The relationship between multispectral satellite-derived vegetation indices and forage quantity and quality indicators in Mountain Zebra National Park

by

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Declaration

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Abstract

Climate change and human population growth has put pressure on protected areas and wilderness in southern Africa, consequently limiting food availability for herbivores. This is a major concern as forage quantity and quality available to herbivores affect the health and dynamics of herbivore populations. Therefore, the monitoring and assessment of forage quantity and quality across a landscape can potentially help ecologists make appropriate management decisions for herbivore populations in protected areas. Remote sensing measuring techniques, specifically multispectral satellite-derived vegetation indices (VI's), can be a useful tool in providing information and knowledge about forage quantity and quality for herbivores, and the possible changes in these resources. However, for the accurate interpretation and implementation of multispectral satellite-derived VI's, their relationship between forage quantity and quality indicators within the desired area needs to be determined. Therefore, this study assessed the relationship between multispectral remote sensors, onboard the MODIS and Sentinel-2 satellites, and forage quantity and quality indicators in MZNP. Forage biomass was estimated and used as a forage quantity indicator and forage nutrients were analysed and used as an indicator for forage quality. Correlations and regression techniques were applied, and results showed different multispectral satellite-derived VI's have, at different strengths, relationships with the different forage quantity and quality indicators. The MODIS Normalized Difference Vegetation Index (NDVI), rather than the MODIS Enhanced Vegetation Index (EVI), showed a strong relationship with biomass and was more related to the amount of high forage quality in MZNP. The Sentinel-2 Chlorophyll Red-Edge index (Chlred-edge) had a very strong relationship with forage quality indicator total N concentration. Strong relationships were also found between the Green Chlorophyll Index (Clgreen), NDVI and MODIS NDVI and the forage quality indicators fiber (NDF, NDFd and ADL) and potassium. Herbivore faecal samples from the dominant ungulate species in MZNP were also analysed for forage quality indicators and related to the multispectral satellite-derived VI's, to determine the relationship between VI's and the diets of the herbivores in MZNP. Results showed associations between the MODIS NDVI and EVI can be generally related to dietary nitrogen, phosphorus and magnesium for the park's dominant ungulate species. The research in this study also found valuable information on the relationship between remote sensing and forage quantity and quality, which up to now has lacked sufficient research. This study shows the implementation of multispectral satellite-derived VI's can assist with the monitoring and assessment of forage quantity and quality for the herbivores of MZNP and will aid in making appropriate herbivore management decisions. The information uncovered by this study also demonstrates relationships between VI's and forage quantity and quality that require improved understanding across a wider range of ecosystems.

Uittreksel

Klimaatsverandering en bevolkingsaanwas plaas al grooter druk op bewaringsgebiede in Suidelike-Afrika wat ‘n bedreiging ten opsigte van die beskikbaarheid van weiding vir weidende diere kan lei. Hierdie is ‘n bron van kommer aangesien die kwantiteit en kwaliteit van weiding onontbeerlik vir die instandhouding van diereprestasie en -gesondheid van weidende diere is. Daarom kan die monitering en bepaling van ruvoerkwaliteit en -kwantiteit van veld moontlik bydrae om ekoloë te help om bestuursbesluite ten opsigte van weidende diere in beskemde gebiede te maak. Afstands-sensor-metingstegnologie, spesifiek “multispectral satellite-derived vegetation indices (VI’s)”, is nuttige tegnologie om inligting en kennis oor beskikbare ruvoerkwaliteit en -kwantiteit vir herkouers asook die moontlike variasie daarvan te verskaf. ‘n Verhouding tussen weidingskwaliteit en -kwantiteit indikator binne die verlangde gebied moet bepaal word ten einde akurate interpretasie en implementering van “multispectral satellite-derived VI’s” moontlik te maak. Hierdie studie het dus die verhouding tussen “multispectral” afstand sensors aan boord die MODIS en Sentinal-2 sateliette en die weidingskwaliteit en -kwantiteit indikatore in MZNP beoordeel. Die weidingsbiomassa is geskat en gebruik as aanduiding van weidingskwaliteit terwyl die weidingsnutrïentanalises as aanduiding van die kwaliteit gedien het. Korrelasie en regressietegnieke is toegepas waarna resultate verskille in weidingskwaliteit en -kwantiiteit indikatore deur verskille in strekte en verhoudings van “multispectral satellite-derived VI’s.” uitgewys het. Die “MODIS Normalized Difference Vegetation Index (NDVI)” was meer akkuraat om die hoeveelheid hoë kwaliteit weiding in MZNP uit te wys en het ‘n hoër verwantskap teenoor die MODIS Enhanced Vegetation Index (EVI) getoon. Die Sentinel-2 Chlorophyll Red-Edge index (Chlred-edge) het ‘n sterk verwantskap met ruvoerkwaliteit, veral totale N-konsentrasie, getoon. Verdere sterk verwantskappe is tussen Green Chlorophyll Index (Clgreen), NDVI en MODIS NDVI en ruvoer-eienskappe (NBV, NBVd en SBV) en kalium bepaal. Mismonsters van die vernaamste wildspesies in MZNP is ook vir ruvoerkwaliteit ontleed en met die multispectral satellite-derived VI inligting vergelyk om soedoende die verwantskap tussen VI’s sowel as die diet van herkouers te ondersoek. ‘n Positiewe verwantskap tussen MODIS NDVI and EVI is bepaal en hou in die algemeen verband met dieetstikstof, -fosfor en -magnesium.

Navorsing van hierdie studie dra waardevolle inligting by tot die verwantskap tussen afstandsmeting en ruvoerkwaliteit en -kwantiteit wat tot op hede ontoereikend was. Hierdie studie het aangetoon dat multispectral satellite-derived VI’s” kan bydrae tot die monitering en beoordeling van ruvoerkwaliteit en -kwantiteit van herkouers in MZNP. Hierdie tegnologie kan dus help om korrekte wildsbestuursbesluite te neem. Inligting van hierdie studie demonsteer verder ‘n verwantskap tussen VI’s en ruvoerkwaliteit en -kwantiteit in ag genome ‘n verbeterde begrip van die wyer ekosisteem.

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Notes

The language and style used in this thesis are in accordance with the requirements of the International Journal of Applied Earth Observation and Geoinformation. This thesis represents a compilation of manuscripts, where each chapter is an individual entity and some repetition between chapters is therefore unavoidable

Contents

List of Tables

List of Figures

Chapter One:
Thesis introduction

2.4.1 Background

Protected areas and wilderness are under increasing pressure due to climate change and high human population growth (Seto et al., 2012; Stolter et al., 2018). In southern Africa, climate change induces erratic rainfalls and increased temperatures and as a result drought has become prominent (Collier et al., 2008; Dai, 2013). While the growing human population in southern Africa has caused an increase in the fencing of protected areas in order to protect both people and wildlife (Hayward & Kerley, 2008). Fences have caused the severing of wildlife dispersal routes, therefore limiting the amount of forage quantity and quality available to wildlife (Newmark, 2008), which has been augmented by increasing drought. Due to these pressures, a major concern is forage quantity and quality available for herbivores in protected areas, as these natural resources have a major effect on the health and dynamics of herbivore populations (Mutanga et al., 2004; Seagle and McNaughton, 1992; Skidmore et al., 2005; Stolter et al., 2018). Forage quantity and quality are important resources for herbivores in order to meet their nutritional demands for body maintenance, bone growth, weight gain, pregnancy, and lactation. A herbivore's failure to meet minimum nutritional requirements will result in weight loss, reduced fertility, decreased milk production, and lowered reproductive rates, as well as a weakened immune system, resulting in greater susceptibility to infectious diseases and parasites (Barboza et al., 2008; Robbins, 2012). Therefore, the understanding, monitoring and mapping of forage quantity and quality available for herbivores, can help ecologists in making appropriate management decisions for herbivore populations in protected areas (Knight et al., 2016; Olson et al., 2010; Sadie J Ryan et al., 2012; Skidmore et al., 2005; Stolter et al., 2018).

The successful monitoring of forage quantity and quality available to herbivores has often been impeded by field techniques, which can be expensive, tedious and labour intensive (Ryan et al., 2012; Southwood and Henderson, 2009; Xie et al., 2008; Zhao et al., 2007). Remote sensing measuring techniques, however, can be a useful tool in providing timely and spatially explicit information about forage quantity and quality (Ramoelo et al., 2015b; Ryan et al., 2012; Stolter et al., 2018). Satellite-derived vegetation indices (VI's) from multispectral remote sensors, are specifically a useful technique for obtaining information about the vegetation as they are computationally simple, freely available and provide high temporal and spatial resolutions (Hill, 2013; Li et al., 2014; Xie et al., 2008). There is now a variety of studies demonstrating the relationship between multispectral satellite-derived VI's and forage quantity and quality for herbivores in protected areas (Christianson and Creel, 2009; Garroutte et al., 2016; Kawamura et al., 2005; Ramoelo et al., 2015a; Ryan et al., 2012; Wittemyer et al., 2007). The underlying relationship is based on the assumption that VI's are an optical measure of vegetation canopy "greenness" (Glenn et al., 2008; Kumar et al., 2002), and for herbivores, green, photosynthetic vegetation is more nutritious and preferentially selected (Boone et al., 2006; Cross et al., 2004; Murray and Illius, 2000; Wilmshurst et al., 1999).

In light of the benefits of multispectral satellite-derived VI's, the 2016-2026 SANParks Mountain Zebra National Park (MZNP) management plan, part of the park's herbivory and habitat-vegetation management programs, aims to implement this remote sensing technique. The implementation of the multispectral satellite-derived VI's will assist in monitoring the condition of forage quantity and quality available for the range of herbivores present, in order to assist with making appropriate management decisions for their herbivore populations. The monitoring of forage quantity and quality for herbivores in MZNP is particularly important, as the park carries high densities of grazing ungulates due to the mosaic of vegetation types (varying in species composition, sward structure and height) and the persistence of grazing lawns found in the reserve (Novellie, 1990; Novellie and Gaylard, 2013). Intensive management is often practiced in MZNP, as the park is a small reserve and therefore there is not enough space for natural disturbance regimes, where fences restrict the spatial scale over which grazing and predator-prey dynamics can play out (Ferreira and Hofmeyr, 2014; Lindsey et al., 2009; Owen-Smith and Novellie, 1982). SANParks therefore often practice intensive management to mimic these natural processes, as small reserves, like MZNP, run the risk of massive herbivore die-offs and habitat degradation (Lindsey et al., 2009; Novellie, 1990; Novellie et al., 1991). One management practice employed, is the anthropological control of herbivore populations through either culling or live removals, and in some cases re-introduction or augmentation of populations (Knight et al., 2016; Lindsey et al., 2009). The assessment of forage quantity and quality available to herbivores in MZNP can thus assist with making appropriate recommendations for these management practices (Grant et al., 2011; Novellie and Gaylard, 2013; Scholes and Kruger, 2011).

The monitoring of forage quantity and quality for herbivores using multispectral satellite-derived VI's is based on the assessment of forage quantity and quality indicators (Garroutte et al., 2016; Kawamura et al., 2005; Ramoelo et al., 2012a). Studies tend to use biomass as an indicator of forage quantity (Garroutte et al., 2016; Sannier et al., 2002; Wessels et al., 2006), while different nutrients and their concentrations in the forage are generally used as indicators for forage quality (Kawamura et al., 2005; Ramoelo et al., 2015b; Skidmore et al., 2005). For MZNP, many permutations of multispectral satellite-derived VI's can be implemented, with each one having its own strengths and weaknesses in application, and some being more optimal at retrieving certain forage quantity and quality indicators than others (Frampton et al., 2013; Kumar et al., 2002). The multispectral satellite-derived Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and VI's incorporating red edge bands have, in particular, shown to have a relationship with forage quantity and quality indicators (Garroutte et al., 2016; Kawamura et al., 2005; Ramoelo et al., 2012b; Ullah et al., 2012). There are now many studies that show the relationship between multispectral satellite-derived VI's and forage quantity (e.g. Kawamura et al., 2008; Sannier et al., 2002; Wessels et al., 2006). However, limited research exists on the relationship between remotely sensed data and forage quality, with only specific forage nutrients (i.e., forage Nitrogen) having a relationship with multispectral satellite-derived VI's (Albayrak, 2008; Pullanagari et al., 2012; Starks et al., 2004; Zhao et al., 2007). Studies have also shown that the relationships between multispectral satellite-derived VI's and forage quantity and quality indicators vary across different landscapes, areas and vegetation types (Garroutte et al., 2016; Kawamura et al., 2005; Mutanga et al., 2004; Ramoelo et al., 2012b). Therefore, to provide confidence in the biological significance of the VI's estimates, and to ensure the appropriate implementation of VI's for MZNP management purposes, assessing the VI's relationships with forage quantity and quality indicators within the desired area is a prerequisite.

In this study, the relationship is investigated between formulated VI's derived from multispectral remote sensors, onboard the MODIS Terra and Sentinel-2 satellites, and forage quantity and quality indicators in MZNP. The satellites and their derived VI's were assessed because of their easy availability, free cost and strong relationship with forage quantity and quality indicators (Frampton et al., 2013; Garroutte et al., 2016; Kawamura et al., 2008; Ramoelo et al., 2015). This makes them suitable candidates for the operational requirements for MZNP and their management practices. Investigation of the studies VI's involves the determination of the relationship between *in situ* measured vegetation condition indicators (forage quantity and quality) and the VI's used (Ramoelo et al., 2018). This study aims to determine the relationship between multispectral satellite-derived VI's and forage quantity and quality for herbivores in MZNP. The aim is met with the objective to determine which forage quantity and quality indicators have a relationship with the different multispectral satellite-derived VI's in MZNP. However, before the VI's can be implemented in MZNP, the relationship between the forage quality indicators, related to the VI's, and the diets of the park's herbivores must be considered. Therefore, herbivore faecal samples are collected, analysed for specific forage quality indicators and related to the VI's. The objective of this component of the study is to determine the association between multispectral satellite-derived VI's, to assess forage quality indicators in the forage, and the utilization of these forage quality indicators in the diets of the herbivores in MZNP. The information provided in this study intends to determine the applicability and suitability of the different multispectral satellite-derived VI's to assess forage quantity and quality available for herbivores in MZNP, in order to assist in making appropriate management decisions for MZNP management practices.

Studying in MZNP aids management practices for the reserve's herbivore population, while MZNP provides an opportunity to study in a protected area that carries high densities of grazing ungulates. The vegetation types in MZNP also do not carry a high density of trees and thus there is a minimal effect of trees on the grass signal obtained by the remote sensors. Therefore, allowing the study to focus on the relationship between multispectral satellite-derived VI's and pasture type vegetation. Due to the benefits multispectral satellite-derived VI's can potentially have and because of the limited research available, there is a need to understand their relationship with forage quantity and quality, in respect to the different VI's available, the different forage quantity and quality indicators and the effects of the different environmental variables (e.g. season and vegetation type). Studying in MZNP provides the opportunity to understand further into this dynamic relationship between multispectral satellite-derived VI's and forage quantity and quality, and the information found cannot only be used for MZNP but as a model for much needed further research.

2.4.1 References

Albayrak, S., 2008. Use of reflectance measurements for the detection of N, P, K, ADF and NDF contents in sainfoin pasture. Sensors 8, 7275–7286.

Barboza, P.S., Parker, K.L., Hume, I.D., 2008. Integrative wildlife nutrition. Springer Science & Business Media.

Boone, R.B., Thirgood, S.J., Hopcraft, J.G.C., 2006. Serengeti wildebeest migratory patterns modeled from rainfall and new vegetation growth. Ecology 87, 1987–1994.

Christianson, D., Creel, S., 2009. Fecal chlorophyll describes the link between primary production and consumption in a terrestrial herbivore. Ecol. Appl. 19, 1323–1335.

Collier, P., Conway, G., Venables, T., 2008. Climate change and Africa. Oxford Rev. Econ. Policy 24, 337–353.

Cross, P.C., Owen-Smith, N., Macandza, V.A., 2004. Forage selection by African buffalo in the late dry season in two landscapes. South African J. Wildl. Res. delayed open access 34, 113–121.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Chang. 3, 52.

Ferreira, S.M., Hofmeyr, M., 2014. Managing charismatic carnivores in small areas: large felids in South Africa. South African J. Wildl. Res. delayed open access 44, 32–42.

Frampton, W.J., Dash, J., Watmough, G., Milton, E.J., 2013. Evaluating the capabilities of Sentinel-2 for quantitative estimation of biophysical variables in vegetation. ISPRS J. Photogramm. Remote Sens. 82, 83–92. https://doi.org/10.1016/j.isprsjprs.2013.04.007

Garroutte, E.L., Hansen, A.J., Lawrence, R.L., 2016. Using NDVI and EVI to map spatiotemporal variation in the biomass and quality of forage for migratory elk in the Greater Yellowstone Ecosystem. Remote Sens. 8, 404.

Glenn, E., Huete, A., Nagler, P., Nelson, S., 2008. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape. Sensors 8, 2136–2160.

Grant, R.C.C., Peel, M.J.S., Bezuidenhout, H., 2011. Evaluating herbivore management outcomes and associated vegetation impacts. Koedoe 53, 116–130.

Hill, M.J., 2013. Vegetation index suites as indicators of vegetation state in grassland and savanna: An analysis with simulated SENTINEL 2 data for a North American transect. Remote Sens. Environ. 137, 94–111. https://doi.org/10.1016/j.rse.2013.06.004

Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, G., Wang, S., 2005. Monitoring of forage conditions with MODIS imagery in the Xilingol steppe, Inner Mongolia. Int. J. Remote Sens. 26, 1423–1436.

Kawamura, K., Watanabe, N., Sakanoue, S., Inoue, Y., 2008. Estimating forage biomass and quality in a mixed sown pasture based on partial least squares regression with waveband selection. Grassl. Sci. 54, 131–145.

Knight, M.H., Novellie, P., Holness, S., du Toit, J., Ferreira, S., Hofmeyr, M., Grant, C., Herbst, M., Gaylard, A., 2016. Hands-on Approaches to Managing Antelopes and their Ecosystems: A South African Perspective. Antelope Conserv. From Diagnosis to Action 137.

Kumar, L., Schmidt, K., Dury, S., Skidmore, A., 2002. Imaging spectrometry and vegetation science, in: Imaging Spectrometry. Springer, pp. 111–155.

Li, X., Du, Y., Ling, F., 2014. Super-resolution mapping of forests with bitemporal different spatial resolution images based on the spatial-temporal Markov random field. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 7, 29–39.

Lindsey, P.A., Romanach, S.S., Davies-Mostert, H.T., 2009. The importance of conservancies for enhancing the value of game ranch land for large mammal conservation in southern Africa. J. Zool. 277, 99–105.

Murray, M.G., Illius, A.W., 2000. Vegetation modification and resource competition in grazing ungulates. Oikos 89, 501–

508.
Mutanga, O., Prins, H.H.T., Skidmore, A.K., van Wieren, S., Huizing, H., Grant, R., Peel, M., Biggs, H., 2004. Explaining grass-nutrient patterns in a savanna rangeland of southern Africa. J. Biogeogr. 31, 819–829.
Newmark, W.D., 2008. Isolation of African protected areas. Front. Ecol. Environ. 6, 321–328.
Novellie, P., 1990. Habitat use by indigenous grazing ungulates in relation to sward structure and veld condition. J. Grassl. Soc. South. Africa 7, 16–23.
Novellie, P., Gaylard, A., 2013. Long-term stability of grazing lawns in a small protected area, the Mountain Zebra National Park. koedoe 55, 0.
Novellie, P., Hall-Martin, A.J., Joubert, D., 1991. The problem of maintaining large herbivores in small conservation areas: deterioration of the grassveld in the Addo Elephant National Park. Koedoe 34, 41–50.
Olson, K.A., Murray, M.G., Fuller, T.K., 2010. Vegetation composition and nutritional quality of forage for gazelles in Eastern Mongolia. Rangel. Ecol. Manag. 63, 593–598.
Owen-Smith, N., Novellie, P., 1982. What should a clever ungulate eat? Am. Nat. 119, 151–178.
Pullanagari, R.R., Yule, I.J., Hedley, M.J., Tuohy, M.P., Dynes, R.A., King, W.M., 2012. Multi-spectral radiometry to estimate pasture quality components. Precis. Agric. 13, 442–456.
Ramoelo, A., Cho, M., Mathieu, R., Skidmore, A.K., 2015a. Potential of Sentinel-2 spectral configuration to assess rangeland quality. J. Appl. Remote Sens. 9, 94096.
Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., van de Kerchove, R., Kaszta, Z., Wolff, E., 2015b. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. Int. J. Appl. Earth Obs. Geoinf. 43, 43–54. https://doi.org/10.1016/j.jag.2014.12.010
Ramoelo, A., Cho, M.A., Mathieu, R.S.A., Skidmore, A.K., Schlerf, M., Heitkönig, I.M.A., 2012a. Estimating grass nutrients and biomass as an indicator of rangeland (forage) quality and quantity using remote sensing in Savanna ecosystems.
Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R., Heitkönig, I.M.A., 2012b. Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. Int. J. Appl. Earth Obs. Geoinf. 19, 151–162.
Ramoelo, A., Stolter, C., Joubert, D., Cho, M.A., Groengroeft, A., Madibela, O.R., Zimmermann, I., Pringle, H., 2018. Rangeland monitoring and assessment: a review. Klaus Hess Publishers.
Robbins, C., 2012. Wildlife feeding and nutrition. Elsevier.
Ryan, S.J., Cross, P.C., Winnie, J., Hay, C., Bowers, J., Getz, W.M., 2012. The utility of normalized difference vegetation index for predicting African buffalo forage quality. J. Wildl. Manage. 76, 1499–1508.
Ryan, S.J., Cross, P.C., Winnie, J., Hay, C., Bowers, J., Getz, W.M., 2012. The utility of normalized difference vegetation index for predicting African buffalo forage quality. J. Wildl. Manage. 76, 1499–1508. https://doi.org/10.1002/jwmg.407
Sannier, C.A.D., Taylor, J.C., Plessis, W. Du, 2002. Real-time monitoring of vegetation biomass with NOAA-AVHRR in Etosha National Park, Namibia, for fire risk assessment. Int. J. Remote Sens. 23, 71–89.
Scholes, R.J., Kruger, J.M., 2011. A framework for deriving and triggering thresholds for management intervention in uncertain, varying and time-lagged systems. koedoe 53, 179–186.
Seagle, S.W., McNaughton, S.J., 1992. Spatial variation in forage nutrient concentrations and the distribution of Serengeti grazing ungulates. Landsc. Ecol. 7, 229–241.
Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109, 16083–16088.
Skidmore, A.K., Mutanga, O., Schmidt, K., Ferwerda, J.G., 2005. Modelling herbivore grazing resources using hyperspectral remote sensing and GIS, in: AGILE 2005: 8th Conference on Geographic Information Science, Lisboa, AGILE, Denver, USA. Citeseer.
Southwood, T.R.E., Henderson, P.A., 2009. Ecological methods. John Wiley & Sons.
Starks, P.J., Coleman, S.W., Phillips, W.A., 2004. Determination of forage chemical composition using remote sensing. Rangel. Ecol. Manag. 57, 635–641.
Stolter, C., Ramoelo, A., Kesch, K., Madibela, O.R., Cho, M.A., Joubert, D.F., 2018. Forage quality and availability for large herbivores in southern African rangelands. Klaus Hess Publishers.
Ullah, S., Si, Y., Schlerf, M., Skidmore, A.K., Shafique, M., Iqbal, I.A., 2012. Estimation of grassland biomass and nitrogen using MERIS data. Int. J. Appl. earth Obs. Geoinf. 19, 196–204.
Wessels, K.J., Prince, S.D., Zambatis, N., MacFadyen, S., Frost, P.E., Van Zyl, D., 2006. Relationship between herbaceous biomass and 1-km2 Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa. Int. J. Remote Sens. 27, 951–973.
Wilmshurst, J.F., Fryxell, J.M., Farm, B.P., Sinclair, A.R.E., Henschel, C.P., 1999. Spatial distribution of Serengeti wildebeest in relation to resources. Can. J. Zool. 77, 1223–1232.
Wittemyer, G., Barner Rasmussen, H., Douglas-Hamilton, I., 2007. Breeding phenology in relation to NDVI variability in free-ranging African elephant. Ecography (Cop.). 30, 42–50.

Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. J. Plant Ecol. 1, 9–23. https://doi.org/10.1093/jpe/rtm005

Zhao, D., Starks, P.J., Brown, M.A., Phillips, W.A., Coleman, S.W., 2007. Assessment of forage biomass and quality parameters of bermudagrass using proximal sensing of pasture canopy reflectance. Grassl. Sci. 53, 39–49.

Chapter Two:
Use of multispectral satellite remote sensing derived vegetation indices to assess vegetation conditions: a review

2.1 Introduction

The monitoring and mapping of land use and cover is crucial to the efficient management of the land and its resources (Islam et al., 2011). Satellite remote sensing has long been considered an ideal technology (Franklin and Wulder, 2002). Multispectral remote sensors, in particular, are favoured by most studies (Govender et al., 2007) as it provides a practical and economical means for monitoring the earth (Nordberg and Evertson, 2005). Consequently, numerous earth observation satellites have been launched providing frequent remotely sensed data (Mutanga et al., 2016). Part of this data relates to information about the vegetation based on its unique spectral characteristics (Frampton et al., 2013). Thus, allowing for the potential of vegetation conditions (Mutanga et al., 2016) and dynamics to be assessed and monitored, as the satellites advantageously allow for synoptic coverage and repeated temporal sampling (Xie et al., 2008). Many techniques utilizing remotely sensed data have evolved to assess vegetation conditions with vegetation indices (VI's) providing one of the best possible methods (Frampton et al., 2013). The use of VI's has now shown in many studies to share a relationship with vegetation conditions and are widely used to provide quantitative ground measurements of biophysical parameters of the vegetation (Frampton et al., 2013).

Being able to monitor and assess vegetation conditions means that satellite-derived VI's holds great potential for successful land management. Their true value, however, is evident when it is applied as its success and limitations are realised. This paper evaluates the present value of satellite-derived VI's focusing on their application within three important fields of land management: conservation, precision agriculture and animal husbandry. Studies using the most popular and widely used multispectral satellite-derived VI's are discussed, and a background on satellite remote sensors and the formation of VI's is given.

2.2 Satellite remote sensing data sources

Remote sensors obtain and analyse electromagnetic radiation (visible, infrared, ultraviolet and microwave wavelengths) that is reflected, scattered or radiated from various objects on Earth (Kumar et al., 2002; Xie et al., 2008). Thus, capturing data about the land, oceans and atmosphere based on their unique spectral characteristics (Govender et al., 2007; Xie et al., 2008). There are many different remote sensors with different features and properties making them suitable for different objectives. Remote sensors have also progressed remarkably over the years with technological advancements in efficiency, cost, robustness and resolution (Houborg et al., 2015; Mutanga et al., 2016). Understanding these variations and changes is important, as they do affect the outcome of the formulated VI's and thus their relationship with vegetation conditions.

Remote sensors can come from a range of airborne to space-borne media, from multispectral (includes a dozen of spectral bands) to hyperspectral sensors (contains hundreds of spectral bands) and from different spatial resolutions and temporal frequencies (Govender et al., 2008; Kumar et al., 2002; Xie et al., 2008). Unmanned aerial vehicles (UAV's) and airborne aircrafts may provide high detailed imagery but are confined to smaller areas due to their limited payload, high cost and short flight endurance (Matese et al., 2015). Satellite remote sensors, particularly multispectral, are however freely available (Nagendra and Rocchini, 2008) and are thus preferred in most studies. Advantageously, satellite-derived remote sensors also allow for systematic observations at various spatial and temporal scales potentially providing large data archives (Irons et al., 2012; Tucker et al., 2005; Xie et al., 2008).

In the field of vegetation mapping the most commonly applied multispectral satellite remote sensors include Landsat (mainly TM and ETM+), SPOT, MODIS, NOAA–AVHRR, IKONOS and QuickBird (Table 2.1). Studies generally use remote sensors with low resolutions for large-scale mapping and identifying high-level vegetation classes (Xie et al., 2008). Higher resolution imagery is used more for fine detailed classifications and small-scale mapping (Beeri et al., 2007; Rounsevell et al., 2006).

The Landsat remote sensor, which is limited to low, coarse resolution, has the longest history and widest use for monitoring the earth from space (Irons et al., 2012; Xie et al., 2008). The Landsat sensor has the benefit of a large historical dataset, which helps to map long-term vegetation cover changes at regional scales (Irons et al., 2012; Roy et al., 2016). The Advanced Very High-Resolution Radiometer (AVHRR) is another remote sensor with a long history of land observation (García-Mora et al., 2012). The AVHRR is a popular tool because of its low cost and high probability of obtaining a cloud free image (Oesterheld et al., 1998; Wessels et al., 2006). The AVHRR remote sensor does, however, have calibrating and spectral limitations, which tend to produce substantial errors (Wang et al., 2003; Xie et al., 2008). Vegetation mapping by medium resolution sensor SPOT (VGT) and coarse resolution remote sensor MODIS represent improved measurements of surface vegetation cover (García-Mora et al., 2012; Tucker et al., 2005). The SPOT (VGT) and The MODIS sensor provides upgraded radiometric and geometric properties with more precise data processing methods (Tucker et al., 2005; Zhang et al., 2003). Unlike coarse and medium resolution sensors, high resolution sensors

(IKONOS and QuickBird) are less affected by spatial heterogeneity and are capable of direct identification of certain species and species communities (Turner et al., 2003). Problematically, data retrieved by IKONOS and QuickBird must be purchased on-demand, is expensive and requires greater computational resources (Marshall and Thenkabail, 2015). Hyperspectral remote sensing, on the other hand, encompasses hundreds of spectral bands, thus providing more vegetation information which can be used for more accurate vegetation mapping (Marshall and Thenkabail, 2015). The Hyperion instrument, on board the Earth Observing-1 (EO-1) satellite, is the world's first and currently only satellite that carries a hyperspectral sensor (Turner et al., 2003). The Hyperion with its high spatial resolution can provide detailed accurate information however, it does not provide global coverage and has a long revisit rate (16 days: Davis et al., 2008). The processing of hyperspectral data also remains a challenge, as specialized, cost-effective and computationally efficient procedures are still required to process a large number of spectral bands (Varshney and Arora, 2004). Ideally, specific bands found using hyperspectral remote sensors, which best characterize different vegetation characteristics, should be incorporated into multispectral systems (Govender et al., 2008; Mutanga et al., 2016).

The demand for quick, accurate, up-to-date and cost-effective information about land cover has pushed the launch of new multispectral remote sensing satellites such as the RapidEye (2008), WorldView-2 (2009), LANDSAT-8 (2013) and Sentinel-2 (2014) (Palchowdhuri et al., 2018). These remote sensors open up new perspectives by offering high spatial and spectral resolutions with rapid revisit rates (Houborg et al., 2015; Xie et al., 2008). The new Landsat-8 (2013) satellite provides free data that extends the Landsat record (Roy et al., 2016) with improvements in satellite, sensor and data processing capabilities (Irons et al., 2012). The RapidEye and WorldView-2 remote sensing instruments include a band in the red-edge spectrum recognized as key for improving chlorophyll and nitrogen retrieval capabilities (Ramoelo et al., 2012, 2015b). However, their potential for more precise vegetation condition monitoring has not been fully realised due to their expensive acquisition (Houborg et al., 2015). The Sentinel-2 satellites (S-2A, S-2B) aim to solve the expensive acquisition costs by delivering multispectral data (including 2 narrow bands in the red-edge) at high resolutions, with the opportunity to monitor the state and function of vegetation routinely and globally at no cost (Frampton et al., 2013; Houborg et al., 2015).

Table 2.1: The main features and vegetation mapping applications for the different satellite remote sensors.

Satellite remote sensors	Features	Vegetation mapping applications
SPOT	Multispectral medium spatial resolution from 2.5 m to 1 km. Revisit frequency of 1 day	Vegetation mapping at a regional scale. Higher resolution can map at community and species level.
MODIS	Multispectral medium spatial resolution from 250 m to 1 km. Revisit frequency of 1-2 days.	Vegetation mapping for large scale cover types.
AVHRR	Multispectral low spatial resolution of 1 km with data from the NOAA satellite series (1980 to present)	Vegetation mapping for large scale cover types.
IKONOS	Multispectral high spatial resolution from 1 m to 4 m. Revisit frequency 1-3 days.	Vegetation mapping for local and regional scale. Suitable for mapping at community and species level.
Quickbird	Multispectral high spatial resolution from 0.6 m to 2.4 m. Revisit frequency 1-3.5 days	Vegetation mapping for local and regional scale. Suitable for mapping at community and species level.
Hyperion	Hyperspectral high spatial resolution of 30 m. Revisit frequency of 5 days. Contains hundreds of spectral bands.	Vegetation mapping for local and regional scale. Suitable for mapping at community and species level.
Sentinel-2	Multispectral high spatial resolution of 20 m. Revisit frequency 5 days. Contains 13 spectral bands.	Vegetation mapping for local and regional scale. Contains red-edge bands that are known to share a strong relationship with forage nitrogen.
Landsat	Multispectral spatial resolution at 15 m, 30 m and 100 m. Revisit frequency of 8 days.	Vegetation mapping for local to regional scale. Continues Landsat TM data records with greater accuracy than its predecessors.
RapidEye	Multispectral high spatial resolution of 6.5 m. Contains only five spectral bands. Revisit frequency of 1 day.	Vegetation mapping for local and regional scale. Contains a red-edge band that is known to share a strong relationship with forage nitrogen.
Worldview-2	Multispectral high spatial resolution of 1.84 m. Contains only eight spectral bands. Revisit frequency of 1.1 days.	Vegetation mapping for local and regional scale. Suitable for highly dense vegetation types. Contains red-edge band that are known to share a strong relationship with forage nitrogen.

2.3 Vegetation Indices

Satellite-derived VI's provide one of the best possible methods to assess and monitor vegetation conditions, as they have the benefit of being computationally simple, non-destructive, generally less site-specific and more universally applicable than other methods (Frampton et al., 2013). Essentially, VI's are a spectral transformation of two or more bands (Huete et al., 1999), a ratio formulated from different reflective wavelengths measured and obtained by a remote sensor. Vegetation indices can be simply divided according to the wavelength characteristics used in their formula (broadband and narrowband indices: Agapiou et al., 2012). Broadband VI's use, in principle, wider bands that encompass a basic average of spectral information over a large range, while the narrowband VI's use spectral data from more distinct short bands (Hansen and Schjoerring, 2003). Both band types aim to enhance vegetation sensitivity with minimal variations in external influences (atmosphere, view and sun angles, clouds) and non-vegetation influences (canopy background, litter: Huete et al., 1999). Thus producing information purely based on surface vegetation.

There are many permutations of VI's, each designed for a separate purpose and validated at varying levels using different datasets (Frampton et al., 2013). The first VI's formulated were broadband VI's built on the observation that chlorophyll absorbs light in the red part of the electromagnetic spectrum, while cell walls strongly scatter light in the near-infrared spectrum (NIR: Glenn et al., 2008). The information found formed the Simple Ratio (SR), a contrast between the near-infrared and red wavebands (Jordan, 1969). The SR forms the base of most VI's, in particular, the most commonly used Normalised Difference Vegetation Index (NDVI: Rouse Jr et al., 1973). The NDVI is aimed for Leaf Area Index (LAI) retrieval and its long term use means a large number of data records for operational monitoring studies can be found (Huete et al., 2002). The NDVI normalizes values between -1 to +1; with dense vegetation having a high NDVI, while NDVI values reflecting soil and water are low to negative (Huete et al., 1997). The strength of the NDVI is its ability to reduce many forms of multiplicative noise (illumination differences, cloud shadows, and certain topographic variations: Ahmad, 2012). Despite its usefulness in vegetation studies, the use of NDVI does have some limitations. These impediments include spatial scaling problems, insensitivity (saturation) under high biomass conditions and a high susceptibility to canopy background brightness (e.g. high soil reflectances at low canopy densities; Huete et al., 2002; Huete, 1988; Xue and Su, 2017). To enhance the vegetation signal with improved sensitivity to canopy structure and high biomass regions the Enhanced Vegetation Index (EVI) was designed (Huete et al., 2002, 1997; Wang et al., 2003). The EVI improves vegetation monitoring (Jiang et al., 2008) by using the red and NIR bands, as the NDVI, but with the addition of the blue band. Results in studies have shown that EVI and NDVI values differ, with NDVI being generally higher than EVI values (Evrendilek and Gulbeyaz, 2008; Kawamura et al., 2005; Li et al., 2010). The reason for higher NDVI values could be due to the VI's known saturation under high biomass conditions and susceptibility to canopy background brightness (Huete et al., 2002; Huete, 1988; Kawamura et al., 2005). For example, research by Huete (2002) found the mean EVI value in the dry cerrado regions in Brazil was 0.4 with a corresponding NDVI value of 0.7 (difference, 0.3). While the difference between NDVI and EVI values decreased in the primary and secondary forest sites, the EVI values approached 0.8, while the NDVI became asymptotic at about 0.9 (difference, approximately 0.1). Despite the impediment of the NDVI, studies that have compared the relationship between the NDVI and EVI with vegetation parameters have found mixed results. A study by van Leeuwen (1999) found the EVI to be superior to the NDVI when relating the VI's to photosynthetically active radiation, leaf area index and biomass of vegetation. While other studies have found the NDVI to explain more variation in biomass and quality than the EVI (Garroutte et al., 2016; Li et al., 2010). A study by Kawamura, (2005) also found total and live biomass results more related to NDVI values, however, the study found forage crude protein to be more related to the EVI. Variations in study results could be due to the different localities the research was conducted, as other studies have shown the relationships between VI's and vegetation parameters vary across different landscapes and vegetation types (Garroutte et al., 2016; Guerschman et al., 2009; Mutanga et al., 2004; Ramoelo et al., 2012; Sims et al., 2008). Another vegetation index developed to minimise non-photosynthetic effects, is the Green Normalised Difference Vegetation Index (GNDVI: Gitelson et al., 1996). The GNDVI is a variation of the NDVI but replaces information obtained by red reflectance with information from the green reflectance spectrum (Gitelson et al., 1996). The GNDVI is more sensitive to chlorophyll concentrations than NDVI but does encounter issues at low LAI when background variation has a higher influence (Glenn et al., 2008).

