Peter Berk[1], Denis Stajnko[1], Andrej Paušič[1], Mario Lešnik[1], Igor Petrovič[2] ***Professional paper***

Monitoring mechanical cover crop control in vineyard with the vegetation index obtained by multispectral UAS flights

Abstract
The wine industry in Central Europe faces numerous challenges, as winegrowers must compete in an increasingly globalized market while adapting to the growing demand for organically cultivated vineyards. This study aimed to evaluate the potential of the Normalized Difference Vegetation Index (NDVI) for assessing vineyard conditions following two mechanical treatments: rolling and mulching. The results revealed higher NDVI values during rolling, with an average of 0.82, compared with 0.73 for mulching. Analysis of fuel consumption further demonstrated that rolling required significantly less fuel, with an average consumption of 2.00 L ha^{-1}, compared with 4.90 L ha^{-1} for mulching. These findings suggest that rolling is a more fuel-efficient and environmentally favorable approach to cover crop management in vineyard inter-row areas. From an ecological perspective, monitoring vineyards using unmanned aerial systems (UAS) can support improved erosion control, help mitigate soil fertility degradation, and enhance the capacity to prevent or manage the adverse effects of severe drought.
Keywords: *UAS, monitoring, vineyard, mulcher, roller, multispectral imagery*

Introduction

In the context of modern agriculture, increasing attention is being directed toward the implementation of advanced digital technologies that enable the production of safe and high-quality food while simultaneously ensuring the protection of the environment and natural resources, particularly water resources. The integration of digital technologies, including sensors and intelligent machinery or devices designed to support agricultural operations, has the potential to sustainably improve agricultural production processes while reducing negative environmental impacts and the depletion of natural resources (Villa-Henriksen et al., 2020; Khan et al., 2021).

Viticulture represents a significant agricultural and food-production sector, largely due to its substantial economic contribution to global agriculture (Pisciotta et al., 2022). Grapevines are among the most intensively cultivated perennial crops worldwide, with approximately 7.3 million hectares of vineyards globally dedicated to the production of wine grapes, table grapes, and dried grapes (sultanas) (OIV, 2022). The introduction of modern technologies into sustainable grape production was first reported by Bramley and Proffitt (1999) in Australia at the end of the last century, marking the early development of what is now referred to as precision viticulture. Over the past decade, the adoption of modern technologies for vineyard management in developed European Union countries has increased

*1 Assist. prof. dr. **Peter Berk**, Prof. dr. **Denis Stajnko**, Dr. **Andrej Paušič**, Prof. dr. Mario Lešnik, University of Maribor, Faculty of Agriculture and Life Sciences, Pivola 10, 2311 Hoče, Slovenia*
*2 **Igor Petrovič**, Aviation division Laboratory for aeronautics, University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva cesta 6, 1000 Ljubljana, Slovenia*
*Autor za koresponednciju: **denis.stajnko@um.si***

substantially, representing a major step forward for the viticulture sector toward more sustainable and environmentally responsible grape production (Santesteban, 2019).

The development of precision viticulture has been driven by a series of technological advancements that have enabled site-specific vineyard management. These advancements can generally be categorized into three main technological domains. First, Global Navigation Satellite Systems (GNSS) allow precise and accessible determination of a point's position on the Earth's surface using geodetic coordinates, including longitude, latitude, and altitude (Catania et al., 2020). Second, Geographic Information Systems (GIS) provide tools for collecting, storing, integrating, analysing, and visualizing spatial data, enabling the identification of spatial variability within vineyards and supporting site-specific management decisions. Third, remote sensing technologies, including satellite imagery, airborne sensors, and unmanned aerial systems (UAS), facilitate the non-invasive monitoring of vineyard conditions by providing spatial information on vegetation vigour, canopy development, and plant health. When integrated with GNSS and GIS, these technologies enable more precise assessment of vineyard variability, support targeted agronomic interventions, and contribute to more sustainable resource management.

