



Harnessing Landsat fractional cover time series to monitor dryland ecological integrity at multiple scales

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Abstract

Inadequate environmental management in drylands can have serious consequences shifting ecosystems into alternate stable states where key ecosystem services are compromised. Open access Earth observation data can provide continuous and consistent measurements globally, thus providing valuable information on remote dryland locations. The most widely employed remote sensing indicators are spectral indices of vegetation greenness, such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) and are not specifically fit for drylands where background soil has a strong influence and senescent vegetation often dominates. Methodological advances in the past decade now allow the quantification of vegetation fractional cover (VFC) into three categories: photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV) and bare soil (BS). Although monitoring applications have been derived from this product, significant knowledge gaps remain regarding the relationships between vegetation cover fractions and descriptors of ecosystem condition. Our work addressed these gaps at regional and continental scale. At the regional scale we explored links between VFC time series statistics and field measurements of woodland ecosystem quality (soil health and vegetation structure complexity) and elastic net regression to assess combinations of fractional cover statistics for predicting ecosystem quality. We found that time series statistics were robust predictors of soil health and vegetation structure complexity. At the continental scale we demonstrated how vegetation structure components (i.e. woody and herbaceous cover) can be accurately predicted by VFC time series statistics (RMSE<14.75%). Moreover, we found links between field-measured vegetation structure complexity metrics (i.e., growth form and height class diversity) and different combinations of cover-fraction time-series statistics depending on vegetation type and climate.

Introduction

Drylands are vulnerable to degradation due to inadequate land management practices and climate change (D'Odorico et al. 2013). Monitoring methods that enable access to these large and remote areas are needed

to inform more sustainable land management practices that can adapt to a changing climate. Multi-spectral satellite remote sensing can be a suitable technique to systematically collect information in dryland ecosystems. A large majority of the methods employed so far relied on vegetation greenness as an indicator of ecosystem health (Soubry et al. 2021). However, drylands are often dominated by senescent vegetation that is hard to separate from soil signals in terms of visible and short infrared wavelength reflectance (Roberts et al. 1993). Moreover, vegetation in this state can still provide crucial functions in drylands such as protecting the soil from erosion (Ludwig et al. 2005), and forage and habitat provision (Moore et al. 2004; Zou et al. 2016). Methods have been developed in the past decade that estimate vegetation fractional cover (VFC) i.e., the proportion of photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV) and bare soil (BS) (Guerschman et al. 2015). Consistent and continuous observation of such features not only allows to track directional change but also deepen the knowledge on temporal dynamics in dryland systems (Francis et al. 2023; Shumack et al. 2021).

The combination of remote sensing products and field observations of ecosystem condition is a fundamental step towards robust monitoring schemes that facilitate adaptive land management (Lawley et al. 2016). Several attempts of modelling vegetation/rangeland condition from remote sensing have been made with varying degrees of field data integration (Lawley et al. 2016; Retallack et al. 2023). In Australia, VFC time series data are increasingly being employed to this end (Department of Environment and Science 2021; Love et al. 2020; Williams et al. 2021). However, only the ‘Spatial Biocondition’ classification model was trained and evaluated employing over 9,000 field observations within the state of Queensland (Department of Environment and Science 2021). Moreover, links between VFC statistics and the variables that determine condition (e.g., vegetation structure, phenology and ground cover dynamics) have not been thoroughly explored.

Here we employed open-source field observations to explore relationships between time series statistics of remotely sensed VFC and dryland ecosystem condition. Our analyses aimed to answer two main questions:

1. How well do VFC time series statistics predict semi-arid woodland ecosystem condition? Which variables are more important?
2. How well do VFC time series statistics characterise vegetation structural complexity across multiple vegetation types and climatic regimes?

