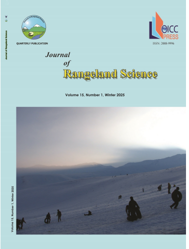

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The use of modified and unmodified digital cameras to monitor small-scale Savannah Rangeland vegetation

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Abstract:

Savannah rangelands provide a significant source of income for rural communities, which use them to manufacture a variety of products. Traditionally, rangeland managers used visual and/or physical monitoring methods that were time-consuming, labour-intensive, and expensive. The applicability of these methods to assessing rangeland vegetation remains largely unknown. Photographs taken digital integrating analyzed qualitatively or statistically, and analysis can focus on individual species or integrate data from the entire field of view into a community or canopy-level picture. This technique attempts to bridge the gap between ground-based observations and satellite remote sensing. What motivated the review of this digital camera is that the system has proven to be inexpensive in other studies and because images can be analyzed either quantitatively or qualitatively, and the analysis can focus on individual species or integrate across the field of view or canopy-level perspective. Digital cameras were discovered to be scientific instruments capable of accurately estimating and measuring vegetation parameters only recently in crop sciences, where they are used to detect flowering success or track phenological stages in monospecific crop stands. By reducing the labour-intensive nature of monitoring at the field scale with camera-based remote sensing, these effective applications demonstrate the vast potential of camera-based remote sensing. Digital Image Analysis (DIA) offers a more continuous method of capturing data, storing and transferring it electronically to a computer, and processing it with image-analysis software. The number of data that can be collected each day at a given time is limited as opposed to visual estimations.

Keywords: Digital cameras; Near-surface remote sensing; Technologies; Rangelands; Repeat photography

Introduction

Savannah rangelands are the most prevalent land use type on Earth, comprising an estimated 25% of the planet's land area (Taugourdeau et al., 2022; Richardson, 2019). The primary purpose of rangelands is to provide forage for animals (Zerga, 2015). Rangelands are ecologically significant terrestrial ecosystems because they protect fragile soil profiles, sequester large quantities of carbon dioxide (CO_2), and act as watersheds for large river systems (Inoue et al., 2015). Additionally, rangelands are essential for providing secondary resources, such as firewood, wild foods, medicinal plants, and even water (Maphanga et al., 2022). Moreover, rangelands are a significant source of income for rural communities that produce various goods (Zerga, 2015). The management and conservation of rangelands are crucial not only for the survival of livestock and wildlife, but also for the overall survival of biodiversity and the sustainability of livelihoods (Maphanga et al., 2022). Regular and accurate monitoring of rangelands is necessary for appropriate management decisions. Forage, firewood, medicinal plants, and wild fruits determine the economic value of a rangeland (Taugourdeau et al., 2022; Richardson, 2019).