A central objective of vineyard monitoring is the collection of large amounts of georeferenced data, which can be obtained using a wide range of sensors. In recent years, modern electroluminescence technologies have become increasingly widespread with the introduction of silicon-based sensors (Nijland et al., 2014). These sensors are typically based on either Charge-Coupled Device (CCD) or Complementary Metal-Oxide-Semiconductor (CMOS) technology. Both sensor types rely on photodiodes as their fundamental component photosensitive elements that generate an electrical charge when exposed to incident light (Arya et al., 2015).

Based on the energy source used for detection, sensors are commonly classified as passive or active. Passive sensors detect electromagnetic radiation that is either reflected or naturally emitted by vegetation and rely on natural illumination sources, such as sunlight (Ferro and Catania, 2023). In contrast, active sensors emit their own energy and measure the electromagnetic radiation reflected from the target object after artificial illumination. This capability allows active sensors to operate under varying ambient light conditions and at any time of the day.

Measurements of electromagnetic reflectance can be performed across a wide range of wavelengths, typically from approximately 350 to 25,000 nm (Ferro and Catania, 2023). This spectral range encompasses several bands commonly used in precision viticulture, including the visible (VIS), near-infrared (NIR), short-wave infrared (SWIR), and thermal infrared (TIR) regions. Among the various sensor technologies used in vineyard monitoring, multispectral sensors are the most widely applied (Ferro and Catania, 2023), followed by thermal, hyperspectral, RGB, and LiDAR sensors.

Season-long monitoring of vineyards using multispectral imagery enables early detection of potential issues, facilitates timely management interventions, and improves harvest planning. Aerial remote sensing can be performed using satellite imagery, such as Sentinel-2, which provides readily available multispectral data, or through the use of unmanned aircraft systems (UAS). UAS platforms can operate at lower altitudes, enabling the acquisition of imagery with higher spatial resolution and stronger correlation with proximal sensing measurements (Kasimati et al., 2023).

In recent years, automated and modular crop monitoring systems have emerged as advanced technological solutions that enable efficient and flexible data acquisition in agricultural systems. Among these technologies, unmanned aerial vehicles (UAVs) represent a particularly promising tool for precision agriculture. UAV platforms can be equipped with a variety of sensors, including multispectral, hyperspectral, thermal, and RGB sensors, enabling rapid and relatively simple collection of field data compared with traditional monitoring methods.

Although these technologies are now widely applied in agriculture, their initial development was primarily intended for military applications. Over time, their capabilities have been adapted to civilian and scientific uses, including environmental monitoring and agricultural management. UAV-based monitoring systems offer several advantages over terrestrial sensing systems, particularly in their ability to cover large areas within a short period of time. Furthermore, compared with satellite and conventional airborne platforms, UAVs can operate at low altitudes, allowing the acquisition of imagery with very high spatial resolution.

For these reasons, UAV-based monitoring systems are increasingly used in precision viticulture. Their operation is relatively straightforward, as they can be remotely controlled from ground stations using dedicated software or mobile applications that manage flight planning and mission execution. Once a flight plan is defined, the UAV autonomously follows the programmed trajectory (Rejeb et al., 2022). In addition, UAV platforms are commonly integrated with Global Positioning System (GPS) and Real-Time Kinematic (RTK) technologies, which provide highly accurate positional information in real time and enable precise georeferencing of the acquired imagery (Ferro and Catania, 2023).

In this study, we evaluate the potential application of an unmanned aircraft system (UAS) for monitoring the vegetation status of cover crops in a vineyard following alternative mechanical control practices. Specifically, different mechanical tools a mulcher and a crop roller were used for cover crop suppression. The UAS platform was equipped with a multispectral sensor, enabling the acquisition of spectral data and the digital reconstruction of the vegetation status of the vineyard cover crop.

Vegetation index analysis was performed to assess the effects of mechanical suppression on cover crop dynamics. In addition, fuel consumption associated with the different mechanical tools used for cover crop management was evaluated in order to compare their operational efficiency.