After the success of the NDVI and its refinements, subsequent work made use of narrow-band VI's due to new developments in the spectral capabilities of remote sensors to better characterize the red-edge (RE: Frampton et al., 2013). The RE refers to the region located between the Red and NIR bands and is often achieved by calculation of the red-edge position (REP), which is recognised as the point of maximum slope along these bands (Horler et al., 1983). Indices incorporating the REP are less sensitive to background effects (Elvidge and Chen, 1995). There are also specific bands located within the RE spectrum, called red edge bands, which have now been incorporated into VI's (Frampton et al., 2013). A study by Gitelson et al. (2006, 2003) presented a simple index based on a NIR band and a red-edge band called the red-edge chlorophyll index ($Chlr_{ed\text{-}edge}$). The same study also presented a variant using a green band instead of the red-edge band called the green chlorophyll index (CI_{green}). A major advantage of these two VI's is their linear relationship with chlorophyll and the absence of the saturation effect as obtained with REP values (Clevers and Kooistra, 2012).

2.4 Application

Satellite-derived vegetation indices, in their simplest form, are optical measures of canopy "greenness", a composite property of leaf chlorophyll content, leaf area, canopy cover and structure (Jiang et al., 2008). Canopy light absorption is tightly related to the green leaf area index (LAI), and the photosynthetic pigments of green leaves are responsible for the absorption of photosynthetically active radiation (PAR: Boegh et al., 2002). Thus, this allows for canopy photosynthetic rates, LAI, absorbed PAR, and chlorophyll concentrations to be identified by wave reflectance's, as they are all intercorrelated (Boegh et al., 2002). Knowledge of these variables can indicate plant health, gross primary productivity (Gitelson et al., 2006) and the physiological status of vegetation (Glenn et al., 2008).

There are now numerous studies that show relationships between satellite-derived VI's and leaf area (Omer et al., 2016; Wang et al., 2005), canopy chlorophyll content (Clevers and Gitelson, 2013; Wong and He, 2013), green vegetation fraction (Gutman and Ignatov, 1998; Zeng et al., 2000), gross primary productivity (GPP) (Sims et al., 2008; Xiao et al., 2004), fraction of photosynthetically active radiation (FAPAR) (Chen, 1996; Cristiano et al., 2010) and quantity and quality of the vegetation (Kawamura et al., 2005; Ramoelo et al., 2015a; Ryan et al., 2012). The ability to assess vegetation conditions means that satellite-derived VI's can be utilised in the fields of conservation, precision agriculture and animal husbandry.

2.4.1 Conservation

Satellite-derived VI's have become crucial in conservation, assisting in the assessment of ecosystems that have experienced increased threats from climate change and human-induced activities (Lu et al., 2015; Pettorelli et al., 2011; Turner et al., 2003). For example, Tang et al. (2011) provided a global analysis of the role of protected areas in maintaining ecological processes. The study was done by using the NDVI as a measure of the variation over a 25-year period of plant production in the core, boundary and surroundings of more than 1000 protected areas. Work done by Pelkey et al. (2000), also using the NDVI time series, showed that national parks in Tanzania presented significantly better conservation status than the non-protected areas. Zhang et al. (2009) used MODIS VI's to show changes in vegetation conditions in the Three Gorges Reservoir area (China) after the construction of a hydropower. Satellite-derived VI's are also used to identify agricultural practices, which is important as cultivation of the land intensifies and opportunities for expansion are being exhausted (Ozdogan et al., 2010). The intensification of agricultural practices has dramatically altered the relationship between humans and environmental systems across the world (Ozdogan et al., 2010). Therefore, it's important to monitor this landscape change and researchers are using the MODIS NDVI and EVI to map crop classes at farm field-level (Brown et al., 2013). Thus allowing for the monitoring of deforestation trends (Clark et al., 2010; Jin and Sader, 2005), cropping frequency changes (i.e., number of crops per year: Epiphanio et al., 2010; Wardlow et al., 2007) and effectiveness of agri-environmental governance systems (Rudorff et al., 2011). There is, however, a need for remote sensing research communities and environmentalists to shift towards embracing the newly launched readily available multispectral sensors (i.e., RapidEye, Worldview-2 and Sentinel-2: Timothy et al., 2016). Literature shows that VI's from these sensors perform better than traditional multispectral methods due to their enhanced sensitivity to vegetation properties, such as plant productivity, biomass and chlorophyll content (Eckert, 2012; Mutanga et al., 2012).

Satellite-derived VI's have also been applied to assist monitoring programs on climate change and provide key inputs into climate models. This is because land cover (including vegetation type), LAI and FAPAR are all Global Climate Observing System (GCOS) Essential Climate Variables (ECVs), required by the United Nations Framework Convention on Climate Change (UNFCCC: Secretariat, 2009). Studies also use satellite-derived VI's in combination with data from flux towers and meteorological stations to measure carbon and moisture fluxes (Glenn et al., 2008). For example, Potter et al. (2007) used the MODIS EVI with flux tower data for carbon fixation measurements across the United States.

The conservation of biodiversity has also been assisted by the use of satellite-derived VI's, with high-resolution sensors IKONOS, QuickBird and Hyperion used to identify plant species richness which can assist ecological research and monitoring programs. For example, Walsh et al. (2008) used QuickBird and hyperspectral Hyperion data to map and analyse the dynamics of different invasive plant species on the Galapagos, deriving recommendations for control and land-use management. Problematically, limitations associated with such high resolution datasets include cost, availability and large data volumes (Mutanga et al., 2016). Other satellite-derived VI's from coarse resolution sensors (e.g. MODIS) have been applied successfully to monitor and assess herbivore population dynamics. The success in these studies is due to the biology of herbivores, which are tightly coupled to the quantity and quality of forage plants and their life histories and behaviour (i.e., species distribution and abundance) are structured around seasonal patterns of plant growth (Pettorelli et al., 2009; Ryan et al., 2007). For example, the MODIS NDVI and EVI based estimates of vegetation growth were used to assist in understanding migratory elk (*Cervus elaphus*) movements in the Greater Yellowstone Ecosystem (Garroutte et al., 2016). Similarly, Sesnie et al. (2012) modelled the habitat suitability and movements of desert bighorn sheep (*Ovis canadensis nelson*) in the Sonoran Desert, by using MODIS VI's. Studies have also correlated NDVI and EVI with reproductive timing in both African buffalo (*Syncerus caffer*: Ryan et al., 2007) and caribou (*Rangifer tarandus*: Couturier et al., 2009). Many studies have provided valuable knowledge for appropriate conservation and wildlife management practices using satellite-derived VIs (Hamel et al., 2009). The utility of remote sensing to inform decisions pertaining to biodiversity conservation has therefore been demonstrated, but there is scope to improve this with multiscale remote sensing data.

2.4.2 Precision agriculture

Remote sensing techniques are widely used in agriculture and agronomy (Atzberger, 2013) because they can characterize the extent, distribution and condition of croplands (Frolking et al., 2002; Thenkabail et al., 2009). Measuring forage quantity, satellite-derived VI's can also estimate crop yields (Doraiswamy et al., 2003). There are now many successful studies that use VI's derived from coarse satellite sensors (e.g. MODIS and AVHRR) for crop yield/production estimations (Bala and Islam, 2009; Ren et al., 2008; Vicente-Serrano et al., 2006). Applying satellite-derived VI's can also assist crop forecasting. Realising the considerable potential, NASA and the USDA Foreign Agricultural Service (FAS) have initiated the Global Agricultural Monitoring (GLAM) Project (Becker-Reshef et al., 2010, 2009). The GLAM project provides data from NASA's MODIS to ensure regular, timely, objective crop production forecasts on a global scale (Atzberger, 2013). The use of high spatial resolution and newly launched satellite remote sensors can provide even more precise data sources for determining plant growth and yield patterns (Yang et al., 2006). For instance, Yang et al. (2006) showed that the remote sensor QuickBird can be precise in mapping grain sorghum yields and Upadhyay et al. (2012) showed the use of WorldView-2 to be even more effective than the QuickBird. Studies also showed that the popular NDVI presented complications for assessing crop vegetation due to confounding soil background effects and that the GNDVI performed much better (Chang et al., 2005; Shanahan et al., 2001). Despite the benefits of using VI's, only larger commercial farms can often afford to pay for high resolution remote sensing data (Mulla, 2013).

The advancements in optical sensor technology has facilitated a great opportunity for understanding vegetation health, which was a research area that was previously regarded as complex (Mutanga et al., 2016). Essentially, plant leaf chlorophyll content and other photosynthetic variables can be good indicators of photosynthetic activity, mutations, stress and nutritional status of crops (Wu et al., 2008). Thus, studies have successfully used satellite-derived VI's in assessing nutrient and water stress (Clay et al., 2006; Tilling et al., 2007), infestations of weeds (Thorp and Tian, 2004) and diseases (Abdel-Rahman et al., 2014; Oumar and Mutanga, 2011) in crops and plantation forests.

Satellite observations can also be used for the monitoring of drought conditions (Gu et al., 2007). Droughts are one of the major natural hazards affecting the agricultural sector and the economies of countries worldwide (Peters et al., 2002). Reliance on weather data alone is not sufficient in monitoring areas of drought (Peters et al., 2002) and currently VI's play an important role for vegetation drought monitoring (Brown et al., 2008; Gu et al., 2007; Karnieli et al., 2010; Kogan, 1995). The monitoring is based on using the high temporal scale capabilities that satellites provide, as VI's are compared against each other over a large time scale with their minimum and maximum values compiled per pixel over time (Peters et al., 2002). The concept was developed by Kogan, (1990) who used the NDVI statistical range to develop the Vegetation Condition Index, which is an indicator of environmental stress. Burgan and Hartford (1993) used a similar concept to monitor drought where the "relative greenness" of vegetation identified by remote sensors were expressed. This "relative greenness" was calculated as a percentage value of each vegetation index pixel with the average greenness over the historical record of that same pixel. The MODIS NDVI and EVI, in particular, have been used to monitor drought conditions in various parts of the world. For example, Zhang et al. (2012) used the MODIS EVI to show drought effects in southwestern China during spring. While Son et al. (2012) used instead the MODIS NDVI to identify agricultural drought in the Lower Mekong Basin. Drought monitoring has become even more crucial in today's world, with droughts becoming more prominent in specific areas due to climate change (Collier et al., 2008; Dai, 2013).

Another use of the MODIS NDVI and EVI is the prediction of evapotranspiration of crops which can be monitored over entire irrigation districts (Glenn et al., 2011). Monitoring crop evapotranspiration agricultural water can be reduced by matching irrigation rates to the actual water needs of crops (Glenn et al., 2011). A study by Maselli et al. (2014) successfully monitored daily evapotranspiration of crops using a combination of MODIS NDVI and ground meteorological data in Central Italy. Monitoring the evapotranspiration of crops can allow for successful resource water management especially for planning responses to ongoing climate change (Mu et al., 2011, 2007).

2.4.3 Animal husbandry

Satellite remote sensing is a powerful tool for assisting in grassland resource management (Tueller, 1989) and has thus been increasingly applied in animal science (Pullanagari et al., 2013). Remote sensing VI's have gained considerable attention in research specifically for their shared relationship with forage quantity and quality indicators (Garroutte et al., 2016). The information found is useful to guide farmers, planners and managers towards sustainable management of their grazing land (Ramoelo et al., 2012). For instance, work done by Kawamura et al. (2005) and Long et al. (2010) have been successful in determining livestock carrying capacity by using the MODIS NDVI and EVI as a monitoring tool for forage quantity (biomass) and quality (forage nutrients) indicators. While other studies, to determine diet quality, have been successful in relating forage quality indicators in the faeces of herbivores (particularly faecal nitrogen and minerals) to the MODIS NDVI and EVI (Creech et al., 2016; Hamel et al., 2009; Lendrum et al., 2014; Ryan et al., 2012; Villamuelas et al., 2016). Numerous studies have also successfully shown a relationship between satellite-derived VI's and the forage quantity indicator biomass (e.g. Garroutte et al., 2016; Kawamura et al., 2005; Ramoelo et al., 2015b). However, there is an apparent lack of studies on the relationship between remote sensing data and forage quality indicators (forage nutrients: Zhao et al., 2007).

Forage quality refers to key nutrient components such as protein, fiber, minerals, ash, organic matter digestibility (OMD), sugars and metabolizable energy (Pullanagari et al., 2013). The components and their concentrations in the forage can be used as forage quality indicators (Ball et al., 2001; Barboza et al., 2008; Pullanagari et al., 2013). The estimation of these forage quality indicators using traditional NDVI and simple ratio (SR) is sometimes not conducive, as they are insensitive to subtle concentration changes of the nutrients within the forage (Ramoelo et al., 2012). The use of new satellite multispectral remote sensors have been successful in retrieving more accurate readings of forage quality indicators. Work done by Ramoelo et al. (2015b, 2012) using the satellites WorldView-2 and RapidEye remote sensors (with the red edge band capability) demonstrated higher accurate detection of forage nitrogen. Clevers and Gitelson (2013) also showed high accurate readings of nitrogen levels but using the Sentinel-2 Red-Edge Chlorophyll Index ($CI_{red\text{-}edge}$) and Green Chlorophyll Index (CI_{green}). The Sentinel-2 Chlorophyll Red-Edge Index (Chlred-edge) is another variant and although the product is easily available and accessible no studies, to our knowledge, have applied the index to identify forage quality indicators.

Regarding the other forage quality indicators, Mutanga et al. (2004) found that concentrations of phosphorus, potassium, calcium and magnesium in grass pastures could only be predicted using the full wavelength range of a hyperspectral remote sensor. Starks et al. (2006) investigated neutral and acid detergent fiber (NDF, ADF) and crude protein (CP) concentrations with multispectral wavebands and VI's (NDVI and SR) and found that each could only explain a small portion of the variability in the forage. The reason for limited studies on forage quality indicators is because the most important wavebands for their estimations are often not found on the more appropriate and suitable multispectral sensors or have not even yet been determined (Mutanga et al., 2016; Zhao et al., 2007). Multispectral remote sensors that do obtain suitable wavebands that share a relationship with forage nutrients have high costs and restricted accessibility (i.e. RapidEye and Worldview; Timothy et al., 2016). The Sentinel-2, however, contains optimal bands for forage quality assessments with data being freely available. The Sentinel-2, therefore, is now the current focus of research, as there is a lack of implemented multispectral remote sensing VI's and hyperspectral data is still required to find correlations between specific wavebands and biochemical concentrations.

Table 2.2 shows the available research and statistical analysis used by studies to determine the relationship between remotely sensed data and forage quantity and quality indicators. The conventional approach relates a specific forage quantity or quality (nutrient) indicator to wavebands or VI's derived from remote sensing data using a variety of statistical regression techniques (Darvishzadeh et al., 2008; Haboudane et al., 2004; Hansen and Schjoerring, 2003; Mutanga et al., 2004). Common and simple statistical techniques include stepwise multiple linear regression (SMLR: Ramoelo et al., 2012). However, SMLR suffers from overfitting and multicollinearity (Curran et al., 1997; Kokaly et al., 2009). To date, there are a series of machine learning techniques such as random forest (RF: Mutanga et al., 2012) and artificial neural network (ANN) that are also now applicable (Knox et al., 2011; Skidmore et al., 2010). These latter techniques, particularly RF, were found to be more robust and they circumvent the overfitting and multicollinearity problem when estimating vegetation parameters (Mutanga et al., 2012; Ramoelo et al., 2015a).

Table 2.2: Studies showing the relationship between remote sensing data and forage quantity and quality indicators. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Red-Edge Chlorophyll Index. CP = Crude Protein, N = Nitrogen, P = Phosphorus, K =potassium, NDF = Neutral Detergent Fibre, ADF = Acid Detergent Fibre.

Forage quantity and quality indicators	Remote sensor	Vegetation Index	Grassland type	Statistical analysis	Outcome	Reference
CP and biomass	MODIS	NDVI EVI	Rangeland	Simple linear regression (linear and exponential terms fitted).	EVI explained 74% of standing CP and NDVI explained 77-83% of biomass ($P \leq 0.01$).	Kawamura et al. (2005)
CP and biomass	MODIS	NDVI EVI	Rangeland	Simple linear regression (linear term fitted).	NDVI performed the best and explained 9-14% CP and 55% biomass ($P \leq 0.05$).	Garroutte et al. (2016)
N	Sentinel-2	Separate wavebands	Rangeland	RF, SMLR, PCA and PLSR.	Explained 90% forage N variation ($P \leq 0.05$).	Ramoelo et al. (2015a)
N	Sentinel-2	$Chl_{red\text{-}edge}$ CI_{green}	Cropland	CV% (ratio of RMSEP using simple linear regression and content value).	$Chl_{red\text{-}edge}$ ($R^2 = 0.80$; $P \leq 0.05$) and CI_{green} ($R^2 = 0.80$; $P \leq 0.05$).	Clevers and Gitelson (2013)
N, P, K, NDF and ADF	Handheld spectro-radiometer	Multiple wavebands	Managed pasture	SLR to obtain coefficient of determination (r^2).	r^2 for N, P, K, NDF and ADF (0.87, 0.91, 0.83, 0.86 and 0.93: $P \leq 0.05$).	Albayrak (2008)
CP, NDF, ADF and biomass.	Handheld spectro-radiometer	Multiple wavebands and reflectance ratios	Managed pasture	Pearson's correlation coefficient (r).	r^2 of reflectance ratios and NDVI small but significant ($P \leq 0.05$).	Starks et al. (2006)
CP, NDf, ADF and biomass	Handheld spectroradiometer	Multiple wavebands and reflectance ratios	Managed pasture	Simple linear regression, MLR and PLSR.	CP ($R^2 = 0.61$), NDF and ADF (R^2=0.13 – 0.35).Biomass (R^2=0.13). All significant: $P < 0.001$).	Zhao et al. (2007)

MLR: multiple linear regressions; RF: random forest; SLR: stepwise linear regression; SMLR: stepwise multiple linear regression; PCA: principal component analysis; PLSR: partial least square regression. CV%: coefficient of variance. RMSEP: root mean square error of prediction.

2.5. Conclusion

The use of remote sensing is beneficial for effective and sustainable land management. Multispectral satellite remote sensors, compared to other devices, can provide more informative and easily accessible information about vegetation condition, which has assisted towards the advancement of conservation, precision agriculture and animal husbandry management. The application of VI's to interpret remote sensing data appears to be one of the best possible methods, as it is simple and universally applicable. The progress of technology also holds incredible potential for successful new developments and modifications of remote sensors and its derived VI's. A major limitation seems to be the high cost of obtaining data from some remote sensors, particularly from the newly available sensor's "RapidEye, Worldview-2, IKONOS, etc.". The high cost is problematic as studies have shown that new, more refined sensors, can provide improved results. Thus, the monitoring and assessing of vegetation conditions using remote sensors has not reached its full potential. The Sentinel-2 satellite seems to rectify this impediment, but more field studies, validation and re-calibration is required. Studies also show that hyperspectral remote sensing holds great promise but its accessibility, data handling and cost inhibit the sensors progress. The potential solution is finding optimal bands in hyperspectral systems and incorporating them into multispectral sensors. Therefore, the future of remote sensing and its subsequent VI's lies in the ability to move from impractical large data sets and high costs to practical low data volumes, cost efficiency and high temporal frequencies and spatial resolutions. Ultimately, the goal is to provide valuable information which can meet the operational requirements for land managers.

2.6. References

Abdel-Rahman, E.M., Mutanga, O., Odindi, J., Adam, E., Odindo, A., Ismail, R., 2014. A comparison of partial least squares (PLS) and sparse PLS regressions for predicting yield of Swiss chard grown under different irrigation water sources using hyperspectral data. Comput. Electron. Agric. 106, 11–19.

Agapiou, A., Hadjimitsis, D., Alexakis, D., 2012. Evaluation of broadband and narrowband vegetation indices for the identification of archaeological crop marks. Remote Sens. 4, 3892–3919.

Ahmad, F., 2012. A review of remote sensing data change detection: Comparison of Faisalabad and Multan Districts, Punjab Province, Pakistan. J. Geogr. Reg. Plan. 5, 236–251.

Albayrak, S., 2008. Use of reflectance measurements for the detection of N, P, K, ADF and NDF contents in sainfoin pasture. Sensors 8, 7275–7286.

Atzberger, C., 2013. Advances in remote sensing of agriculture: Context description, existing operational monitoring systems and major information needs. Remote Sens. 5, 949–981.

Bala, S.K., Islam, A.S., 2009. Correlation between potato yield and MODIS-derived vegetation indices. Int. J. Remote Sens. 30, 2491–2507.

Ball, D.M., Collins, M., Lacefield, G.D., Martin, N.P., Mertens, D.A., Olson, K.E., Putnam, D.H., Undersander, D.J., Wolf, M.W., 2001. Understanding forage quality. Am. Farm Bur. Fed. Publ. 1.

Barboza, P.S., Parker, K.L., Hume, I.D., 2008. Integrative wildlife nutrition. Springer Science & Business Media.

Becker-Reshef, I., Justice, C., Doorn, B., Reynolds, C., Anyamba, A., Tucker, C.J., Korontzi, S., 2009. NASA's contribution to the Group on Earth Observations (GEO) Global Agricultural Monitoring System of Systems. NASA Earth Obs. 21, 24–29.

Becker-Reshef, I., Justice, C., Sullivan, M., Vermote, E., Tucker, C., Anyamba, A., Small, J., Pak, E., Masuoka, E., Schmaltz, J., 2010. Monitoring global croplands with coarse resolution earth observations: The Global Agriculture Monitoring (GLAM) project. Remote Sens. 2, 1589–1609.

Beeri, O., Phillips, R., Hendrickson, J., Frank, A.B., Kronberg, S., 2007. Estimating forage quantity and quality using aerial hyperspectral imagery for northern mixed-grass prairie. Remote Sens. Environ. 110, 216–225.

Boegh, E., Søgaard, H., Broge, N., Hasager, C.B., Jensen, N.O., Schelde, K., Thomsen, A., 2002. Airborne multispectral data for quantifying leaf area index, nitrogen concentration, and photosynthetic efficiency in agriculture. Remote Sens. Environ. 81, 179–193.

Brown, J.C., Kastens, J.H., Coutinho, A.C., de Castro Victoria, D., Bishop, C.R., 2013. Classifying multiyear agricultural land use data from Mato Grosso using time-series MODIS vegetation index data. Remote Sens. Environ. 130, 39–50.

Brown, J.F., Wardlow, B.D., Tadesse, T., Hayes, M.J., Reed, B.C., 2008. The Vegetation Drought Response Index (VegDRI): A new integrated approach for monitoring drought stress in vegetation. GIScience Remote Sens. 45, 16–46.

Burgan, R.E., Hartford, R.A., 1993. Monitoring vegetation greenness with satellite data. US Department of Agriculture, Forest Service, Intermountain Research Station ….

Chang, K.-W., Shen, Y., Lo, J.-C., 2005. Predicting rice yield using canopy reflectance measured at booting stage. Agron. J. 97, 872–878.

Chen, J.M., 1996. Canopy architecture and remote sensing of the fraction of photosynthetically active radiation absorbed by boreal conifer forests. IEEE Trans. Geosci. Remote Sens. 34, 1353–1368.

Clark, M.L., Aide, T.M., Grau, H.R., Riner, G., 2010. A scalable approach to mapping annual land cover at 250 m using MODIS time series data: A case study in the Dry Chaco ecoregion of South America. Remote Sens. Environ. 114, 2816–2832.

Clay, D.E., Kim, K.-I., Chang, J., Clay, S.A., Dalsted, K., 2006. Characterizing water and nitrogen stress in corn using remote sensing. Agron. J. 98, 579–587.

Clevers, J.G.P.W., Gitelson, A.A., 2013. Remote estimation of crop and grass chlorophyll and nitrogen content using red-edge bands on Sentinel-2 and-3. Int. J. Appl. Earth Obs. Geoinf. 23, 344–351.

Clevers, J.G.P.W., Kooistra, L., 2012. Using hyperspectral remote sensing data for retrieving canopy chlorophyll and nitrogen content. IEEE J. Sel. Top. Appl. earth Obs. Remote Sens. 5, 574–583.

Collier, P., Conway, G., Venables, T., 2008. Climate change and Africa. Oxford Rev. Econ. Policy 24, 337–353.

Couturier, S., Côté, S.D., Otto, R.D., Weladji, R.B., Huot, J., 2009. Variation in calf body mass in migratory caribou: the role of habitat, climate, and movements. J. Mammal. 90, 442–452.

Creech, T.G., Epps, C.W., Monello, R.J., Wehausen, J.D., 2016. Predicting diet quality and genetic diversity of a desert-adapted ungulate with NDVI. J. Arid Environ. 127, 160–170.

Cristiano, P.M., Posse, G., Di Bella, C.M., Jaimes, F.R., 2010. Uncertainties in fPAR estimation of grass canopies under different stress situations and differences in architecture. Int. J. Remote Sens. 31, 4095–4109.

Curran, P.J., Kupiec, J.A., Smith, G.M., 1997. Remote sensing the biochemical composition of a slash pine canopy. IEEE Trans. Geosci. Remote Sens. 35, 415–420.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Chang. 3, 52.

Darvishzadeh, R., Skidmore, A., Schlerf, M., Atzberger, C., Corsi, F., Cho, M., 2008. LAI and chlorophyll estimation for a heterogeneous grassland using hyperspectral measurements. ISPRS J. Photogramm. Remote Sens. 63, 409–426.

Davis, R.E., Painter, T.H., Forster, R., Cline, D., Armstrong, R., Haran, T., McDonald, K., Elder, K., 2008. NASA Cold land processes experiment (CLPX 2002/03): spaceborne remote sensing. J. Hydrometeorol. 9, 1427–1433.

Doraiswamy, P.C., Moulin, S., Cook, P.W., Stern, A., 2003. Crop yield assessment from remote sensing. Photogramm. Eng. Remote Sens. 69, 665–674.

Eckert, S., 2012. Improved forest biomass and carbon estimations using texture measures from WorldView-2 satellite data. Remote Sens. 4, 810–829.

Elvidge, C.D., Chen, Z., 1995. Comparison of broad-band and narrow-band red and near-infrared vegetation indices. Remote Sens. Environ. 54, 38–48.

Epiphanio, R.D.V., Formaggio, A.R., Rudorff, B.F.T., Maeda, E.E., Luiz, A.J.B., 2010. Estimating soybean crop areas using spectral-temporal surfaces derived from MODIS images in Mato Grosso, Brazil. Pesqui. Agropecuária Bras. 45, 72–80.

Evrendilek, F., Gulbeyaz, O., 2008. Deriving vegetation dynamics of natural terrestrial ecosystems from MODIS NDVI/EVI data over Turkey. Sensors 8, 5270–5302.

Frampton, W.J., Dash, J., Watmough, G., Milton, E.J., 2013. Evaluating the capabilities of Sentinel-2 for quantitative estimation of biophysical variables in vegetation. ISPRS J. Photogramm. Remote Sens. 82, 83–92. https://doi.org/10.1016/j.isprsjprs.2013.04.007

Franklin, S., Wulder, M., 2002. Remote sensing methods in medium spatial resolution satellite data land cover classification of large areas. Prog. Phys. Geogr. 26, 173–205. https://doi.org/10.1191/0309133302pp332ra

Frolking, S., Qiu, J., Boles, S., Xiao, X., Liu, J., Zhuang, Y., Li, C., Qin, X., 2002. Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China. Global Biogeochem. Cycles 16, 31–38.

García-Mora, T.J., Mas, J.-F., Hinkley, E.A., 2012. Land cover mapping applications with MODIS: a literature review. Int. J. Digit. Earth 5, 63–87.

Garroutte, E.L., Hansen, A.J., Lawrence, R.L., 2016. Using NDVI and EVI to map spatiotemporal variation in the biomass and quality of forage for migratory elk in the Greater Yellowstone Ecosystem. Remote Sens. 8, 404.

Gitelson, A.A., Gritz, Y., Merzlyak, M.N., 2003. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. J. Plant Physiol. 160, 271–282.

Gitelson, A.A., Kaufman, Y.J., Merzlyak, M.N., 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sens. Environ. 58, 289–298.

Gitelson, A.A., Keydan, G.P., Merzlyak, M.N., 2006. Three-band model for noninvasive estimation of chlorophyll, carotenoids, and anthocyanin contents in higher plant leaves. Geophys. Res. Lett. 33.

Glenn, E., Huete, A., Nagler, P., Nelson, S., 2008. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape. Sensors 8, 2136–2160.

Glenn, E.P., Neale, C.M.U., Hunsaker, D.J., Nagler, P.L., 2011. Vegetation index-based crop coefficients to estimate evapotranspiration by remote sensing in agricultural and natural ecosystems. Hydrol. Process. 25, 4050–4062.

Govender, M., Chetty, K., Bulcock, H., 2007. A review of hyperspectral remote sensing and its application in vegetation and water resource studies. Water Sa 33.

Govender, M., Chetty, K., Naiken, V., Bulcock, H., 2008. A comparison of satellite hyperspectral and multispectral remote sensing imagery for improved classification and mapping of vegetation 34, 147–154.

Gu, Y., Brown, J.F., Verdin, J.P., Wardlow, B., 2007. A five-year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States. Geophys. Res. Lett. 34.

Guerschman, J.P., Hill, M.J., Renzullo, L.J., Barrett, D.J., Marks, A.S., Botha, E.J., 2009. Estimating fractional cover of photosynthetic vegetation, non-photosynthetic vegetation and bare soil in the Australian tropical savanna region upscaling the EO-1 Hyperion and MODIS sensors. Remote Sens. Environ. 113, 928–945. https://doi.org/10.1016/j.rse.2009.01.006

Gutman, G., Ignatov, A., 1998. The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models. Int. J. Remote Sens. 19, 1533–1543.

Haboudane, D., Miller, J.R., Pattey, E., Zarco-Tejada, P.J., Strachan, I.B., 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. Remote Sens. Environ. 90, 337–352.

Hamel, S., Garel, M., Festa-Bianchet, M., Gaillard, J., Côté, S.D., 2009. Spring Normalized Difference Vegetation Index (NDVI) predicts annual variation in timing of peak faecal crude protein in mountain ungulates. J. Appl. Ecol. 46, 582–589.

Hansen, P.M., Schjoerring, J.K., 2003. Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least squares regression. Remote Sens. Environ. 86, 542–553.

Horler, D.N.H., DOCKRAY, M., Barber, J., 1983. The red edge of plant leaf reflectance. Int. J. Remote Sens. 4, 273–288.

Houborg, R., Fisher, J.B., Skidmore, A.K., 2015. Advances in remote sensing of vegetation function and traits. Int. J. Appl. Earth Obs. Geoinf. 43, 1–6. https://doi.org/10.1016/j.jag.2015.06.001

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.

Huete, A., Justice, C., Van Leeuwen, W., 1999. MODIS vegetation index (MOD13). Algorithm Theor. basis Doc. 3, 213.

Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). Remote Sens. Environ. 25, 295–309. https://doi.org/10.1016/0034-4257(88)90106-X

Huete, A.R., Liu, H.Q., Batchily, K. V, Van Leeuwen, W., 1997. A comparison of vegetation indices over a global set of TM images for EOS-MODIS. Remote Sens. Environ. 59, 440–451.

Irons, J.R., Dwyer, J.L., Barsi, J.A., 2012. The next Landsat satellite: The Landsat data continuity mission. Remote Sens. Environ. 122, 11–21.

Islam, M.R., Garcia, S.C., Henry, D., 2011. Use of normalised difference vegetation index, nitrogen concentration, and total nitrogen content of whole maize plant and plant fractions to estimate yield and nutritive value of hybrid forage maize. Crop Pasture Sci. 62, 374–382. https://doi.org/10.1071/CP10244

Jiang, Z., Huete, A.R., Didan, K., Miura, T., 2008. Development of a two-band enhanced vegetation index without a blue band. Remote Sens. Environ. 112, 3833–3845.

Jin, S., Sader, S.A., 2005. MODIS time-series imagery for forest disturbance detection and quantification of patch size effects. Remote Sens. Environ. 99, 462–470.

Jordan, C.F., 1969. Derivation of leaf-area index from quality of light on the forest floor. Ecology 50, 663–666.

Karnieli, A., Agam, N., Pinker, R.T., Anderson, M., Imhoff, M.L., Gutman, G.G., Panov, N., Goldberg, A., 2010. Use of NDVI and land surface temperature for drought assessment: Merits and limitations. J. Clim. 23, 618–633.

Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, G., Wang, S., 2005. Monitoring of forage conditions with MODIS imagery in the Xilingol steppe, Inner Mongolia. Int. J. Remote Sens. 26, 1423–1436.

Knox, N.M., Skidmore, A.K., Prins, H.H.T., Asner, G.P., van der Werff, H.M.A., de Boer, W.F., van der Waal, C., de Knegt, H.J., Kohi, E.M., Slotow, R., 2011. Dry season mapping of savanna forage quality, using the hyperspectral Carnegie Airborne Observatory sensor. Remote Sens. Environ. 115, 1478–1488.

Kogan, F.N., 1995. Application of vegetation index and brightness temperature for drought detection. Adv. Sp. Res. 15, 91–100.

Kogan, F.N., 1990. Remote sensing of weather impacts on vegetation in non-homogeneous areas. Int. J. Remote Sens. 11, 1405–1419.

Kokaly, R.F., Asner, G.P., Ollinger, S. V, Martin, M.E., Wessman, C.A., 2009. Characterizing canopy biochemistry from imaging spectroscopy and its application to ecosystem studies. Remote Sens. Environ. 113, S78–S91.

Kumar, L., Schmidt, K., Dury, S., Skidmore, A., 2002. Imaging spectrometry and vegetation science, in: Imaging Spectrometry. Springer, pp. 111–155.

Lendrum, P.E., Anderson Jr, C.R., Monteith, K.L., Jenks, J.A., Bowyer, R.T., 2014. Relating the movement of a rapidly migrating ungulate to spatiotemporal patterns of forage quality. Mamm. Biol. 79, 369–375.

Li, Z., Li, X., Wei, D., Xu, X., Wang, H., 2010. An assessment of correlation on MODIS-NDVI and EVI with natural vegetation coverage in Northern Hebei Province, China. Procedia Environ. Sci. 2, 964–969.

Long, Y.U., Li, Z., Wei, L.I.U., Hua-Kun, Z., 2010. Using remote sensing and GIS technologies to estimate grass yield and livestock carrying capacity of alpine grasslands in Golog Prefecture, China. Pedosphere 20, 342–351.

Lu, L., Kuenzer, C., Wang, C., Guo, H., Li, Q., 2015. Evaluation of three MODIS-derived vegetation index time series for dryland vegetation dynamics monitoring. Remote Sens. 7, 7597–7614.

Marshall, M., Thenkabail, P., 2015. Advantage of hyperspectral EO-1 Hyperion over multispectral IKONOS, GeoEye-1, WorldView-2, Landsat ETM+, and MODIS vegetation indices in crop biomass estimation. ISPRS J. Photogramm. Remote Sens. 108, 205–218. https://doi.org/10.1016/j.isprsjprs.2015.08.001

Maselli, F., Papale, D., Chiesi, M., Matteucci, G., Angeli, L., Raschi, A., Seufert, G., 2014. Operational monitoring of daily evapotranspiration by the combination of MODIS NDVI and ground meteorological data: Application and evaluation in Central Italy. Remote Sens. Environ. 152, 279–290.

Matese, A., Toscano, P., Di Gennaro, S.F., Genesio, L., Vaccari, F.P., Primicerio, J., Belli, C., Zaldei, A., Bianconi, R., Gioli, B., 2015. Intercomparison of UAV, aircraft and satellite remote sensing platforms for precision viticulture. Remote Sens. 7, 2971–2990. https://doi.org/10.3390/rs70302971

Mu, Q., Zhao, M., Heinsch, F.A., Liu, M., Tian, H., Running, S.W., 2007. Evaluating water stress controls on primary production in biogeochemical and remote sensing based models. J. Geophys. Res. Biogeosciences 112.

Mu, Q., Zhao, M., Running, S.W., 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115, 1781–1800.

Mulla, D.J., 2013. Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. Biosyst. Eng. 114, 358–371.

