and O.

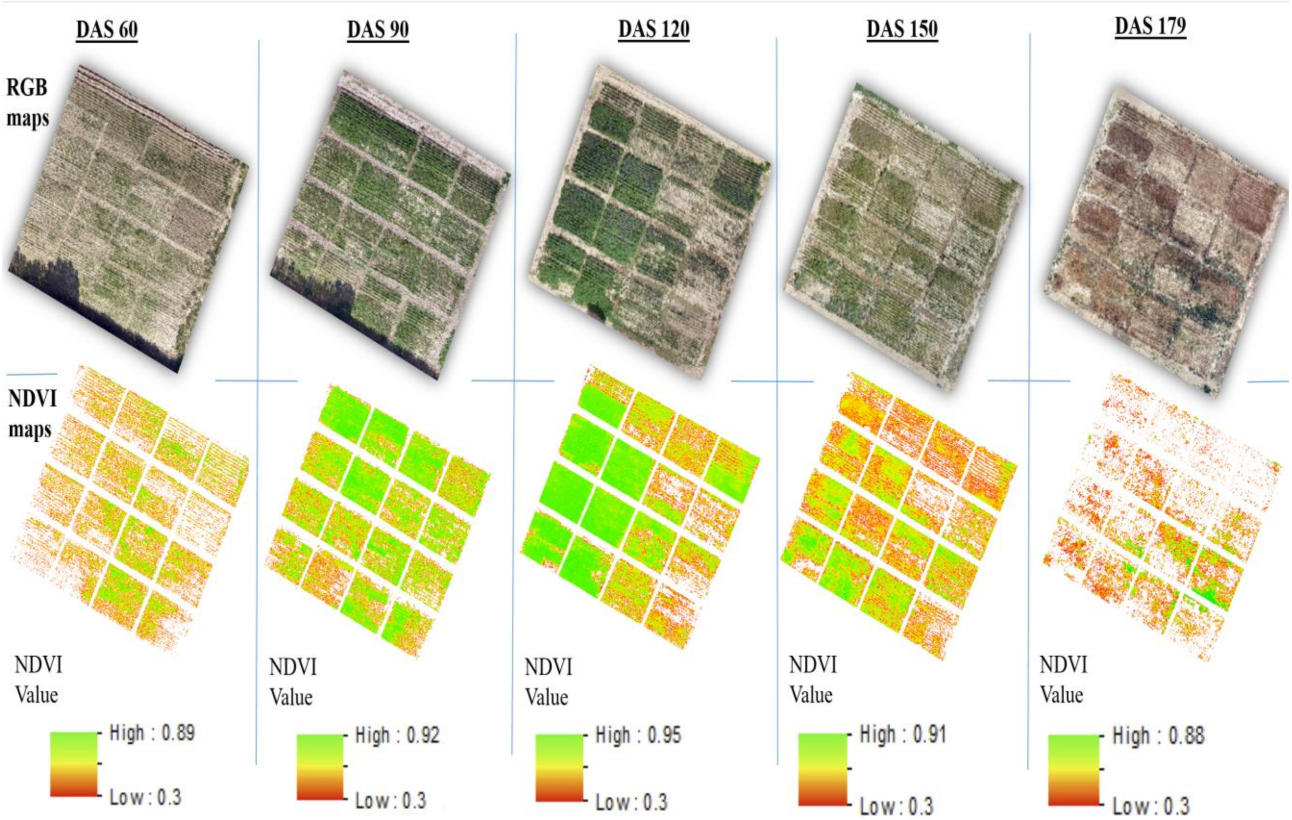
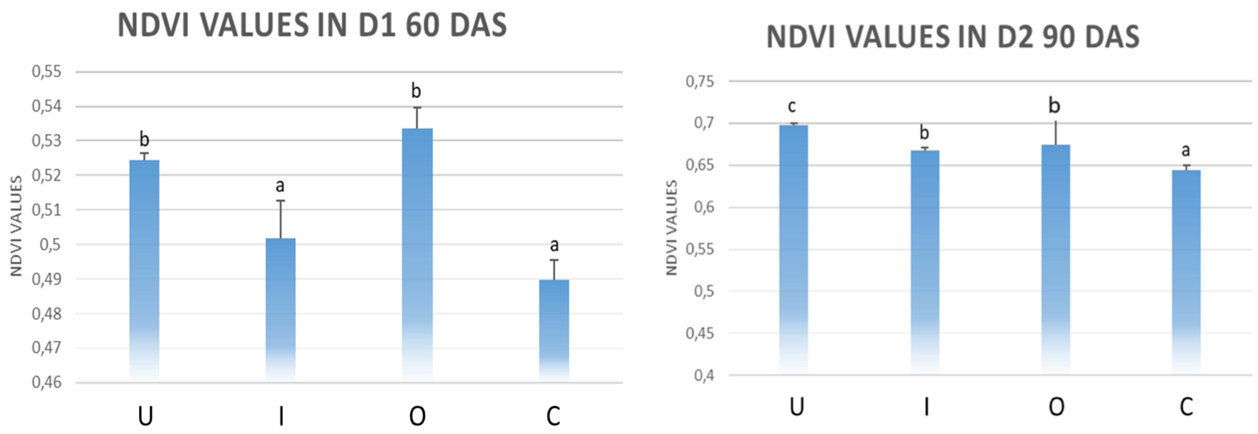