Thus, local knowledge tools and findings would benefit the management, evaluation, and restoration of savannah rangelands. Healthy savanna rangelands provide valuable ecosystem services to the national economy through wildlife production, livestock grazing enhancement, and tourism (Maphanga et al., 2022). Engler et al. (2018) estimates the annual economic loss at $700 million, affecting 65 000 communal households and 6 283 commercial farmers in Latin America. Stafford et al. (2017) estimated US$5.8 billion in ecosystem services from Namibia's restoration of bush encroachment. Given the importance of savannah rangelands still facing resource depletion and overuse, effective management is crucial, and innovations have been introduced to improve management. In South Africa, where a large proportion of the population relies on rangeland-related livelihoods, the development of technologies to improve rangeland monitoring and management is crucial (Dube et al., 2022; Maphanga et al., 2022). The primary indicators of rangeland degradation are a shift in species composition, loss of biodiversity, decrease in biomass production, less plant cover, low small ruminant productivity, and soil erosion (Ward, 2005; Jiang et al., 2022). Understanding the environmental conditions, plant health, and productivity is required to accurately determine the number of livestock that can exist in a sustainable manner (Chianucci et al., 2021). Therefore, an accurate assessment of the current physical and physiological state of the savanna rangeland is necessary to make informed decisions (Nijland et al., 2014). Subsequently, the need for remotely sensed data to monitoring techniques savannah rangeland on a small scale continues to exist. Digital cameras have been used in recent monitoring experiments. Such techniques (commonly known as near-surface remote sensing) have proven effective for crop monitoring at the microscale level (Perez et al., 2000). Many scientists have successfully implemented the use of ground-based remote sensing by employing digital cameras centered on mixed spectrum cameras to study plant health (Bater et al., 2011) and vegetation cover, such as in precision agriculture (Bauer et al., 2011), forests (Sonnentag et al., 2012; Nijland et al., 2014), ecology (Browning et al., 2019), crops (Sakamoto et al., 2011), and grasslands (Bueren et al., 2015). Owing to the high temporal resolution of consumer-grade digital cameras, near-surface remote sensing has the potential to assist small-scale rangeland monitoring and provide accurate assessments (Sakamoto et al., 2011; Berra et al., 2017). It is anticipated that a combination of portable spectrometers, consumer-grade cameras, and filter-modified digital cameras will offer spectral resolutions comparable to those of contemporary satellites (Gobbett et al., 2013). According to Inoue et al. (2015) and Richardson et al. (2009), consumer-grade digital cameras are the most accurate and cost-effective means for collecting biomass data in a fixed area. Because digital cameras are less expensive and easier to operate than other types of equipment (e.g., field spectroradiometers), they can be used as components of a global network to enable the continuous, small-scale, and precise monitoring of ecological and environmental variations in numerous ecosystems (Inoue et al., 2015; Corti et al., 2019). This technique attempts to bridge the gap between ground-based observations and satellite remote sensing. What motivated the review of this digital camera is that the system has proven to be inexpensive in other studies and because images can be analyzed either quantitatively or qualitatively, and the analysis can focus on individual species or integrate across the field of view or canopy-level perspective. Although several scientists have conducted experiments involving the use of digital cameras for crop monitoring (Corti et al., 2019), these approaches have not been examined or implemented in rangelands. It is uncertain whether similar applications used in cropping contexts can be applied to complex rangeland ecosystems, which have a greater variety of vegetation in terms of composition, structure, and spatiotemporal dynamics. This research examines the suitability of near-surface remote sensing for monitoring vegetation in natural rangeland areas.

Martial and method

The literature search included English articles with peer reviews and pertinent reports. Extensive project reports, published papers, and websites were mined for all of the data used in the evaluation and review. Google Scholar and Web of Science were utilized to locate all pertinent articles and reports. The criteria for selection included the following: (1) the use of digital cameras in rangelands (savannah) using remote sensing; (2) application of modified digital camera in monitoring rangeland; (3) the assessment of savannah rangeland using digital cameras;(4)the use of near surface technologies to monitor savannah rangelands; (5) the application of remote sensing in the assessment and monitoring using low cost technologies ; and (6)modified digital camera use in ecological monitoring, just to mention few. Mkwanazi et al. (2021) suggest using alternate sources, such as the general Google search engine, when scientific databases do not have access to publications. The current inquiry ensued after the aforementioned proposition. Mkwanazi et al. (2021) performed supplementary searches by referring to the bibliographies of prominent publications. This approach ensured the inclusion of a diverse range of articles from different locations throughout the continent. Another search was conducted to identify several relevant publications and reports associated with the subject. This subsequent search used the snowball method based on the pertinent references obtained from the prior search. One of the constraints of the literature search tactics was the difficulty in finding relevant academic articles that were published in English.

Results and discussion

Overview of most dominant threat to savannah rangelands

Global rangeland degradation is primarily caused by the lack of grazing management plans, removal of plants for fuelwood, and clear ownership authority (Zerga, 2015; Inoue et al., 2015). Overgrazing and inadequate management account for 49% (O'connor et al., 2014) of soil degradation in Africa, with 10% (Browning et al., 2019) bush encroachment reducing grazing capacity by 7% and eliminating it by 90% in East Africa (Tilahun et al., 2017). Grazing management is crucial for the survival of arid and semiarid grasslands and savannahs. Overgrazing and plant invasion are well-documented, with experts linking overgrazing to invasion (Jia et al., 2014; Browning et al., 2019). Rising temperatures and extreme events like drought and unpredictable precipitation also affect rangeland systems. Bush encroachment and drought are connected, with drought affecting 200 million people in Southern Africa and Zimbabwe losing 10,000 cattle due to lack of pasture and water (O., 2011; Matope et al., 2020). Seasonal fluctuation also impacts overgrazing, making rangelands vulnerable to invasion. Unrestrained grazing can harm communities or protected grazing land, and vegetation loss in semiarid savannah grasslands can cause soil erosion (Angassa et al., 2012; Zhang et al., 2021). Soil texture and anthropogenic CO_2 levels in the southwestern United States can also contribute to bush invasion. Palmer and Fortescue (2003) hypothesize that if global temperatures increase by 3-5 degrees by the end of the century, grasses will outcompete shrubs.