Mutanga, O., Adam, E., Cho, M.A., 2012. High density biomass estimation for wetland vegetation using WorldView-2 imagery and random forest regression algorithm. Int. J. Appl. Earth Obs. Geoinf. 18, 399–406.

Mutanga, O., Dube, T., Ahmed, F., 2016. Progress in remote sensing: vegetation monitoring in South Africa. South African Geogr. J. 98, 461–471. https://doi.org/10.1080/03736245.2016.1208586

Mutanga, O., Skidmore, A.K., Prins, H.H.T., 2004. Predicting in situ pasture quality in the Kruger National Park, South Africa, using continuum-removed absorption features. Remote Sens. Environ. 89, 393–408.

Nagendra, H., Rocchini, D., 2008. High resolution satellite imagery for tropical biodiversity studies: The devil is in the detail. Biodivers. Conserv. 17, 3431–3442. https://doi.org/10.1007/s10531-008-9479-0

Nordberg, M., Evertson, J., 2005. Vegetation index differencing and linear regression for change detection in a Swedish mountain range using Landsat TM® and ETM+® imagery. L. Degrad. Dev. 16, 139–149.

Oesterheld, M., DiBella, C.M., Kerdiles, H., 1998. Relation between NOAA-AVHRR satellite data and stocking rate of rangelands. Ecol. Appl. 8, 207–212.

Omer, G., Mutanga, O., Abdel-Rahman, E., Adam, E., 2016. Empirical prediction of Leaf Area Index (LAI) of endangered tree species in intact and fragmented indigenous forests ecosystems using WorldView-2 data and two robust machine learning algorithms. Remote Sens. 8, 324.

Oumar, Z., Mutanga, O., 2011. The potential of remote sensing technology for the detection and mapping of Thaumastocoris peregrinus in plantation forests. South. For. A J. For. Sci. 73, 23–31.

Ozdogan, M., Yang, Y., Allez, G., Cervantes, C., 2010. Remote sensing of irrigated agriculture: Opportunities and challenges. Remote Sens. 2, 2274–2304.

Palchowdhuri, Y., Valcarce-Diñeiro, R., King, P., Sanabria-Soto, M., 2018. Classification of multi-temporal spectral indices for crop type mapping: a case study in Coalville, UK. J. Agric. Sci. 156, 24–36.

Pelkey, N.W., Stoner, C.J., Caro, T.M., 2000. Vegetation in Tanzania: assessing long term trends and effects of protection using satellite imagery. Biol. Conserv. 94, 297–309.

Peters, A.J., Walter-Shea, E.A., Ji, L., Vina, A., Hayes, M., Svoboda, M.D., 2002. Drought monitoring with NDVI-based standardized vegetation index. Photogramm. Eng. Remote Sensing 68, 71–75.

Pettorelli, N., Bro-Jørgensen, J., Durant, S.M., Blackburn, T., Carbone, C., 2009. Energy availability and density estimates in African ungulates. Am. Nat. 173, 698–704.

Pettorelli, N., Ryan, S., Mueller, T., Bunnefeld, N., Jędrzejewska, B., Lima, M., Kausrud, K., 2011. The Normalized Difference Vegetation Index (NDVI): unforeseen successes in animal ecology. Clim. Res. 46, 15–27.

Potter, C., Klooster, S., Huete, A., Genovese, V., 2007. Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. Earth Interact. 11, 1–21.

Pullanagari, R.R., Dynes, R.A., King, W.M., Yule, I.J., Thulin, S., Knox, N.M., Ramoelo, A., Michalk, D., Millar, G., Badgery, W., 2013. Remote sensing of pasture quality, in: Proc. 22nd International Grasslands Congress 2013. p. 6.

Ramoelo, A., Cho, M., Mathieu, R., Skidmore, A.K., 2015a. Potential of Sentinel-2 spectral configuration to assess rangeland quality. J. Appl. Remote Sens. 9, 94096.

Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z., Wolff, E., 2015b. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. Int. J. Appl. Earth Obs. Geoinf. 43, 43–54.

Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R., Heitkönig, I.M.A., 2012. Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. Int. J. Appl. Earth Obs. Geoinf. 19, 151–162.

Ren, J., Chen, Z., Zhou, Q., Tang, H., 2008. Regional yield estimation for winter wheat with MODIS-NDVI data in Shandong, China. Int. J. Appl. Earth Obs. Geoinf. 10, 403–413.

Rounsevell, M.D.A., Reginster, I., Araújo, M.B., Carter, T.R., Dendoncker, N., Ewert, F., House, J.I., Kankaanpää, S., Leemans, R., Metzger, M.J.M., 2006. A coherent set of future land use change scenarios for Europe. Agric. Ecosyst. Environ. 114, 57–68.

Rouse Jr, J.W., Haas, R.H., Schell, J.A., Deering, D.W., 1973. Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation.

Roy, D.P., Kovalskyy, V., Zhang, H.K., Vermote, E.F., Yan, L., Kumar, S.S., Egorov, A., 2016. Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. Remote Sens. Environ. 185, 57–70.

Rudorff, B.F.T., Adami, M., Aguiar, D.A., Moreira, M.A., Mello, M.P., Fabiani, L., Amaral, D.F., Pires, B.M., 2011. The soy moratorium in the Amazon biome monitored by remote sensing images. Remote Sens. 3, 185–202.

Ryan, S.J., Cross, P.C., Winnie, J., Hay, C., Bowers, J., Getz, W.M., 2012. The utility of normalized difference vegetation index for predicting African buffalo forage quality. J. Wildl. Manage. 76, 1499–1508.

Ryan, S.J., Knechtel, C.U., Getz, W.M., 2007. Ecological cues, gestation length, and birth timing in African buffalo (Syncerus caffer). Behav. Ecol. 18, 635–644.

Secretariat, G., 2009. Implementation plan for the global observing system for climate in support of the UNFCCC (2010 Update), in: Proceedings of the Conference of the Parties (COP), Copenhagen, Denmark. Citeseer, pp. 7–19.

Sesnie, S.E., Dickson, B.G., Rosenstock, S.S., Rundall, J.M., 2012. A comparison of Landsat TM and MODIS vegetation indices for estimating forage phenology in desert bighorn sheep (Ovis canadensis nelsoni) habitat in the Sonoran Desert, USA. Int. J. Remote Sens. 33, 276–286.

Shanahan, J.F., Schepers, J.S., Francis, D.D., Varvel, G.E., Wilhelm, W.W., Tringe, J.M., Schlemmer, M.R., Major, D.J., 2001. Use of remote-sensing imagery to estimate corn grain yield. Agron. J. 93, 583–589.

Sims, D.A., Rahman, A.F., Cordova, V.D., El-Masri, B.Z., Baldocchi, D.D., Bolstad, P. V, Flanagan, L.B., Goldstein, A.H., Hollinger, D.Y., Misson, L., 2008. A new model of gross primary productivity for North American ecosystems based solely on the enhanced vegetation index and land surface temperature from MODIS. Remote Sens. Environ. 112, 1633–1646.

Skidmore, A.K., Ferwerda, J.G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H.T., Balcik, F.B., Venus, V., 2010. Forage quality of savannas—Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. Remote Sens. Environ. 114, 64–72.

Son, N.T., Chen, C.F., Chen, C.R., Chang, L.Y., Minh, V.Q., 2012. Monitoring agricultural drought in the Lower Mekong Basin using MODIS NDVI and land surface temperature data. Int. J. Appl. Earth Obs. Geoinf. 18, 417–427.

Starks, P.J., Zhao, D., Phillips, W.A., Coleman, S.W., 2006. Herbage mass, nutritive value and canopy spectral reflectance of bermudagrass pastures. Grass Forage Sci. 61, 101–111.

Tang, Z., Fang, J., Sun, J., Gaston, K.J., 2011. Effectiveness of protected areas in maintaining plant production. PLoS One 6, e19116.

Thenkabail, P., Lyon, J.G., Turral, H., Biradar, C., 2009. Remote sensing of global croplands for food security. CRC Press.

Thorp, K.R., Tian, L.F., 2004. A review on remote sensing of weeds in agriculture. Precis. Agric. 5, 477–508.

Tilling, A.K., O'Leary, G.J., Ferwerda, J.G., Jones, S.D., Fitzgerald, G.J., Rodriguez, D., Belford, R., 2007. Remote sensing of nitrogen and water stress in wheat. F. Crop. Res. 104, 77–85.

Timothy, D., Onisimo, M., Riyad, I., 2016. Quantifying aboveground biomass in African environments: A review of the trade-offs between sensor estimation accuracy and costs. Trop. Ecol. 57, 393–405.

Tucker, C.J., Pinzon, J.E., Brown, M.E., Slayback, D.A., Pak, E.W., Mahoney, R., Vermote, E.F., El Saleous, N., 2005. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. Int. J. Remote Sens. 26, 4485–4498.

Tueller, P.T., 1989. Technology for rangeland management. Invit. Synth. Pap. 42, 442.

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., Steininger, M., 2003. Remote sensing for biodiversity science and conservation. Trends Ecol. Evol. 18, 306–314. https://doi.org/10.1016/S0169-5347(03)00070-3

Upadhyay, P., Ghosh, S.K., Kumar, A., Roy, P.S., Gilbert, I., 2012. Effect on specific crop mapping using WorldView-2 multispectral add-on bands: soft classification approach. J. Appl. Remote Sens. 6, 63524.

Van Leeuwen, W.J.D., Huete, A.R., Laing, T.W., 1999. MODIS vegetation index compositing approach: A prototype with AVHRR data. Remote Sens. Environ. 69, 264–280.

Varshney, P.K., Arora, M.K., 2004. Advanced image processing techniques for remotely sensed hyperspectral data. Springer Science & Business Media.

Vicente-Serrano, S.M., Cuadrat-Prats, J.M., Romo, A., 2006. Early prediction of crop production using drought indices at different time-scales and remote sensing data: application in the Ebro Valley (north-east Spain). Int. J. Remote Sens. 27, 511–518.

Villamuelas, M., Fernández, N., Albanell, E., Gálvez-Cerón, A., Bartolomé, J., Mentaberre, G., López-Olvera, J.R., Fernández-Aguilar, X., Colom-Cadena, A., López-Martín, J.M., 2016. The Enhanced Vegetation Index (EVI) as a

proxy for diet quality and composition in a mountain ungulate. Ecol. Indic. 61, 658–666.
Walsh, S.J., McCleary, A.L., Mena, C.F., Shao, Y., Tuttle, J.P., González, A., Atkinson, R., 2008. QuickBird and Hyperion data analysis of an invasive plant species in the Galapagos Islands of Ecuador: Implications for control and land use management. Remote Sens. Environ. 112, 1927–1941.
Wang, Q., Adiku, S., Tenhunen, J., Granier, A., 2005. On the relationship of NDVI with leaf area index in a deciduous forest site. Remote Sens. Environ. 94, 244–255.
Wang, Z., Liu, C., Huete, A., 2003. From AVHRR-NDVI to MODIS-EVI: Advances in vegetation index research. Acta Ecol. Sin. 23, 979–987.
Wardlow, B.D., Egbert, S.L., Kastens, J.H., 2007. Analysis of time-series MODIS 250 m vegetation index data for crop classification in the US Central Great Plains. Remote Sens. Environ. 108, 290–310.
Wessels, K.J., Prince, S.D., Zambatis, N., MacFadyen, S., Frost, P.E., Van Zyl, D., 2006. Relationship between herbaceous biomass and 1-km2 Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa. Int. J. Remote Sens. 27, 951–973.
Wong, K.K., He, Y., 2013. Estimating grassland chlorophyll content using remote sensing data at leaf, canopy, and landscape scales. Can. J. Remote Sens. 39, 155–166.
Wu, C., Niu, Z., Tang, Q., Huang, W., 2008. Estimating chlorophyll content from hyperspectral vegetation indices: Modeling and validation. Agric. For. Meteorol. 148, 1230–1241.
Xiao, X., Zhang, Q., Braswell, B., Urbanski, S., Boles, S., Wofsy, S., Moore III, B., Ojima, D., 2004. Modeling gross primary production of temperate deciduous broadleaf forest using satellite images and climate data. Remote Sens. Environ. 91, 256–270.
Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. J. Plant Ecol. 1, 9–23. https://doi.org/10.1093/jpe/rtm005
Xue, J., Su, B., 2017. Significant remote sensing vegetation indices: A review of developments and applications. J. Sensors 2017.
Yang, C., Everitt, J.H., Bradford, J.M., 2006. Comparison of QuickBird satellite imagery and airborne imagery for mapping grain sorghum yield patterns. Precis. Agric. 7, 33–44.
Zeng, X., Dickinson, R.E., Walker, A., Shaikh, M., DeFries, R.S., Qi, J., 2000. Derivation and evaluation of global 1-km fractional vegetation cover data for land modeling. J. Appl. Meteorol. 39, 826–839.
Zhang, J., Zhengjun, L., Xiaoxia, S., 2009. Changing landscape in the Three Gorges Reservoir Area of Yangtze River from 1977 to 2005: Land use/land cover, vegetation cover changes estimated using multi-source satellite data. Int. J. Appl. earth Obs. Geoinf. 11, 403–412.
Zhang, L., Xiao, J., Li, J., Wang, K., Lei, L., Guo, H., 2012. The 2010 spring drought reduced primary productivity in southwestern China. Environ. Res. Lett. 7, 45706.
Zhang, X., Friedl, M.A., Schaaf, C.B., Strahler, A.H., Hodges, J.C.F., Gao, F., Reed, B.C., Huete, A., 2003. Monitoring vegetation phenology using MODIS. Remote Sens. Environ. 84, 471–475.
Zhao, D., Starks, P.J., Brown, M.A., Phillips, W.A., Coleman, S.W., 2007. Assessment of forage biomass and quality parameters of bermudagrass using proximal sensing of pasture canopy reflectance. Grassl. Sci. 53, 39–49.

Chapter Three:

The relationship between multispectral satellite-derived vegetation indices and forage quantity and quality indicators in Mountain Zebra National Park

3.1 Abstract

Multispectral satellite-derived vegetation indices (VI's) can provide an inexpensive and time-efficient technique to monitor and assess forage quantity and quality of the vegetation. The assessment of forage quantity and quality can help ecologists manage herbivore populations in protected areas. However, before VI's can be implemented for sustainable management strategies, it's recommended that their relationship with the different forage quantity and quality indicators within the desired area is assessed. Therefore, this study determined the relationship between different VI's derived from multispectral remote sensors, on board the MODIS and Sentinel-2 satellites, and the different forage quantity and quality indicators in Mountain Zebra National Park. Forage biomass was estimated and used as a forage quantity indicator and forage nutrients were analysed and used as an indicator for forage quality. Correlations and regression techniques were applied and results showed that different multispectral satellite-derived VI's had relationships with different forage quantity and quality indicators and that these relationships were driven by season and area. The MODIS Normalized Difference Vegetation Index (NDVI) had a strong relationship with forage quantity, while the Sentinel-2 Chlorophyll Red-Edge index ($Chl_{red\text{-}edge}$) had a very strong relationship with forage quality indicator N. Strong relationships were also found between the Green Chlorophyll Index (Cl_{green}), NDVI and MODIS NDVI and the forage quality indicators fibre (NDF and ADL), fibre quality (NDFd) and forage K. This study shows the suitability and applicability of the multispectral satellite-derived VI's for MZNP herbivore management and also provides valuable information for remote sensing research.

3.2 Introduction

Forage quantity and quality available to herbivores in southern Africa has become limited due to climate change (inducing drought) and high rural population growth (causing fencing of protected areas).

Forage quantity and quality play an important role for herbivores as their need to fulfil nutritional demands affects their distribution, movements and survival (Burkepile et al., 2013; Grant et al., 1995; McNaughton, 1988; Novellie et al., 1988; Olson et al., 2010; Ryan, 2006). Therefore, it has become critically important to monitor and assess forage quantity and quality available for herbivores in protected areas, in order to enable effective management practices (Grant et al., 2011; Knight et al., 2016; Novellie and Gaylard, 2013; Stolter et al., 2018).

Remote sensing techniques, specifically, multispectral satellite-derived vegetation indices (VI's) have been demonstrated to be a rapid and inexpensive means for estimating forage quantity and quality of the vegetation for herbivores (Garroutte et al., 2016; Kawamura et al., 2005; Ramoelo et al., 2015a; Ryan et al., 2012; Zhao et al., 2007). Multispectral satellite-derived VI's have therefore gained attention from ecologists, as field techniques can often be expensive and logistically complicated (Ryan et al., 2012; Southwood and Henderson, 2009). Subsequently, the 2016-2026 Mountain Zebra National Park (MZNP) management plan aims to implement multispectral satellite-derived VI's for their herbivory and habitat-vegetation management programs. The implementation of VI's will be used to monitor and assess forage quantity and quality conditions for the range of herbivores present, in order to assist with making appropriate management decisions for the reserves herbivore populations.

The use of multispectral satellite-derived VI's to monitor and assess forage quantity and quality for herbivores is based on the assessment of forage quantity and quality indicators. Studies tend to use biomass as an indicator of forage quantity (Kawamura et al., 2005; Ramoelo et al., 2015b; Skidmore et al., 2005), while different nutrients and their concentrations in the forage are generally used as indicators for forage quality (Ball et al., 2001; Mutanga and Skidmore, 2004; Pullanagari et al., 2013). For MZNP, many permutations of multispectral satellite-derived VI's can be implemented, with each one having its own strengths and weaknesses in application and some being more optimal at retrieving certain forage quantity and quality indicators than others (Frampton et al., 2013; Kumar et al., 2002). The multispectral MODIS Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are known to have a strong relationship with forage quantity indicator biomass (Gao et al., 2013; Kawamura et al., 2005; Liu et al., 2017; Timothy et al., 2016). The MODIS EVI, in particular, is an enhancement from the saturation problems faced by the NDVI and is known to provide better estimates of forage quantity (Huete et al., 2002, 1999; Van Leeuwen et al., 1999).

Despite strong relationships found between multispectral satellite-derived VI's and forage quantity, there is limited research on remote sensing data and forage quality indicators (forage nutrients: Ryan et al., 2012; Starks et al., 2004). Some studies have had success using hyperspectral remote sensing to estimate forage quality indicator nitrogen (N) and even less success estimating fiber (neutral detergent fibre [NDF] and acid detergent fibre [ADF]) and minerals (phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) and sodium (Na): Albayrak, 2008; Mutanga and Skidmore, 2004; Starks et al., 2004; Zhao et al., 2007). Hyperspectral remote sensing is also expensive and computationally complicated, unlike multispectral remote sensors (Govender et al., 2008; Mutanga et al., 2016; Varshney and Arora, 2004). The multispectral MODIS and Sentinel-2 derived VI's are however known to have relationships with forage N (Frampton et al., 2013; Garroutte et al., 2016; Kawamura et al., 2005). The Sentinel-2, in particular, has proven potentially successful (Clevers and Gitelson, 2013; Ramoelo et al., 2015a) as the satellite and its remote sensor provides the benefit of high spatial and spectral resolutions with rapid revisit rates and also advantageously includes red-edge bands (ESA, 2011). Studies have shown red-edge based VI's (e.g. $CIr_{ed\text{-}edge}$ and $Chl_{red\text{-}edge}$) and VI's like the Sentinel-2 CI_{green} (a variant that substitutes a red-edge band for a green band) can provide better estimates of forage N (Cho et al., 2013; Clevers and Gitelson, 2013; Clevers and Kooistra, 2012; Ramoelo et al., 2015a). There is however very little information available on multispectral satellite-derived VI's and other forage quality indicators such as fiber (NDF and ADF), starch and minerals (K, P, Mg, Ca and Na).

The relationship between multispectral satellite-derived VI's and forage quantity and quality indicators also varies across different seasons, areas and vegetation types (Garroutte et al., 2016; Kawamura et al., 2005; Mutanga et al., 2004; Ramoelo et al., 2012). Therefore, given the different multispectral satellite-derived VI's available, the different forage quantity and quality indicators, the effects of different environmental variables and the lack of research, the assessment of this dynamic relationship in the desired area is recommended. The information found thus provides confidence in the biological significance of the VI's estimates and ensures their appropriately implemented for management purposes.

In this study, the relationship is investigated between formulated VI's derived from multispectral remote sensors, on board the MODIS Terra and Sentinel-2 satellites, and forage quantity and quality indicators in MZNP. The satellites and their derived VI's were assessed because of their demonstrated relationship with forage quantity and quality in other research. The multispectral satellite-derived VI's are also freely available, low computational and time-efficient compared to other remotely sensed VI's (Martinez-Uso et al., 2007; Matese et al., 2015; Mutanga et al., 2016; Singh et al., 2018), thus making them suitable candidates for the operational requirements for MZNP management. The objective of this study is to determine which forage quantity and quality indicators have a relationship with the different multispectral satellite-derived VI's in MZNP. The information provided in this study aims to determine the applicability and suitability of the different multispectral satellite-derived VI's, in order to assist in making appropriate management decisions for MZNP management and their herbivore populations.

Studying in MZNP provides the opportunity to study in a protected area that carries high densities of grazing ungulates, while the information assist MZNP with their herbivore management practices. The vegetation types in MZNP also do not carry a high density of trees. Therefore, there is minimal effect of trees on the grass signal obtained by the remote sensors, thus allowing the study to focus on the relationship between multispectral satellite-derived VI's and pasture type vegetation. In this study, we predict, because of the enhanced capabilities of the MODIS EVI compared to the NDVI, the EVI will have a stronger relationship with forage quantity indicator biomass. For forage quality, we predict the Sentinel-2 VI's will have better relationships with forage nutrients than the MODIS VI's, due to the high spatial and spectral resolutions of the Sentinel-2 remote sensor. We also predict only certain multispectral satellite-derived VI's will have a relationship with specific forage quality indicators, with the Sentinel-2 $Chl_{red\text{-}edge}$ and CI_{green} having a strong relationship with forage N. Any other relationships found between the multispectral satellite-derived VI's and the other forage quality indicators (fiber, minerals and starch) are expected to be weak. The relationships found in this study between VI's and forage quantity and quality are also expected to be shaped by season and area.

3.3 Methodology

3.3.1 Study Area

The MZNP is a 28,412-ha game reserve situated near the town of Cradock in the Eastern Cape Province, South Africa (Figure 3.1). Monthly minimum and maximum temperatures vary from 6°C to 28°C in summer (from September to March) and from 0°C to 20°C in winter (from April to August: Brown and Bezuidenhout, 2000). The reserve receives approximately 400 mm of rainfall with the majority falling in the summer months. Periodic light snow occurs during the winter months and frost is common between May and October (Novellie and Gaylard, 2013). The park is positioned in a transition zone comprising of the Nama-Karoo, Grassland and Albany Thicket biome. According to Acocks (1988), the area can be classified as False Karroid Broken Veld, whereas Hoffman (1996) classifies it as Eastern Mixed Nama Karoo. The low rainfall of these areas ensures that the predominant soil type is lime-rich and prone to erosion (Hall-Martin and Carruthers, 2003). Bezuidenhout et al. (2015) have classified, mapped and described all 13 plant communities found within the park (Table 3.1).

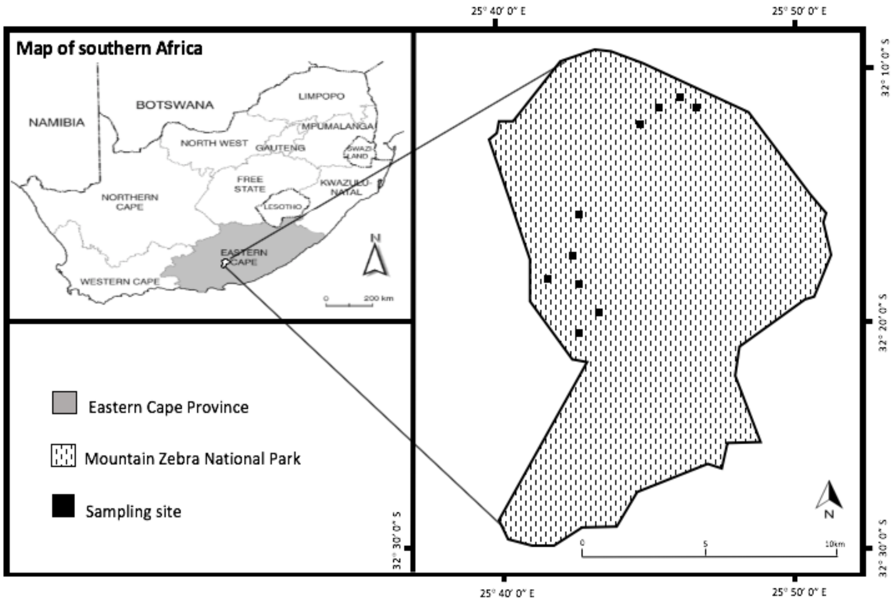


Figure 3.1: Study area locality map with indication of sampling sites.

Table 3.1: Three major landscapes and plant communities of MZNP: The Mountain highland rugged landscape with four plant communities (B), the Middle plateau rolling landscape with four plant communities (M) and the Valley bottomlands undulating plains landscape with five plant communities (V: from Bezuidenhout et al., 2015).

Mountain highlands rugged landscape (B)	Plant communities
B1	*Eragrostis lehmanniana - Eragrostis curvula* Grassland
B2	*Merxmuellera disticha - Euryops annuus* Grassland
B3	*Merxmuellera disticha - Felicia filifolia* Grassland
B4	*Searcia lucida - Diospyros lycioides* Woodland
Middle plateau rolling landscape (M)	
M1	*Carissa macrocarpa - Rhigozum obovatum Shrubland*
M2	*Pentzia globosa - Searsia longispina* Shrubland
M3	*Enneapogon scoparius - Acacia karroo Woodland*
M4	*Searsia lucida - Buddleja glomerata* Shrubland
Valley bottomland undulating plains landscape (V)	
V1	*Pentzia incana - Eragrostis lehmanniana* Forbland
V2	*Sporobolus africanus - Enneapogon scoparius* Grassland
V3	*Pentzia globosa - Eragrostis obtusa* Forbland
V4	*Aristida adscensionis - Chloris virgata* Grassland
V5	*Lycium oxycarpum - Acacia karroo* Woodland

Two areas within the reserve were studied, the Rooiplaat area found in the western boundary of the reserve and the Welgedacht area found along its eastern boundary (Figure 3.2). The two areas were selected because they experience high densities of wildlife numbers throughout the year (Bezuidenhout et al., 2015) particularly grazing ungulate species such as Black Wildebeest (*Connochaetes gnou*), Blesbok (*Damaliscus dorca*), Cape Mountain Zebra (*Equus z. zebra*), Red Hartebeest (*Alcephalus busephalus*) and Springbok (*Antidorcas marsupialis*). Eland (*Taurotragus orys*) is also known to utilize these two study areas periodically. The Rooiplaat area, which is at 1360 m above sea level, consists of the Eragrostis lehmanniana - Eragrostis curvula Grassland community (B1: Table 1), described as part of the Mountain highlands rugged landscape. This grassland community is found on a relatively level sandstone and doleritic plateau and comprises of soils that are relatively shallow and not highly leeched (Van der Walt, 1980). The vegetation, which is virtually treeless (Penzhorn, 1982), consists of rocky plateau grassland, degraded plateau grassland and degraded shrubland (Van der Walt, 1980). The comparative hot dry climate, nutrient-rich soils and high grazing pressure determine primarily the “sweet” over-utilized nature of this area (Van der Walt, 1980). The dominant plant species found are Themeda triandra, Eragrostis curvula and Tragus koeleroides. Other prominent grass species found are Eragrostis lehmanniana and Eustachys paspaloides, while dwarf shrubs Pentzia incana, Pentzia globose, Melolobium microphyllum and Felicia filifolia are also prevalent.

The Welgedacht area mainly consists of the Sporobolus africanus - Enneapogon scoparius Grassland community (V2: Table 3.1) and the Pentzia globose - Eragrotis obtuse Forbland community (V3: Table 3.1). The two adjacent communities, which are at an altitude of roughly 1017 m, are found in the valley bottomland undulating plains landscape. The geology of the land type is mudstone, shale and sandstone (Toerien, 1972) and comprises of soil forms Glenrosa and Oakleaf (Brown and Bezuidenhout, 2005). The dominant vegetation in the area is a mixture of grassy and dwarf shrubland, with trees usually occurring along drainage lines (Van der Walt, 1980) and rock cover being very low (Brown and Bezuidenhout, 2005). The area was incorporated into the reserve less than 30 years ago and large sections have been overgrazed due to previous farming practices (Brown and Bezuidenhout, 2005). The dominant plant species found in the bordering V2 plant community are Tragus koelerioides and Aristida congesta subsp. congesta with prevailing dwarf shrubs Pentzia globose and Asparagus suaveolens. The dominant grass species found within the plant community V3 are Eragrostis obtusa, Aristida congesta subsp. congesta, Eragrostis lehmaniana and the pioneer grass Cynodon incompletus. The dwarf shrub Pentzia globose is also prominent within the V3 plant community. Dominant plant species that were recorded in the study areas were based on research done by van der Walt (1980) and Brown and Bezuidenhout (2005), as well as identified according to Germishuizen and Meyer (2003) in the collected forage samples during this study.

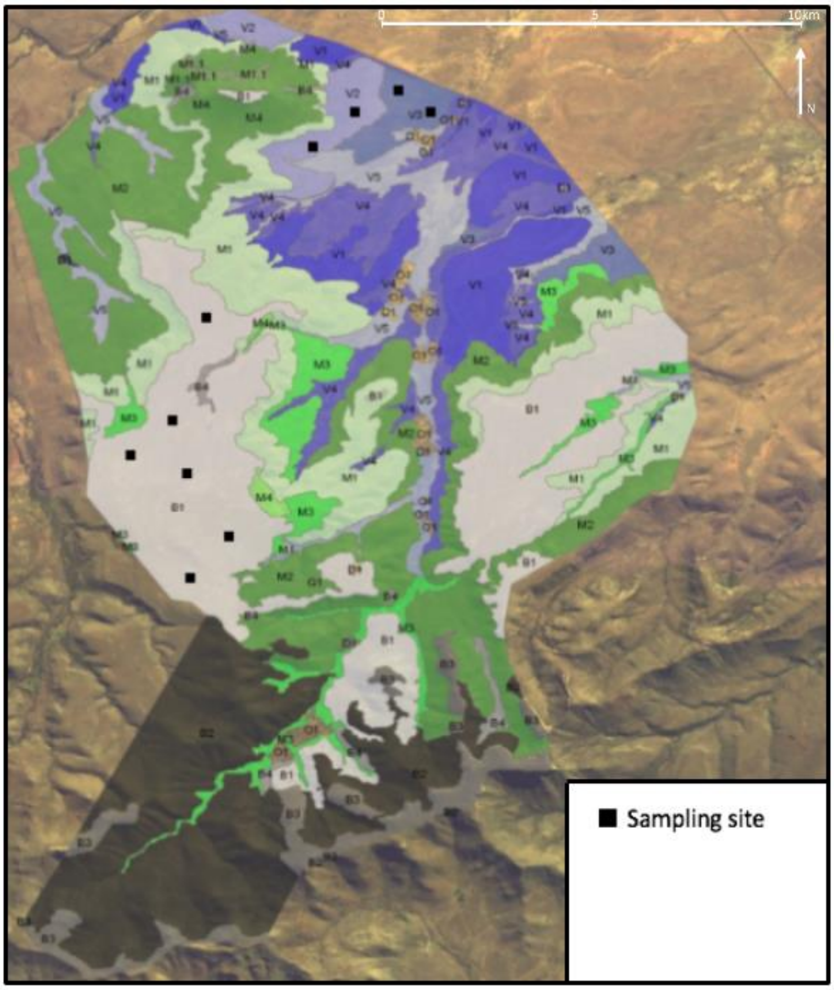


Figure 3.2: Vegetation map of Mountain Zebra National Park (From: Bezuidenhout et al. 2015). Sampling sites are shown within the selected study areas: Rooiplaat area, plant community *Eragrostis lehmanniana - Eragrostis curvula* Grassland (B1). Welgedacht area, plant community *Sporobolus africanus - Enneapogon scoparius* Grassland (V2) and *Pentzia globose - Eragrotis obtuse* Forbland (V3).

3.3.2 Sampling sites

There are no clear stipulated *in situ*-based methods for relating multispectral satellite-derived VI's to forage quantity and quality indicators. The method in this study was extrapolated from studies that did relatable research and had similar objectives (Garroutte et al., 2016; Kawamura et al., 2005; Ramoelo et al., 2015a). Ten sampling sites were selected in November 2017 (six in the Rooiplaat area and four in the Welgedacht area). Each sampling site represents a single pixel from the multispectral MODIS remote sensor (250 m x 250 m). The selection process of the study pixels (sampling sites) was done by locating all the MODIS pixels within the two study areas (using ArcGIS [version 10.5, ESRI, USA]). The pixels that had a buffer (waterholes, roads, etc.) greater than a 250 m radius were chosen (using Google EarthTM). A field reconnaissance for the selection of the pixels that were the most visibly homogeneous was then chosen as a sampling site. Navigation to the pixels was assisted using a handheld Geographical Positioning System (GPS), Garmin Oregon 550 (Garmin, Olathe, KS, USA), with positional accuracy ≥ 3 m). Data collection days occurred on the 28-29 November 2017, 31 January- 5 February, 23-27 March, 5-9 June and 27 July- 7 August 2018. The dates were selected to coincide with the four seasons of changing grass sward characteristics in MZNP (Winkler and Owen-Smith, 1995). The different seasons of grass growth were characterized as the (i) late growing season (Dec-Feb) when the sward was tall with an abundant supply of green material, (ii) early dormant season (March-May) when the grasses were mature and green, but plant growth had ceased, (iii) late dormant season (June-Aug) when grasses were dry and senescent and (iv) early growing season (Sep-Nov) when the grasses are mainly dry but some new growth has emerged (Winkler and Owen-Smith, 1995). Some specific forage nutrients, specifically starch, are known to fluctuate throughout the day (Ball et al., 2001) thus field collection times throughout all collection periods were kept constant, with fieldwork only occurring in the morning.

3.3.3 Ground sampling - forage quantity

To evaluate forage quantity, biomass was estimated (Kawamura et al., 2005; Ramoelo et al., 2015a; Sannier et al., 2002) using a disk pasture meter (DPM) which was developed by Bransby and Tainton (1977). The use of a DPM to estimate biomass in MZNP has been done before by De Klerk et al. (2001). In this study, as shown in Figure 3.3, the MODIS study pixel at each sampling site was divided into 4 equal blocks (125 m x 125 m). Within each block, ten vertical transect lines were placed 10 m apart. Along each transect line, a DPM reading was taken every 10 meters until 13 readings had been done. Navigation was assisted using a Garmin Oregon 550 GPS. The procedure generated over 100 DPM readings for each study pixel which is recommended by Bransby & Tainton (1977) and Trollope and Potgieter (1986). The average of all readings taken within the studied pixel was then calculated (which provides a representative sample of the entire pixel). The reading was then converted into total biomass (kg/ha) for the studied pixel by using an established regression table developed by Trollope and Potgieter (1986) and modified by Zambatis et al. (2006).

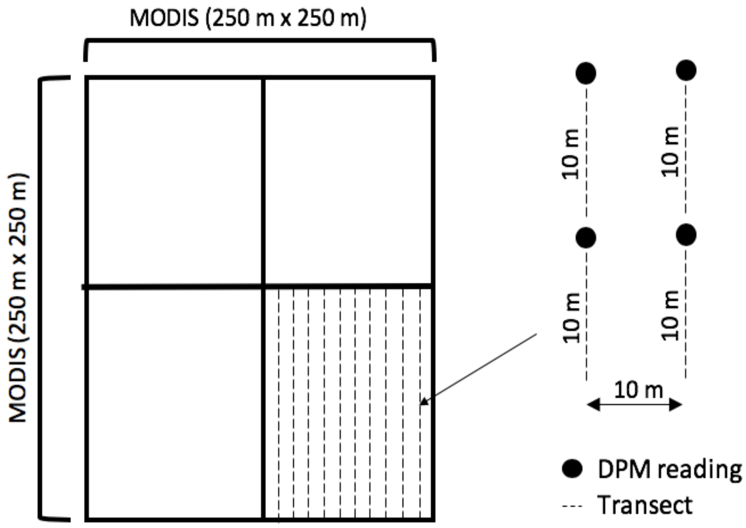


Figure 3.3: Method for estimating biomass for MODIS study pixel (250 m x 250 m) at each sampling site using a disc pasture meter. Transect lines shown in only one block.

3.3.4 Ground sampling - forage quality

Forage samples within the MODIS study pixel at each sampling site were collected from five systematically placed quadrats (1 m^2: Figure 3.4). The quadrats were systematically placed to ensure the MODIS pixels vegetation variability is captured and the edging effect from adjacent pixels is reduced (Prabhakara et al., 2015). Within the MODIS study pixel, where the quadrats were placed, Sentinel-2 pixels (20 m x 20 m) were then located (using ArcGIS software; ESRI, USA). This made the placement of the quadrat in each Sentinel-2 pixel random, which is often done in studies for smaller pixels in order to capture their vegetation variability (Ramoelo et al., 2015a, 2015b; Skidmore et al., 2010). Within each quadrat (using the Garmin Oregon 550 GPS for navigation) all forage was clipped at 1 cm above ground, pooled and bagged (brown paper bag) for drying and later chemical analysis (Knox et al., 2011). Forage samples were also weighed on site. To avoid repeat sampling, each quadrat was moved within a 5 m^2 area during each sampling period using the GPS (Garroutte et al., 2016).