Materials and methods

For the experimental study, a vineyard located at the agricultural holding Greif (Bistriška cesta 21, 2313 Fram, Slovenia) was used on June 19th 2022. The experimental plot covered an area of 4,675 m^2 and is located at 46°27′10.3″ N, 15°38′19.8″ E (Figure 1).

The vineyard is managed under an intensive production system and is planted with grafted grapevines of the Sauvignon Blanc variety, three years of age, grafted onto the rootstock Kober 5BB. This rootstock is widely used in several wine-growing regions of Slovenia due to its favorable agronomic characteristics and compatibility with various grapevine cultivars. In addition to its good compatibility with Sauvignon Blanc, Kober 5BB also exhibits very good compatibility with Laški Riesling and good compatibility with cultivars such as Šipon, Rhein Riesling, and Regent. The rootstock was selected based on professional viticultural criteria. Previous studies have reported that Kober 5BB is characterized by higher chlorophyll content in the leaves and a larger leaf wall area, which may influence vine vigor and canopy development (Keller et al., 2001).

The vineyard planting geometry consists of an inter-row spacing of 2.5 m and an average distance of 1.7 m between vines within the row. The vines are trained using a two-cane pruning system with a spur, where each cane retains up to ten buds and the spur retains three or more buds. The grapevine trunk height is approximately 0.9 m.

In the field experiment, different mechanical modular systems were used for the management of the inter-row vegetation in the vineyard. The mechanical system consisted of the following components: an Antonio Carraro SRX 10900 R tractor, an ILMER LMG245 mulcher, and an AGROMET EJEA roller.

The Antonio Carraro SRX 10900 R tractor, with an overall width of 1,060 mm, is specifically designed for vineyard operations, allowing maneuverability within narrow rows while maintaining a minimal turning radius and reducing soil compaction. Its weight distribution is optimized for the use of mounted implements, which helps minimize soil compaction within the rows and reduces the risk of damage to vine roots. During the field experiment, the tractor's on board measurement system was used to record instantaneous fuel consumption during the different operations (mulching and rolling), expressed in L h^{-1}. The tractor operating speed, controlled using cruise control, was maintained at 6 km h^{-1} during mulching and 8.3 km h^{-1} during rolling operations.

The ILMER LMG245 mulcher is equipped with elevated blade holders and strongly curved oscillating blades. These oscillating blades enable the rotary mower to achieve efficient cutting performance even under demanding field conditions (Figure 2a). The AGROMET EJEA roller is designed for organic vineyard management and is intended for the maintenance of inter-row vegetation. In the present experiment, a roller with a mass of 800 kg and a diameter of 550 mm was used. The implement is designed for inter-row widths ranging from 2.20 m to 2.50 m (Figure 2b).

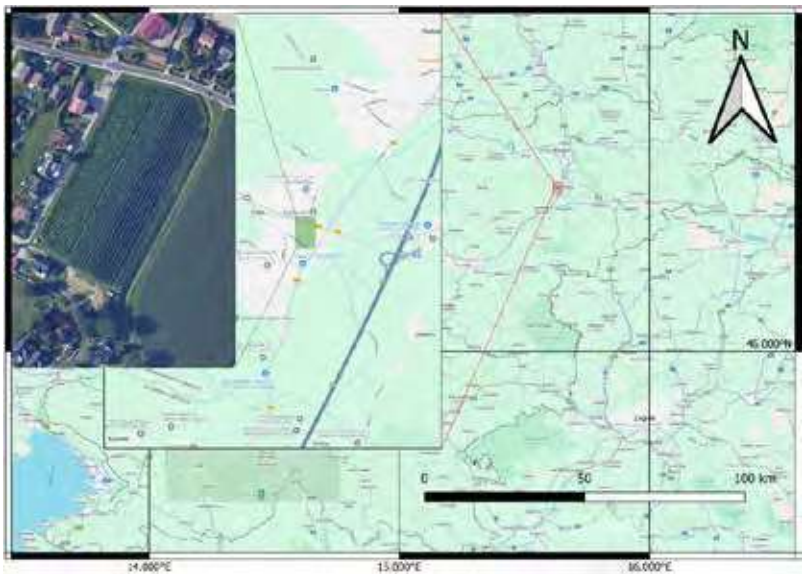


Figure 1. Location of the experimental vineyard used for monitoring cover crop vegetation status.
Slika 1. Lokacija pokusnog vinograda u kojem je praćeno stanje vegetacije pokrovnih usjeva