The use of digital cameras to monitor vegetation in different fields.

Numerous of the earliest applications of digital camera technology for phenology monitoring originated in agriculture. Numerous studies have utilized digital cameras successfully to monitor plant health and vegetation cover in precision agriculture von. By combining a high temporal resolution with a certain degree of spatial resolution, near-surface remote sensing of rangelands has the potential to observe, for example, the entire canopy and seasonal changes in the optical properties of vegetated surfaces (Richardson et al., 2009). The majority of researchers have employed camera-based monitoring of vegetation phenology (Zaller et al., 2015) using standard or ordinary consumer-grade digital cameras, which typically record three-band images (red, green and blue; RGB). This was adequate for colour reproduction in the visible spectrum (400nm-700nm) as seen by the human eye (Petach et al., 2014). This did not yield sufficient information regarding the vegetation's health, as measured by the NDVI. Some researchers saw the need to develop or modify the digital camera in order to acquire the near infrared (NIR) in order to expand the scope (Fernandez et al., 2019). For example, each camera-pair consisted of a 'normal', unmodified camera and a filter- modified camera which is equipped with an 830nm long-pass filter, converting the camera to be sensitive only in the >830nm near-infrared range. This ensured consistent rectification of digital images to the same area of ground over a defined period. The pair of cameras is then mounted, resulting in an offset in the lens-centre of both cameras of as little as 8cm shown in figure 1. Simultaneous triggering of both cameras thus allowed to construct four-channel multi-spectral images including red, green, and blue (RGB) and near-infrared (NIR) bands. figure 1 below shows the set-up of the digital cameras.

With an NIR-band camera, it is possible to detect plant stress in the transition band from red to NIR (660 to 740 nm), which corresponds to the plant's stress (Rabatel and Labbe, 2016). Most commonly, responses in the near- infrared (NIR) in combination with the red or the other visible bands are used (e.g. NDVI or EVI; (Tucker, 1979; Huete et al., 2002; Zhang et al., 2020)), while only a few approaches exclusively rely on the final (e.g. excess green index; (Nijland et al., 2014)). This was supported by Berraetal (2015), who stated that monitoring vegetation with consumer-grade digital cameras typically requires the combination of visible and NIR wavelengths in order to exploit the well- known spectral characteristics of healthy plant leaves. Most researchers have used this technique to obtain all four spectral channel bands (red, green, blue, and near infrared) of digital cameras by coupling and mounting the cameras on a tower (Richardson et al., 2009; Inoue et al., 2015). This technique, which requires mounting the cameras on a tower or other high platforms, yields data at a scale of observation that is intermediate (Rabatel et al., 2014). These ensure that the obtained images represent the combined brightness levels of four colour channels spanning the visible to near-infrared portion of the electromagnetic spectrum (Ritchie et al., 2008). In each observation point, three reflectance panels (100% white; 50% black / 50% white, i.e. grey; 100% black) are placed to be visible for reflectance calibration of the image. This is to standardize and normalize the reflectance of the images according to brightness and spectral differences in the incident light throughout the study period. Repeated images from the cameras permit sampling at a very high temporal resolution, frequently at different intervals, such as every hour, to monitor vegetation processes. This method of using both RGB and NIR cameras requires simultaneous image capture and expo-