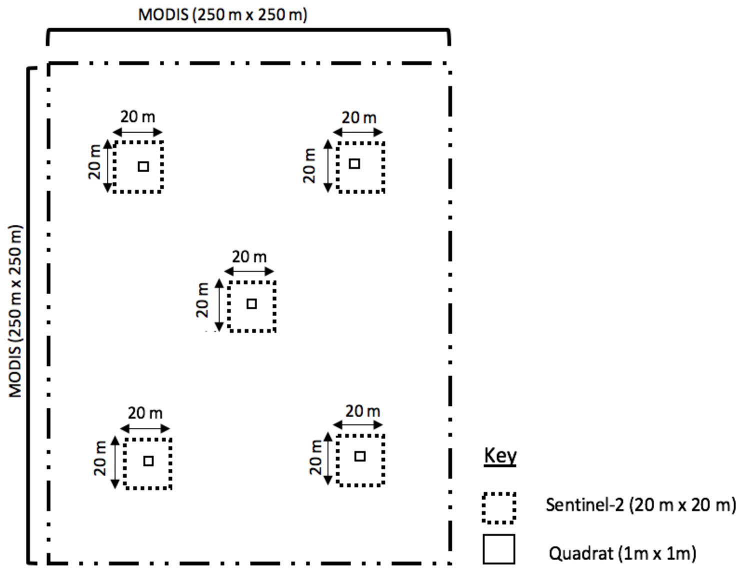


Figure 3.4: Method for forage sample collection with the positioning of the quadrats (1 m^2) within the MODIS (250 m x 250 m) and Sentinel-2 study pixels (20 m x 20 m) at each sampling site.

3.3.5 Chemical Analyses

Forage samples were analysed for forage nutrients that are used as forage quality indicators because they are known to affect intake, palatability, digestibility and an animal's performance (Ball et al., 2001; Barboza et al., 2008; Leslie Jr, 1985). All forage samples were transported to the Department of Animal Sciences laboratory at Stellenbosch University for analysis. Samples collected from each quadrat were analysed individually. Firstly, samples were oven-dried at 50°C for 48 h and then ground to 1 mm using a Thomas Model 4 Wiley® Mill (Thomas Scientific, Swedesboro, NJ, USA). The milled samples were analysed for chemical composition and reported on a dry matter (DM) basis. Ash and N were first analysed according to AOAC International (2002). To analyse N a LECO FP 528 Nitrogen Determinator Combustion tool was used. The minerals phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) were then analysed in faecal and forage samples according to the method by ALASA (1998). Forage samples were also analysed for NDF and acid detergent lignin (ADL) according to Mertens (2002) and Raffrenato et al. (2011), respectively. Forage *in vitro* NDF digestibility (NDFd) at 24 h was then analysed according to Goering and Van Soest (1970) using the ANKOM Daisy II incubator (ANKOM Technol. Corp., Fairport, NY, USA).

3.3.6 Vegetation Indices acquisition

Vegetation Indices were processed and packaged using ArcGIS (version 10.5; ESRI, USA) and acquired from the Centre for Geographical Analysis (Stellenbosch University; Table 4.2). The MODIS product MOD13Q1 (Version 6: Didan, 2015), which provides a 16 day composite value at a resolution of 250 m^2, was downloaded from Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Centre (LAAD DAAC). The MODIS Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) were then processed and packaged. Sentinel-2 data was downloaded from the Copernicus Open Access Hub, which serves data for the European Space Agency (ESA): https://www.sentinel-hub.com/develop/documentation/eo_products/Sentinel2EOproducts.
Sentinel-2 data was processed and packaged to develop the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Enhanced Vegetation Index 2 (EVI2), Green Normalized Difference Vegetation Index (GNDVI), Green Chlorophyll Index (CI_{green}) and Chlorophyll Red-edge Index ($Chl_{red\text{-}edge}$). The resolution of all Sentinel-2 vegetation indexes in this study are 20 m^2 with a 5-day revisit rate (ESA, 2011). If the image acquired during data collection days was not cloud free, the following revisit value was selected that had no cloud and shadow contamination. Data acquired from the MODIS and Sentinel-2 occurred from November 2017 to June 2019.

Table 3.2: Satellite-derived vegetation indices. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Difference Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chlred_{-edge}$ = Chlorophyll Red-Edge Index.

Vegetation indices	General Formula	Reference
NDVI	$(R_{NIR} - R_{RED})/(R_{NIR} + R_{RED})$	Rouse et al. (1974)
EVI	$(R_{NIR} - R_{RED})/[(R_{NIR} + 6R_{RED} - 7.5 * R_{BLUE}) + 1]$	Huete et al. (1997)
EVI2	$2.5 * [(R_{NIR} - R_{RED})/[(R_{NIR} + 2.4 * R_{RED}) + 1]$	Jiang et al. 2008
GNDVI	$R_{NIR} - (R_{540:570})/R_{NIR} + (R_{540:570})$	Gitelson et al. 1996
CI_{green}	$(R_{NIR}/R_{GREEN})-1$	Gitelson et al. (2003, 2006)
$Chl_{red\text{-}edge}$	$((R_{760:800}]/[R_{690:720})) \wedge (-1)$	Gitelson et al. (2006)

3.3.7 Data Analysis

Statistical analyses were specifically done to determine the relationships between the multispectral satellite-derived VI's and forage quantity and quality indicators in MZNP. Biomass was assessed as an indicator of forage quantity and its relationship with the MODIS VI's was determined. While forage nutrients and their concentrations were assessed as indicators of forage quality and their relationships with the MODIS and Sentinel-2 VI's were determined. Firstly, general trends were identified and discussed by examining means and standard deviations for the different multispectral satellite-derived VI’s and the forage quantity and quality indicators. The means for the VI’s and forage quantity and quality indicators were analysed throughout the study period in the different areas and during the different seasons of grass growth. Pearson's correlation coefficients (Zar, 1999) were then computed between biomass (forage quantity) and the MODIS VI’s for each sampling site (MODIS pixel) throughout the study period and during the different seasons of grass growth. Results were then used to assess the relationship between the forage quantity indicator biomass and the MODIS VI’s. For forage quality, each quadrat was analysed for forage nutrients. The forage nutrients analysed in a quadrat were used to represent the forage quality indicators for the VI’s derived from the Sentinel-2 pixel that overlaid that quadrat. Each forage nutrient analysed in the five quadrats at each sampling site was then added together and averaged to represent the forage quality indicators for the VI’s derived from that MODIS pixel that overlaid those five quadrats. Pearson's correlation coefficients (Zar, 1999) and simple linear regressions (with both linear and quadratic terms fitted) were then computed between the MODIS and Sentinel-2 VI’s and the different forage quality indicators. Only the VI’s that had the strongest correlations and highest respective R^2 values (from the linear regression models) for each forage quality indicator were discussed and their relationship strength assessed. Multiple linear regressions were then run using PROC REG of SAS 9.3 (SAS Institute, Inc., Cary, NC – USA) for all VI’s to determine the overall relationship between all the forage quality indicators and the VI’s. Season had an overall effect in the multiple regression models thus Pearson’s correlation coefficients between the forage quality indicators and the VI’s during the different seasons were then computed. All statistics were done using SAS® 9.3 (SAS Institute, Inc., Cary, NC – USA).

3.4 Results and discussion

Tables 1, 2, 3, 4 and 5 in Appendix, show the means and standard deviations for the MODIS and Sentinel-2 VI’s throughout the study period in the different areas and during the different seasons of grass growth. Figure 3.5 shows graphically the MODIS and Sentinel-2 VI’s differed from each other. The difference between the multispectral satellite-derived VI’s are to be expected due to their different captured wavebands and algorithms (Kumar et al., 2002). Despite differences between the VI’s, the same vegetation index was found to be similar in the two different areas (Figure 3.5). The reason could possibly be due to the different forage quantity and quality indicators, which were also found to be similar in the two areas (Figure 3.6).

Figure 3.5: Graph showing the means of the MODIS and Sentinel-2 vegetation indices throughout the study period in the different areas. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge Index.

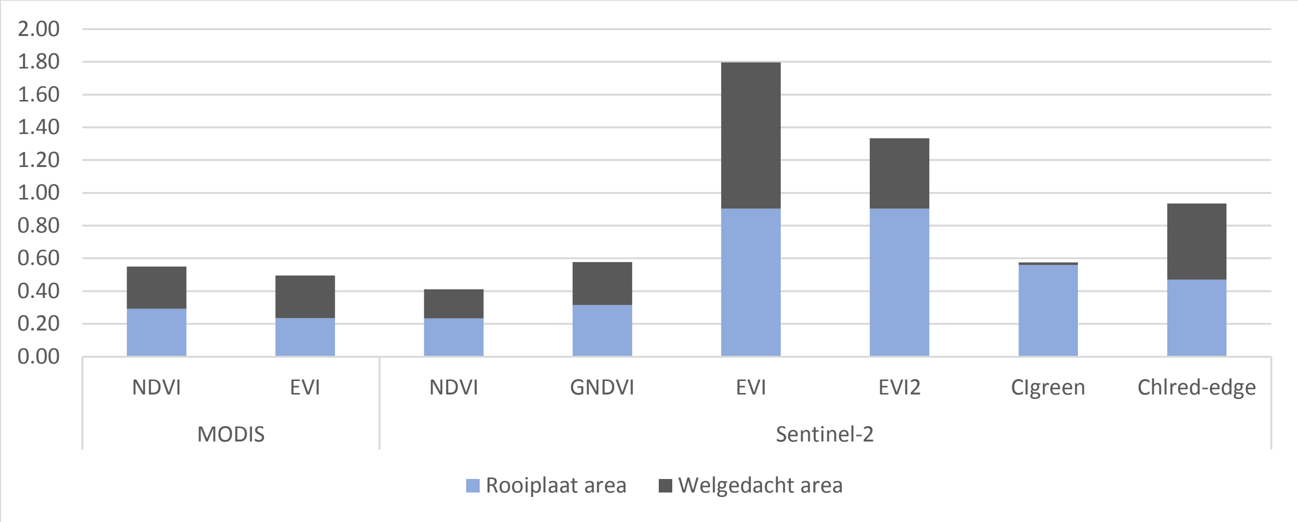
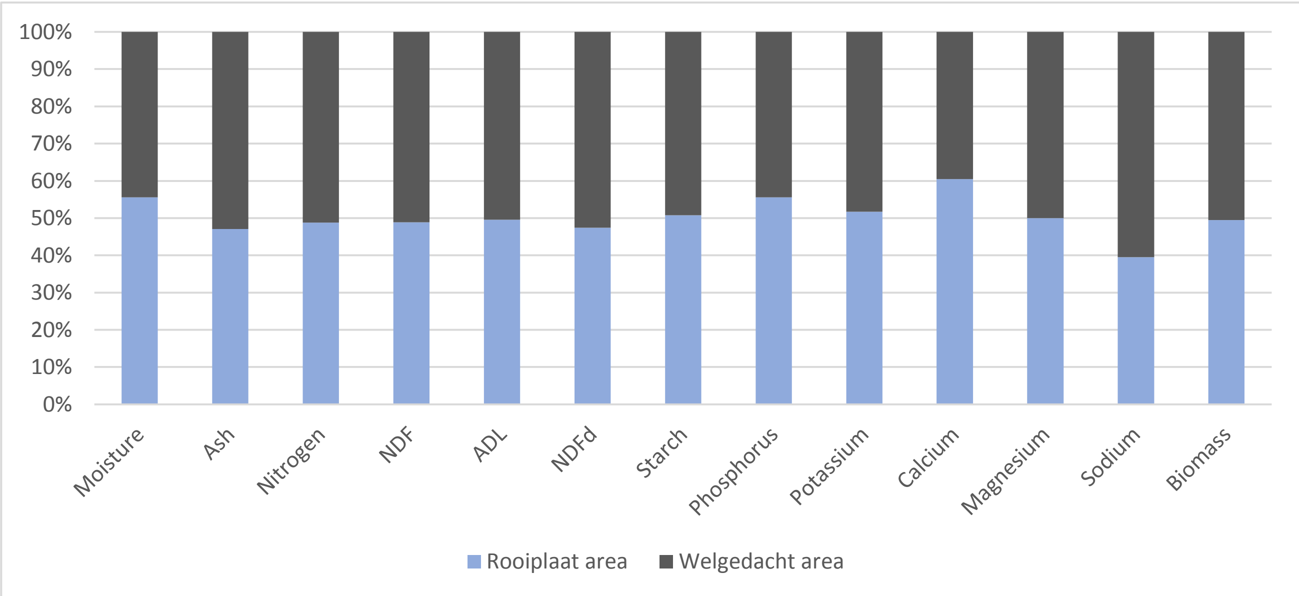


Figure 3.6: Graph showing the percentage of the different forage quantity and quality indicators throughout the study period in the different areas. NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility.



In Figure 3.7 the VI's increased from early growing to early dormant season and then decreased during the late dormant season. It is important to note the $Chl_{red\text{-}edge}$ equation is inversed (over one: Gitelson et al., 2006) and therefore when the VI's give positive values the $Chl_{red\text{-}edge}$ is expected to give negative values and vice versa. The seasonal trends of the VI's could possibly be due to some of the forage quality indicators (i.e., forage quality indicator N and K), which also followed the same seasonal trend (Figures 3.8). The forage quantity indicator biomass and the other forage quality indicators were found, however, to fluctuate differently during the different seasons (Appendix, Table 4). The reason for the seasonal trend between the VI's and the forage quality indicators N and K, is possibly because forage N and K are related to the photosynthetic process of plants and thus chlorophyll content (Al-Abbas et al., 1974; Glenn et al., 2008; Kumar et al., 2002; Sweeney, 1989), while VI's are a reflectance of vegetation canopy "greenness", which is caused by chlorophyll concentrations (Glenn et al., 2008; Kumar et al., 2002). Therefore, in MZNP, from the early growing to early dormant season, new green grass begins to emerge and grows until the early dormant season, causing an abundant supply of green material (Winkler and Owen-Smith, 1995). The increase in forage N and K is related to the increase of green vegetation in MZNP, which subsequently causes an increase in the VI's values. After the early dormant season in MZNP grass growth ceases and becomes dry and senescent with fiber concentrations in the forage increasing as they move into the late dormant season (Ball et al., 2001; Winkler and Owen-Smith, 1995). The increase in fiber concentrations during the late dormant season is confirmed in this study as NDF and ADL increase while NDFd decreases during the late dormant period (Figure 3.9). Therefore as a plant moves into the late dormant season, becoming mature and senescent, fiber (i.e. NDF and ADL) concentrations increase while specific forage nutrients such as N and K decrease (Ball et al., 2001; Codron et al., 2007) causing a decrease in chlorophyll concentration, vegetation canopy "greenness" and thus values from multispectral satellite-derived VI's.

Figure 3.7: Graph showing the means of the MODIS and Sentinel-2 vegetation indices during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge Index.

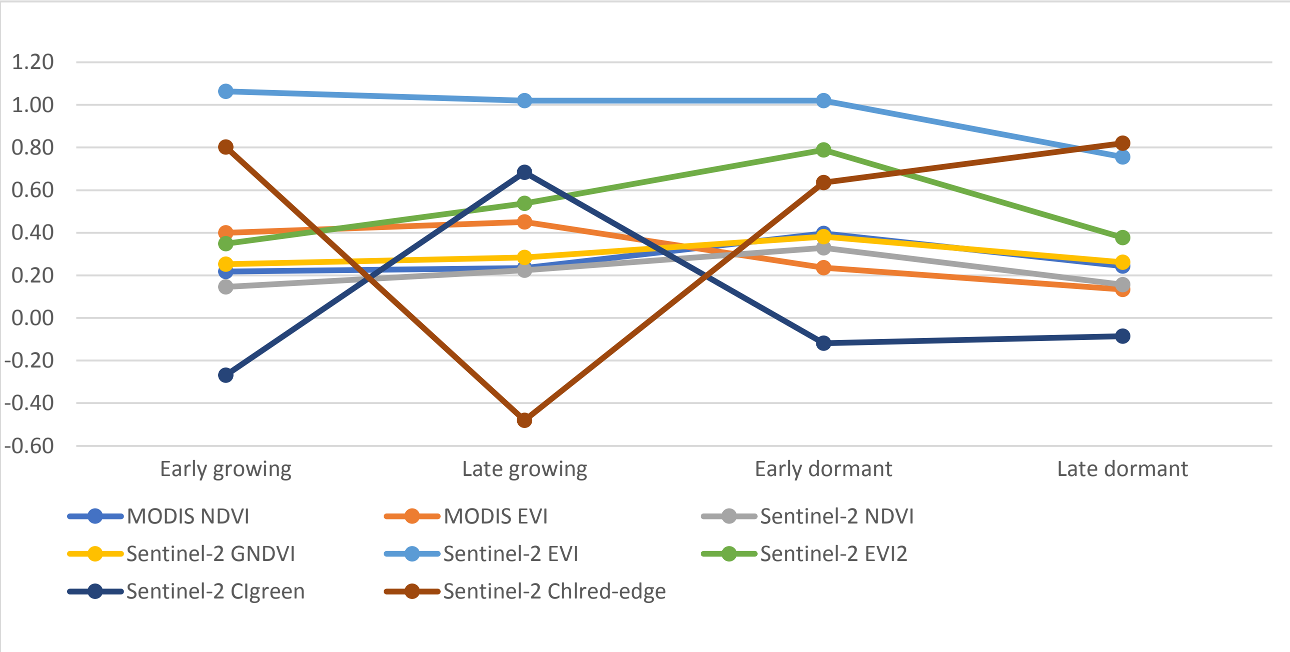


Figure 3.8: Graphs showing the percentage of the different forage quality indicator nitrogen and potassium during the different seasons of grass growth.

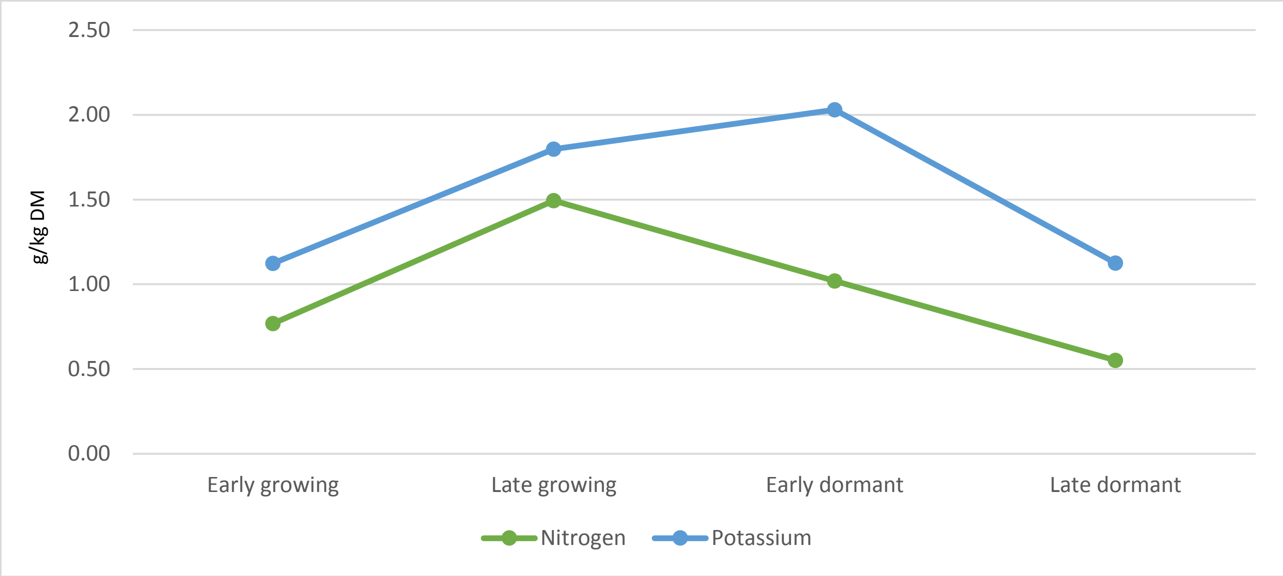
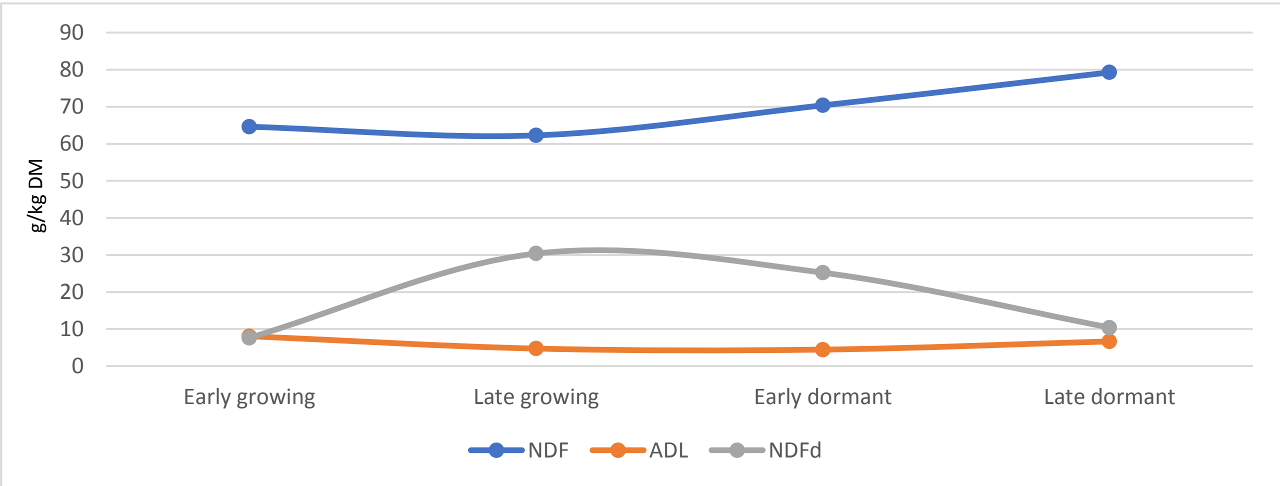


Figure 3.9: Graphs showing the percentage of the different forage quality indicator nitrogen and potassium during the different seasons of grass growth. NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility.



The general trends found in this study suggest multispectral satellite-derived VI's have relationships with specific forage quantity and quality indicators in MZNP. Despite general trends found, the values for the different VI's differed from each other and fluctuated during the different seasons of grass growth. The VI's also fluctuated differently with some of the concentrations of the forage quality indicators during the different grass growing seasons. These differences and variations found, therefore, highlight the importance of further investigation into the relationship between the multispectral satellite-derived VI's and the different forage quantity and quality indicators in MZNP.

3.4.1 Forage quantity

In Table 2, in Appendix, biomass in the Rooiplaat and Welgedacht area were found to be very similar (2001±507.280 kg/ha; 20143±456.143 kg/ha). Due to the similarity of biomass within the two areas, results were rather focused on biomass throughout the study period and during the different seasons of grass growth. Table 3 shows Pearson's correlation coefficients between the MODIS NDVI and EVI and the estimated biomass when pooling all samples together and during the different seasons of grass growth. When pooling all samples together, results showed the NDVI having a high positive significant correlation with biomass (r = 0.469, P ≤ 0.001; Table 3). The EVI, on the other hand, resulted in significant correlations only when data were analysed within each grass growing season. The NDVI also showed significance during all seasons, in particular during the early dormant season (r = 0.527, P ≤0.001). During the early dormant period, as seen in Table 4, the mean biomass was very high (2348±369 kg/ha). The NDVI during the early dormant season was also found to be very high (0.397±0.051). The NDVI also showed a very strong high significant negative correlation during the early growing season (r = -0.887, P ≤ 0.001: Table 3). During the early growing period biomass was also high ($\bar{x}$ =2376±113 kg/ha) however the mean NDVI was at its lowest (0.219±0.041: Table 4). Results show that contrary to what has been found in other studies, the NDVI had a much stronger relationship with biomass than the EVI.

Table 3. 3 : Correlations between the MODIS NDVI and EVI and forage quantity indicator biomass during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced vegetation index.

MODIS vegetation indices	n	Biomass	Seasons	Biomass
NDVI	368	0.469***	Early growing	-0.887***
			Late growing	0.431*
			Early dormant	0.527***
			Late dormant	0.193*
EVI	368	-0.076	Early growing	-0.888***
			Late growing	0.739***
			Early dormant	0.470***
			Late dormant	0.184**

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

Table 3.4: Means and standard deviations of the MODIS NDVI and EVI and the forage quantity indicator biomass during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index. Total number of observations: 368.

Seasons	Biomass		NDVI		EVI	
	$\bar{x}$ (kg/ha)	σ (kg/ha)	$\bar{x}$ (kg/ha)	σ (kg/ha)	$\bar{x}$ (kg/ha)	σ (kg/ha)
Early growing	2376	113.18	0.219	0.041	0.400	0.392
Late growing	1619	413.16	0.234	0.031	0.451	0.048
Early dormant	2348	369.99	0.397	0.051	0.236	0.028
Late dormant	1936	454.35	0.244	0.034	0.136	0.017

Figures 3.10 and 3.11 show graphically the similar seasonal trend of the forage quantity indicator biomass and the MODIS NDVI. During the early dormant season, both the NDVI and biomass are very high resulting in the strong positive correlation. While during the early growing season biomass remains high while the NDVI is at its lowest, resulting in the very strong negative correlation.

Figure 3.10: Graph showing the means of forage quantity indicator biomass during the different seasons of grass growth.

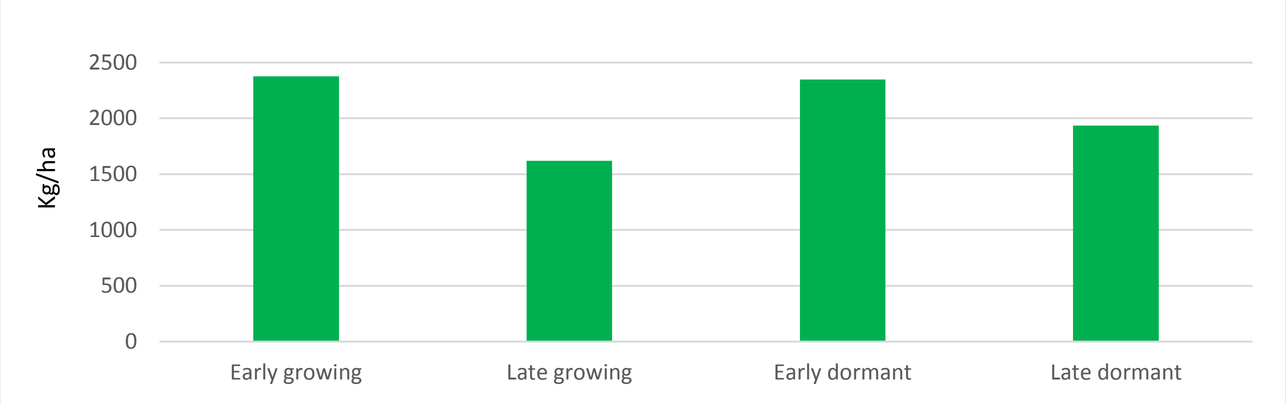
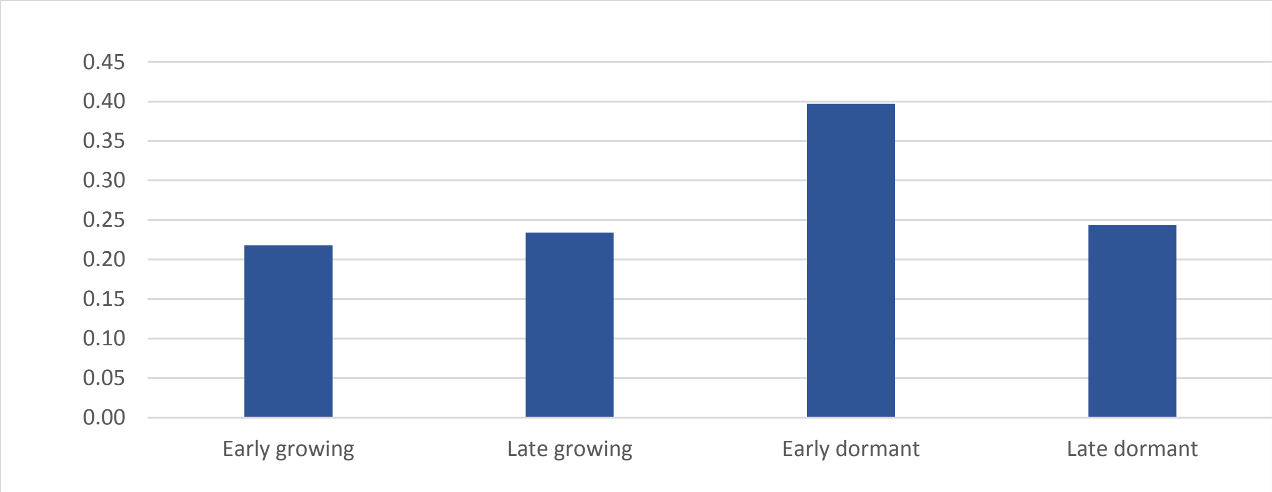


Figure 3.11: Graph showing the means of the MODIS NDVI during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index.



The results show, as predicted, that seasonality shapes the relationship between the NDVI and the forage quantity indicator biomass. The reason for the seasonal relationship could possibly be because the NDVI is a reflectance of vegetation canopy "greenness" and is therefore more correlated with seasonal fluctuations of chlorophyll content (photosynthetically active vegetation [PAV]) or green biomass (GBM) rather than overall biomass (PAV and non-PAV: Gamon et al., 1995; Goward et al., 1985; Pettorelli et al., 2011; Todd et al., 1998). Being more correlated with GBM is the possible reason for the positive correlation between NDVI and biomass during the early dormant season, as the grass in MZNP is mature and green and in abundant supply causing biomass and NDVI to be high. While the negative correlation found during the early growing season is because biomass is still relatively high, but the grass is still mainly dry and senescent causing the NDVI values to be low. Our results are similar to other studies where the MODIS NDVI and EVI have shown strong positive relationships with biomass during the season when vegetation was photosynthetically active (Garroutte et al., 2016; Kawamura et al., 2005; Sannier et al., 2002; Wessels et al., 2006). For herbivores in seasonal environments, green, photosynthetic vegetation is more nutritious than dormant vegetation, and is preferentially selected (Cross et al., 2004; Murray and Illius, 2000; Shrader et al., 2006; Wilmshurst et al., 1999). In forage, PAV is directly and causally related to the production and availability of carbohydrates, N and other nutrients that are often limiting for herbivores (Augustine et al., 2003; Frank and McNaughton, 1993; McNaughton et al., 1997; Mehaffey et al., 2005). The increase in forage nutrients in PAV is confirmed in this study, as the means of forage quality nutrients starch, N, P, K and Mg are relatively high during the late growing to early dormant season when green vegetation in MZNP is in abundant supply (Appendix, Table 4 and 5). Therefore, we recommend the NDVI's relationship with forage quantity indicator biomass, for MZNP, is more appropriately related to the quantity of high forage quality for herbivores. Moreover, our results suggest the MODIS NDVI, rather than the MODIS EVI, can potentially be useful in quantifying high forage quality in MZNP. The reason is possibly because the vegetation in the study areas is predominantly grasslands and is thus less dense than other vegetation types, and in savannas and grasslands the NDVI can yield reasonable estimates of biomass (Skidmore et al., 2005).

3.4.2 Forage quality

All multispectral satellite-derived VI's used throughout the study period, had, at different strengths, a significant correlation with a specific forage quality indicator (forage nutrient), despite predicting only certain VI's would have a relationship with specific forage quality indicators.

In Tables 3.5 and 3.6 moisture in the forage had highly significant correlations for all the multispectral satellite-derived VI's ($P \leq 0.001$: Tables 5 and 6). Moisture can negatively affect the relationship strength between the VI's and the other forage quality indicators (forage nutrients), as the presence of water molecules in the vegetation can mask the absorption features of the other biochemical compounds (Clevers, 1999; Curran et al., 2001; Kokaly and Clark, 1999; Kumar et al., 2002). Nevertheless, strong relationships were still found between the multispectral satellite-derived VI's and the other forage quality indicators in this study. Further research would be required to determine the extent to which moisture content affects the relationship strength between VI's and the other forage nutrient concentrations in MZNP.

Tables 3.5 and 3.6 also showed correlations between the multispectral satellite-derived VI's and forage quality indicator forage ash, which were found to be highly variable. Results in this study showed that the mean forage ash values were considerably high throughout the study period (Appendix, Tables 2 and 4), being above 10% in most of the collected forage samples, which usually indicates soil contamination and could be the reason such variation was found (Ball et al., 2001; Cherney et al., 1983; Hoffman, 2005).

Table 3.5: Correlations between the MODIS NDVI and EVI and selected forage quality indicators (forage nutrients) throughout the study period. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index. NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = NDF digestibility. Total number of observations: 368.

Forage quality indicators	MODIS vegetation Indices	
	NDVI	EVI
Moisture	0.430***	0.507***
Ash	-0.297***	0.727***
Nitrogen	0.129*	0.498***
NDF	-0.047	-0.659***
ADL	-0.564***	-0.273***
NDFd	0.401***	0.438***
Starch	0.452***	0.115*

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

Table 3.6: Correlations between the Sentinel-2 vegetation indices and selected forage quality indicators (forage nutrients) throughout the study period. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge Index. NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = NDF digestibility. Total number of observations for Sentinel-2 EVI: 208. Total number of observations for the other Sentinel-2 vegetation indices: 212.

Forage quality indicators	Sentinel-2 vegetation indices					
	NDVI	GNDVI	EVI	EVI2	CI_{green}	$Chl_{red\text{-}edge}$
Moisture	0.443***	0.270***	0.352***	0.443***	0.544***	-0.714***
Ash	-0.067	-0.195**	0.135	-0.067	-0.448***	-0.570***
Nitrogen	0.249***	0.097	0.340***	0.249***	0.667***	-0.786***
NDF	-0.237***	-0.137*	-0.384***	-0.237***	-0.628***	0.727***
ADL	-0.589***	-0.449***	-0.258***	-0.589***	-0.432***	0.524***
NDFd	0.494***	0.307***	0.278***	0.494***	0.611***	-0.748***
Starch	0.322***	0.351***	0.186**	0.322***	0.044	0.064

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

The MODIS EVI, in Table 3.5, showed a highly significant positive correlation with the forage quality indicator forage N ($r = 0.498$, $P \leq 0.001$). The correlation was found to be stronger than the correlations between forage N and the MODIS NDVI and Sentinel-2 NDVI ($r = 0.129$, $P \leq 0.05$; $r = 0.249$, $P \leq 0.001$: Table 3.5 and 3.6). The results found are to be expected as the EVI was developed to be more robust than the NDVI and more likely to share a stronger relationship with forage N (Gao et al., 2000; Huete et al., 2002; Kawamura et al., 2005). Interestingly, contrary to our prediction, the MODIS EVI also had a stronger correlation than the higher resolution Sentinel-2 EVI, which was also highly significant but had a weak correlation (r = 0.249, P ≤ 0.001: Tables 3.5 and 3.6). No other studies to our knowledge have compared the EVI, or any other VI's, from the MODIS and Sentinel-2 remote sensors with forage N, and our study highlights the need for further investigation into this subject. The multispectral satellite-derived VI's, however, in this study that showed the strongest significant correlations with forage N were the Sentinel-2 $Chl_{red\text{-}edge}$ and CI_{green} (r = -0.786, P ≤ 0.001; r = 0.667, P ≤ 0.001: Table 3.6). Notably, when correlation values between the different VI's and the forage quality indicators are positive, the correlations between the $Chl_{red\text{-}edge}$ and forage quality indicators are expected to be negative and vice versa, because the $Chl_{red\text{-}edge}$ equation is inversed (over one: Gitelson et al., 2006). The Sentinel-2 $Chl_{red\text{-}edge}$ and CI_{green} as well as the MODIS EVI also all showed highly significant high R^2 values for forage N (R^2 = 0.941, P ≤ 0.001; R^2 = 0.617, P ≤ 0.001; R^2 = 0.538, P ≤ 0.001: Tables 3.7). The results show, as predicted, the Sentinel-2 $Chl_{red\text{-}edge}$ and the CI_{green} had the strongest relationships with forage quality indicator N, with the MODIS EVI noticeably also having a strong relationship with forage N, which was not predicted. The Sentinel-2 $Chl_{red\text{-}edge}$ had, however, the strongest relationship in comparison to the other VI's and highlights the importance of incorporating red edge bands into the algorithms of VI's, in order to assess forage N. For MZNP management the implementation of the MODIS EVI and Sentinel-2 $Chl_{red\text{-}edge}$ and CI_{green} to monitor and assess the forage quality indicator forage N is recommended. The successful monitoring of forage N can be very beneficial for MZNP and the management of their ungulate populations. The reason is because forage N is related to protein content (Clifton et al., 1994; Wang et al., 2004) which is one of the most limiting nutrients for grazers (Grant et al., 2000; Owen-Smith and Novellie, 1982; Prins, 1996; Scholes and Walker, 1993), and studies have shown deficiencies of forage N affects the distribution and movements of African grazing ungulates (Ben-Shahar and Coe, 1992; Seagle and McNaughton, 1992; Stapelberg et al., 2008).