Figure 2a. ILMER LMG245 mulcher
Slika 2a. Malčer ILMER LMG245.



Figure 2b. AGROMET EJEA roller
Slika 2b. Valjak AGROMET EJEA.

Two different mechanical treatment systems were applied in the experiment: rolling and mulching. Rolling operations were performed in vineyard rows 5 to 9, while mulching operations were carried out in rows 9 to 13 (Figure 3). The experimental vineyard plot had an average slope of approximately 0%.



Figure 3. Inter-row vegetation management in the vineyard using different mechanical modular systems (yellow arrows: mulching; red arrows: rolling). **/ Slika 3.** Održavanje međuredne vegetacije u vinogradu primjenom različitih mehaničkih modularnih sustava (žute strelice: malčiranje; crvene strelice: valjanje)

The unmanned aircraft system (UAS) used for multispectral image acquisition was the DJI Mavic 3M (SZ DJI Technology Co., Ltd., Shenzhen, China), shown in Figure 4. The platform is equipped with integrated GPS and GLONASS receivers for positioning, which are further enhanced by a Real-Time Kinematic (RTK) module connected to the Slovenian national network of fixed Global Navigation Satellite System (GNSS) reference stations (SIGNAL). Using RTK correction, the absolute positioning accuracy of the UAS is expected to be within approximately 10 cm.

The multispectral imaging system includes four spectral bands: Green (G) (560 ± 16 nm), Red (R) (650 ± 16 nm), Red Edge (RE) (730 ± 16 nm), and Near-Infrared (NIR) (860 ± 26 nm). These bands are captured using a 1/2.8-inch CMOS image sensor with a spatial resolution of 5 megapixels. In addition, the UAS is equipped with an RGB camera featuring a 4/3-inch CMOS sensor with a resolution of 20 megapixels.



Figure 4. Unmanned aircraft system (UAS) used for multispectral image acquisition: DJI Mavic 3M (SZ DJI Technology Co., Ltd., Shenzhen, China)
Slika 4. Bespilotni zračni sustav (UAS) korišten za multispektralno snimanje: DJI Mavic 3M (SZ DJI Technology Co., Ltd., Shenzhen, Kina)

The flight mission was planned using the DJI Pilot 2 application (SZ DJI Technology Co., Ltd., Shenzhen, China), following a nadir mapping strategy at an altitude of 12 m above ground level, with 90% frontal and 90% side overlap. A total of 417 images were acquired for each sensor type (RGB, G, R, RE, NIR), resulting in a dataset of 2,085 images. Based on the camera specifications and flight altitude, the average ground sampling distance (GSD) was 0.42 cm/pixel for RGB imagery and 0.67 cm/pixel for multispectral imagery.

All acquired images were imported into Pix4Dmapper photogrammetric software (Pix4D SA, Prilly, Switzerland, version 4.8.4) for the reconstruction of a 3D model of the vineyard. RGB images were processed using a 3D mapping project template to generate an orthophoto of the vineyard. Multispectral images were processed using the agriculture multispectral template, producing

maps of spectral reflectance values at the pixel level, which were subsequently used to calculate vegetation indices. The processing time required approximately 1 h 42 min for the 3D reconstruction and 2 h 26 min for the multispectral mapping, using a workstation equipped with a 13th Gen Intel® Core™ i7-13700K processor, 64 GB RAM, and an NVIDIA GeForce RTX 3070 Ti graphics card.