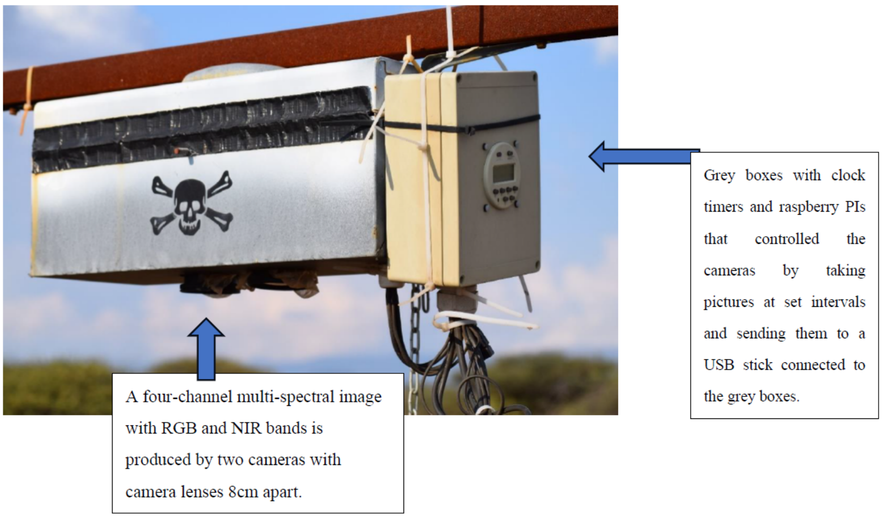

Figure 1. Example of the field setup of the camera system to monitor vegetation.

sure adjustment between cameras (Putra et al., 2020). The methodology was developed to test a simple calibration system and determine the accuracy and effectiveness of using a consumer-grade digital camera to observe the reflectance of vegetation during the growing season. Several scientists have demonstrated, in agricultural studies, that fully automated robotic weed control systems based on digital images have the potential to achieve a high level of automation. However, few researchers have used digital cameras to track the temporal variation of grassland or rangeland structure and function (Migliavacca et al., 2011; Gobbett et al., 2013; Handcock et al., 2015). Table1 indicates the use of both modified and unmodified inexpensive digital cameras in various field of studies which yielded successful results.

The application methodology and current state of the art in the use of digital cameras

Advances in digital electronics and computational capabilities have significantly increased the value of remote sensing in vegetation and environmental sciences. Vegetation information is derived from indices that compare vegetation reflectance in different spectral regions, with near-infrared (NIR) responses often combined with red or other visible bands. Contemporary remote sensing technologies in vegetation science are diverse and include near-surface remote sensing techniques (NSRS), such as off-the-shelf digital cameras, filter-modified digital cameras, and portable field spectrometers. NSRS has great potential to reduce labor costs in large-scale monitoring and experimental studies, but it suffers from technology-specific drawbacks related to adaptability, susceptibility to environmental conditions, usability, and asset cost. DCOTS are easy to use, inexpensive, and durable, but have limited applicability in NSRS approaches due to their limited visible light spectrum. PFS provide information in the entire electromagnetic spectrum but are susceptible to errors, require trained operators, and are expensive.

In conclusion, all three technologies are qualified and capable of assessing a variety of variables of broad interest in vegetation (Table2). In addition, these methods are more efficient, less labour-intensive, and minimally invasive than traditional field-methods, which may involve destructive sampling. However, assessments of these technologies' precision and comparisons between them are uncommon. In addition, the few available studies are limited to anthropogenically shaped environments (Sakamoto et al., 2011; Sonnentag et al., 2012), which may hinder the adoption of these technologies in natural environments such as smallholder farms, common gardens, and rangelands. This thesis intends to address this research gap and evaluate the absolute and relative performance of the respective technologies for capturing the target variables described in Table2 in a near-natural rangeland setting.

Overview of near-surface remote sensing using consumer grade cameras

Previous studies have used a single normal camera with a three-band wavelength (red, green, and blue) to monitor vegetation phenology over a growing season. Richardson et al. (2009) conducted a study in Bartlett experimental forest, examining the timing and rate of phenological changes in both temporal and spatial variation. The study used a digital camera mounted on a tower to obtain daily images of plants between 12 and 14 p.m., focusing on the region of interest. The data showed spatial variation in spring and autumn phenology across plant leaves and inter-annual variation in green-up and senescence timing and rate. Digital monitoring of vegetation phenology is widely used to quantify climate variability and change responses. Digital repeat photography can characterize canopy greenness seasonality. However, it's unclear if these applications can be applied to semi-arid savannah rangeland environments with diverse

Table 1. The application of digital cameras in different fields of study.