Results for forage quality indicator forage fiber, in Table 3.6, showed the CI_{green} had a negatively strong correlation with NDF (r = -0.628, P ≤ 0.001) and a positively strong correlation with NDFd (r = -0.628, P ≤ 0.001), both of which were highly significant. On the other hand, the $Chl_{red\text{-}edge}$ showed a strong positive correlation with NDF (r = 0.727, P ≤ 0.001) and a strong negative correlation with NDFd (r = -0.748, P ≤ 0.001), both of which were also highly significant. Table 7 showed the $Chl_{red\text{-}edge}$ and CI_{green} both had highly significant high R^2 values for NDF (R^2 = 0.538, P ≤ 0.001; R^2 = 0.467, P ≤ 0.001). Table 3.7 also showed the $Chl_{red\text{-}edge}$ and CI_{green} both had highly significant high R^2 values for NDFd (R2 = 0.674; P ≤ 0.001; R2 = 0.437, P ≤ 0.001). In Tables 3.5 and 3.6, the MODIS NDVI and Sentinel-2 NDVI had highly significant strong negative correlations with ADL (r = -0.564, P ≤ 0.001; r = -0.589, P ≤ 0.001). Results also showed ADL had a strong negative correlation with CI_{green} (r = -0.589, P ≤ 0.001) and a strong positive correlation with $Chl_{red\text{-}edge}$ (r = 0.524, P ≤ 0.001), both of which were highly significant. For ADL the MODIS NDVI and Sentinel-2 NDVI and $Chl_{red\text{-}edge}$ had highly significant low R^2 values (R^2 = 0.318, P ≤ 0.001; R^2 = 0.347, P ≤ 0.001; R^2 = 0.274, P ≤ 0.001), while the

CI_{green} showed no significance (P > 0.05). We predicted relationships found between multispectral satellite-derived VI's and forage quality indicators (besides from forage N) would be weak. Contrary to our prediction the $Chlr_{ed\text{-}edge}$ and CIgreen had strong relationships with NDFd and strong negative relationships with NDF, while the MODIS NDVI and Sentinel-2 NDVI and $Chl_{red\text{-}edge}$ had strong negative relationships with ADL. The results show that the multispectral satellite-derived VI's, mentioned above, are related to low forage fiber and high fiber digestibility, which we advocate as an important relationship for good forage quality. The reason is because as fiber increases forage quality tends to decline with high NDF and ADL concentrations closely associated with low intake potential, digestibility and nutritive values of forage (Ball et al., 2001; Barboza et al., 2008; Laca et al., 2001). While NDFd explains the amount of NDF that can be broken down by the herbivore (Hoffman et al., 2001) and positively relates to better feed intake and an animal's performance (Jalali et al., 2012; Oba and Allen, 1999). Overall the results, in Tables 3.5, 3.6 and 3.7, show the Sentinel-2 $Chl_{red\text{-}edge}$ shared the most comprehensive relationship with the forage quality indicator fiber (NDF, NDFd and ADL). Therefore, for MZNP management in order to assess forage fiber, specifically good forage quality (low forage fiber and high fiber digestibility), and the implementation of the Sentinel-2 $Chl_{red\text{-}edge}$ is recommended. We also recommend the inclusion of the Sentinel-2 CI_{green} for monitoring NDF and NDFd and the MODIS and Sentinel-2 NDVI for ADL.

The forage quality indicator starch, in Tables 3.5 and 3.6, showed a moderate positive correlation with the MODIS NDVI (r = 0.452, P ≤ 0.001) and the Sentinel-2 NDVI and GNDVI (r = 0.322, P ≤ 0.001; r = 0.351, P ≤ 0.001), all of which were highly significant. Table 3.7 showed the MODIS NDVI and Sentinel-2 NDVI had highly significant low R^2 values for forage starch (R^2 = 0.205, P ≤ 0.001; R^2 = 0.123, P ≤ 0.001), while the GNDVI was not significant (P > 0.05: Tables 3.7). Results show forage starch has a relationship with the MODIS NDVI and Sentinel-2 NDVI however, as predicted, the relationship is weak. To our knowledge, there are no studies available that have tested the relationship between multispectral satellite-derived VI's and forage starch. Our results suggest further investigation is required, particularly, between forage starch and the NDVI and its derivatives (e.g. GNDVI). For MZNP we recommend that the MODIS and Sentinel-2 NDVI be used to assess forage starch. We do advise the estimates from the MODIS and Sentinel-2 NDVI to assess forage starch be taken with caution, and other field studies in conjunction with the VI's be conducted to ensure more precise forage starch estimates.

Table 3. 7: Simple linear regressions for prediction of forage quality indicators from the MODIS (A - B) and Sentinel-2 (C-I) vegetation indices. A = NDVI. B = EVI. C = NDVI. D = GNDVI. E = EVI. F = EVI2. G = CI_{green}. H = $Chl_{red\text{-}edge}$. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, Clgreen = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge index. Nutrients NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility. Total number of observations for MODIS VI's: 368. Total number of observations for Sentinel-2 EVI: 208. Total number of observations for the other vegetation indices: 212.

A	Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
	Ash	20.950	-66.571	90.300	0.151	<0.0001
	Nitrogen	0.688	0.666	[c]	0.017	0.0132
	NDF	55.746	117.697	-192.136	0.029	0.0050
	ADL	8.431	-9.324	[c]	0.318	<0.0001
	NDFd	4.596	47.512	[c]	0.161	<0.0001
	Starch	2.316	3.896	[c]	0.205	<0.0001
	Phosphorus	[b]	1.563	-2.712	0.723	<0.0001
	Potassium	-0.810	7.327	-7.391	0.460	<0.0001
	Calcium	1.541	-3.001	[c]	0.078	<0.0001
	Magnesium	0.312	-0.468	[c]	0.069	<0.0001
	Sodium	[b]	0.200	-0.418	0.307	<0.0001

B	Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
	Ash	6.671	15.844	-6.401	0.547	<0.0001
	Nitrogen	[b]	5.369	-4.823	0.941	<0.0001
	NDF	87.067	-80.818	57.223	0.573	<0.0001
	ADL	8.620	-18.043	18.126	0.588	<0.0001
	NDFd	-5.653	147.473	-140.403	0.791	<0.0001
	Starch	2.891	3.260	-3.181	0.072	<0.0001
	Phosphorus	0.184	0.218	-0.334	0.027	0.0065
	Potassium	0.774	-0.649	[c]	0.126	<0.0001
	Calcium	0.434	1.739	1.739	0.013	0.0922
	Magnesium	[b]	1.124	-1.047	0.699	<0.0001
	Sodium	[b]	0.121	-0.104	0.315	<0.0001

C	Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
	Ash	[b]	82.915	-159.530	0.880	<0.0001
	Nitrogen	[b]	7.489	-12.247	0.772	<0.0001
	NDF	81.952	-126.557	213.075	0.117	<0.0001
	ADL	7.219	-8.746	[c]	0.347	<0.0001
	NDFd	-2.488	142.963	-177.793	0.275	<0.0001
	Starch	1.842	10.896	-14.554	0.123	<0.0001
	Phosphorus	[b]	2.101	-4.375	0.681	<0.0001
	Potassium	[b]	6.608	-10.325	0.708	<0.0001
	Calcium	0.429	-0.385	[c]	0.030	0.0113
	Magnesium	[a]				
	Sodium	[a]				

D	Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
	Ash	11.841	-8.07	[c]	0.038	0.0043
	Nitrogen	[a]				
	NDF	89.315	-151.226	234.349	0.063	0.0011
	ADL	7.745	-8.089	[c]	0.202	<0.0001
	NDFd	[a]				
	Starch	[a]				
	Phosphorus	-0.220	3.069	-5.065	0.075	0.0003
	Potassium	0.518	1.148		0.020	0.0389
	Calcium	[b]	2.902	-5.485	0.780	<0.0001
	Magnesium	[a]				
	Sodium	[a]				

F

Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
Ash	[b]	17.499	-7.243	0.879	<0.0001
Nitrogen	0.439	0.557	[c]	0.102	<0.0001
NDF	76.071	-10.656	[c]	0.148	<0.0001
ADL	6.317	-1.070	[c]	0.067	0.0002
NDFd	10.448	8.892	[c]	0.077	<0.0001
Starch	2.814	0.625	[c]	0.035	0.0072
Phosphorus	[b]	0.421	-0.177	0.684	<0.0001
Potassium	0.440	0.464	[c]	0.063	0.0003
Calcium	[b]	0.717	-0.330	0.762	<0.0001
Magnesium	[a]				
Sodium	[a]				

G

Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
Ash	[b]	34.558	-27.712	0.880	<0.0001
Nitrogen	[b]	3.121	-2.127	0.772	<0.0001
NDF	81.954	-52.754	37.019	0.117	<0.0001
ADL	7.220	-3.645	[c]	0.347	<0.0001
NDFd	[b]	50.806	-24.105	0.829	<0.0001
Starch	1.842	4.542	-2.529	0.123	<0.0001
Phosphorus	[b]	0.876	-0.760	0.681	<0.0001
Potassium	[b]	2.754	-1.793	0.708	<0.0001
Calcium	0.429	-0.160		0.030	0.0113
Magnesium	[a]				
Sodium	[a]				

H

Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
Ash	7.736	-2.212	13.590	0.452	<0.0001
Nitrogen	0.705	0.348	1.521	0.538	<0.0001
NDF	69.769	-5.836	-21.409	0.467	<0.0001
ADL	5.477	-1.550	[c]	0.186	<0.0001
NDFd	14.694	6.919	23.403	0.437	<0.0001
Starch	[a]				
Phosphorus	0.243	0.275	-0.332	0.157	<0.0001
Potassium	0.713	0.512	0.758	0.292	<0.0001
Calcium	0.372	0.317	-0.342	0.136	<0.0001
Magnesium	[a]				
Sodium	[a]				

I

Forage quality indicators	Intercept	Linear coefficient	Quadratic coefficient	R^2	P
Ash	8.905	-4.895	5.622	0.369	<0.0001
Nitrogen	1.323	-0.812	[c]	0.617	<0.0001
NDF	57.977	9.708	7.541	0.538	<0.0001
ADL	4.7577	1.285	[c]	0.274	<0.0001
NDFd	36.266	-5.223	-30.256	0.670	<0.0001
Starch	4.391	0.644	-2.576	0.078	0.0002
Phosphorus	0.133	-0.133	0.288	0.071	0.0004
Potassium	1.162	-0.652	[c]	0.350	<0.0001
Calcium	0.191	-0.208	0.502	0.108	<0.0001
Magnesium	[a]				
Sodium	[a]				

[a] Regression model not significant; only significant models shown.

[b] Intercept not different from zero; model without intercept used.

[C] Quadratic coefficient model not significant; model without quadratic coefficient model used.

Tables 3.8 and 3.9 show the MODIS NDVI and Sentinel-2 $Chl_{red\text{-}edge}$ and CI_{green} had highly significant strong correlations with the forage quality indicator K (r = 0.659, P ≤ 0.001; r = -0.592, P ≤ 0.001; r = 0.521, P ≤ 0.001). Table 3.7 shows the MODIS NDVI and Sentinel-2 $Chl_{red\text{-}edge}$ had the highest R^2 values for forage K and were highly significant (R^2 = 0.460, P ≤ 0.001; R^2= 0.350, P ≤ 0.001). Tables 3.8 and 3.9 also showed the Sentinel-2 CI_{green} had the strongest correlations with the other forage quality minerals in this study (forage P, Ca, Mg and Na), all of which were highly significant. The CI_{green} showed, in Table 3.7, highly significant low R^2 values for forage P and Ca (R^2 = 0.157, P ≤ 0.001; R^2 = 0.136, P ≤ 0.001) and no significant R^2 values for forage Mg and Na (P > 0.05). Our results show the VI's, as predicted, had weak relationships with forage quality indicators P, Ca, Mg and Na however, contrary to our prediction the MODIS NDVI and Sentinel-2 $Chl_{red\text{-}edge}$ had a moderate relationship with forage quality indicator K. Other studies have found more success in finding stronger relationships between remote sensing data and forage minerals however, they could only estimate forage mineral concentrations using the wavelength range of a hyperspectral remote sensor (Mutanga et al., 2004; Skidmore et al., 2010; Zhao et al., 2007). This study, therefore, brings to light the lack of important wavebands found on more appropriate and suitable multispectral sensors for forage mineral estimations. For MZNP, based on our results, we recommend the MODIS NDVI and Sentinel-2 $Chl_{red\text{-}edge}$ be used to assess forage quality indicator K. We also recommend the implementation of the Sentinel-2 CI_{green} to assess forage minerals P and Ca. We do, however, advise the estimates from the multispectral satellite-derived VI's to assess forage minerals be taken with caution, and other field studies in conjunction with the VI's be conducted to ensure more precise forage mineral estimates.

Table 3.8: Correlations between the MODIS NDVI and EVI and selected forage quality indicators throughout the study period. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index. Total number of observations: 368.

Forage quality indicators	MODIS vegetation Indices	
	NDVI	EVI
Phosphorus	-0.087	-0.100
Potassium	0.659***	-0.355***
Calcium	-0.174*	-0.058
Magnesium	-0.262***	0.246***
Sodium	-0.142**	0.156**

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

Table 3.9: Correlations between the Sentinel-2 vegetation indices and selected forage quality indicators throughout the study period. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge index. Nutrients NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility. Total number of observations for Sentinel-2 EVI: 208. Total number of observations for the other vegetation indices: 212.

Forage quality indicators	Sentinel-2 vegetation indices					
	NDVI	GNDVI	EVI	EVI2	CI_{green}	$Chl_{red\text{-}edge}$
Phosphorus	-0.053	0.076	0.160*	-0.053	0.313***	-0.163*
Potassium	0.245***	0.142*	0.251***	0.245***	0.521***	-0.592***
Calcium	-0.174*	-0.058	0.099	-0.174**	0.314***	-0.157**
Magnesium	-0.109	-0.021	0.098	-0.109	0.328***	-0.203**
Sodium	-0.108	-0.063	0.110	-0.108	0.233***	-0.188**

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

Tables 3.10 and 3.11 show multiple linear regressions for the prediction of forage quality indicators from the MODIS and Sentinel-2 VI's. The MODIS NDVI and EVI were affected by a lot of forage quality indicators and showed low RMSE and high R^2 values (R^2 = 0.951; RMSE = 0.018; R^2 = 0.994; RMSE = 0.013: Table 3.10). A reason for the large number of affected variables for the MODIS NDVI and EVI is possibly because of its large spatial resolution, as its larger pixels would consist of more variation in the vegetation. In Table 3.11 the Sentinel-2 NDVI and EVI2 were affected by forage quality indicator P and showed low RMSE and high R^2 values (R^2 = 0.741; RMSE = 0.046; R^2 = 0.731; RMSE = 0.111). The GNDVI and EVI were only affected by forage quality indicator ash and also showed low RMSE and high R^2 values (R^2 = 0.652; RMSE = 0.044; R^2 = 0.283; RMSE = 0.225: Table 3.11). The $Chl_{red\text{-}edge}$ was affected by forage quality indicators P and ash and also had a low RMSE and high R^2 value (R2 = 0.652; RMSE = 0.044: Table 3.11). The CI_{green} was also affected by forage quality indicator P but as well as forage quality indicator N and also had a low RMSE and high R^2 value (R^2 = 0.949; RMSE = 0.084: Table 11). These results show, even more so, that multispectral satellite-derived VI's are affected by forage quality indicators.

Table 3.10: Multiple linear regressions for prediction of forage quality indicators from the MODIS vegetation indices. NDVI = normalized difference vegetation index, EVI = enhanced vegetation index, EVI2= enhanced vegetation index 2, GNDVI= green normalized vegetation index, Chl_{green} = green chlorophyll index, $Chl_{red\text{-}edge}$ = red-edge chlorophyll index. Nutrients NDF= Neutral Detergent Fibre, ADL= Acid Detergent Lignin, NDFd= Neutral Detergent Fibre digestibility. Total number of observations= 368.

Vegetation Indices	n	Regression equation	RMSE	R^2
NDVI	368	- 0.014 + 0.001 Moisture + 0.002 Ash - 0.085 Nitrogen + 0.005 NDF - 0.161 Phosphorus - 0.019 Potassium + 0.147 Magnesium + 0.137 Sodium	0.018	0.951
EVI	368	0.485 - 0.003 Ash - 0.093 Nitrogen + 0.004 NDF - 0.002 NDFd - 0.005 Starch - 0.122 Phosphorus - 0.013 Potassium - 0.019 Calcium + 0.121 Magnesium + 0.259 Sodium	0.013	0.994

Area*Season had an overall effect.

Table 3. 11: Multiple linear regressions for prediction of forage quality indicators from the Sentinel -2 vegetation Indices. NDVI = normalized difference vegetation index, EVI = enhanced vegetation index, EVI2= enhanced vegetation index 2, GNDVI= green normalized vegetation index, Cl_{green} = green chlorophyll index, $Chl_{red\text{-}edge}$ = red-edge chlorophyll index.

Vegetation Indices	n	Regression equation	RMSE	R^2
NDVI	212	0.223 - 0.069 Phosphorus	0.046	0.741
GNDVI	212	0.299 - 0.003 Ash	0.044	0.652
EVI	208	0.902 + 0.458 Ash	0.283	0.225
EVI2	212	0.534 - 0.167 Phosphorus	0.111	0.731
Cl_{green}	212	0.78 - 0.064 Nitrogen + 0.188 Phosphorus	0.084	0.949
$Chl_{red\text{-}edge}$	212	-0.481 - 0.006 Ash + 0.059 Phosphorus	0.055	0.990

Area*Season had an overall effect.

Tables 3.10 and 3.11 also show that area and season had an overall effect on the multispectral VI's. The results show, as predicted, the relationship between multispectral satellite-derived VI's and forage quality indicators are shaped by season and site. This is to be expected as studies have shown the concentration of biochemical compounds in the forage is affected by site specific factors, both abiotic and biotic (Mutanga and Skidmore, 2004; Seagle and McNaughton, 1992). Adding to this, our results also show fluctuating correlations of each forage nutrient and the different VI's during the different seasons (Appendix: Tables 1, 2, 3 and 4). This is to be expected as MZNP experiences seasonal climatic patterns (Pond et al., 2002) with nutrient concentrations known to fluctuate as the plant matures (Ball et al., 2001; Owen-Smith and Novellie, 1982). Another possible reason for the seasonal effect is that the heterogeneity of the vegetation can cause some plant species to prevail over others during different periods of the season. Although we recognize area to also have an effect on forage quality and subsequently the satellite-derived VI's no further analysis was done due to a lack of sampling size, because of time constraints. We do, however, from these results, highlight the importance of considering other ancillary variables when applying VI's to assess forage quality. To our knowledge, few studies have highlighted this need to integrate environmental or ancillary variables with VI's (Cho et al., 2009; Knox et al., 2011; Ramoelo et al., 2011).

3.5 Conclusion

The MODIS and Sentinel-2 satellite-derived VI's share relationships, at different strengths, with the different forage quantity and quality indicators in MZNP. We show the MODIS NDVI, rather than EVI, had a strong relationship with forage quantity indicator biomass. The result is interesting since the EVI is an enhancement over the saturation problems faced by the NDVI, and is thus expected to have a stronger relationship with forage quantity. Our results also show the MODIS NDVI should rather be implemented to assess the amount of high forage quality for herbivores in MZNP. Results also showed the Sentinel-2 $Chl_{red-edge}$ had a very strong relationship with forage quality indicator N and this study highlights the importance of red edge bands in the algorithms of VI's. Along with the Sentinel-2 $Chl_{red-edge}$, the Sentinel-2 CI_{green} and MODIS EVI also shared strong relationships with forage N. Despite predicting any other relationships between the multispectral satellite-derived VI's and the other forage quality indicators would be weak, strong relationships were found between the Sentinel-2 CI_{green}, NDVI and MODIS NDVI and the forage quality indicators fibre (NDF, NDFd and ADL) and forage K. The strong relationships found are very interesting, as there are no studies available, to our knowledge, that have researched the relationship between multispectral satellite-derived VI's and forage fiber and K. Our study also shows that, although weak, significant relationships exist between the Sentinel-2 and MODIS NDVI and the forage quality indicator starch. A weak but also significant relationship was found between the Sentinel-2 CI_{green} and forage quality indicators P and Ca. Despite the weak relationship found, our results highlight the importance of further investigation into these relationships as limited research is available. This study also shows the relationship between multispectral satellite-derived VI's and forage quantity and quality indicators are driven by season and area and highlights the importance of adding ancillary and environmental variables into models when determining their relationship. The relationships found in this study highlight the importance of assessing VI's and their relationship with forage quantity and quality indicators within the desired area, in order to ensure confidence in the biological significance of the VI's estimates.

The information in this study shows the suitability and applicability of multispectral satellite-derived VI's to monitor forage quantity and quality for herbivores in MZNP. The implementation of multispectral satellite-derived VI's will aid appropriate management decisions for the park's herbivore populations. We recommend, because of the no cost and easy accessibility of the VI's, the VI's that shared the best relationship with each forage quantity and quality indicator be implemented. We do, however, make note that VI's are limited to estimates of forage quantity and quality of the vegetation and do not consider the diets of the herbivore, nor differentiate the diets of the different herbivore species, making generalizations regarding forage quantity and quality for herbivores potentially misleading. We, therefore, suggest the target herbivore species and their dietary requirements and physiologies are taken into account. We also suggest estimates from the multispectral satellite-derived VI's be used in conjunction with other methods and variables for accurate management decisions.

This study provides important information about the relationship between multispectral satellite-derived VI's and forage quantity and quality indicators. Despite the benefits of multispectral satellite-derived VI's, there is a limited amount of research available and our study provides much needed information. We advocate the valuable information found in this study to be used as a model for much for further required research.

3.6 References

Acocks, J.P.H., 1988. Veld types of South Africa.

Al-Abbas, A.H., Barr, R., Hall, J.D., Crane, F.L., Baumgardner, M.F., 1974. Spectra of Normal and Nutrient-Deficient Maize Leaves 1. Agron. J. 66, 16–20.

ALASA, 1998. Handbook of feeds and plant analysis. Method 6.1.1 - Dr Ashing. palic, D. (Ed).

Albayrak, S., 2008. Use of reflectance measurements for the detection of N, P, K, ADF and NDF contents in sainfoin pasture. Sensors 8, 7275–7286.

AOAC., 1996. Official methods of analysis of the AOAC International. 16th edition. Association of Official Analytical Chemists (AOAC) International, Arlington, Virginia, USA.

Augustine, D.J., McNaughton, S.J., Frank, D.A., 2003. Feedbacks between soil nutrients and large herbivores in a managed savanna ecosystem. Ecol. Appl. 13, 1325–1337.

Ball, D.M., Collins, M., Lacefield, G.D., Martin, N.P., Mertens, D.A., Olson, K.E., Putnam, D.H., Undersander, D.J., Wolf, M.W., 2001. Understanding forage quality. Am. Farm Bur. Fed. Publ. 1.

Barboza, P.S., Parker, K.L., Hume, I.D., 2008. Integrative wildlife nutrition. Springer Science & Business Media.

Ben-Shahar, R., Coe, M.J., 1992. The relationships between soil factors, grass nutrients and the foraging behaviour of wildebeest and zebra. Oecologia 90, 422–428.

Bezuidenhout, H., Brown, L.R., Bradshaw, P., 2015. Broad vegetation description for Mountain Zebra National Park, Eastern Cape, South Africa. Internal SANParks report. South African National Parks, Scientific Services, Kimberley.

Bransby, D.I., Tainton, N.M., 1977. The disc pasture meter: possible applications in grazing management. Proc. Annu. Congr. Grassl. Soc. South. Africa 12, 115–118.

Brown, L.R., Bezuidenhout, H., 2005. The vegetation of the farms Ingleside and Welgedacht of the Mountain Zebra National Park, Eastern Cape.

Brown, L.R., Bezuidenhout, H., 2000. The phytosociology of the De Rust section of the Mountain Zebra National Park, Eastern Cape.

Burkepile, D.E., Burns, C.E., Tambling, C.J., Amendola, E., Buis, G.M., Govender, N., Nelson, V., Thompson, D.I., Zinn, A.D., Smith, M.D., 2013. Habitat selection by large herbivores in a southern African savanna: the relative roles of bottom-up and top-down forces. Ecosphere 4, 1–19.

Cherney, J.H., Robinson, D.L., Kappel, L.C., Hembry, F.G., Ingraham, R.H., 1983. Soil Contamination and Elemental Concentrations of Forages in Relation to Grass Tetany 1. Agron. J. 75, 447–451.

Cho, M., van Aardt, J., Main, R., Majeke, B., Ramoelo, A., Mathieu, R., Norris-Rogers, M., Du Plessis, M., 2009. Integrating remote sensing and ancillary data for regional ecosystem assessment: Eucalyptus grandis agro-system in KwaZulu-Natal, South Africa, in: 2009 IEEE International Geoscience and Remote Sensing Symposium. IEEE, p. IV-264.

Cho, M.A., Ramoelo, A., Debba, P., Mutanga, O., Mathieu, R., Van Deventer, H., Ndlovu, N., 2013. Assessing the effects of subtropical forest fragmentation on leaf nitrogen distribution using remote sensing data. Landsc. Ecol. 28, 1479–1491.

Clevers, J., 1999. The use of imaging spectrometry for agricultural applications. ISPRS J. Photogramm. Remote Sens. 54, 299–304.

Clevers, J.G.P.W., Gitelson, A.A., 2013. Remote estimation of crop and grass chlorophyll and nitrogen content using red-edge bands on Sentinel-2 and-3. Int. J. Appl. Earth Obs. Geoinf. 23, 344–351.

Clevers, J.G.P.W., Kooistra, L., 2012. Using hyperspectral remote sensing data for retrieving canopy chlorophyll and nitrogen content. IEEE J. Sel. Top. Appl. earth Obs. Remote Sens. 5, 574–583.

Clifton, K.E., Bradbury, J.W., Vehrencamp, S.L., 1994. The fine-scale mapping of grassland protein densities. Grass Forage Sci. 49, 1–8.

Codron, D., Lee-Thorp, J.A., Sponheimer, M., Codron, J., 2007. Nutritional content of savanna plant foods: implications for browser/grazer models of ungulate diversification. Eur. J. Wildl. Res. 53, 100–111.

Cross, P.C., Owen-Smith, N., Macandza, V.A., 2004. Forage selection by African buffalo in the late dry season in two landscapes. South African J. Wildl. Res. delayed open access 34, 113–121.

Curran, P.J., Dungan, J.L., Peterson, D.L., 2001. Estimating the foliar biochemical concentration of leaves with reflectance spectrometry: testing the Kokaly and Clark methodologies. Remote Sens. Environ. 76, 349–359.

De Klerk, J., Bezuidenhout, H., Brown, L.R., Castley, G., 2001. The estimation of herbage yields under fire and grazing treatments in the Mountain Zebra National Park.

Didan, K., 2015. MOD13Q1 MODIS/Terra vegetation indices 16-day L3 global 250m SIN grid V006. NASA EOSDIS L. Process. DAAC.

Frampton, W.J., Dash, J., Watmough, G., Milton, E.J., 2013. Evaluating the capabilities of Sentinel-2 for quantitative estimation of biophysical variables in vegetation. ISPRS J. Photogramm. Remote Sens. 82, 83–92. https://doi.org/10.1016/j.isprsjprs.2013.04.007

Frank, D.A., McNaughton, S.J., 1993. Evidence for the promotion of aboveground grassland production by native large herbivores in Yellowstone National Park. Oecologia 96, 157–161.

Gamon, J.A., Field, C.B., Goulden, M.L., Griffin, K.L., Hartley, A.E., Joel, G., Penuelas, J., Valentini, R., 1995. Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. Ecol. Appl. 5, 28–41.

Gao, T., Xu, B., Yang, X., Jin, Y., Ma, H., Li, J., Yu, H., 2013. Using MODIS time series data to estimate aboveground biomass and its spatio-temporal variation in Inner Mongolia's grassland between 2001 and 2011. Int. J. Remote Sens. 34, 7796–7810.

Gao, X., Huete, A.R., Ni, W., Miura, T., 2000. Optical–biophysical relationships of vegetation spectra without background contamination. Remote Sens. Environ. 74, 609–620.

Garroutte, E.L., Hansen, A.J., Lawrence, R.L., 2016. Using NDVI and EVI to map spatiotemporal variation in the biomass and quality of forage for migratory elk in the Greater Yellowstone Ecosystem. Remote Sens. 8, 404.

Gitelson, A.A., Keydan, G.P., Merzlyak, M.N., 2006. Three-band model for noninvasive estimation of chlorophyll, carotenoids, and anthocyanin contents in higher plant leaves. Geophys. Res. Lett. 33.

Glenn, E., Huete, A., Nagler, P., Nelson, S., 2008. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape. Sensors 8, 2136–2160.

Goering, H.K., Van Soest, P.J., 1970. Forage fiber analysis. Agricultural handbook no. 379. US Dep. Agric. Washington, DC 1–20.

Govender, M., Chetty, K., Naiken, V., Bulcock, H., 2008. A comparison of satellite hyperspectral and multispectral remote sensing imagery for improved classification and mapping of vegetation 34, 147–154.

Goward, S.N., Tucker, C.J., Dye, D.G., 1985. North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. Vegetatio 64, 3–14.

Grant, C.C., Meissner, H.H., Schultheiss, W.A., 1995. The nutritive value of veld as indicated by faecal phosphorous and nitrogen and its relation to the condition and movement of prominent ruminants during the 1992-1993 drought in the Kruger National Park. Koedoe 38, 17–31.

Grant, C.C., Peel, M.J.S., Van Ryssen, J.B.J., 2000. Nitrogen and phosphorus concentration in faeces: an indicator of range quality as a practical adjunct to existing range evaluation methods. African J. Range Forage Sci. 17, 81–92.

Grant, R.C.C., Peel, M.J.S., Bezuidenhout, H., 2011. Evaluating herbivore management outcomes and associated vegetation impacts. Koedoe 53, 116–130.

Hall-Martin, A., Carruthers, J., 2003. South African National Parks: A Celebration. SANParks, Johannesbg.

Hoffman, P.C., 2005. Ash content of forages. Focus Forage 7, 1–2.

Hoffman, P.C., Shaver, R.D., Combs, D.K., Undersander, D.J., Bauman, L.M., Seeger, T.K., 2001. Understanding NDF digestibility of forages. Focus forage 3, 1–3.

Hoffman, T., 1996. Eastern Mixed Nama Karoo. Veg. South Africa, Lesotho Swazil. 52–57.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.

Huete, A., Justice, C., Van Leeuwen, W., 1999. MODIS vegetation index (MOD13). Algorithm Theor. basis Doc. 3, 213.

Jalali, A.R., Nørgaard, P., Weisbjerg, M.R., Nielsen, M.O., 2012. Effect of forage quality on intake, chewing activity, faecal particle size distribution, and digestibility of neutral detergent fibre in sheep, goats, and llamas. Small Rumin. Res. 103, 143–151.

Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, G., Wang, S., 2005. Monitoring of forage conditions with MODIS imagery in the Xilingol steppe, Inner Mongolia. Int. J. Remote Sens. 26, 1423–1436.

Knight, M.H., Novellie, P., Holness, S., du Toit, J., Ferreira, S., Hofmeyr, M., Grant, C., Herbst, M., Gaylard, A., 2016. Hands-on Approaches to Managing Antelopes and their Ecosystems: A South African Perspective. Antelope

Conserv. From Diagnosis to Action 137.

Knox, N.M., Skidmore, A.K., Prins, H.H.T., Asner, G.P., van der Werff, H.M.A., de Boer, W.F., van der Waal, C., de Knegt, H.J., Kohi, E.M., Slotow, R., 2011. Dry season mapping of savanna forage quality, using the hyperspectral Carnegie Airborne Observatory sensor. Remote Sens. Environ. 115, 1478–1488.

Kokaly, R.F., Clark, R.N., 1999. Spectroscopic determination of leaf biochemistry using band-depth analysis of absorption features and stepwise multiple linear regression. Remote Sens. Environ. 67, 267–287.

Kumar, L., Schmidt, K., Dury, S., Skidmore, A., 2002. Imaging spectrometry and vegetation science, in: Imaging Spectrometry. Springer, pp. 111–155.

Laca, E.A., Shipley, L.A., Reid, E.D., 2001. Structural anti-quality characteristics of range and pasture plants. J. Range Manag. 413–419.

Leslie Jr, D.M., 1985. Fecal indices to dietary quality of cervids in old-growth forests. J. Wildl. Manage. 49, 142–146.

Liu, S., Cheng, F., Dong, S., Zhao, H., Hou, X., Wu, X., 2017. Spatiotemporal dynamics of grassland aboveground biomass on the Qinghai-Tibet Plateau based on validated MODIS NDVI. Sci. Rep. 7, 4182.

MartÍnez-UsÓMartinez-Uso, A., Pla, F., Sotoca, J.M., García-Sevilla, P., 2007. Clustering-based hyperspectral band selection using information measures. IEEE Trans. Geosci. Remote Sens. 45, 4158–4171.

Matese, A., Toscano, P., Di Gennaro, S.F., Genesio, L., Vaccari, F.P., Primicerio, J., Belli, C., Zaldei, A., Bianconi, R., Gioli, B., 2015. Intercomparison of UAV, aircraft and satellite remote sensing platforms for precision viticulture. Remote Sens. 7, 2971–2990. https://doi.org/10.3390/rs70302971

McNaughton, S.J., 1988. Mineral nutrition and spatial concentrations of African ungulates. Nature 334, 343.

McNaughton, S.J., Banyikwa, F.F., McNaughton, M.M., 1997. Promotion of the cycling of diet-enhancing nutrients by African grazers. Science (80-.). 278, 1798–1800.

Mehaffey, M.H., Fisher, D.S., Burns, J.C., 2005. Photosynthesis and nutritive value in leaves of three warm-season grasses before and after defoliation. Agron. J. 97, 755–759.

Mertens, D.R., 2002. Gravimetric determination of amylase-treated neutral detergent fiber in feeds with refluxing in beakers or crucibles: collaborative study. J. AOAC Int. 85, 1217–1240.

Murray, M.G., Illius, A.W., 2000. Vegetation modification and resource competition in grazing ungulates. Oikos 89, 501–508.

Mutanga, O., Dube, T., Ahmed, F., 2016. Progress in remote sensing: vegetation monitoring in South Africa. South African Geogr. J. 98, 461–471. https://doi.org/10.1080/03736245.2016.1208586

Mutanga, O., Skidmore, A.K., 2004. Integrating imaging spectroscopy and neural networks to map grass quality in the Kruger National Park, South Africa. Remote Sens. Environ. 90, 104–115.

Mutanga, O., Skidmore, A.K., Prins, H.H.T., 2004. Predicting in situ pasture quality in the Kruger National Park, South Africa, using continuum-removed absorption features. Remote Sens. Environ. 89, 393–408.

Novellie, P., Gaylard, A., 2013. Long-term stability of grazing lawns in a small protected area, the Mountain Zebra National Park. koedoe 55, 0.

Novellie, P.A., Fourie, L.J., Kok, O.B., Van Der Westhuizen, M.C., 1988. Factors affecting the seasonal movements of Cape mountain zebras in the Mountain Zebra National Park. African Zool. 23, 13–19.

Oba, M., Allen, M.S., 1999. Evaluation of the importance of the digestibility of neutral detergent fiber from forage: effects on dry matter intake and milk yield of dairy cows. J. Dairy Sci. 82, 589–596.

Olson, K.A., Murray, M.G., Fuller, T.K., 2010. Vegetation composition and nutritional quality of forage for gazelles in Eastern Mongolia. Rangel. Ecol. Manag. 63, 593–598.

Owen-Smith, N., Novellie, P., 1982. What should a clever ungulate eat? Am. Nat. 119, 151–178.

Penzhorn, B.L., 1982. Habitat selection by Cape mountain zebras in the Mountain Zebra National Park. South African J. Wildl. Res. delayed open access 12, 48–54.

Pettorelli, N., Ryan, S., Mueller, T., Bunnefeld, N., Jędrzejewska, B., Lima, M., Kausrud, K., 2011. The Normalized Difference Vegetation Index (NDVI): unforeseen successes in animal ecology. Clim. Res. 46, 15–27.

Pond, U., Beesley, B.B., Brown, L.R., Bezuidenhout, H., 2002. Floristic analysis of the Mountain Zebra National Park, Eastern Cape.

Prabhakara, K., Hively, W.D., McCarty, G.W., 2015. Evaluating the relationship between biomass, percent groundcover and remote sensing indices across six winter cover crop fields in Maryland, United States. Int. J. Appl. Earth Obs. Geoinf. 39, 88–102.

Prins, H., 1996. Ecology and behaviour of the African buffalo: social inequality and decision making. Springer Science & Business Media.

Pullanagari, R.R., Dynes, R.A., King, W.M., Yule, I.J., Thulin, S., Knox, N.M., Ramoelo, A., Michalk, D., Millar, G., Badgery, W., 2013. Remote sensing of pasture quality, in: Proc. 22nd International Grasslands Congress 2013. p. 6.