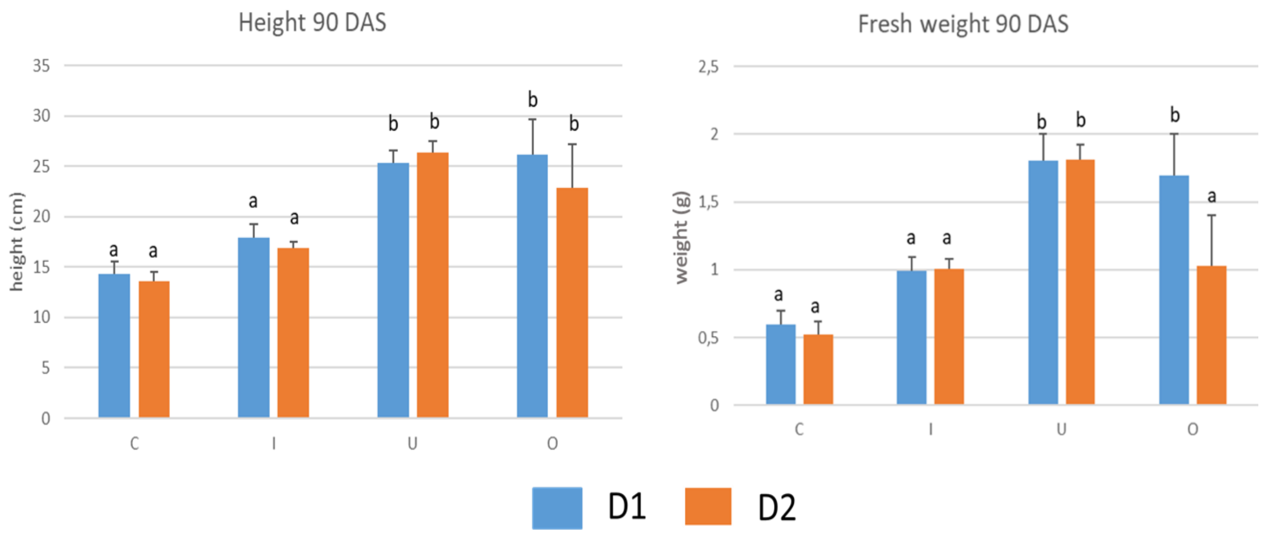
Figure 2. RGB (Red, Green, Blue/ The three primary colors used in digital imaging to create a wide spectrum of colors) and NDVI maps of the field throughout the crop season. Each column presents corresponding RGB and NDVI maps for specific timeframes, denoted in DAS.

Similarly, in D2 90 DAS NDVI values in C were lower (compared to U, I and O) by 7, 3 and 4 %, respectively Figure 3. Interestingly, the higher NDVI values in the fertilized plots (U, I, O) coincide with the improved agronomic traits observed in the same plots 90 DAS Figure 4. This finding implies a correlation between the NDVI values during the early vegetive stages and the performance of the crop. Papadopoulos et al. (2023) reported similar findings in *Carthamus tinctorius* L., whilst studying the effects of fertilization and tillage on the crop via the utilization of UAV and NDVI. In the same study, authors concluded that NDVI values could be used as a performance indicator in the early growth stages (0 - 100 DAS), similarly to our findings. This hypothesis is further validated in the study of Angelopoulou et al. (2020), where authors concluded that there was a correlation between NDVI values prior to 90 DAS and the overall performance of false flax (*Camelina sativa* [L.] Crtz.).



(a) (b)

Figure 3. Comparative NDVI Values Across Different Treatments and Densities at (a) 60 and (b) 90 DAS.



(a) (b)

Figure 4. Agronomic traits of flax at 90 DAS: (a) Plant height and (b) Fresh weight per plant

CONCLUSIONS

The findings of this study underscore the influence of fertilization strategies on the agronomic traits of flax, with NDVI values derived from UAV multispectral imaging proving to be a robust indicator of the crop's performance, particularly in its early growth stages. Specifically, the application of fertilizers resulted in significantly higher NDVI values up to 90 DAS, reflecting an enhanced vegetative development as compared to the control plots. This correlation between NDVI values and agronomic traits was most pronounced during the initial 90 DAS, pinpointing this period as critical for assessing the impact of fertilization on flax performance. These insights not only validate the use of NDVI as a reliable tool for monitoring crop development but also highlight the potential of UAV-based remote sensing in precision agriculture, offering a pathway for timely and informed crop management decisions. Ultimately, this study contributes to the evolving field of precision agriculture, providing valuable data that can aid in optimizing flax cultivation for improved yield and sustainability.

Author Contributions: I.K. Conceived and designed the analysis; P.S. and A.M. Collected the data; I.R., A.M., G.P. and P.S. Contributed data or analysis tools; A.M. Performed the analysis; G.P. and I.R. Wrote the paper. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare that they do not have any conflict of interest.

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