Methods

We obtained ecosystem condition indicators depicting woodland soil health and vegetation structure complexity of 450 ‘NSW grazing study’ sites (State Government of NSW and NSW Department of Climate Change 2023). Soil health indicators were related to soil surface characteristics (i.e., landscape function analysis – nutrient cycling index (Tongway and Hindley 2000)) and topsoil physicochemical properties (i.e., total C, total N, total P and bulk density (Eldridge et al. 2016)). Structural complexity was obtained as an index following Val et al. (2018).

Further characterisation of vegetation structural complexity was undertaken based on TERN Ausplots surveys from dryland (i.e., areas with a rainfall to potential evapotranspiration ratio lower than 0.65) rangelands across the Australian continent (Munroe et al. 2021; TERN 2024). Point-intercept data of 740 plots were processed into woody and herbaceous fractional cover, and five metrics of structural complexity: height coefficient of variation (heightcv), growth form Shannon diversity (GFdiversity), height class Shannon diversity (HCdiversity), plot scale vegetation volume (vegvol, obtained as the product of average height and total cover), and volume coefficient of variation (volcv). Sites were classified according to

combined major vegetation groups (NVIS Technical Working Group 2017) and agroclimatic zone (Hutchinson et al. 2005).

Time series of Landsat fractional cover (Joint Remote Sensing Research Program 2021) spanning 5, 10 and 30 years before field sampling were extracted for all overlapping pixels of each ‘NSW grazing study’ site. Time series statistics (seven for each cover fraction) were then calculated. Apart from typically used central tendency metrics (mean and median) we explored measurements of stability (standard deviation), persistence (intra and inter-annual minima), and dominance (intra and inter-annual maxima). Preliminary analysis showed little difference in model performance among time series extents; the process above was repeated for AusPlot sites using 10-year time series.

Models of woodland ecosystem condition indicators and vegetation structure were fitted through elastic net regression, a method for fitting multiple regression in cases where predictors are highly correlated employing coefficient shrinkage (Zou and Hastie 2005). Optimum parameters (α and λ) values were obtained (from a list of 275 possible combinations) through 250-fold cross validation. Model performance was assessed on the entire dataset through the root mean square error (RMSE) for accuracy assessment and the normalised RMSE (NRMSE = RMSE/standard deviation of observed values) for predictive power comparison across different variables. Models with NRMSE values close to 1 have null predictive power. Coefficient values and selection frequency of predictors across the candidate models were used to assess their importance.

Results

Woodland ecosystem condition

VFC time series yielded good models of woodland ecosystem condition (Figure 1). Although NRMSE was often well below 1, models of soil chemistry were the most accurate. Time series statistics of all cover fractions were found to be important predictors in elastic net models of ecosystem quality variables. Soil C and N were highly correlated with each other, thus shared the same main predictors (i.e., PVmedian, PVmean). Soil P was also related to C and N, however it was more strongly predicted by the annual maximum of green vegetation and negatively influenced by the annual persistence of the dead fraction. The average interannual minimum photosynthetic vegetation fraction was the most important remote sensing predictor of vegetation structure complexity and nutrient cycling index, as it was the most frequently included variable and displayed the highest relative importance in the tested models. Even though vegetation structural complexity displayed a moderately high NRMSE (>0.65), elastic net models were capable of distinguishing between low, medium, and high levels (Figure 1). This result encouraged more detailed analysis of vegetation structural components and continuous measurements of its complexity.