Spectral data from the red and near-infrared bands were extracted from georeferenced images at each pixel, and the Normalized Difference Vegetation Index (NDVI) was computed following the approach described by Kasimati et al. (2023) according to the equation:

(1)

where the NIR parameter represents near-infrared light and R visible imaging parameter.

Results and discussion

The calculated NDVI values are graphically presented in Figure 5. Eight rows are displayed with the same orientation as in Figure 3. The four rows on the left (highlighted in yellow) correspond to the mulching treatment, whereas the four rows on the right (highlighted in red) represent the rolling treatment. NDVI values are visualized according to the legend, with red tones indicating lower values and green tones indicating higher values. A clear distinction between the two treatments can be observed: the mulched rows (left side) exhibit lower vegetation vigor and consequently lower NDVI values, while the rolled rows (right side) show higher NDVI values, indicating greater vegetation vigor.

The numerical NDVI values for each row are presented in Table 1. Aggregated values for all mulched and rolled areas are reported in the columns M_{All} and R_{All}, respectively. Large differences between minimum and maximum NDVI values are observed in both treatments, indicating considerable variability within the rows regardless of the management operation. However, the difference in mean NDVI values between treatments is substantial, with an average value of 0.73 for the mulched rows and 0.82 for the rolled rows.

Greater variability within individual rows is evident in the mulched treatment, as reflected by the higher standard deviation values. This variability may be partially attributed to uneven mulching of the soil surface. Slightly lower NDVI values observed in row R1 can be explained by exposing of bare soil which reduced the overall vegetation signal, thereby lowering the NDVI values in this row.

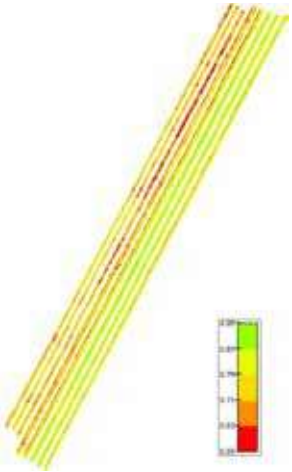


Figure 5. Normalized difference vegetation index (NDVI) values in the inter-row areas of the vineyard
Slika 5. Vrijednosti normaliziranog diferencijalnog vegetacijskog indeksa (NDVI) u međurednom prostoru vinograda

Table 1. Summary statistics of normalized difference vegetation index (NDVI) values for the vineyard inter-rows / **Tablica 1.** Deskriptivna statistika vrijednosti normaliziranog diferencijalnog vegetacijskog indeksa (NDVI) u međurednom prostoru vinograda.

	M1	M2	M3	M4	M_{All}	R1	R2	R3	R4	R_{All}
Min	0.37	0.36	0.32	0.31	0.31	0.29	0.53	0.38	0.36	0.29
Avg	0.74	0.76	0.69	0.73	0.73	0.78	0.85	0.84	0.81	0.82
Max	0.92	0.92	0.88	0.90	0.90	0.93	0.95	0.94	0.93	0.95
St dev	0.06	0.06	0.08	0.08	0.08	0.09	0.04	0.04	0.06	0.07
Var	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01

Table 2. Fuel consumption analysis for different mechanical soil management operations in vineyard inter-row areas. / **Tablica 2.** Analiza potrošnje goriva pri različitim mehaničkim zahvatima održavanja tla u međurednom prostoru vinograda.

Mechanical operation in vineyard June 19th 2022	**Time consumption (min) for area 425 m²**	**Time consumption (min) for area 1 ha**	**Fuel consumption L h^{-1}**	**Fuel consumption L ha^{-1}**
Driving up, operation mulching (tractor speed: 6 km h^{-1})	1.41	33.17	8.50	4.70
Driving down, operation mulching (tractor speed: 6 km h^{-1})	1.55	36.47	8.30	5.05
Driving up, a rolling operation (tractor speed: 8.3 km h^{-1})	1.08	25.41	5.20	2.20
Driving down, a rolling operation (tractor speed: 8.3 km h^{-1})	1.08	25.41	4.70	2.00
Driving up, a rolling operation (tractor speed: 8.3 kmh^{-1})	1.10	25.88	4.40	1.90
Driving down, a rolling operation (tractor speed: 8.3 km h^{-1})	1.11	26.11	4.30	1.87