Raffrenato, E., Van Amburgh, M.E., 2011. Improved methodology for analyses of acid detergent fiber and acid detergent lignin. J. Dairy Sci. 94, 3613–3617.

Ramoelo, A., Cho, M., Mathieu, R., Skidmore, A.K., 2015a. Potential of Sentinel-2 spectral configuration to assess rangeland quality. J. Appl. Remote Sens. 9, 94096.

Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z., Wolff, E., 2015b. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. Int. J. Appl. Earth Obs. Geoinf. 43, 43–54.

Ramoelo, A., Cho, M.A., Mathieu, R.S.A., Skidmore, A.K., Schlerf, M., Heitkonig, I.M.A., Prins, H.H.T., 2011. Integrating environmental and in situ hyperspectral remote sensing variables for grass nitrogen estimation in savannah ecosystems.

Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R., Heitkönig, I.M.A., 2012. Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. Int. J. Appl. Earth Obs. Geoinf. 19, 151–162.

Ryan, S.J., 2006. Spatial ecology of African buffalo and their resources in a savanna ecosystem.

Ryan, S.J., Cross, P.C., Winnie, J., Hay, C., Bowers, J., Getz, W.M., 2012. The utility of normalized difference vegetation index for predicting African buffalo forage quality. J. Wildl. Manage. 76, 1499–1508.

Sannier, C.A.D., Taylor, J.C., Plessis, W. Du, 2002. Real-time monitoring of vegetation biomass with NOAA-AVHRR in Etosha National Park, Namibia, for fire risk assessment. Int. J. Remote Sens. 23, 71–89.

Scholes, R.J., Walker, B.H., 1993. Nylsvley: the study of an African savanna.

Seagle, S.W., McNaughton, S.J., 1992. Spatial variation in forage nutrient concentrations and the distribution of Serengeti grazing ungulates. Landsc. Ecol. 7, 229–241.

Shrader, A.M., Owen-Smith, N., Ogutu, J.O., 2006. How a mega-grazer copes with the dry season: food and nutrient intake rates by white rhinoceros in the wild. Funct. Ecol. 20, 376–384.

Singh, L., Mutanga, O., Mafongoya, P., Peerbhay, K.Y., 2018. Multispectral mapping of key grassland nutrients in KwaZulu-Natal, South Africa. J. Spat. Sci. 63, 155–172.

Skidmore, A.K., Ferwerda, J.G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H.T., Balcik, F.B., Venus, V., 2010. Forage quality of savannas—Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. Remote Sens. Environ. 114, 64–72.

Skidmore, A.K., Ferwerda, J.G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H.T., Balcik, F.B., Venus, V., 2010. Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z. and Wolff, E., 2015. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. Internation. Remote Sens. Environ. 114, 64–72. https://doi.org/10.1016/j.rse.2009.08.010

Skidmore, A.K., Mutanga, O., Schmidt, K., Ferwerda, J.G., 2005. Modelling herbivore grazing resources using hyperspectral remote sensing and GIS, in: AGILE 2005: 8th Conference on Geographic Information Science, Lisboa, AGILE, Denver, USA. Citeseer.

Southwood, T.R.E., Henderson, P.A., 2009. Ecological methods. John Wiley & Sons.

Stapelberg, F.H., Van Rooyen, M.W., Bothma, J. du P., 2008. Spatial and temporal variation in nitrogen and phosphorus concentrations in faeces from springbok in the Kalahari. African J. Wildl. Res. 38, 82–88.

Starks, P.J., Coleman, S.W., Phillips, W.A., 2004. Determination of forage chemical composition using remote sensing. Rangel. Ecol. Manag. 57, 635–641.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O.R., Cho, M.A., Joubert, D.F., 2018. Forage quality and availability for large herbivores in southern African rangelands. Klaus Hess Publishers.

Sweeney, R.A., 1989. Generic combustion method for determination of crude protein in feeds: Collaborative study. Journal-Association Off. Anal. Chem. 72, 770–774.

Timothy, D., Onisimo, M., Riyad, I., 2016. Quantifying aboveground biomass in African environments: A review of the trade-offs between sensor estimation accuracy and costs. Trop. Ecol. 57, 393–405.

Todd, S.W., Hoffer, R.M., Milchunas, D.G., 1998. Biomass estimation on grazed and ungrazed rangelands using spectral indices. Int. J. Remote Sens. 19, 427–438.

Toerien, D.K., 1972. Geologie van die Bergkwagga Nasionale Park. Koedoe 15, 77–82.

Trollope, W.S.W., Potgieter, A.L.F., 1986. Estimating grass fuel loads with a disc pasture meter in the Kruger National Park. J. Grassl. Soc. South. Africa 3, 148–152.

Van der Walt, P.T., 1980. A phytosociological reconnaissance of the Mountain Zebra National Park. Koedoe African Prot. Area Conserv. Sci. 23, 1–32.

Van Leeuwen, W.J.D., Huete, A.R., Laing, T.W., 1999. MODIS vegetation index compositing approach: A prototype with AVHRR data. Remote Sens. Environ. 69, 264–280.

Varshney, P.K., Arora, M.K., 2004. Advanced image processing techniques for remotely sensed hyperspectral data. Springer Science & Business Media.

Wang, Z.J., Wang, J.H., Liu, L.Y., Huang, W.J., Zhao, C.J., Wang, C.Z., 2004. Prediction of grain protein content in winter wheat (Triticum aestivum L.) using plant pigment ratio (PPR). F. Crop. Res. 90, 311–321.

Wessels, K.J., Prince, S.D., Zambatis, N., MacFadyen, S., Frost, P.E., Van Zyl, D., 2006. Relationship between herbaceous biomass and 1-km2 Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South

Africa. Int. J. Remote Sens. 27, 951–973.

Wilmshurst, J.F., Fryxell, J.M., Farm, B.P., Sinclair, A.R.E., Henschel, C.P., 1999. Spatial distribution of Serengeti wildebeest in relation to resources. Can. J. Zool. 77, 1223–1232.

Winkler, A., Owen-Smith, N., 1995. Habitat utilisation by Cape mountain zebras in the Mountain Zebra National Park, South Africa. Koedoe 38, 83–93.

Zambatis, N., Zacharias, P.J.K., Morris, C.D., Derry, J.F., 2006. Re-evaluation of the disc pasture meter calibration for the Kruger National Park, South Africa. African J. Range Forage Sci. 23, 85–97.

Zar, J.H., 1999. Biostatistical analysis. Pearson Education India.

Zhao, D., Starks, P.J., Brown, M.A., Phillips, W.A., Coleman, S.W., 2007. Assessment of forage biomass and quality parameters of bermudagrass using proximal sensing of pasture canopy reflectance. Grassl. Sci. 53, 39–49.

Chapter Four:

Association between multispectral satellite-derived VI's, to assess forage quality indicators, and the diets of herbivores in MZNP.

4.1 Abstract

Multispectral satellite-derived vegetation indices (VI's) can be a rapid and inexpensive technique to assess forage quality for herbivores, which can, therefore, assist ecologists in modelling the survival and productivity of herbivore populations. However, many studies that have researched remote sensing and VI's to assess forage quality for herbivores have neglected to consider the diets of the herbivore species. Acknowledging VI's are related to forage quality for herbivores, this study determined the association between the MODIS Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) and the diets of herbivores in Mountain Zebra National Park (MZNP). Results showed there are associations between the NDVI and EVI and dietary nitrogen (N), phosphorus (P) and magnesium (Mg). Associations that were found were weak however a strong association was found between the EVI and dietary N of herbivores during the early grass growing season. The other associations found were also affected by season of grass growth, however, the different herbivore species did not affect these associations. The information found in this study shows the applicability and suitability of multispectral satellite-derived VI's for MZNP management purposes. The research in this study also assists with a better understanding of the association between VI's and the diets of herbivores.

4.2 Introduction

In southern Africa, climate change has induced prominent droughts, while high human population growth has caused fencing of protected areas, resulting in limited forage quantity and quality available for herbivores. This has become a major concern, as herbivore population health and dynamics are highly affected by forage nutrients and their concentrations in the forage (Ryan et al., 2012; Seagle and McNaughton, 1992; Skidmore et al., 2010; Villamuelas et al., 2016). Therefore, the monitoring and assessment of forage quantity and quality for herbivores in protected areas has become crucial. Problematically field techniques can be expensive, tedious and labour intensive. Multispectral satellite-derived vegetation indices (VI's) can provide a possible alternative as they are cost-effective, time efficient and have been demonstrated in research to share relationships with forage quality indicators (forage nutrients: Garroutte et al., 2016; Kawamura et al., 2005; Ramoelo et al., 2015; Ryan et al., 2012). Thus, multispectral satellite-derived VI's can be implemented to understand, monitor and map forage quality nutrients across a landscape, which can potentially help ecologists model the distribution, survival and productivity of herbivore populations (Olson et al., 2010; Ryan et al., 2012; Seagle and McNaughton, 1992; Skidmore et al., 2005).

The 2016-2026 Mountain Zebra National Park (MZNP) management plan aims to implement multispectral satellite-derived VI's for their herbivory and habitat-vegetation management programs. The implementation of multispectral satellite-derived VI's will monitor and assess forage quality conditions, in order to assist with making appropriate management decisions for the park's herbivore populations. Appropriate management decision will ensure the persistence of suitable habitats for the range of herbivores present on the reserve. The monitoring of forage quality conditions for herbivores in MZNP is particularly important, as the park carries high densities of grazing ungulates due to the mosaic of vegetation types (varying in species composition, sward structure and height) and the persistence of grazing lawns found in the park (Novellie, 1990; Novellie and Gaylard, 2013). Problematically, VI's are limited to estimates of forage quality indicators of the vegetation and don't consider the diets of the herbivore, nor differentiate the diets of the different herbivore species. Therefore, generalizations about VI's regarding forage quality for herbivores can be potentially misleading. Thus, before multispectral satellite-derived VI's can be implemented in MZNP to assess forage quality for herbivores, the association between the VI's to assess forage quality indicators and the utilization of these forage quality indicators in the diets of the park's herbivores must first be determined. The information found provides a better understanding between VI's and forage quality available for herbivores in MZNP, and thus ensures their accurately interpreted and implemented for MZNP management purposes.

Many studies that have researched remote sensing and VI's to assess forage quality for herbivores have neglected to consider the diets of the herbivore species (Garroutte et al., 2016; Kawamura et al., 2005; Mutanga and Skidmore, 2004; Ramoelo et al., 2015b). There are, to our knowledge, very few studies that do consider herbivore diets when relating VI's to forage quality (i.e. Christianson and Creel, 2009; Creech et al., 2016; Hamel et al., 2009; Ryan et al., 2006; Villamuelas et al., 2016). These studies analyse herbivore faecal samples for forage quality indicators (nutrients) and relate it to the multispectral satellite-derived VI's. The use of faecal sampling and analysis is advantageous because the information found is easy to acquire, reflects the dietary decisions of target species and can be less labour intensive and tedious than other field methods (Ryan et al., 2012; Southwood and Henderson, 2009). The MODIS Normalized Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI) are generally applied in studies relating forage quality indicators, assessed by VI's, and the diets of herbivores. The MODIS NDVI and EVI are preferred because their coarser resolution encompasses a larger area taking into account a wider range of vegetation, thus compensating for the mobility of the herbivores. The studies that do relate VI's with forage quality indicators in herbivore faeces have only, to our knowledge, tested for forage quality indicator nitrogen (N) and phosphorus (P). Results showed only forage quality indicator N had an association with the VI's and the diets of the herbivores.

In this study, we acknowledge the MODIS NDVI and EVI are related to forage quality indicators in the forage. Our objective is rather to determine the association between the MODIS NDVI and EVI, to assess the forage quality indictors in the forage, and the utilization of these forage quality indicators in the diets of the herbivores in MZNP. We predict there will be a strong association between the MODIS NDVI and EVI and dietary N of herbivores. We also predict there will be associations between the NDVI and EVI and the other forage quality indicators in the diets of the herbivores, however, the associations are expected to be weak. We also expect the associations to be affected by seasonality and the different herbivore species. The information provided in this study will give insight into the suitability and applicability of multispectral satellite-derived VI's for the management of herbivores in MZNP. Studying in MZNP also provides the opportunity to research the association between VI's and the diets of herbivores in a protected area that carries high densities of grazing ungulates. The research in this study will also assist with a better understanding about the association between VI's and the diets of herbivores and can be used as a model for further research.

4.3 Methodology

4.3.1 Study Area

The MZNP is a 28 412-ha game reserve situated near the town of Cradock in the Eastern Cape Province, South Africa (Figure 4.1). Monthly minimum and maximum temperatures vary from 6°C to 28°C in summer (from September to March) and from 0°C to 20°C in winter (from April to August: Brown and Bezuidenhout, 2000). The reserve receives approximately 400 mm of rainfall with the majority falling in the summer months. Periodic light snow occurs during the winter months and frost is common between May and October (Novellie and Gaylard, 2013). The park is positioned in a transition zone comprising of the Nama-Karoo, Grassland and Albany Thicket biome. According to Acocks (1988), the area can be classified as False Karroid Broken Veld, whereas Hoffman (1996) classifies it as Eastern Mixed Nama Karoo. The low rainfall of these areas ensures that the pre-dominant soil type is lime-rich and prone to erosion (Hall-Martin and Carruthers, 2003). Bezuidenhout et al. (2015) have classified, mapped and described all 13 plant communities in the park (Table 4.1).

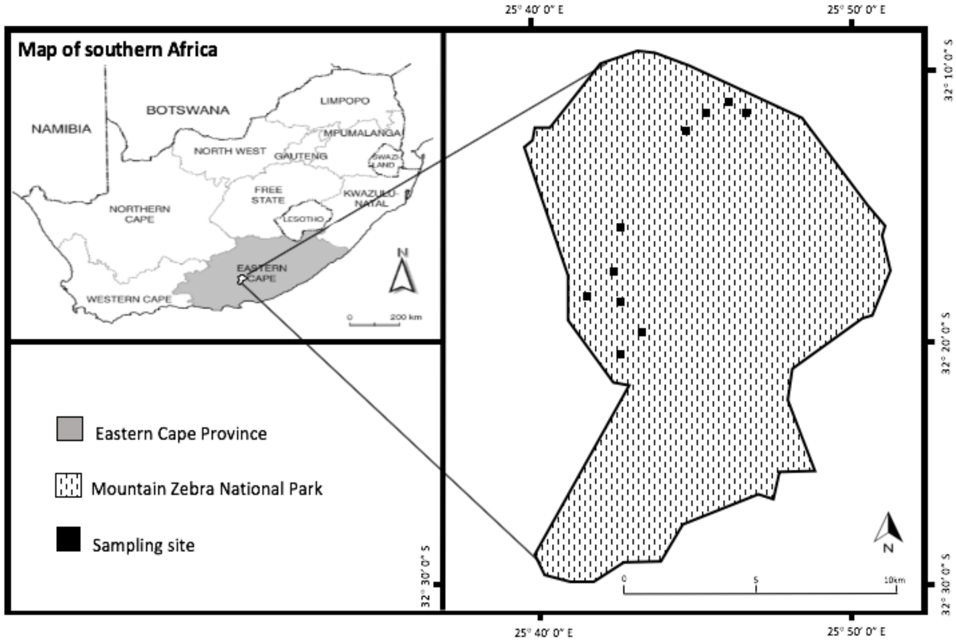


Figure 4.1: Study area locality map with indication of sampling sites.

Table 4.1: Three major landscapes and plant communities of MZNP (B, M,V). (i) The Mountain highland rugged landscape with four plant communities, (ii) Middle plateau rolling landscape with four plant communities and (iii) Valley bottomlands undulating plains landscape with five plant communities (from: Bezuidenhout et al., 2015).

Mountain highlands rugged (B)	Plant communities
B1	*Eragrostis lehmanniana - Eragrostis curvula* Grassland
B2	*Merxmuellera disticha - Euryops annuus* Grassland
B3	*Merxmuellera disticha - Felicia filifolia* Grassland
B4	*Searcia lucida - Diospyros lycioides* Woodland
Middle plateau rolling (M)	
M1	*Carissa macrocarpa - Rhigozum obovatum Shrubland*
M2	*Pentzia globosa - Searsia longispina* Shrubland
M3	*Enneapogon scoparius - Acacia karroo Woodland*
M4	*Searsia lucida - Buddleja glomerata* Shrubland
Valley bottomland undulating plains (V)	
V1	*Pentzia incana - Eragrostis lehmanniana* Forbland
V2	*Sporobolus africanus - Enneapogon scoparius* Grassland
V3	*Pentzia globosa - Eragrostis obtusa* Forbland
V4	*Aristida adscensionis - Chloris virgata* Grassland
V5	*Lycium oxycarpum - Acacia karroo* Woodland

The study focused on two areas within the reserve, the Rooiplaat area, in the western boundary, and the Welgedacht area, along the eastern boundary (Figure 4.2). The two areas were selected because they experience high densities of wildlife numbers throughout the year (Bezuidenhout et al., 2015) particularly grazing ungulate species such as Black Wildebeest (*Connochaetes gnou*), Blesbok (*Damaliscus dorca*), Cape Mountain Zebra (*Equus z. zebra*), Red Hartebeest (*Alcephalus busephalus*) and Springbok (*Antidorcas marsupialis*). Eland (*Taurotragus orys*) is also known to utilize these two study areas periodically. This study focused on the dominant ungulate species found within the two study areas.

The Rooiplaat area, which is at 1360 m above sea level, consists of the Eragrostis lehmanniana - Eragrostis curvula Grassland community (B1) described as part of the Mountain highlands rugged landscape. The community is found on a relatively level sandstone and doleritic plateau and comprises of soils that are relatively shallow and not highly leeched (Van der Walt, 1980). Before the expansion of the park in 1996, the area endured high fixed grazing intensity (Van der Walt, 1980). The vegetation, which is virtually treeless (Penzhorn, 1982a), consists of rocky plateau grassland, degraded plateau grassland and degraded shrubland (Van der Walt, 1980). The comparative hot dry climate, nutrient rich soils and high grazing pressure determine primarily the “sweet” over-utilized nature of the area (Van der Walt, 1980). The dominant plant species found are Themeda triandra, Eraggrotic curvula and Tragus koeleroides. Other prominent grass species found are Eragrostis lehmanniana and Eustachys paspaloides while dwarf shrubs Pentzia incana, Pentzia globose, Melolobium microphyllum and Felicia filifolia are also prevalent.

The Welgedacht area mainly consists of the Sporobolus africanus - Enneapogon scoparius Grassland community (V2) and the Pentzia globose - Eragrotis obtuse Forbland community (V3). The two adjacent communities, which are at an altitude of roughly 1017 m, are found in the valley bottomland undulating plains landscape. The geology of this land type is mudstone, shale and sandstone (Toerien, 1972) and comprises of soil forms Glenrosa and Oakleaf (Brown and Bezuidenhout, 2005). The dominant vegetation in the two areas is a mixture of grassy and dwarf shrubland with trees usually occurring along drainage lines (Van der Walt, 1980). The rock cover within the terrain is very low (Brown and Bezuidenhout, 2005). The Welgedacht area was incorporated into the reserve less than 30 years ago and large sections have been overgrazed due to previous farming practices (Brown and Bezuidenhout, 2005). The dominant grass species found within the plant community V3 are Eragrostis obtusa, Aristida congesta subsp. Congesta, Eragrostis lehmaniana and the pioneer grass Cynodon incompletus. The dwarf shrub Pentzia globose is also prominent within the V3 community. The dominant plant species found in the bordering V2 plant community are Tragus koelerioides and Aristida congesta subsp. Congesta with prevailing dwarf shrubs Pentzia globose and Asparagus suaveolens. Dominant plant species that were listed for the Rooiplaat and Welgedacht area were based on research done by Van der Walt (1980) and Brown and Bezuidenhout (2005), as well as identified according to Germishuizen and Meyer (2003) in the forage samples collected during this study.

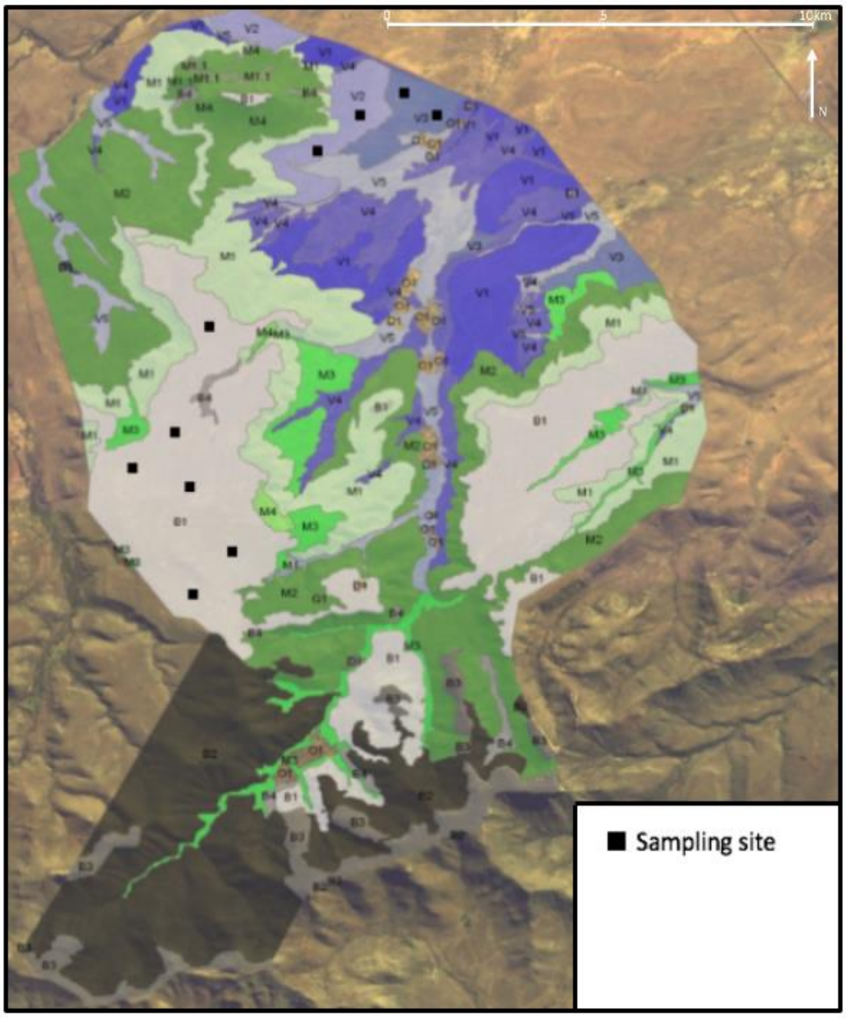


Figure 4.2: Vegetation map of Mountain Zebra National Park (From: Bezuidenhout et al. 2015). Sampling sites are shown within the selected study areas: Rooiplaat area, plant community Eragrostis lehmanniana - Eragrostis curvula Grassland (B1). Welgedacht area, plant community Sporobolus africanus - Enneapogon scoparius Grassland (V2) and Pentzia globose - Eragrotis obtuse Forbland (V3).

4.3.2 Sampling sites

Ten sampling sites were selected in November 2017 (six in the Rooiplaat area and four in the Welgedacht area: Figure 2). Each sampling site represents a single pixel from the MODIS remote sensor (250 m x 250 m). The selection process of these study pixels was done by locating all the MODIS pixels within the two study areas (using ArcGIS [version 10.5, ESRI]). The pixels that had a buffer (waterholes, roads, etc.) greater than a 250 m radius were then chosen (using Google EarthTM). A field reconnaissance for the selection of the pixels that were the most visibly homogeneous was then chosen as a sampling site. Navigation to the pixels was assisted using a handheld Geographical Positioning System (GPS), Garmin Oregon 550 (Garmin, Olathe, KS, USA), with positional accuracy $\geq$ 3 m. Data collection occurred on the 28-29 November 2017, 31 January-5 February, 23-27 March, 5-9 June and 27 June-7 July 2018. The dates were selected to coincide with the four seasons of changing grass sward characteristics in MZNP (Winkler, 2008).

The different seasons of grass growth were characterized as the (i) late growing season (Dec-Feb) when the sward was tall with an abundant supply of green material, (ii) early dormant season (March-May) when the grasses were mature and green but plant growth had ceased, (iii) late dormant season (June-Aug) when grasses were dry and senescent and (iv) early growing season (Sep-Nov) when the grasses are mainly dry but some new growth has emerged (Winkler and Owen-Smith, 1995). Some specific forage nutrients, specifically starch, are known to fluctuate throughout the day (Ball et al., 2001) thus field collection times throughout all collection periods were kept constant, with fieldwork only occurring in the morning.

4.3.3 Ground sampling

During data collection periods five faecal samples were collected at random within each sampling site. Navigation was assisted using a Garmin Oregon 550 GPS. Faecal samples from the dominate ungulate species found within the two study areas were collected, which were Black Wildebeest, Blesbok, Cape Mountain Zebra, Red Hartebeest, Springbok and Eland. The collected faecal samples were identified, weighed on site and bagged (brown paper bag) for drying and later chemical analysis. Samples were identified using a scat identification guide for African mammals by Murray et al. (2011). Samples were not pooled, instead, faecal samples of different individuals were used to reduce the possibility of dietary preference of any one animal from outweighing the results of the analysis (Anthony and Smith, 1974). Samples were only collected that was less than a week after deposition, using the procedure by Leite and Stuth (1994). Forage samples within each sampling site were then collected from five systematically placed quadrats (1 m^2). All forage above ground within each quadrat was clipped (>1 cm: Garroutte et al., 2016; Knox et al., 2011). Collected forage samples were then weighed on site and bagged (brown paper bag) for drying and later chemical analysis (Knox et al., 2011). The GPS was also used to locate each quadrat within the field. To avoid repeat sampling, quadrats were moved within a 5 m^2 area at each sampling period also using the GPS.

4.3.4 Chemical Analysis

Forage and faecal samples were analysed for nutrients that are used as forage quality indicators because they are known to affect intake, palatability, digestibility and an animal's performance (Ball et al., 2001; Barboza et al., 2008; Leslie Jr, 1985). All faecal and forage samples were transported to the Department of Animal Science laboratory, at Stellenbosch University, and individually analysed. All samples were first oven dried at 50°C for 48 h and analysed for chemical composition on a dry matter (DM) basis. Faecal samples were milled at 1.5 mm and forage samples were milled at 1 mm using a Thomas Model 4 Wiley® Mill (Thomas Scientific, Swedesboro, NJ, USA). Both faecal and forage samples were analysed for ash and nitrogen (N) according to AOAC International (2002). For N analysis a LECO FP 528 Nitrogen Determinator Combustion tool was used. The minerals phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) were then analysed in faecal and forage samples according to the method by ALASA (1998). Forage samples were then analysed further for neutral detergent fiber (NDF) and acid detergent lignin (ADL) according to Mertens (2002) and Raffrenato et al. (2011), respectively. Forage in vitro NDF digestibility (NDFd) at 24 h was analysed according to Goering and Van Soest (1970) using the ANKOM Daisy II incubator (ANKOM Technol. Corp., Fairport, NY - USA).

4.3.5 Vegetation Indices acquisition

Vegetation Indices were acquired from the Centre for Geographical Analysis (Stellenbosch University; Table 4.2). The MODIS product MOD13Q1 (Version 6; Didan, 2015) was downloaded from Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Centre (LAAD DAAC). The product provides a 16-day composite value at a resolution of 250 m x 250 m. The MODIS NDVI and EVI were processed and packaged using ArcGIS (version 10.5; ESRI).

Table 4.2: MODIS vegetation indexes. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index.

Vegetation indices	General Formula	Reference
NDVI	(RNIR −RRED)/(RNIR +RRED)	Rouse et al. (1973)
EVI	(NIR−RED)/[(NIR+6RED−7.5BLUE) +1]	Huete et al. (1997)

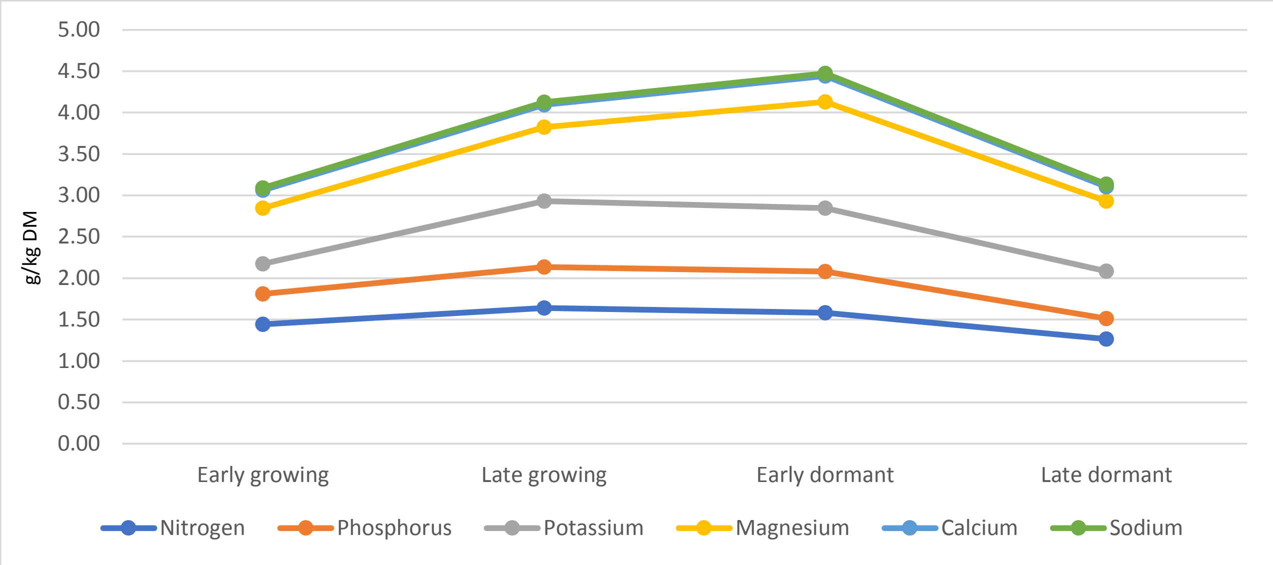
4.3.6 Statistical Analysis

Means and standard deviations were determined for the MODIS NDVI and EVI for forage quality indicators in the forage and the herbivore faeces during the entire data collection period and the different seasons of grass growth in MZNP. Forage quality indicators in the faeces for each species were taken into account. Forage quality indicators in the faeces of all species were also pooled and taken into account. General trends from the results were identified and first discussed. Pearson’s correlation coefficients (Zar, 1999) were then run between the forage quality indicators in the forage and in the faeces combined from all herbivore species throughout the study period, in order to determine if a relationship exists between the diets of the herbivores in the study and the forage quality indicators (forage nutrients) in the forage. Pearson’s correlation coefficients (Zar, 1999) and simple linear regressions were then run between each forage quality indicator in the herbivore faeces, of all combined species, and the MODIS NDVI and EVI. Both linear and quadratic models were fitted using PROC REG of SAS version 9.3 (SAS Institute, Inc., Cary, NC, USA). The forage quality indicators in the faeces that had the strongest correlations and highest respective R^2 values (from the linear regression models) with either the MODIS NDVI or EVI or both were only discussed. Pearson's correlation coefficients were then determined between the forage quality indicators in the faeces and the MODIS NDVI and EVI during the different seasons of grass growth in MZNP. Pearson's correlation coefficients were also run between the forage quality indicators in the faeces from the different herbivore species and the MODIS NDVI and EVI, to determine if any specific species outweighed the results. All statistics were done using SAS v.9.3 (SAS Institute, Inc., Cary, NC, USA).

4.5 Results and Discussion

Results showed the means for the different forage quality indicators in the faeces varied between the different herbivore species (Appendix, Table 9). The variation could be explained because of the different digestive strategies and capabilities, physiologies and morphologies among the herbivore species in this study. Differences between the forage quality indicators in the faeces from different African herbivore species have been found in other studies (Botha and Stock, 2005; Grant et al., 1995; Weel et al., 2015). Despite the variation, a general trend was found between the forage quality indicators in the faeces from all the species when combined during the different seasons of grass growth (Appendix, Table 10). Results here showed the forage quality indicators in the faeces (i.e., faecal nitrogen (Nf), faecal phosphorus (Pf), faecal potassium (Kf) and faecal magnesium (Mgf)) increased during the early growing to early dormant season and then dropped dramatically when moving into the late dormant season. Seasonal changes in forage quality indicators in the faeces from African herbivores have also been shown in other studies (Grant et al., 2000; Mbatha and Ward, 2006; Ryan et al., 2012; Weel et al., 2015). Noticeably in Table 11, in Appendix, the MODIS NDVI and EVI follow a seasonal trend similar to the concentrations of N_f, P_f, K_f and Mg_f. A similar seasonal trend was also found between the means for some of the forage quality indicators in the forage (i.e., forage N and K: Appendix, Table 12). Figures 4.3, 4.4 and 4.5 show graphically the similar seasonal trend by the forage quality indicators in the forage and herbivore faeces and the MODIS NDVI and EVI during the different periods of grass growth.

Figure 4.3: Graph showing the means of the forage quality indicators in the faeces from all combined herbivore species during the different seasons of grass growth.



We do, however, from these results, highlight the importance of considering other ancillary variables when applying VI's to assess forage quality. To our knowledge, few studies have highlighted this need to integrate environmental or ancillary variables with VI's (Cho et al., 2009; Knox et al., 2011; Ramoelo et al., 2011).

Figure 4.4: Graph showing the means of the MODIS vegetation indices during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index.

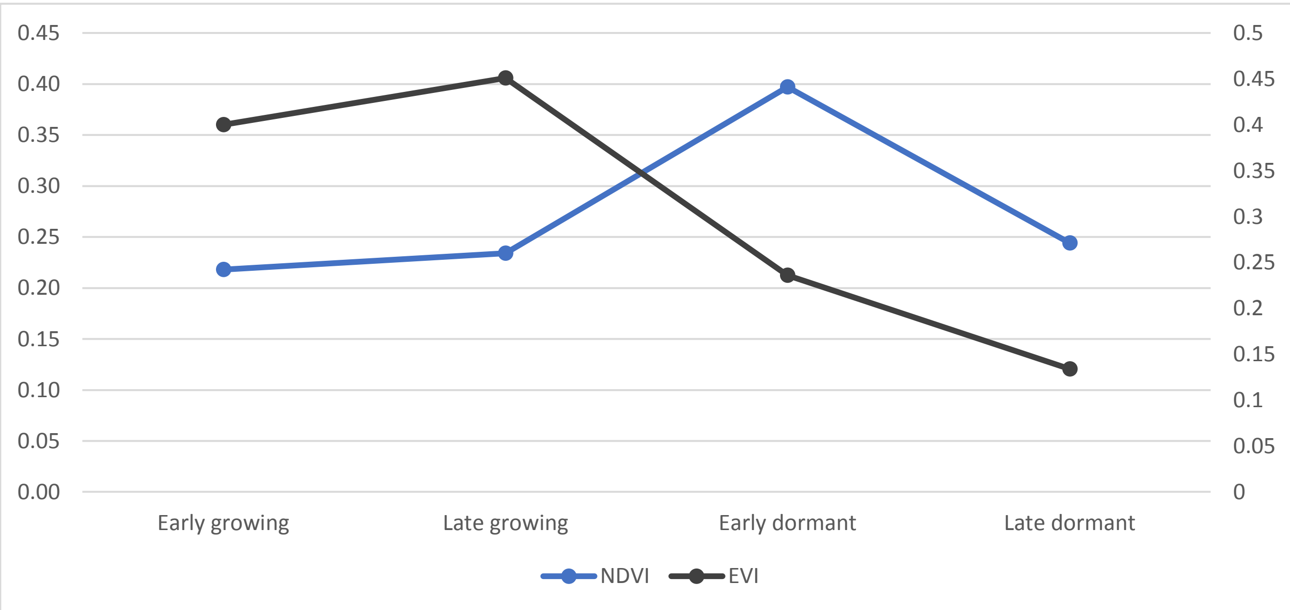
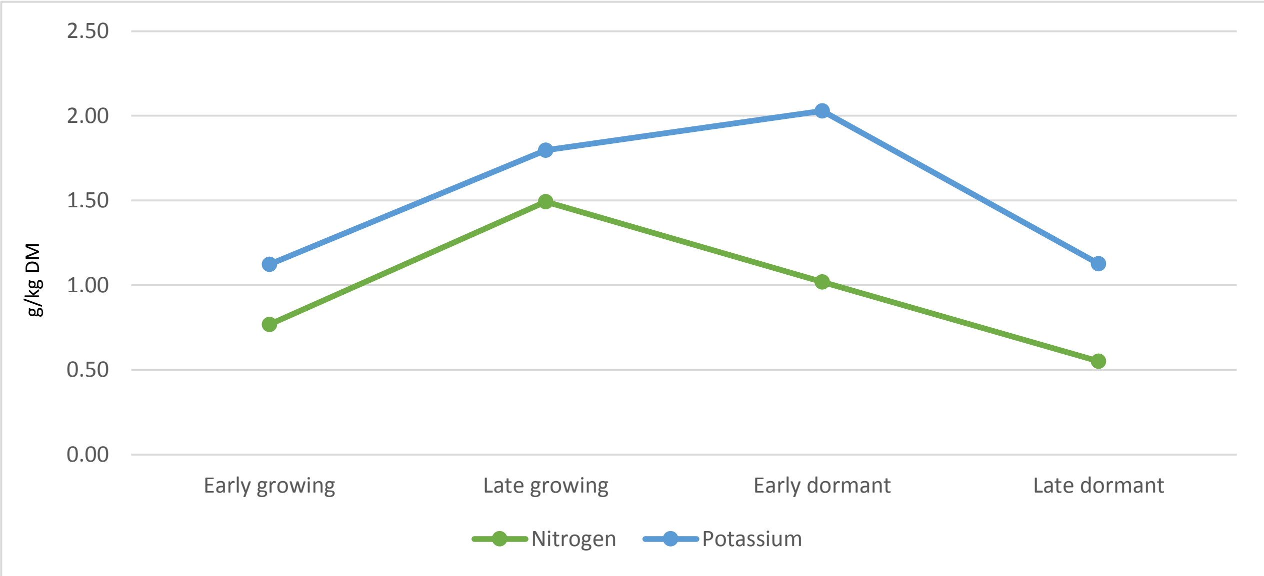


Figure 4.5: Graph showing the means of the forage quality indicator in the forage during the different seasons of grass growth.