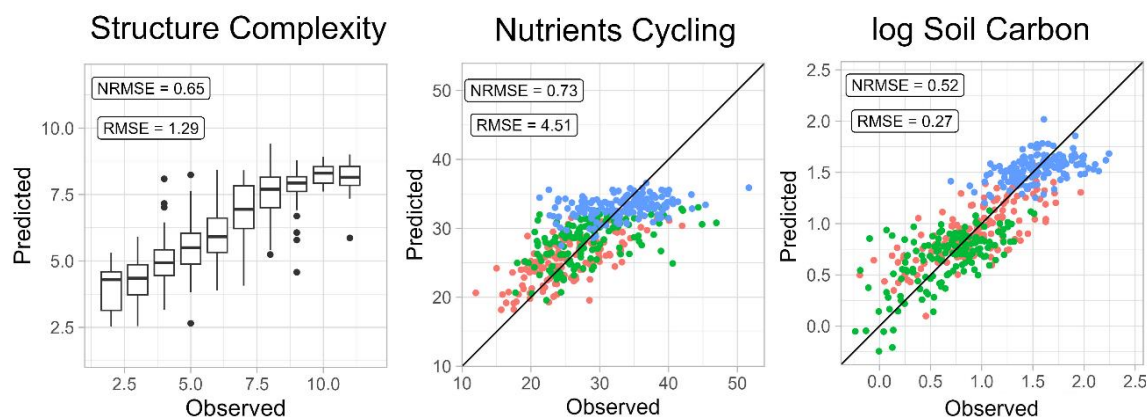


Figure 1. Box and scatter plots of modelled against observed values of the vegetation structural complexity index (dimensionless, left), the nutrients cycling index (dimensionless, centre) and the natural logarithm of soil carbon content (%), right). Root mean square error (RMSE) and its normalization by the standard deviation of observed values (NRMSE) are shown for all 3 models. Different colours indicate different woodland communities (i.e., blue = river red gum, red = black box, and green = white cypress pine).

Vegetation structure and structural complexity

Elastic net modelling based on Landsat fractional cover produced low-bias models of vegetation type cover across dryland ecosystems (Figure 2). Woody cover was more accurately modelled than herbaceous cover. Different fractional cover statistics were important for the prediction of vegetation cover type. In woody cover models, time series statistics related to both inter-annual and intra-annual variability were important. Variables related to the persistence of the green fraction were the most frequently included and most important positive predictors, whereas statistics related to the occurrence of high levels of bare soil were also important but negatively related to woody cover. Herbaceous cover was positively related to statistics describing the variability of both dry and photosynthetic vegetation.

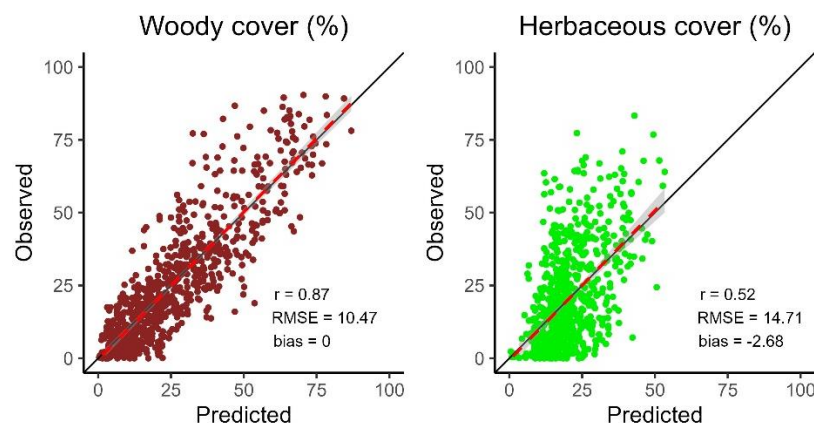


Figure 2. Scatterplots showing the observed and estimated woody component (left) and herbaceous component (right) of 740 AusPlot sites across the Australian drylands. The black line corresponds to the 1:1 agreement, the red dashed line represents the best linear fit between predicted and observed values. Pearson's correlation coefficient (r), root mean square error (RMSE), and bias (calculated as the mean difference between observed and predicted) are displayed.

VFC time series statistics produced structure complexity models of varied performance at the continental drylands scale (Figure 3). Elastic net models of vegetation volume and height class diversity performed the best, other models had an error close to the sample variability (i.e., $\text{NRMSE} > 0.85$). Models calibrated within specific vegetation - climatic groups were able to satisfactorily predict these metrics ($\text{NRMSE} < 0.72$). The most important predictors of HC diversity were related to the occurrence and persistence of green cover and had positive coefficient values, while the temporal stability of the non-photosynthetic fraction was positively related to HC diversity. Vegetation volume was strongly related to the persistence of the remotely sensed green vegetation fraction. Predictor importance across specific vegetation-climate group models was variable.