Camera types	Region	Study	Author
The type of cameras used were Pentax Optio w60 digital cameras which are inexpensive, waterproof and had an inbuilt interval meter to enable automatic shooting at fixed interval.	Majura Southeastern Australia,	Pasture monitoring using remotely sensed has proven the benefit of the usefulness of this application by measuring pasture characteristics such as growth rate and biomass.	Gobbett et al. (2013)
The camera system consisted of a digital camera (Coolpix 4500; Nikon, Tokyo, Japan)	Central mountain region of Japan where the ecosystem is dominantly short grass (grassland)	The usefulness of the ground-based remote sensing using digital cameras for continuous observations of grassland.	Inoue et al. (2015)
using two sets of cameras, one infrared camera (modified) and RGB camera (unmodified), combined with a spectrometer	University of British Columbia botanical garden in Vancouver, Canada,	the utilization of customer grade digital cameras specifically with infrared conversions for vegetation monitoring.	Nijland et al. (2014)
PhenoCam network, different digital cameras are employed to take repeated landscape images at different intervals	Twelve sites were located in the United States and one site, Chibougamou, was located in Canada.	Phenological research in forest ecosystems using digital repeat photography	Sonnentag et al. (2012)
Campbell digital camera (model CC640 Campbell Scientific, Logan, UT, USA)	the North-Western Italian Alps (Aosta Valley - Torgnon)	Using digital repeat photography and eddy covariance data to model grassland phenology and photosynthetic CO2 uptake	Migliavacca et al. (2011)

Table 2. List of selected vegetation variables, designated fieldwork and NSRS methods and metrics to estimate those and the employed spectral portion of the metrics (if applicable). Selection represents current state-of-the-art NSRS applications and summarizes the target variables of this study.

Vegetation Variable	Technology	Method / Metric	Spectral Portion	References
Aboveground Green Biomass	Fieldwork	Peak standing crop (g m^{-2})		**Inoueetal2014<empty citation>**
	DC_{OTS}	Ratio of green channel	RGB	
	DC_{OTS}+ DC_{MOD}	NDVI / EVI	NIR, Red	
	PFS	PLSR (e.g. Lignin / Chlorophyll a)	NIR, SWIR	
Canopy Chlorophyll Content	Fieldwork	Chlorophyll meter (SPAD)	-	**Saberioonetal2014<empty citation>**
	DC_{OTS}	Principal component analysis index	RGB	
	DC_{OTS} +DC_{MOD}	MTCI	NIR, Red	
	PFS	PLSR (e.g. via reflectance of Chlorophyll a)	NIR,SWIR	
Forage Quality Metrics	Fieldwork	Menke-Steingass method (MJ g^{-1})	-	**Perbandtetal2011<empty citation>**
	PFS	Metabolizable energy	NIR, SWIR	
	PFS	Crude Protein	NIR, SWIR	
Green Vegetation Cover	Fieldwork	Line-intercept method %	-	**Rasmussenetal2007<empty citation>**
	DC_{OTS}	Excess green index	RGB	
	DC_{OTS}+ DC_{MOD}	NDVI / EVI	NIR, Red	
	PFS	PLSR (e.g. via Chlorophyll a)	NIR, SWIR	
Leaf Area Index	Fieldwork	PAR meter (m^2 m^{-2})	-	**Campbell1986<empty citation>**; Sakamoto et al. (2011)
	DC_{OTS}	Excess green index+ Gap fraction	RGB	
	DC_{OTS}+ DC_{MOD}	Green chlorophyll index	NIR, Green	
	PFS	PLSR (e.g. via Chlorophyll a / Nitrogen)	NIR, SWIR	
Plant Phenology	Fieldwork	Ocular assessment of phonological stage	-	**CampanellaandBertiller2008<empty citati** Nijland et al. (2014)
	DC_{OTS}	Green chromatic coordinate	RGB	
	DC_{OTS}+ DC_{MOD}	NDVI / EVI	NIR, Red	
	PFS	PLSR (e.g. via Chlorophyll a / Nitrogen)	NIR, SWIR	

Abbreviations: EVI - Enhanced Vegetation Index, MTCI - MERIS Terrestrial Chlorophyll Index, NDVI - Normalized Difference Vegetation Index), PAR - Photosynthetic active radiation, PLSR - Partial least squares regression coefficients.

vegetation composition. Traditional monitoring techniques are time-consuming and costly. Near-surface remote sensing technologies have gained ground in crop monitoring since the 1990s, but few studies have attempted to track grasslands. Most studies are conducted in uniform vegetation stands.