The reason for the general seasonal trend is possibly because forage N and K are related to the photosynthetic process of plants and thus chlorophyll content (Al-Abbas et al., 1974; Glenn et al., 2008; Kumar et al., 2002; Sweeney, 1989), while VI's are a reflectance of vegetation canopy "greenness", which is caused by chlorophyll concentrations (Glenn et al., 2008; Kumar et al., 2002). Therefore, in MZNP from the early growing to early dormant season new green grass begins to emerge and grows until the early dormant season, causing an abundant supply of green material (Winkler and Owen-Smith, 1995). The increase in forage N and K is related to the increase in green vegetation in MZNP which subsequently causes an increase in the VI's values. The results show that the increase of the VI's values caused by the increase in forage quality indicators is associated with more forage quality indicators in the faeces of the herbivores. After the early dormant season in MZNP grass growth ceases and moves into the late dormant season becoming dry and senescent (Ball et al., 2001; Winkler and Owen-Smith, 1995). The dry senescent grass is related to a decrease in forage concentrations N and minerals (Ball et al., 2001; Codron et al., 2007), which causes a decrease in chlorophyll concentration, vegetation canopy "greenness" and thus values from the VI's. These results show the decrease in the VI's values caused by the decreased forage quality indicators is associated with less forage quality indicators in the faeces of the herbivores.

The results found, show there is an association between VI's, to assess forage quality indicators in the forage, and the forage quality indicators utilized in the diets of the herbivore species. However, the forage quality indicators in the faeces varied between the different herbivore species, while the VI's and forage quality indicators in the forage and faeces fluctuated during the different seasons of grass growth. Therefore, further statistics were conducted to provide more information about the association between the VI's, to assess forage quality indicators, and the diets of the herbivores in MZNP.

Table 4.3 shows correlations between the forage quality indicators in the forage and the faeces combined from all herbivore species throughout the study period. Results show that each of the forage quality indicators in the faeces, except for faecal sodium (Na_f) and faecal calcium (Ca_f), correlated at different strengths and significance with the same forage quality indicator in the forage. The results show the forage quality indicators in the faeces are related to the forage quality indicators in the forage. Therefore, these results suggest there is a relationship between the forage quality indicators (forage nutrients) present in the forage and the diets of the herbivore species in this study.

Table 4.3: Correlations between the forage quality indicators in the forage and in the faeces combined from all herbivore species throughout the study period. Total number of observations: 368.

Forage quality indicators in the faeces	Forage quality indicators in the forage						
	Ash	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sodium
Ash	0.177***	0.174***	-0.081	0.063	-0.141**	-0.035	0.050
Nitrogen	0.298***	0.550**	-0.129	0.049	-0.083	0.195**	0.069
Phosphorus	0.317***	0.584***	0.159*	0.071	0.127	0.344***	0.263***
Potassium	0.147*	0.282***	0.278***	0.007	0.281***	0.288***	0.288***
Calcium	0.055	0.057	-0.043	0.07	-0.072	-0.041	-0.045
Magnesium	0.241**	0.460***	0.163*	0.155*	0.090	0.250***	0.181*
Sodium	0.082	0.011	0.077	-0.021	0.077	0.069	0.118

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

Table 4 shows correlations between the MODIS vegetation indices and the forage quality indicators in the faeces combined from all herbivore species throughout the study period. Only a few forage quality indicators in the faeces had a significant correlation with either the NDVI or EVI ($P \leq 0.05$). Results showed faecal ash (Ash_f) shared a positive significant correlation with the EVI ($r = 0.161$, $P \leq 0.01$). We suggest however the correlation found between Ash_f and the EVI be taken with consideration. The reason is because of the big difference found in this study between the mean Ash_f and the mean ash in the forage ($\bar{x}$ = 23.48±7.172 g/kg DM; $\bar{x}$ = 9.976±2.429 g/kg DM). The high mean Ash_f value, compared to the mean ash in the forage, could be explained by endogenous losses of minerals from the herbivore via their faeces (Underwood, 1999) or from soil contamination of the faecal samples during data collection (e.g. Fries et al., 1982). Other possible reasons could be from the herbivore ingesting soil inadvertently through the consumption of forage (Turner et al., 2013; WJ III and Alldredge, 1979) or intentionally consuming soil for trace minerals to buffer their digestive system (Ayotte et al., 2006; Kreulen, 1985). Results in Table 3.4 also showed a positive significant correlation between N_f and the NDVI ($r = 0.277$, $P \leq 0.001$) and the EVI ($r = 0.220$, $P \leq 0.01$). A positive significant correlation was also found between P_f and the NDVI ($r = 0.188$, $P \leq 0.05$) and the EVI ($r = 0.209$, $P \leq 0.01$). While Mg_f had a positive significant correlation with only the NDVI ($r = 0.192$, $P \leq 0.01$).

Table 4.4: Correlations between the MODIS vegetation indices and the forage quality indicators in the faeces combined from all herbivore species throughout the study period. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index. Total number of observations: 368.

Faecal quality indicators in the faeces	$\bar{x}$ (g/kg DM)	σ (g/kg DM)	MODIS vegetation indices	
			NDVI	EVI
Ash	25.335	7.172	0.093	0.161**
Nitrogen	1.434	0.304	0.277***	0.220**
Phosphorus	0.370	1.105	0.188*	0.209**
Potassium	0.69	1.346	0.220	0.125
Calcium	0.954	6.186	0.020	-0.034
Magnesium	0.231	0.836	0.192**	0.140
Sodium	0.031	0.039	-0.171*	-0.001

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

In Tables 3.5 and 3.6 N_f, P_f and Mgf resulted in significant regressions, with, however, R^2 always less than 0.25. The largest R^2 was obtained when regressing N_f on the EVI (0.241). The minerals P_f and Mg_f were found to be significant for the NDVI ($P \leq 0.01$) and highly significant for the EVI ($P \leq 0.001$). Contrary to our predictions there was a weak, rather than strong, association between the MODIS NDVI and EVI and dietary N of herbivores. There were, however, as predicted, weak associations between the NDVI and EVI and other forage quality indicators in the diets of the herbivores.

Table 4.5: Simple linear regression for the prediction of forage quality indicators in the faeces combined from all herbivore species from the MODIS NDVI. NDVI = Normalized Difference Vegetation Index.

[a]

Faecal nutrients	n	Intercept	Linear coefficient	Quadratic coefficient	R^2	*P*
Moisture	[a]					
Ash	368	22.986	8.419	[c]	0.009	0.0734
Nitrogen	184	1.139	1.055	[c]	0.077	0.0001
Phosphorus	184	0.234	0.494	[c]	0.034	0.0123
Potassium	[a]					
Calcium	[a]					
Magnesium	184	0.158	0.265	[c]	0.034	0.0119
Sodium	184	0.054	-0.084	[c]	0.029	0.0207

Regression model not significant; only significant models shown.

[b] Intercept not different from zero; model without intercept used.

[C] Quadratic coefficient model not significant; model without quadratic coefficient model used.

Table 4.6: Simple linear regression for the prediction of forage quality indicators in the faeces combined from all herbivore species from the MODIS EVI. EVI = Enhanced Vegetation Index.

Faecal nutrients	n	Intercept	Linear coefficient	Quadratic coefficient	R^2	*P*
Moisture	[a]					
Ash	368	23.699	6.679	[c]	0.026	0.0019
Nitrogen	184	1.017	2.642	-2.560	0.241	<0.0001
Phosphorus	184	0.133	1.491	-1.405	0.165	<0.0001
Potassium	[a]					
Calcium	[a]					
Magnesium	184	0.137	0.602	-0.584	0.089	0.0002
Sodium	[a]					

[a] Regression model not significant; only significant models shown.

[b] Intercept not different from zero; model without intercept used.

[C] Quadratic coefficient model not significant; model without quadratic coefficient model used.

Table 3.7 shows correlations between the MODIS vegetation indices and the forage quality indicators in the faeces combined from all herbivore species during the different seasons of grass growth. Results show only a few forage quality indicators in the faeces had significant correlations with the VI's during the different seasons of grass growth. The significant correlations also varied between the different seasons. These results show, as predicted, the associations between the NDVI and EVI and the diets of herbivores are affected by season.

A weak positive correlation was found with significance between N_f and the NDVI ($r = 0.061$, $P \leq 0.01$) during the early grass growing season. While during the same season a strong positive correlation was found with significance between N_f and the EVI ($r = 0.608$, $P \leq 0.01$). Despite results showing there is a weak association between the VI's and dietary N of herbivores throughout the study period, results show there is a strong association between the EVI and dietary N of herbivores during the early growing season. Other studies have also found positive associations between dietary N of herbivores and the MODIS NDVI or EVI during the early grass growing period (Hamel et al., 2009; Lendrum et al., 2014; Villamuelas et al., 2016). The reason is possibly because in MZNP during the early grass growing season new green growth emerges (Winkler and Owen-Smith, 1995) and for herbivores new green, photosynthetic vegetation is more nutritious than dormant vegetation, and is preferentially selected (Cross et al., 2004; Murray and Illius, 2000; Shrader et al., 2006). The green photosynthetic vegetation is related to chlorophyll content which is related to N concentration in the forage (Haboudane et al., 2004; Hansen and Schjoerring, 2003; Leslie Jr et al., 2008; Mehaffey et al., 2005). The increase in the "greenness" of the vegetation causes an increase of forage N available for herbivores, while the green vegetation also causes the values of the VI's to increase (Glenn et al., 2008; Hamel et al., 2009; Kumar et al., 2002; Villamuelas et al., 2016). Tables 10, 11 and 12, in Appendix, confirm forage quality indicator N is high in the forage and herbivore faeces as well as the value of the MODIS EVI are also high. We, therefore, recommend during the early grass growing season the MODIS EVI can be implemented to monitor and assess forage N available to the herbivores in MZNP.

Table 4. 7: Correlations between the MODIS vegetation indices and the forage quality indicators in the faeces combined from all herbivore species during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index.

Forage quality indicators in the faeces	Seasons	n	x̅ (g/kg DM)	σ (g/kg DM)	MODIS vegetation indices	
					NDVI	EVI
Ash	Early growing	16	28.362	7.538	-0.233	0.233
	Late growing	72	25.852	6.216	0.197	0.026
	Early dormant	94	27.012	6.418	-0.155	-0.136
	Late dormant	17	23.619	7.483	0.342	0.004
Nitrogen	Early growing	16	1.444	0.253	0.061**	0.608**
	Late growing	36	1.638	0.258	-0.003	-0.215
	Early dormant	47	1.581	0.268	0.064	0.069
	Late dormant	85	1.264	0.252	0.040	-0.008
Phosphorus	Early growing	16	0.364	0.136	0.357	-0.357
	Late growing	36	0.496	0.261	0.030	-0.343
	Early dormant	47	0.499	0.186	-0.150	-0.155
	Late dormant	85	0.250	0.134	-0.68***	-0.703***
Potassium	Early growing	16	0.874	0.266	0.274	-0.275
	Late growing	36	0.797	0.503	0.126	-0.202
	Early dormant	47	0.765	0.412	-0.100	-0.124
	Late dormant	85	0.571	0.298	-0.373***	-0.374***
Calcium	Early growing	16	0.674	0.482	-0.197	0.198
	Late growing	36	0.892	0.742	-0.277	-0.326
	Early dormant	47	1.283	1.328	-0.191	-0.174
	Late dormant	85	0.845	1.251	-0.454***	-0.458***
Magnesium	Early growing	16	0.216	0.059	0.242	-0.242
	Late growing	36	0.271	0.115	-0.076	-0.326*
	Early dormant	47	0.312	0.112	-0.341*	-0.298*
	Late dormant	85	0.174	0.088	-0.667***	-0.659***
Sodium	Early growing	16	0.026	0.023	-0.492	0.493
	Late growing	36	0.032	0.034	0.129	-0.163
	Early dormant	47	0.031	0.035	-0.386**	-0.418**
	Late dormant	85	0.032	0.046	-0.479***	-0.461***

***Correlation is significant at 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

For P_f and Mg_f a noticeable strong negative correlation was found with the NDVI (r = -0.68, P ≤ 0.001; r = -0.703, P ≤ 0.001) and the EVI (r = -0.667, P ≤ 0.001; r = -0.659, P ≤ 0.001) during the late dormant season, which were all highly significant (Table 3.7). These results show there is a strong negative association between the NDVI and EVI and dietary P and Mg of herbivores in MZNP. The association found was not expected as there is no research, to our knowledge, that have found this association. The reason could possibly because during the late dormant season in MZNP grasses are dry and senescent (Winkler and Owen-

Smith, 1995) with the digestibility of the vegetation declining as fibrous, cell wall structures in the forage accumulate (Ball et al., 2001; Van Soest, 1994). The dry senescent grass is related to a decrease in forage N and mineral concentrations which causes a decrease in chlorophyll concentration, vegetation canopy "greenness" and thus values from multispectral satellite-derived VI's (Ball et al., 2001; Kumar et al., 2002; Spears, 1994). The results in this study confirm low mineral concentrations in the forage as well as low NDVI and EVI values during the late dormant season (Appendix, Tables 11 and 12). However, the mineral concentrations in the herbivore faeces, although decreased, remained relatively high compared to the mineral concentrations in the forage (Appendix, Table 10). The high dietary minerals of the herbivores could be from the intentional consumption of soil by the herbivores for trace minerals to buffer their digestive system or to compensate for the low concentrations of minerals found in the forage (Ayotte et al., 2006; Kreulen, 1985; Penzhorn, 1982b). A study by Penzhorn (1982b) showed Cape Mountain Zebra in MZNP to deliberately ingest soil when minerals were found to be deficient in their diets. Therefore, we recommend caution is taken for the VI's estimates and dietary P and Mg of herbivores in MZNP during the late dormant season.

Studies that determine associations between the MODIS NDVI and EVI, to assess forage quality, and the diets of herbivores through faecal analysis focus on one specific species. Due to the number of different dominate ungulate species in MZNP, this study focused on several. Results in Table 14, in Appendix, show N_f from only the black wildebeest and blesbok had a significant correlation with the NDVI ($r = 0.414$, $P \leq 0.05$; $r = 0.854$, $P \leq 0.001$). While only N_f from the species zebra had a significant correlation with the EVI ($r = 0.540$, $P \leq 0.001$). For P_f, only blesbok and springbok showed a significant correlation with the NDVI ($r = 0.844$, $P \leq 0.001$; $r = 0.264$, $P \leq 0.001$). Regarding Mg_f, blesbok was the only species to show a positive significant correlation with the NDVI ($r = 0.608$, $P \leq 0.05$). No species showed significant correlations between P_f and Mg_f and the EVI ($P > 0.05$). Although blesbok showed strong significant correlations with N_f, P_f and Mg_f, its low sampling size is concerning. Overall the forage quality indicators in the faeces from the different herbivore species showed no significant correlations with the NDVI or EVI. Therefore, it can be suggested that no particular herbivore species dramatically outweighed the results. The results thus show, contrary to our predictions, associations between the VI's and the diets of herbivores is not affected by the different herbivore species. The NDVI and EVI can, therefore, be generally associated with dietary nitrogen, phosphorus and magnesium for the dominant ungulate species in MZNP. There is very little research, to our knowledge, that have related VI's to dietary P and Mg, with most studies focusing on dietary N, and our study highlights the need for further research to be conducted into this relationship.

4.6 Conclusion

Many studies that have researched remote sensing and VI's to asses forage quality for herbivores have neglected to consider the diets of the herbivore species. This study shows there are associations between VI's and the diets of herbivores. We showed the MODIS NDVI and EVI have associations, although weak, with dietary N, P and Mg of herbivores in MZNP. Despite weak associations found between dietary N and NDVI and EVI, a strong association was found during the early growing season. We, therefore, recommend during the early grass growing season the MODIS EVI can be implemented to monitor and assess forage N available to the herbivores in MZNP. The associations found between VI's and dietary P and Mg of herbivores, to our knowledge, have seldom been investigated and we recommend further research into these associations. Our results also show that the associations between VI's and the diets of herbivores are affected by season. However, the different herbivore species, contrary to our predictions, did not affect the associations between the VI's and the diets of herbivores in MZNP. The VI's can, therefore, be generally associated with dietary N, P and Mg for the different herbivore species in MZNP. A major drawback however identified in this study is the low sampling size when considering individual herbivore species, which was due to time constraints and financial reasons. Notwithstanding the similar amount of sampling size in other comparable studies we still consider it to be a constraint. We also make note that the use of forage quality indicators in herbivore faeces is not a true measurement of the forage quality indicators in the herbivores diet. We, therefore, suggest using the results in this study as descriptive information about the diets of the ungulates in MZNP in association with the MODIS NDVI and EVI. The information found in this study does, however, show the applicability and suitability of multispectral satellite-derived VI's for MZNP management purposes and ensures their more precisely implemented for the park's herbivory management program. The research in this study also assists with a better understanding about the association between VI's and the diets of herbivores and can be used as a model for further research.

4.7 References

Acocks, J.P.H., 1988. Veld types of South Africa.

ALASA, 1998. Handbook of feeds and plant analysis. Method 6.1.1 - Dr Ashing. palic, D. (Ed).

Al-Abbas, A.H., Barr, R., Hall, J.D., Crane, F.L., Baumgardner, M.F., 1974. Spectra of Normal and Nutrient-Deficient Maize Leaves 1. Agron. J. 66, 16–20.

Anthony, R.G., Smith, N.S., 1974. Comparison of rumen and fecal analysis to describe deer diets. J. Wildl. Manage. 535–540.

AOAC., 1996. Official methods of analysis of the AOAC International. 16th edition. Association of Official Analytical Chemists (AOAC) International, Arlington, Virginia, USA.

Ayotte, J.B., Parker, K.L., Arocena, J.M., Gillingham, M.P., 2006. Chemical composition of lick soils: functions of soil ingestion by four ungulate species. J. Mammal. 87, 878–888.

Ball, D.M., Collins, M., Lacefield, G.D., Martin, N.P., Mertens, D.A., Olson, K.E., Putnam, D.H., Undersander, D.J., Wolf, M.W., 2001. Understanding forage quality. Am. Farm Bur. Fed. Publ. 1.

Barboza, P.S., Parker, K.L., Hume, I.D., 2008. Integrative wildlife nutrition. Springer Science & Business Media.

Bezuidenhout, H., Brown, L.R., Bradshaw, P., 2015. Broad vegetation description for Mountain Zebra National Park, Eastern Cape, South Africa. Internal SANParks report. South African National Parks, Scientific Services, Kimberley.

Botha, M.S., Stock, W.D., 2005. Stable isotope composition of faeces as an indicator of seasonal diet selection in wild herbivores in southern Africa. S. Afr. J. Sci. 101, 371–374.

Brown, L.R., Bezuidenhout, H., 2005. The vegetation of the farms Ingleside and Welgedacht of the Mountain Zebra National Park, Eastern Cape.

Brown, L.R., Bezuidenhout, H., 2000. The phytosociology of the De Rust section of the Mountain Zebra National Park, Eastern Cape.

Christianson, D., Creel, S., 2009. Fecal chlorophyll describes the link between primary production and consumption in a terrestrial herbivore. Ecol. Appl. 19, 1323–1335.

Codron, D., Lee-Thorp, J.A., Sponheimer, M., Codron, J., 2007. Nutritional content of savanna plant foods: implications for browser/grazer models of ungulate diversification. Eur. J. Wildl. Res. 53, 100–111.

Creech, T.G., Epps, C.W., Monello, R.J., Wehausen, J.D., 2016. Predicting diet quality and genetic diversity of a desert-adapted ungulate with NDVI. J. Arid Environ. 127, 160–170.

Cross, P.C., Owen-Smith, N., Macandza, V.A., 2004. Forage selection by African buffalo in the late dry season in two landscapes. South African J. Wildl. Res. delayed open access 34, 113–121.

Didan, K., 2015. MOD13Q1 MODIS/Terra vegetation indices 16-day L3 global 250m SIN grid V006. NASA EOSDIS L. Process. DAAC.

Fries, G.F., Marrow, G.S., Snow, P.A., 1982. Soil ingestion by dairy cattle. J. Dairy Sci. 65, 611–618.

Garroutte, E.L., Hansen, A.J., Lawrence, R.L., 2016. Using NDVI and EVI to map spatiotemporal variation in the biomass and quality of forage for migratory elk in the Greater Yellowstone Ecosystem. Remote Sens. 8, 404.

Germishuizen, G., Meyer, N., 2003. Plants of southern Africa: an annotated checklist. National Botanical Institute Pretoria.

Glenn, E., Huete, A., Nagler, P., Nelson, S., 2008. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape. Sensors 8, 2136–2160.

Goering, H.K., Van Soest, P.J., 1970. Forage fiber analysis. Agricultural handbook no. 379. US Dep. Agric. Washington, DC 1–20.

Grant, C.C., Meissner, H.H., Schultheiss, W.A., 1995. The nutritive value of veld as indicated by faecal phosphorous and nitrogen and its relation to the condition and movement of prominent ruminants during the 1992-1993 drought in the Kruger National Park. Koedoe 38, 17–31.

Grant, C.C., Peel, M.J.S., Van Ryssen, J.B.J., 2000. Nitrogen and phosphorus concentration in faeces: an indicator of range quality as a practical adjunct to existing range evaluation methods. African J. Range Forage Sci. 17, 81–92.

Haboudane, D., Miller, J.R., Pattey, E., Zarco-Tejada, P.J., Strachan, I.B., 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. Remote Sens. Environ. 90, 337–352.

Hall-Martin, A., Carruthers, J., 2003. South African National Parks: A Celebration. SANParks, Johannesbg.

Hamel, S., Garel, M., Festa-Bianchet, M., Gaillard, J., Côté, S.D., 2009. Spring Normalized Difference Vegetation Index (NDVI) predicts annual variation in timing of peak faecal crude protein in mountain ungulates. J. Appl. Ecol. 46, 582–589.

Hansen, P.M., Schjoerring, J.K., 2003. Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least squares regression. Remote Sens. Environ. 86, 542–553.

Hoffman, T., 1996. Eastern Mixed Nama Karoo. Veg. South Africa, Lesotho Swazil. 52–57.

Huete, A.R., Liu, H.Q., Batchily, K. V, Van Leeuwen, W., 1997. A comparison of vegetation indices over a global set of TM images for EOS-MODIS. Remote Sens. Environ. 59, 440–451.

Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, G., Wang, S., 2005. Monitoring of forage conditions with MODIS imagery in the Xilingol steppe, Inner Mongolia. Int. J. Remote Sens. 26, 1423–1436.

Knox, N.M., Skidmore, A.K., Prins, H.H.T., Asner, G.P., van der Werff, H.M.A., de Boer, W.F., van der Waal, C., de Knegt, H.J., Kohi, E.M., Slotow, R., 2011. Dry season mapping of savanna forage quality, using the hyperspectral Carnegie Airborne Observatory sensor. Remote Sens. Environ. 115, 1478–1488.

Kreulen, D.A., 1985. Lick use by large herbivores: a review of benefits and banes of soil consumption. Mamm. Rev. 15, 107–123.

Kumar, L., Schmidt, K., Dury, S., Skidmore, A., 2002. Imaging spectrometry and vegetation science, in: Imaging Spectrometry. Springer, pp. 111–155.

Leite, E.R., Stuth, J.W., 1994. Influence of duration of exposure to field conditions on viability of fecal samples for NIRS analysis. J. Range Manag. 312–314.

Lendrum, P.E., Anderson Jr, C.R., Monteith, K.L., Jenks, J.A., Bowyer, R.T., 2014. Relating the movement of a rapidly migrating ungulate to spatiotemporal patterns of forage quality. Mamm. Biol. 79, 369–375.

Leslie Jr, D.M., 1985. Fecal indices to dietary quality of cervids in old-growth forests. J. Wildl. Manage. 49, 142–146.

Leslie Jr, D.M., Bowyer, R.T., Jenks, J.A., 2008. Facts from feces: nitrogen still measures up as a nutritional index for mammalian herbivores. J. Wildl. Manage. 72, 1420–1433.

Mbatha, K.R., Ward, D., 2006. Using faecal profiling to assess the effects of different management types on diet quality in semi-arid savanna. African J. Range Forage Sci. 23, 29–38.

Mehaffey, M.H., Fisher, D.S., Burns, J.C., 2005. Photosynthesis and nutritive value in leaves of three warm-season grasses before and after defoliation. Agron. J. 97, 755–759.

Mertens, D.R., 2002. Gravimetric determination of amylase-treated neutral detergent fiber in feeds with refluxing in beakers or crucibles: collaborative study. J. AOAC Int. 85, 1217–1240.

Murray, K., 2011. Scatalog: quick ID guide to southern African animal droppings. Penguin Random House South Africa.

Murray, M.G., Illius, A.W., 2000. Vegetation modification and resource competition in grazing ungulates. Oikos 89, 501–508.

Mutanga, O., Skidmore, A.K., 2004. Integrating imaging spectroscopy and neural networks to map grass quality in the

Kruger National Park, South Africa. Remote Sens. Environ. 90, 104–115.

Novellie, P., 1990. Habitat use by indigenous grazing ungulates in relation to sward structure and veld condition. J. Grassl. Soc. South. Africa 7, 16–23.

Novellie, P., Gaylard, A., 2013. Long-term stability of grazing lawns in a small protected area, the Mountain Zebra National Park. koedoe 55, 0.

Olson, K.A., Murray, M.G., Fuller, T.K., 2010. Vegetation composition and nutritional quality of forage for gazelles in Eastern Mongolia. Rangel. Ecol. Manag. 63, 593–598.

Penzhorn, B.L., 1982a. Habitat selection by Cape mountain zebras in the Mountain Zebra National Park. South African J. Wildl. Res. delayed open access 12, 48–54.

Penzhorn, B.L., 1982b. Soil-eattng by Cape Mountain Zebras Equus Zebra Zebra in the Mountain Zebra National Park. Koedoe 25, 83–88.

Raffrenato, E., Van Amburgh, M.E., 2011. Improved methodology for analyses of acid detergent fiber and acid detergent lignin. J. Dairy Sci. 94, 3613–3617.

Ramoelo, A., Cho, M., Mathieu, R., Skidmore, A.K., 2015a. Potential of Sentinel-2 spectral configuration to assess rangeland quality. J. Appl. Remote Sens. 9, 94096.

Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., van de Kerchove, R., Kaszta, Z., Wolff, E., 2015b. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. Int. J. Appl. Earth Obs. Geoinf. 43, 43–54. https://doi.org/10.1016/j.jag.2014.12.010

Rouse Jr, J.W., Haas, R.H., Schell, J.A., Deering, D.W., 1973. Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation.

Ryan, S.J., Cross, P.C., Winnie, J., Hay, C., Bowers, J., Getz, W.M., 2012. The utility of normalized difference vegetation index for predicting African buffalo forage quality. J. Wildl. Manage. 76, 1499–1508.

Ryan, S.J., Knechtel, C.U., Getz, W.M., 2006. Range and habitat selection of African buffalo in South Africa. J. Wildl. Manage. 70, 764–776.

Seagle, S.W., McNaughton, S.J., 1992. Spatial variation in forage nutrient concentrations and the distribution of Serengeti grazing ungulates. Landsc. Ecol. 7, 229–241.

Shrader, A.M., Owen-Smith, N., Ogutu, J.O., 2006. How a mega-grazer copes with the dry season: food and nutrient intake rates by white rhinoceros in the wild. Funct. Ecol. 20, 376–384.

Skidmore, A.K., Ferwerda, J.G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H.T., Balcik, F.B., Venus, V., 2010. Forage quality of savannas—Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. Remote Sens. Environ. 114, 64–72.

Skidmore, A.K., Mutanga, O., Schmidt, K., Ferwerda, J.G., 2005. Modelling herbivore grazing resources using hyperspectral remote sensing and GIS, in: AGILE 2005: 8th Conference on Geographic Information Science, Lisboa, AGILE, Denver, USA. Citeseer.

Southwood, T.R.E., Henderson, P.A., 2009. Ecological methods. John Wiley & Sons.

Spears, J.W., 1994. Minerals in forages. Forage Qual. Eval. Util. 281–317.

Sweeney, R.A., 1989. Generic combustion method for determination of crude protein in feeds: Collaborative study. Journal-Association Off. Anal. Chem. 72, 770–774.

Toerien, D.K., 1972. Geologie van die Bergkwagga Nasionale Park. Koedoe 15, 77–82.

Turner, W.C., Imologhome, P., Havarua, Z., Kaaya, G.P., Mfune, J.K.E., Mpofu, I.D.T., Getz, W.M., 2013. Soil ingestion, nutrition and the seasonality of anthrax in herbivores of Etosha National Park. Ecosphere 4, 1–19.

Underwood, E.J., 1999. The mineral nutrition of livestock. Cabi.

Van der Walt, P.T., 1980. A phytosociological reconnaissance of the Mountain Zebra National Park. Koedoe African Prot. Area Conserv. Sci. 23, 1–32.

Van Soest, P.J., 1994. Nutritional ecology of the ruminant (Secon edition) Cornell University. Ithaca, New York, USA.

Villamuelas, M., Fernández, N., Albanell, E., Gálvez-Cerón, A., Bartolomé, J., Mentaberre, G., López-Olvera, J.R., Fernández-Aguilar, X., Colom-Cadena, A., López-Martín, J.M., 2016. The Enhanced Vegetation Index (EVI) as a proxy for diet quality and composition in a mountain ungulate. Ecol. Indic. 61, 658–666.

Weel, S., Watson, L.H., Weel, J., Venter, J.A., Reeves, B., 2015. Cape mountain zebra in the B aviaanskloof Nature Reserve, S outh A frica: resource use reveals limitations to zebra performance in a dystrophic mountainous ecosystem. Afr. J. Ecol. 53, 428–438.

Winkler, A., Owen-Smith, N., 1995. Habitat utilisation by Cape mountain zebras in the Mountain Zebra National Park, South Africa. Koedoe 38, 83–93.

WJ III, A., Alldredge, A.W., 1979. Soil ingestion by mule deer in northcentral Colorado. Rangel. Ecol. Manag. Range Manag. Arch. 32, 67–71.

Zar, J.H., 1999. Biostatistical analysis. Pearson Education India.

Chapter Five:

Research findings, conclusions and management recommendations

5.1 Overview

Multispectral satellite-derived VI's can provide a valuable technique to monitor and assess forage quantity and quantity available for herbivores (Ramoelo et al., 2015; Skidmore et al., 2005; Stolter et al., 2018). Despite the benefits of multispectral satellite-derived VI's, there is still limited research available, with the relationships between remote sensing and forage quantity and quality not fully understood. Studies have, however, found the relationships between multispectral satellite-derived VI's and forage quantity and quality to vary across different landscapes, areas and vegetation types (Garroutte et al., 2016; Kawamura et al., 2005; Mutanga et al., 2004a; Ramoelo et al., 2012). Therefore, in order to provide confidence in the ecological significance of the VI's estimates, and to ensure their appropriate implementation for management practices, assessing the VI's relationships with forage quantity and quality indicators within the desired area is a prerequisite.

The primary objective of this study was to determine the relationship between multispectral satellite-derived VI's and forage quantity and quality for herbivores in MZNP. Biomass was used as an indicator for forage quantity, while forage nutrients were used as indicators for forage quality. The VI's derived from the multispectral remote sensors onboard the MODIS and Sentinel-2 satellites were assessed because of their strong relationship with forage quantity and quality indicators, which has been demonstrated in other research (Frampton et al., 2013; Garroutte et al., 2016; Kawamura et al., 2008; Ramoelo et al., 2015). Herbivore faecal samples were also analysed for forage quality indicators (nutrients) and related to the VI's, to provide a deeper understanding about the association between the VI's and the diets of herbivores in MZNP. The findings of this research, coupled with supporting information from a literature review, will strengthen the implementation of multispectral satellite-derived VI's in MZNP, in order to assist with appropriate herbivore management decisions. In light of the limited research available on the relationship between multispectral satellite-derived VI's and forage quantity and quality, the information in this study also provides a broader understanding of the use of VI's in the management of other systems influenced by herbivory.

5.2 Study findings and conclusions

5.2.1 The relationship between multispectral satellite-derived vegetation indices and forage quantity and quality.

In this study, we showed that MODIS NDVI, rather than EVI, had a strong relationship with forage quantity indicator biomass. The result is interesting since the EVI is an enhancement over the saturation problems faced by the NDVI, and is thus expected to have a stronger relationship with forage quantity (Huete et al., 2010, 2002; Wang et al., 2003). This unexpected finding highlights the importance of assessing the relationship between these VI's and forage quantity before they can be used to estimate park-wide forage quantities. The results also showed the MODIS NDVI was more closely related to the quantity of photosynthetically active vegetation, which is more nutritious and preferentially selected by herbivores (Cross et al., 2004; Mehaffey et al., 2005; Murray and Illius, 2000; Shrader et al., 2006; Wilmshurst et al., 1999). Assessing the amount of forage quality means the NDVI can provide more explicit estimates of the amount of high quality food available to herbivores.

Strong relationships were also found between forage quality indicator N and the Sentinel-2 $Chl_{red\text{-}edge}$, CI_{green} and MODIS EVI. The $Chl_{red\text{-}edge}$, in particular, had a very strong relationship with forage N and our research shows the importance of red edge bands in the algorithms of VI's. The assessment of forage N is important when evaluating forage quality for herbivores, as this nutrient is related to protein content (Clifton et al., 1994; Wang et al., 2004), which is one of the most limiting nutrients for grazers (Grant et al., 2000; Owen-Smith and Novellie, 1982; Prins, 1996; Scholes and Walker, 1993).

This study also represents one of the first studies, to our knowledge, that demonstrates relationships between VI's and forage quality indicators. We found strong relationships between Sentinel-2 $Chl_{red\text{-}edge}$, CI_{green}, NDVI and MODIS NDVI and the forage quality indicator fiber (NDF, NDFd and ADL). This strong relationship is important when evaluating forage quality, as the VI's were found to be related to low forage fiber and high fiber digestibility, a significant relationship when assessing good forage quality for herbivores (Ball et al., 2001; Jalali et al., 2012; Laca et al., 2001). The limited research on VI's and forage quality indicator fiber is concerning, given the strong relationship found in this study and the significance of forage fiber for forage quality for herbivores. We, therefore, highlight the need for further investigation into the relationship between VI's and forage quality indicator fiber, especially when the objective is to implement VI's for herbivore management. Although not as strong, our results also demonstrated a relationship between Sentinel-2 $Chl_{red\text{-}edge}$ and MODIS NDVI with forage K. While the Sentinel-2 CI_{green} exhibited weak, but significant, relationships with forage minerals P and Ca. Forage minerals are important for assessing forage quality for herbivores, as the concentrations of minerals in the forage affect herbivore movement, distribution and survival (Grant et al., 1995; McNaughton, 1988; Olson et al., 2010). Other studies have found stronger relationships between remote sensing data and forage minerals. However, these studies could only estimate forage mineral concentrations using the wavelength range of a hyperspectral remote sensor (Mutanga et al., 2004b; Skidmore et al., 2010; Zhao et al., 2007). Problematically, hyperspectral remote sensing is computationally complicated and expensive (Mutanga et al., 2016; Varshney and Arora, 2004). The results in this component of our study, therefore, highlight the lack of important wavebands (which have relationships with forage minerals) found on more appropriate and suitable multispectral sensors. We, therefore, urge further investigation into the relationship between multispectral VI's and forage minerals.

The results of this study also demonstrated a weak, but significant, relationship between the Sentinel-2 and MODIS NDVI and forage starch. For herbivores, forage starch is another important nutrient as it is related to energy content availability (Ball et al., 2001; McDonald, 2002), which has a strong effect on herbivore population distribution (e.g. Carbone et al., 2007; Pettorelli et al., 2009). There is also very limited understanding about remotely sensed VI's and forage starch. We, therefore, encourage further investigation into the relationship between forage starch and VI's, specifically NDVI and its derivatives.

The relationships found between the VI's and forage quantity and quality indicators in this study demonstrate the suitability and applicability of VI's for MZNP and their management of herbivory. It has also shown how the relationships between VI's and forage quantity and quality are driven by season and area. The low forage sampling sizes for the different areas during this study was a limitation for this component of the work, and thus the effects of the different areas could not be fully investigated. Nevertheless, the study highlights the importance of adding ancillary and environmental variables into models when determining the relationships between VI's and forage quantity and quality. The fact that VI's varied across season and areas, with relationships, at different strengths, with specific forage quantity and quality indicators, highlights the importance of assessing this relationship in the area in question before the VI's are incorporated for use in management decisions.

