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VALIDATION OF FUEL MOISTURE CONTENT ESTIMATES FROM THE AUSTRALIAN FLAMMABILITY MONITORING SYSTEMS FOR COASTAL SHRUBLANDS IN THE PERTH REGION

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	**4**
EXECUTIVE SUMMARY	**5**
END-USER PROJECT IMPACT STATEMENT	**6**
INTRODUCTION	**7**
RESEARCH APPROACH AND FINDINGS	**8**
Methods	8
Results	12
UTILISATION AND IMPACT	**20**
CONCLUSION	**21**
TEAM MEMBERS	**23**
Research Team	23
End-Users	23
REFERENCES	**24**

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This research was part of the Bushfire and Natural Hazards Cooperative Research Centre's Black Summer research program, funded by the Australian Government and the CRC to investigate key issues from the 2019-20 bushfire season.

EXECUTIVE SUMMARY

The Yanchep Bushfire, which burnt around 12 300 ha in December 2019, was triggered by an extreme heatwave event. The burnt area included structures, suburbs, and reserves, with an extensive native vegetation component. The site has very heterogeneous vegetation and incorporates threatened species. Since vegetation moisture is a crucial factor in determining fire behavior, several remote sensing methods have been developed to calculate live fuel moisture content (LFMC) to replace costly and time consuming field based methods. In previous studies, we developed a method to estimate LFMC from coarse resolution (500m) Moderate Resolution Imaging Spectroradiometer (MODIS) data. However, higher spatial resolution satellite sensors can detect LFMC changes in smaller scales which are essential for fire management applications. Therefore, we adapted previous methodology for estimating LFMC using Sentinel 2 imagery to produce LFMC maps at 20m spatial resolution.

In this research, we used field measured LFMC of dominant plant species on three sites in Yanchep to validate Sentinel 2 based LFMC. Spatial and temporal collocations were performed to identify closest matches of observed and estimated LFMC values. Collocated pairs of measurements were analyzed statistically to determine the relationship between the observed and estimated LFMC and with that the performance of the Sentinel-2 LFMC estimates.

Dominant plant species individually showed weaker response to Sentinel-2 based LFMC estimates comparing to the averages of all vegetation species. Moreover, the weighted average of dominant species (by land cover percentage) indicated the highest correlation with estimated LFMC. This demonstrated good performance of the LFMC Sentinel-2 algorithm given the limitations of the field data used as ground truth.

This research will serve as a basis for validating Sentinel 2 based LFMC with ground measurements to better understand uncertainties in both LFMC measured on the ground and retrieve by the satellite. Remote sensing based LFMC maps are an invaluable resource for bushfire risk assessment and prescribed burn activities.

END-USER PROJECT IMPACT STATEMENT

Jackson Parker *Department of Fire and Emergency Services, WA*

In shrubland communities most available fuel is found in the living vegetation foliage. The quantity of Live Fuel Moisture Content (LFMC) available is controlled by soil conditions, plant stress and drought adaptations which vary amongst species and across the landscape. LFMC is critical in determining fire behaviour, damage potential and suppression (Plucinski et al. 2009). However, there is still limited knowledge in the correlation between seasonal variations of LFMC and fire behaviour in the Southern WA shrublands. This gap was recognised in the 2011 Margaret River special enquiry and in response to the Keelty (2011) recommendation number 4, Department of Fire and Emergency in collaboration with Department of Biodiversity, Conservation and Attractions commenced on the research focusing on LFMC of shrubland communities in Northern Perth within Yanchep National Park. This research provides insights into how field data collection to validate satellite based LFMC estimates can be improved and provides for an enhanced understanding in the interpretation of near real time LFMC estimates of temperate shrublands to improve the planning and implementation of prescribed burns, raise community awareness and better preparedness of changes in the seasonal flammability of shrublands.