The applicability of digital camera imagery for evaluating rangeland vegetation is still uncertain. This study aims to explore its potential for small-scale monitoring of savannah rangeland, as it can characterize the entire seasonal trajectory of canopy greenness. The loss and fragmentation of savannah rangeland affects biodiversity, water and carbon fluxes. Therefore, it is crucial to continuously develop new methods to enhance existing methods of monitoring natural rangeland vegetation. Old methods have proven inadequate, prompting the introduction of new methods. The advancement of technologies and strategies in monitoring rangeland degradation has improved our understanding of this phenomenon. Remote sensing offers extensive spatial coverage, is time-efficient, and more accurate than traditional surveys. It is ideal for monitoring vegetation and providing continuous data about its state. The loss and fragmentation of Savannah rangeland in South Africa affects biodiversity, water and carbon fluxes. Therefore, it is crucial to continuously develop new methods to improve existing methods. Remote sensing data has been used to track savannah rangeland quality changes and link them to climate.

Automated sensors systems (digital cameras) have proven valuable for monitoring pasture vegetation, particularly in areas with different climates. In Majura, Southeastern Australia, two types of ground-based remote sensors were used: multispectral sensors and commercially available digital cameras. The study found that temperate grasses predominated in all locations. Near-surface remote sensing is useful for predicting pasture conditions and their response to environmental conditions. These sensors can provide continuous data on the feed base, enabling timely management decisions. Digital cameras have been used in crop monitoring, reducing labor-intensive field-scale monitoring. Digital repeat images from consumer-grade cameras are particularly useful in remote or difficult-to-monitor areas. Images can be analyzed qualitatively or quantitatively, focusing on individual plants or integrating the field of view to produce a community. Digital cameras are cost-effective ways to collect automated data at high temporal resolution and across various ecosystems. Recent experiments have demonstrated the potential for remote monitoring and measurement of phenological events due to the increasing use of low-cost digital cameras.

Camera-based surveillance is commonly used to observe plant phenology, capturing pictures in three color bands (red, green, and blue; RGB). However, this information is insufficient to assess vegetation health, such as the Normalized Difference Vegetation Index (NDVI) (Gehrke and Greiwe, 2014). Researchers have developed or modified digital cameras to capture near infrared (NIR) pictures to expand the range of vegetation monitoring while preserving the original or RGB image. By adjusting camera settings while keeping the original photo as a reference, the plant's chlorophyll concentration can be determined. NIR cameras can identify plant stress by analyzing the transition range between red and NIR light (660 to 740nm), which is associated with plant stress. Researchers often use a combination of visible and NIR wavelengths to monitor vegetation using consumer-grade digital cameras. This method captures all four spectral channel bands (red, green, blue, and near infrared) of digital cameras, connecting them to a tower. This approach has been documented in various studies.

Although this study shows that a single technique may be used to calibrate digital cameras, it is important to exercise care when comparing altered digital cameras, such as those modified to capture near-infrared (NIR) images (Nguy-Robertson et al., 2016). Modifications contradict the notion that the internal camera software would provide the same level of digital noise (DN) when the exposure is adjusted. Oblique perspectives provide additional challenges, including a combination of illuminated and shadowed pixels, as well as the impact of topography on the viewing angle. Consumer-grade digital cameras are well recognized as an inexpensive method for monitoring the health and phenology of plants. The capacity to provide time series data from these cameras contributes to an enhanced comprehension of the connections among environmental factors, vegetation vitality, and productivity.

Conclusion

The use of digital cameras for vegetation monitoring can save time, money, and labour when collecting unbiased and accurate data. Digital Image Analysis (DIA) offers a more continuous method of capturing data, storing and transferring it electronically to a computer, and processing it with image-analysis software. The amount of data that can be collected in a given day at a given time is limited as opposed to visual estimations. It is necessary, however, to refine this method for use in other sections and to evaluate new techniques against established standards. Researchers conducted DIA on perennial grass-dominated rangeland to test the hypothesis that captured images can predict biomass, Leaf Area Index, phenology, cover, and NDVI. These effective applications demonstrate the great potential of camera-based remote sensing for reducing the labour-intensive nature of field-scale monitoring. The transferability of these applications to rangeland environments, which are more complex in terms of vegetation composition, structure, and temporal and spatial dynamics than croplands, can only be conjectured.

Recommendations

In order to provide accurate NDVI measurements, it is essential that the images be captured from a consistent and stable position, with the camera held still at a given height. This is necessary since any movement or instability introduced by handheld photography might lead to variations in the results.

Ground-based digital photos may enhance satellite images by offering superior spatial and temporal resolution. Cellphone applications have the ability to quantify biomass and ecological services by quantitatively analyzing pictures.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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