Table 2 presents fuel consumption data for two different mechanical operations used for the management of vegetated inter-row areas in the vineyard. In the field experiment, two repetitions of the mulching treatment were performed using a mulcher, while four repetitions were conducted using a mechanical roller. For each treatment repetition, fuel consumption was recorded by tractor computer in L ha^{-1}, while the time was measured using stopwatch.

The results indicate that the alternative mechanical management of the vineyard inter-row area using a roller requires lower fuel consumption and allows higher operating

speeds compared with the mulching operation. Therefore, the rolling treatment can be considered a more energy-efficient and environmentally favorable approach for the mechanical management of vineyard inter-row vegetation.

Conclusions

The primary objective of this study was to evaluate normalized difference vegetation index (NDVI) values of the cover crop located in the inter-row areas of a vineyard. The results demonstrate that the use of a multispectral unmanned aerial system (UAS) equipped with high-resolution sensors provides reliable data for the analysis and monitoring of cover crop conditions in vineyards. In addition, the UAS system enables rapid and efficient data acquisition over the study area.

The calculated NDVI values were graphically presented to assess the effects of two mechanical vegetation management operations: mulching and rolling. The analysis revealed higher NDVI values during the rolling operation, with an average NDVI value (R_{All}) of 0.82, compared to the mulching operation, which showed an average NDVI value (M_{All}) of 0.73. Fuel consumption analysis further indicated that the rolling operation required less fuel, with an average consumption of 2.00 L ha^{-1}, compared to 4.90 L ha^{-1} for the mulching operation. Based on these results, rolling can be considered a more efficient and environmentally favorable method for cover crop management in vineyard inter-row areas, however multiple measurements need to be proceed under different vineyards.

Future research should focus on the integration of advanced image analysis and machine learning methods for the automatic detection and mapping of grapevine diseases using multispectral UAS data. Such approaches could enable earlier detection of plant stress, thereby improving vineyard management practices and reducing the need for agrochemical inputs.

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Stručni rad

Praćenje mehaničkog održavanja pokrovnih usjeva u vinogradu primjenom vegetacijskog indeksa dobivenog multispektralnim UAS snimanjem

Sažetak

Vinarstvo u srednjoj Europi suočava se s brojnim izazovima jer se vinogradari moraju natjecati na sve globaliziranijem tržištu, istodobno se prilagođavajući rastućoj potražnji za ekološki obrađivanim vinogradima. Cilj ovog istraživanja bio je ispitati mogućnost primjene normaliziranog diferencijalnog vegetacijskog indeksa (NDVI) za procjenu stanja vinograda nakon primjene dviju mehaničkih metoda održavanja međurednog prostora: valjanja i malčiranja. Rezultati su pokazali više vrijednosti NDVI-ja pri primjeni valjanja, uz prosječnu vrijednost od 0,82, u usporedbi s prosječnom vrijednošću od 0,73 pri primjeni malčiranja. Analiza potrošnje goriva pokazala je da je za valjanje potrebno znatno manje goriva (prosječno 2,00 L ha^{-1}) nego za malčiranje (4,90 L ha^{-1}). Ti rezultati upućuju na to da je valjanje energetski učinkovitija i ekološki prihvatljivija metoda upravljanja pokrovnim usjevima u međurednom prostoru vinograda. S ekološkog stajališta praćenje stanja vinograda primjenom bespilotnih zračnih sustava (UAS) može pridonijeti boljem suzbijanju erozije, ublažavanju degradacije plodnosti tla te jačanju sposobnosti sprječavanja ili ublažavanja štetnih posljedica izrazitih suša.

***Ključne riječi:** UAS, praćenje, vinograd, malčer, valjak, multispektralne snimke*