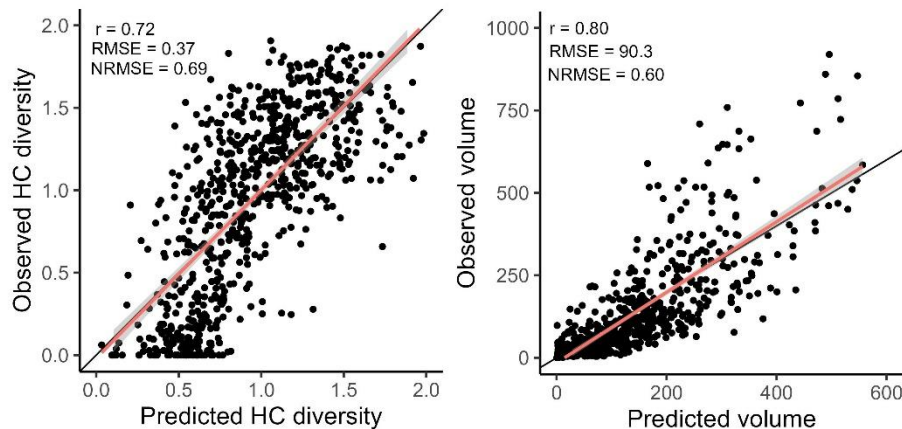


Figure 3. Scatter plots of observed versus modelled structure complexity indicators of all plots (n=740). Vegetation volume is expressed as the product of cover (%) and height (m). The black line corresponds to the 1:1 agreement, the red line represents the best linear fit between predicted and observed values.

Discussion and Conclusions

Variable importance for ecosystem condition indicator models in this study accord with assumptions and findings of previous research, but also revealed new insights. Metrics related to the dominance and stability of remotely-sensed green vegetation were important predictors of structure complexity, the nutrient-cycling index, soil carbon and soil nitrogen in woodlands. This aligns with the criteria employed by expert knowledge-based habitat condition models (Harwood et al. 2016; Love et al. 2020; Williams et al. 2021) and the evaluation of more complex data-driven models of ‘BioCondition’ (Department of Environment and Science 2021). Accordingly, long term seasonal averages of PV have been identified as important predictors of top-soil organic carbon, surpassing descriptors of climate, lithology and relief (Wang et al. 2018). Moreover, these metrics were also important for woody cover models at the continental scale and agrees with previous methods for modelling tree cover (Gill et al. 2017). Conversely, time series metrics of BS and NPV were often negatively related to woodland condition. This followed expectations, as the dominance and variability of BS in semi-arid woodlands are often respectively related to areas of consistently low and frequent heavily grazed vegetation cover, both cases resulting in poor vegetation structure and degraded soils (Eldridge et al. 2017; Val et al. 2018). Bare soil metrics were also previously identified as important predictors of biological condition class (Department of Environment and Science 2021) and top-soil organic carbon (Wang et al. 2018). The temporal variability of PV and NPV were positive predictors of herbaceous cover at the continental drylands scale, reflecting the seasonal behavior of C4 dominated grasslands (Munroe et al. 2022). This was evident in models of heightCV in savannah woodlands where the stability of BS and persistence of PV were important predictors negatively related to this indicator of structural complexity reflecting that the herbaceous stratum is either absent or overshadowed (in terms of relative cover) by the woody component.

Our research demonstrated the relevance of Landsat VFC as a strategic tool to monitor dryland ecosystems. We found significant and ecologically interpretable relationships between time series statistics of satellite observations of PV, NPV and BS and field observations of vegetation structure and structure complexity, and soil health. Our results set a robust basis for the identification of metrics to monitor the state of different dryland systems, and support informed selection of variables for data-driven modelling techniques.

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