5.2.2 Association between multispectral satellite-derived VI's to assess forage quality, and the diets of herbivores.

This component of the study emphasized the importance of understanding the diets of the particular herbivores under investigation when attempting to ascertain the relationship between VI's and forage quality for management purposes. We show that associations exist between the MODIS NDVI and EVI and the diets of herbivores in MZNP. Associations were found between the NDVI and EVI and dietary N, P and Mg of the herbivores. For herbivores, dietary N, P and Mg affect the distribution and survival of herbivore populations, as the nutrients play important roles in the metabolic function of animals (Mattson Jr, 1980; Olson et al., 2010; Seagle and McNaughton, 1992; Stapelberg et al., 2008). In this study, we showed a strong association between EVI and herbivore dietary N during the early growing season. At this time of year, photosynthetically active vegetation is more nutritious and preferentially selected by herbivores (Boone et al., 2006; Cross et al., 2004; Murray and Illius, 2000; Wilmshurst et al., 1999). The early growing season is therefore a critical period for herbivores, since food availability has been limited up until this time, with forage having been dry and senescent during the dry season (Ball et al., 2001; Knox et al., 2011; Mutanga et al., 2016; Shrader et al., 2006). The study also demonstrated weak, but significant, relationships between VI's and dietary P and Mg. However, there is very little understanding about the association between dietary minerals and VI's, and we, therefore, highlight the importance of further investigation into this relationship.

Finally, this component of the study also showed that the relationship between VI's and the diets of herbivores are influenced by season. The results showed the VI's and specific forage quality indicators in the forage and faeces increased till the early dormant season and then decreased sharply into the late dormant period. Our findings also showed the relationship between VI's and the diets of herbivores were not affected by any specific herbivore species. Our findings, therefore, demonstrate that the VI's can be related to the diets of herbivores in general. We recognise that the low faecal sampling size (due to time and budget constraints) is a limitation when considering individual herbivore species. In addition, it's well recognized that herbivore faecal samples do not provide a true measurement of the diets of herbivores, due to endogenous losses of nutrients in the faeces (Leslie Jr et al., 2008; Servello et al., 2005). Nevertheless, the relationships between the VI's and the diets of herbivores demonstrate the suitability and applicability of VI's for assisting with appropriate management decisions for the herbivores in MZNP.

5.3 Management recommendations

This study has demonstrated that multispectral satellite-derived VI's can be a useful technique for monitoring and assessing forage quantity and quality in MZNP. We recommend that the MODIS NDVI should be implemented to assess and monitor good forage quantity. We also recommend that the Sentinel-2 $Chl_{red\text{-}edge}$, CI_{green} and MODIS EVI be used to monitor forage N. Due to the strong association found between the MODIS EVI and dietary N of herbivores during the early growing season, we recommended that the Sentinel-2 $Chl_{red\text{-}edge}$, CI_{green} and MODIS EVI be utilized specifically to assess forage N availability for herbivores during this growing period for grasses. The Sentinel-2 $Chl_{red\text{-}edge}$, CI_{green}, NDVI and MODIS NDVI should be used to assess and monitor low forage fiber (NDF and ADL) and high fiber digestibility (NDFd) for the herbivores in MZNP, while the Sentinel-2 $Chl_{red\text{-}edge}$ and MODIS NDVI is additionally recommended to assess and monitor forage K in MZNP. Since the VI's evaluated in this study are easily accessible and freely available, we advocate the use and comparison of several VI's when assessing a specific forage quality indicator. The spatial patterns of multispectral satellite-derived VI's can be assessed over the long-term, comparing VI's over seasonal and monthly changes and with long-term average VI conditions - ideally comparing specific pixels over time (Gaylard et al., 2015; Smit and Simms, 2015). The long-term temporal patterns of VI's can assist with the assessment of forage conditions and dynamics in the park.

The implementation of multispectral satellite-derived VI's to assess and monitor forage quantity and quality for the herbivores of MZNP will aid in making appropriate herbivore management decisions (e.g. culling, live removals, reintroduction or augmentation of populations). The information uncovered by this study is also very important in a broader sense, as we have demonstrated relationships between VI's and forage quantity and quality that require improved understanding across a wider range of ecosystems.

5.4 References

Ball, D.M., Collins, M., Lacefield, G.D., Martin, N.P., Mertens, D.A., Olson, K.E., Putnam, D.H., Undersander, D.J., Wolf, M.W., 2001. Understanding forage quality. Am. Farm Bur. Fed. Publ. 1.

Boone, R.B., Thirgood, S.J., Hopcraft, J.G.C., 2006. Serengeti wildebeest migratory patterns modeled from rainfall and new vegetation growth. Ecology 87, 1987–1994.

Carbone, C., Rowcliffe, J.M., Cowlishaw, G., Isaac, N.J.B., 2007. The scaling of abundance in consumers and their resources: implications for the energy equivalence rule. Am. Nat. 170, 479–484.

Clifton, K.E., Bradbury, J.W., Vehrencamp, S.L., 1994. The fine-scale mapping of grassland protein densities. Grass Forage Sci. 49, 1–8.

Cross, P.C., Owen-Smith, N., Macandza, V.A., 2004. Forage selection by African buffalo in the late dry season in two landscapes. South African J. Wildl. Res. delayed open access 34, 113–121.

Frampton, W.J., Dash, J., Watmough, G., Milton, E.J., 2013. Evaluating the capabilities of Sentinel-2 for quantitative estimation of biophysical variables in vegetation. ISPRS J. Photogramm. Remote Sens. 82, 83–92. https://doi.org/10.1016/j.isprsjprs.2013.04.007

Garroutte, E.L., Hansen, A.J., Lawrence, R.L., 2016. Using NDVI and EVI to map spatiotemporal variation in the biomass and quality of forage for migratory elk in the Greater Yellowstone Ecosystem. Remote Sens. 8, 404.

Grant, C.C., Meissner, H.H., Schultheiss, W.A., 1995. The nutritive value of veld as indicated by faecal phosphorous and nitrogen and its relation to the condition and movement of prominent ruminants during the 1992-1993 drought in the Kruger National Park. Koedoe 38, 17–31.

Grant, C.C., Peel, M.J.S., Van Ryssen, J.B.J., 2000. Nitrogen and phosphorus concentration in faeces: an indicator of range quality as a practical adjunct to existing range evaluation methods. African J. Range Forage Sci. 17, 81–92.

Gaylard, A., Ferreira, S.M., Bezuidenhout, H., Smit, I.P.J.,2015. Karoo National Park aerial census report. Internal SANParks report. South African National Parks, Scientific Services.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.

Huete, A., Didan, K., van Leeuwen, W., Miura, T., Glenn, E., 2010. MODIS vegetation indices, in: Land Remote Sensing and Global Environmental Change. Springer, pp. 579–602.

Jalali, A.R., Nørgaard, P., Weisbjerg, M.R., Nielsen, M.O., 2012. Effect of forage quality on intake, chewing activity, faecal particle size distribution, and digestibility of neutral detergent fibre in sheep, goats, and llamas. Small Rumin. Res. 103, 143–151.

Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, G., Wang, S., 2005. Monitoring of forage conditions with MODIS imagery in the Xilingol steppe, Inner Mongolia. Int. J. Remote Sens. 26, 1423–1436.

Kawamura, K., Watanabe, N., Sakanoue, S., Inoue, Y., 2008. Estimating forage biomass and quality in a mixed sown pasture based on partial least squares regression with waveband selection. Grassl. Sci. 54, 131–145.

Knox, N.M., Skidmore, A.K., Prins, H.H.T., Asner, G.P., van der Werff, H.M.A., de Boer, W.F., van der Waal, C., de Knegt, H.J., Kohi, E.M., Slotow, R., 2011. Dry season mapping of savanna forage quality, using the hyperspectral Carnegie Airborne Observatory sensor. Remote Sens. Environ. 115, 1478–1488.

Laca, E.A., Shipley, L.A., Reid, E.D., 2001. Structural anti-quality characteristics of range and pasture plants. J. Range Manag. 413–419.

Leslie Jr, D.M., Bowyer, R.T., Jenks, J.A., 2008. Facts from feces: nitrogen still measures up as a nutritional index for mammalian herbivores. J. Wildl. Manage. 72, 1420–1433.

Mattson Jr, W.J., 1980. Herbivory in relation to plant nitrogen content. Annu. Rev. Ecol. Syst. 11, 119–161.

McDonald, P., 2002. Animal nutrition. Pearson education.

McNaughton, S.J., 1988. Mineral nutrition and spatial concentrations of African ungulates. Nature 334, 343.

Mehaffey, M.H., Fisher, D.S., Burns, J.C., 2005. Photosynthesis and nutritive value in leaves of three warm-season grasses before and after defoliation. Agron. J. 97, 755–759.

Murray, M.G., Illius, A.W., 2000. Vegetation modification and resource competition in grazing ungulates. Oikos 89, 501–508.

Mutanga, O., Dube, T., Ahmed, F., 2016. Progress in remote sensing: vegetation monitoring in South Africa. South African Geogr. J. 98, 461–471. https://doi.org/10.1080/03736245.2016.1208586

Mutanga, O., Prins, H.H.T., Skidmore, A.K., van Wieren, S., Huizing, H., Grant, R., Peel, M., Biggs, H., 2004a. Explaining grass-nutrient patterns in a savanna rangeland of southern Africa. J. Biogeogr. 31, 819–829.

Mutanga, O., Skidmore, A.K., Prins, H.H.T., 2004b. Predicting in situ pasture quality in the Kruger National Park, South Africa, using continuum-removed absorption features. Remote Sens. Environ. 89, 393–408.

Olson, K.A., Murray, M.G., Fuller, T.K., 2010. Vegetation composition and nutritional quality of forage for gazelles in Eastern Mongolia. Rangel. Ecol. Manag. 63, 593–598.

Owen-Smith, N., Novellie, P., 1982. What should a clever ungulate eat? Am. Nat. 119, 151–178.

Pettorelli, N., Bro-Jørgensen, J., Durant, S.M., Blackburn, T., Carbone, C., 2009. Energy availability and density estimates in African ungulates. Am. Nat. 173, 698–704.

Prins, H., 1996. Ecology and behaviour of the African buffalo: social inequality and decision making. Springer Science & Business Media.

Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., van de Kerchove, R., Kaszta, Z., Wolff, E., 2015. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. Int. J. Appl. Earth Obs. Geoinf. 43, 43–54. https://doi.org/10.1016/j.jag.2014.12.010

Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R., Heitkönig, I.M.A., 2012. Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. Int. J. Appl. Earth Obs. Geoinf. 19, 151–162.

Scholes, R.J., Walker, B.H., 1993. Nylsvley: the study of an African savanna.

Seagle, S.W., McNaughton, S.J., 1992. Spatial variation in forage nutrient concentrations and the distribution of Serengeti grazing ungulates. Landsc. Ecol. 7, 229–241.

Servello, F.A., Hellgren, E.C., McWilliams, S.R., 2005. Techniques for wildlife nutritional ecology. Tech. Wildl. Investig. Manag. Wildl. Soc. Bethesda, Maryland, USA 554–577.

Shrader, A.M., Owen-Smith, N., Ogutu, J.O., 2006. How a mega-grazer copes with the dry season: food and nutrient intake rates by white rhinoceros in the wild. Funct. Ecol. 20, 376–384.

Skidmore, A.K., Ferwerda, J.G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H.T., Balcik, F.B., Venus, V., 2010. Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z. and Wolff, E., 2015. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. Internation. Remote Sens. Environ. 114, 64–72. https://doi.org/10.1016/j.rse.2009.08.010

Skidmore, A.K., Mutanga, O., Schmidt, K., Ferwerda, J.G., 2005. Modelling herbivore grazing resources using hyperspectral remote sensing and GIS, in: AGILE 2005: 8th Conference on Geographic Information Science, Lisboa, AGILE, Denver, USA. Citeseer.

Smit, I.P.J., Simms, C., 2015. Using high temporal satellite imagery to monitor vegetation condition in Mountain Zebra National Park. Internal SANParks report. South African National Parks, Scientific Services.

Stapelberg, F.H., Van Rooyen, M.W., Bothma, J. du P., 2008. Spatial and temporal variation in nitrogen and phosphorus concentrations in faeces from springbok in the Kalahari. African J. Wildl. Res. 38, 82–88.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O.R., Cho, M.A., Joubert, D.F., 2018. Forage quality and availability for large herbivores in southern African rangelands. Klaus Hess Publishers.

Varshney, P.K., Arora, M.K., 2004. Advanced image processing techniques for remotely sensed hyperspectral data. Springer Science & Business Media.

Wang, Z., Liu, C., Huete, A., 2003. From AVHRR-NDVI to MODIS-EVI: Advances in vegetation index research. Acta Ecol. Sin. 23, 979–987.

Wang, Z.J., Wang, J.H., Liu, L.Y., Huang, W.J., Zhao, C.J., Wang, C.Z., 2004. Prediction of grain protein content in winter wheat (Triticum aestivum L.) using plant pigment ratio (PPR). F. Crop. Res. 90, 311–321.

Wilmshurst, J.F., Fryxell, J.M., Farm, B.P., Sinclair, A.R.E., Henschel, C.P., 1999. Spatial distribution of Serengeti wildebeest in relation to resources. Can. J. Zool. 77, 1223–1232.

Zhao, D., Starks, P.J., Brown, M.A., Phillips, W.A., Coleman, S.W., 2007. Assessment of forage biomass and quality parameters of bermudagrass using proximal sensing of pasture canopy reflectance. Grassl. Sci. 53, 39–49.

Appendix

Table 1: Means and standard deviations of MODIS and Sentinel-2 vegetation indices throughout the study period in the different areas. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge Index.

Satellite remote sensors	Vegetation indices	Areas					
		Rooiplaat			Welgedacht		
		n	x̄	σ	n	x̄	σ
MODIS	NDVI	220	0.293	0.081	148	0.258	0.073
	EVI	220	0.235	0.125	148	0.260	0.226
Sentinel-2	NDVI	130	0.233	0.080	82	0.179	0.092
	GNDVI	130	0.316	0.057	82	0.261	0.083
	EVI	130	0.903	0.274	78	0.894	0.383
	EVI2	130	0.560	0.192	82	0.430	0.221
	CI_{green}	130	0.132	0.308	82	-0.016	0.430
	$Chl_{red\text{-}edge}$	130	0.471	0.509	82	0.465	0.582

Table 2: Means and standard deviations of forage quantity and quality indicators throughout the study period in the different areas. NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility. Biomass (kg/ha). Nutrients (g/kg DM). Total number of observations: Rooiplaat: 220. Welgedacht: 148.

Forage quantity and quality indicators	Areas			
	Rooiplaat		Welgedacht	
	x̄	σ	x̄	σ
Biomass	2001	507.280	2043	456.143
Moisture	40.496	18.405	32.348	16.839
Ash	9.503	2.048	10.680	1.767
Nitrogen	0.857	0.307	0.900	0.529
NDF	71.122	5.703	74.336	10.223
ADL	5.792	1.342	5.886	1.279
NDFd	17.103	8.428	18.965	10.665
Starch	3.444	0.626	3.343	0.763
Phosphorus	0.225	0.143	0.180	0.109
Potassium	0.629	0.309	0.587	0.325
Calcium	0.817	0.939	0.534	0.687
Magnesium	0.181	0.102	0.181	0.187
Sodium	0.017	0.020	0.026	0.045

Table 3: Means and standard deviations of MODIS and Sentinel-2 vegetation indices throughout the study period during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge Index.

Satellite remote sensors	Vegetation indices	n	Seasons	$\bar{x}$	σ
MODIS	NDVI	368	Early growing	0.218	0.041
			Late growing	0.234	0.031
			Early dormant	0.397	0.051
			Late dormant	0.244	0.034
	EVI	368	Early growing	0.40	0.392
			Late growing	0.451	0.048
			Early dormant	0.236	0.028
			Late dormant	0.134	0.017
Sentinel-2	NDVI	212	Early growing	0.146	0.041
			Late growing	0.224	0.053
			Early dormant	0.329	0.067
			Late dormant	0.157	0.050
	GNDVI	212	Early growing	0.252	0.029
			Late growing	0.284	0.046
			Early dormant	0.382	0.041
			Late dormant	0.262	0.065
	EVI	208	Early growing	1.064	0.265
			Late growing	1.020	0.324
			Early dormant	1.020	0.324
			Late dormant	0.756	0.256
	EVI2	212	Early growing	0.349	0.099
			Late growing	0.538	0.126
			Early dormant	0.789	0.161
			Late dormant	0.377	0.120
	CI_{green}	212	Early growing	-0.269	0.149
			Late growing	0.684	0.057
			Early dormant	-0.118	0.057
			Late dormant	-0.086	0.156
	$Chl_{red\text{-}edge}$	212	Early growing	0.802	0.037
			Late growing	-0.480	0.105
			Early dormant	0.635	0.057
			Late dormant	0.820	0.042

Table 4: Means and standard deviations of forage quantity and selected quality indicators throughout the study period during the different seasons of grass growth. NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility. Biomass (kg/ha). Nutrients (g/kg DM).

Forage quantity and quality indicators	Seasons	n	$\bar{x}$	σ
Biomass	Early growing	32	2378	113.183
	Late growing	72	1619	413.16
	Early dormant	94	2348	369.986
	Late dormant	170	1936	454.352
Moisture	Early growing	32	39.117	6.704
	Late growing	72	53.896	7.221
	Early dormant	94	49.413	13.155
	Late dormant	170	23.056	13.833
Ash	Early growing	32	11.761	2.883
	Late growing	72	13.238	2.656
	Early dormant	94	9.227	0.673
	Late dormant	170	8.673	0.961
Nitrogen	Early growing	32	0.769	0.075
	Late growing	72	1.493	0.404
	Early dormant	94	1.019	0.119
	Late dormant	170	0.552	0.090
NDF	Early growing	32	64.616	2.789
	Late growing	72	62.282	5.316
	Early dormant	94	70.392	3.276
	Late dormant	170	79.291	3.760
ADL	Early growing	32	8.047	0.293
	Late growing	72	4.713	0.442
	Early dormant	94	4.443	0.579
	Late dormant	170	6.652	0.514
NDFd	Early growing	32	7.636	0.589
	Late growing	72	30.372	5.569
	Early dormant	94	25.210	1.422
	Late dormant	170	10.405	2.478
Starch	Early growing	32	3.092	0.139
	Late growing	72	3.418	0.389
	Early dormant	94	4.068	0.545
	Late dormant	170	3.088	0.652

Table 5: Means and standard deviations of selected forage quality indicators throughout the study period during the different seasons of grass growth.

Forage quality indicators	Seasons	n	x̄ (g/kg DM)	σ (g/kg DM)
Phosphorus	Early growing	32	0.085	0.016
	Late growing	72	0.240	0.115
	Early dormant	94	0.186	0.038
	Late dormant	170	0.229	0.167
Potassium	Early growing	32	0.355	0.144
	Late growing	72	0.304	0.182
	Early dormant	94	1.011	0.215
	Late dormant	170	0.574	0.175
Calcium	Early growing	32	0.264	0.033
	Late growing	72	1.065	0.500
	Early dormant	94	0.239	0.067
	Late dormant	170	0.583	0.540
Magnesium	Early growing	32	0.086	0.021
	Late growing	72	0.360	0.208
	Early dormant	94	0.116	0.022
	Late dormant	170	0.160	0.085
Sodium	Early growing	32	0.009	0.004
	Late growing	72	0.043	0.060
	Early dormant	94	0.009	0.008
	Late dormant	170	0.020	0.023

Table 6: Correlations between MODIS vegetation indices and selected forage quality indicators during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index. Nutrients NDF = Neutral Detergent Fibre, ADL= Acid Detergent Lignin, NDF= Neutral Detergent Fibre digestibility.

Forage quality indicators	n	Seasons	MODIS vegetation indices	
			NDVI	EVI
Moisture	32	Early growing	-0.543*	0.544*
	72	Late growing	-0.061	-0.161
	94	Early dormant	0.288**	0.208*
	170	Late dormant	0.699***	0.628***
Ash	32	Early growing	-0.999***	-0.999***
	72	Late growing	-0.289*	-0.504***
	94	Early dormant	-0.334*	-0.356***
	170	Late dormant	-0.010	-0.108
Nitrogen	32	Early growing	0.841***	-0.843***
	72	Late growing	-0.111	-0.558***
	94	Early dormant	-0.558***	-0.666***
	170	Late dormant	0.372***	0.381***
NDF	32	Early growing	0.855***	-0.853***
	72	Late growing	0.409***	0.690***
	94	Early dormant	-0.682***	-0.781***
	170	Late dormant	-0.196*	-0.173**
ADL	32	Early growing	0.649***	-0.647***
	72	Late growing	0.116	0.080
	94	Early dormant	0.042	0.205*
	170	Late dormant	-0.087	-0.182*
NDFd	32	Early growing	0.514**	-0.511**
	72	Late growing	0.120	0.018
	94	Early dormant	-0.334***	-0.283**
	170	Late dormant	0.324***	0.34***
Starch	32	Early growing	-0.943***	0.945***
	72	Late growing	0.014	0.018
	94	Early dormant	-0.201	-0.096
	170	Late dormant	-0.061	-0.174*

***Correlation is significant at 0.001 level (two-tailed). ** Correlation is significant at the 0.01 level (two-tailed). *Correlation is significant at the 0.05 level (two-tailed).

Table 7: Correlations between MODIS vegetation indices and selected forage quality indicators during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index. Nutrients NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility.

Forage quality indicators	n	x̄ (g/kg DM)	σ (g/kg DM)	Seasons	MODIS vegetation indices	
					NDVI	EVI
Phosphorus	32	0.085	0.016	Early growing	0.3778*	-0.381*
	72	0.24	0.115	Late growing	-0.021	-0.503***
	94	0.186	0.038	Early dormant	-0.127	-0.243*
	170	0.229	0.165	Late dormant	0.043	0.057
Potassium	32	0.355	0.144	Early growing	-0.771***	-0.773
	72	0.304	0.182	Late growing	-0.167	-0.297*
	94	1.011	0.215	Early dormant	-0.804***	-0.813
	170	0.57	0.175	Late dormant	0.341***	0.329***
Calcium	32	0.264	0.033	Early growing	-0792***	0.794***
	72	1.065	0.499	Late growing	0.086	-0.342**
	94	0.24	0.067	Early dormant	-0.532***	-0.65***
	170	0.583	0.539	Late dormant	-0.017	0.127
Magnesium	32	0.086	0.021	Early growing	0.123	-0.125
	72	0.360	0.208	Late growing	-0.184	-0.55***
	94	0.116	0.022	Early dormant	-0.034	-0.206*
	170	0.16	0.085	Late dormant	0.084	0.126
Sodium	32	0.009	0.004	Early growing	-0.99***	0.999***
	72	0.043	0.06	Late growing	0.348*	0.106
	94	0.009	0.008	Early dormant	-0.52***	-0.627***
	170	0.02	0.023	Late dormant	0.095	0.093

***Correlation is significant at 0.001 level (two-tailed). ** Correlation is significant at the 0.01 level (two-tailed). *Correlation is significant at the 0.05 level (two-tailed).

Table 8: Correlations between the Sentinel-2 vegetation indices and selected forage quality indicators during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, Cl_{green} = Green Chlorophyll Index, $Chl_{red\text{-}edge}$ = Chlorophyll Red-Edge Index. NDF = Neutral Detergent Fibre, ADL = Acid Detergent Lignin, NDFd = Neutral Detergent Fibre digestibility.

Forage quality indicators	n	Seasons	Sentinel-2 vegetation indices					
			NDVI	GNDVI	EVI	EVI2	CL_{green}	$Chl_{red\text{-}edge}$
Ash	30	Early growing	-0.629*	-0.657**	0.889***	-0.629*	-0.674**	0.581*
	100	Late growing	-0.310*	-0.357*	-0.215	-0.320*	0.441**	-0.412**
	100	Early dormant	-0.090	-0.130	0.067	-0.080	-0.435**	0.192
	200	Late dormant	-0.047	-0.218*	-0.259*	-0.047	-0.301**	-0.023
Nitrogen	15	Early growing	0.604*	0.550*	-0.445	0.604*	0.590*	-0655**
	50	Late growing	-0.334*	-0.255	0.230	-0.334*	0.270	-0.457***
	50	Early dormant	-0.292*	-0.305*	0.172	-0.292*	-0.189	0.238
	100	Late dormant	0.252*	-0.006	-0.239**	0.252**	-0.066	-0.326**
NDF	30	Early growing	0.561*	0.587*	-0.768*	0.570*	0.601*	-0.463
	100	Late growing	0.312*	0.208	-0.182	0.312*	0.264	0.442**
	100	Early dormant	0.078	0.190	0.113	0.078	0.046	-0.223
	200	Late dormant	-0.249*	-0.359***	-0.228*	-0.249*	-0.450***	0.143
ADL	30	Early growing	0.192	0.189	-0.497	0.192	-0.230	-0.225
	100	Late growing	-0.080	-0.147	-0.212	-0.080	0.087	0.089
	100	Early dormant	-0.128	-0.096	0.010	-0.128	-0.068	0.105
	200	Late dormant	-0.020	-0.041	0.024	-0.022	-0.083	-0.015
NDFd	15	Early growing	0.108	0.236	-0.191	-0.108	0.146	-0.079
	50	Late growing	-0.416**	-0.339*	0.106	-0.416**	0.398	-0.365**
	50	Early dormant	-0.183	-0.153	-0.005	-0.183	-0.204	0.148
	100	Late dormant	0.161	-0.052	-0.241	-0.022	-0.173	-0.167
Starch	30	Early growing	-0.003	0.167	-0.246	-0.029	0.032	-0.074
	100	Late growing	0.006	0.037	0.102	0.006	0.002	-0.197
	100	Early dormant	-0.251	-0.238	-0.026	-0.251	-0.097	0.218
	200	Late dormant	0.221*	0.282**	0.189	0.222*	0.288**	-0.136

***Correlation is significant at 0.001 level (two-tailed). ** Correlation is significant at the 0.01 level (two-tailed). *Correlation is significant at the 0.05 level (two-tailed).

Table 9: Correlations between the Sentinel-2 vegetation indices and selected forage quality indicators during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index, EVI2 = Enhanced Vegetation Index 2, GNDVI = Green Normalized Vegetation Index, CI_{green} = Green Chlorophyll Index, $Chl_{red-edge}$ = Chlorophyll Red-Edge Index.

Forage quality indicators	n	$\bar{x}$ (g/kg DM)	σ (g/kg DM)	Seasons	Sentinel-2 vegetation indices					
					NDVI	GNDVI	EVI	EVI2	CL_{green}	$Chl_{red-edge}$
Phosphorus	15	0.080	0.022	Early growing	0.311	0.263	-0.126	0.311	-0.409	0.229
	50	0.262	0.139	Late growing	-0.345*	-0.287*	0.157	-0.345	-0.197	0.002
	50	0.186	0.051	Early dormant	-0.341*	-0.265	0.250	-0.341*	-0.484***	0.404
	100	0.228	0.187	Late dormant	0.137	0.354***	0.328***	0.137	0.563***	0.040
Potassium	15	0.330	0.162	Early growing	0.718**	0.672**	-0.368**	-0.717**	0.663**	-0.754**
	50	1.420	0.793	Late growing	-0.263	-0.205	0.191	-0.263	-0.210	-0.436**
	50	1.101	0.358	Early dormant	-0.265	-0.277	0.097	-0.265	0.218	-0.185
	100	0.572	0.268	Late dormant	0.113	0.097	-0.030	0.113	0.168	-0.149
Calcium	15	0.269	0.050	Early growing	-0.480	-0.511	0.205	-0.480	-0.502	0.484
	50	0.412	0.149	Late growing	-0.330*	-0.252	0.190	-0.330*	0.265	-0.386**
	50	0.249	0.076	Early dormant	-0.007	-0.102	0.063	-0.017	0.113	-0.039
	100	0.374	0.245	Late dormant	0.101	0.289**	0.248*	0.101	0.484***	0.048
Magnesium	15	0.080	0.032	Early growing	0.064	0.041	0.242	0.064	0.043	-0.161
	50	0.179	0.083	Late growing	-0.301*	-0.253	0.105	-0.330*	0.273	-0.451***
	50	0.115	0.038	Early dormant	-0.258	-0.232	0.125	-0.258	-0.231	0.294*
	100	0.152	0.105	Late dormant	0.083	0.253	0.223*	0.083	0.437***	0.077
Sodium	15	0.001	0.005	Early growing	-0.689*	-0.668**	-0.024	-0.644	-0.678**	0.647**
	50	0.033	0.055	Late growing	-0.265	-0.228	0.186	-0.265	0.237	-0.406**
	50	0.010	0.012	Early dormant	-0.3618	-0346*	0.026	-0.361*	-0.487***	0.381**
	100	0.020	0.040	Late dormant	0.088	0.181	0.137	0.088	0.285	0.003

***Correlation is significant at 0.001 level (two-tailed). ** Correlation is significant at the 0.01 level (two-tailed). *Correlation is significant at the 0.05 level (two-tailed).

Table 10: Means and standard deviations of the forage quality indicators in the faeces from the different herbivore species throughout the study period.

Forage quality indicators in the faeces	Black wildebeest			Blesbok			Eland			Springbok			Red Hartebeest			Zebra		
	n	x̄ (g/kg) DM	σ (g/kg) DM	n	x̄ (g/kg) DM	σ (g/kg) DM	n	x̄ (g/kg) DM	σ (g/kg) DM	n	x̄ (g/kg) DM	σ (g/kg) DM	n	x̄ (g/kg) DM	σ (g/kg) DM	n	x̄ (g/kg) DM	σ (g/kg) DM
Ash	60	27.977	6.171	32	25.886	4.637	14	17.121	7.410	118	26.155	6.243	46	28.500	5.419	98	22.239	8.195
Nitrogen	30	1.482	0.279	16	1.422	0.305	7	1.455	0.272	59	1.502	0.301	23	1.517	0.298	49	1.284	0.289
Phosphorus	30	0.387	0.198	16	0.326	2.049	7	0.245	0.163	59	0.402	2.196	23	0.428	2.173	49	0.327	0.209
Potassium	30	0.850	0.455	16	0.569	0.329	7	0.292	0.226	59	0.644	0.325	23	0.745	0.268	49	0.718	0.416
Calcium	30	0.653	0.422	16	0.638	0.489	7	1.643	1.202	59	1.009	0.925	23	1.476	0.376	49	0.832	1.363
Magnesium	30	0.216	0.091	16	0.204	0.117	7	0.237	0.111	59	0.236	0.102	23	0.288	1.796	49	0.214	0.114
Sodium	30	0.023	0.034	16	0.0112	0.007	7	0.023	0.012	59	0.029	0.034	23	0.038	0.155	49	0.042	0.051

Table 11: Means and standard deviations of the forage quality indicators in the faeces from all combined herbivore species during the different seasons of grass growth.

Forage quality indicators in the faeces	Seasons	n	x̄ (g/kg DM)	σ (g/kg DM)
Ash	Early growing	32	28.363	7.538
	Late growing	72	25.852	6.216
	Early dormant	94	27.012	6.418
	Late dormant	170	23.619	7.483
Nitrogen	Early growing	16	1.444	0.253
	Late growing	36	1.638	0.258
	Early dormant	47	1.581	0.269
	Late dormant	85	1.264	0.252
Phosphorus	Early growing	16	0.364	0.136
	Late growing	36	0.496	0.362
	Early dormant	47	0.499	0.186
	Late dormant	85	0.250	0.134
Potassium	Early growing	16	0.364	0.136
	Late growing	36	0.797	0.503
	Early dormant	47	0.765	0.412
	Late dormant	85	0.572	0.298
Calcium	Early growing	16	0.674	0.482
	Late growing	36	0.892	0.742
	Early dormant	47	1.283	1.328
	Late dormant	85	0.845	1.251
Magnesium	Early growing	16	0.216	0.059
	Late growing	36	0.271	0.114
	Early dormant	47	0.312	0.112
	Late dormant	85	0.174	0.089
Sodium	Early growing	16	0.026	0.023
	Late growing	36	0.032	0.034
	Early dormant	47	0.031	0.035
	Late dormant	85	0.032	0.046

Table 12: Means and standard deviations of the MODIS vegetation indices during the different seasons of grass growth. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index.

Satellite remote sensors	Vegetation indices	n	Seasons	x̄	σ
MODIS	NDVI	368	Early growing	0.218	0.041
			Late growing	0.234	0.031
			Early dormant	0.397	0.051
			Late dormant	0.244	0.034
	EVI	368	Early growing	0.40	0.392
			Late growing	0.451	0.048
			Early dormant	0.236	0.028
			Late dormant	0.134	0.017

Table 13: Means and standard deviations of the forage quality indicators in the forage during the different seasons of grass growth.

Forage quality indicators in the forage	Seasons			
		n	x̄ (g/kg DM)	σ (g/kg DM)
Moisture	Early growing	32	39.117	6.704
	Late growing	72	53.896	7.221
	Early dormant	94	49.413	13.155
	Late dormant	170	23.056	13.833
Ash	Early growing	32	11.761	2.883
	Late growing	72	13.238	2.656
	Early dormant	94	9.227	0.673
	Late dormant	170	8.673	0.961
Nitrogen	Early growing	32	0.769	0.075
	Late growing	72	1.493	0.404
	Early dormant	94	1.019	0.119
	Late dormant	170	0.552	0.090
Phosphorus	Early growing	32	0.085	0.016
	Late growing	72	0.240	0.115
	Early dormant	94	0.186	0.038
	Late dormant	170	0.229	0.167
Potassium	Early growing	32	0.355	0.144
	Late growing	72	0.304	0.182
	Early dormant	94	1.011	0.215
	Late dormant	170	0.57	0.175
Calcium	Early growing	32	0.264	0.033
	Late growing	72	1.065	0.500
	Early dormant	94	0.239	0.067
	Late dormant	170	0.583	0.540
Magnesium	Early growing	32	0.086	0.021
	Late growing	72	0.360	0.208
	Early dormant	94	0.116	0.022
	Late dormant	170	0.160	0.085
Sodium	Early growing	32	0.009	0.004
	Late growing	72	0.043	0.060
	Early dormant	94	0.009	0.008
	Late dormant	170	0.020	0.023

Table 14: Correlations between the MODIS vegetation indices and the forage quality indicators in the faeces from the different herbivore species throughout the study period. A) Black wildebeest, B) Blesbok, C) Eland, D) Eland, B) Springbok and F) Zebra. NDVI = Normalized Difference Vegetation Index, EVI = Enhanced Vegetation Index.

A)

Forage quality indicators in the faeces	MODIS vegetation indices		
	n	NDVI	EVI
Ash	60	-0.068	-0.111
Nitrogen	30	0.413*	0.186
Phosphorus	30	0.290	0.271
Potassium	30	0.144	0.366*
Calcium	30	0.052	0.040
Magnesium	30	0.229	0.242
Sodium	30	-0.302	0.584***

B)

Forage quality indicators in the faeces	MODIS vegetation indices		
	n	NDVI	EVI
Ash	32	-0.271	0.222
Nitrogen	16	0.854***	0.308
Phosphorus	16	0.844***	0.256
Potassium	16	0.625**	-0.097
Calcium	16	0.315	0.164
Magnesium	16	0.608*	0.234
Sodium	16	0.721*	0.234

C)

Forage quality indicators in the faeces	MODIS vegetation indices		
	n	NDVI	EVI
Ash	14	0.293	-0.582
Nitrogen	7	-0.068	-0.236
Phosphorus	7	0.111	0.234
Potassium	7	0.174	0.021
Calcium	7	-0.424	0.706
Magnesium	7	0.034	0.339
Sodium	7	-0.463	0.757*

D)

Forage quality indicators in the faeces	MODIS vegetation indices		
	n	NDVI	EVI
Ash	46	0.154	0.319*
Nitrogen	23	0.148	0.223
Phosphorus	23	0.112	0.281
Potassium	23	-0.158	0.318
Calcium	23	0.511*	-0.062
Magnesium	23	0.219	0.205
Sodium	23	0.289	0.064

C)

Forage quality indicators in the faeces	MODIS vegetation indices		
	n	NDVI	EVI
Ash	118	0.130	0.261*
Nitrogen	59	0.252	0.059
Phosphorus	59	0.264	0.106
Potassium	59	0.093	0.030
Calcium	59	-0.066	-0.079
Magnesium	59	0.221	0.050
Sodium	59	-0.187	-0.189

D)

Forage quality indicators in the faeces	MODIS vegetation indices		
	n	NDVI	EVI
Ash	98	0.295*	0.265*
Nitrogen	49	0.253	0.540***
Phosphorus	49	0.035	0.278
Potassium	49	-0.219	0.133
Calcium	49	-0.156	-0.203
Magnesium	49	0.1120	0.052
Sodium	49	-0.294*	-0.151

***Correlation is significant at 0.001 level (two-tailed). ** Correlation is significant at the 0.01 level (two-tailed). *Correlation is significant at the 0.05 level (two-tailed).