Ben Miller, *Department of Biodiversity, Conservation and Attractions, WA*

National products such as Australian Flammability Monitoring System (AFMS), based on continental models and remote sensing data are increasing in availability and utility. Their coverage, resolution and relevance is impressive, however all opportunities to validate such approaches using locally relevant data is critical to understand limits to their interpretation, promote local uptake, and identify scenarios where their confidence may vary. Likewise, validation of these products can assist to identify areas where further work may be required. In this case, the validation of AFMS against Live Fuel Moisture Content (LFMC) has shed light on spatial and temporal patterns of LFMC in near-coastal shrublands on the Swan Coastal Plain, as well as variation within members of the community.

INTRODUCTION

Live fuel moisture content (LFMC) is an important variable which influences the ignition, combustion, fuel availability, severity and spread of fire (Yebra et al. 2018). Sharples (2021) also suggested that critically low LFMC was a necessary condition for extreme bushfire development in the 2019/20 season in his submission to Senate Select Committee into Lessons to be Learned in Relation to the Australian Bushfire Season 2019-20.

However, there is still a limited understanding of the relationship between LFMC and fire behavior and of the seasonal variations in LFMC in woody vegetation. To increase this understanding the Western Australian (WA) Department of Fire and Emergency Services – Bushfire Technical Services and the Department of Biodiversity, Conservation and Attractions Parks and Wildlife Service) staff collected vegetation and soil samples to observe temporal variations in LFMC in the shrubland communities of the northern Perth region around Yanchep National Park, from September 2016 to July 2019. Field sampling provides the most accurate measurement of LFMC, it is however, time consuming and costly.

The Australian Flammability Monitoring System (AFMS) provides information on fuel condition and flammability across Australia at 500 m resolution using satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS). It also displays information on soil moisture content near the surface (0-10 cm) and in shallow soils (10-35 cm) as research outcomes from the project "Improving land dryness measures and forecast" led by Bureau of Meteorology. Spatial tools such the AFMS are important, especially for agencies such as the Department of Fire and Emergency Services (DFES) and Department of Biodiversity, Conservation and Attractions (DBCA) due to the large size of the state of WA. Furthermore, there is also consensus between end-users that a higher spatial resolution version of the AFMS is required to enable the identification of local LFMC gradients in the landscape that are currently not identifiable using the 500 m pixel resolution of the MODIS product currently underpinning AFMS. We recently developed a higher resolution (20m) LFMC product using Sentinel-2 satellite images which is under implementation at Geoscience Australia Digital Earth Australia (DEA).

The research presented in this report provides validation of the Sentinel-2 LFMC product for the coastal shrublands of the Perth region. It set the basis for emergency services and land managers to better understand the uncertainties in the satellite and on ground measurements, and more broadly, the seasonal LFMC fluctuations in the woody vegetation at the landscape scale. Findings from this report will better assist DFES and DBCA to conduct prescribed burn activities in a sustainable manner and better understand the bushfire hazard and risk.

RESEARCH APPROACH AND FINDINGS

METHODS

FMC field data

A field campaign was carried out by DFES and DBCA in the proximity of Yanchep National Park (WA) to collect samples of different tree and shrub species for field LFMC estimation (LFMC Observed). Three plots were sampled between September 2016 and July 2019 (Figure 1).

The sampling protocol followed standard methods and was repeated approximately every 16 days to align with Landsat 8 revisit. Fine weather days were selected for sample data collection to avoid abnormal LFMC records due to precipitation events and cloud coverage in the satellite images.

More specifically, for each sampling site, four samples (60 to 100g) of live fuel were collected for each of three dominant species. Samples were weighed in the field to obtain fresh weight, transported to the laboratory, and dried in an oven until they reach a constant weight. LFMC was then retrieved using Eq.1.

$$LFMC\ (\%) = ((wet\ weight - dry\ weight)/dry\ weight)) \times 100 \qquad Eq.\ 1$$

The average of the four samples for each vegetation type was calculated for each observation day.

DFES provided an analysis of the average LFMC for all the plant material species collected at each site and date for the period of 2016 and 2019 but for different plant material species for the period of December 2018 and December 2019. The plant material typesspecies were 'Banksia Upper' or – BU (young growth), and 'Banksia Lower' - BL (older growth), 'Calothamnus' - C and 'Hibbertia' - H, representing foliage from collected from *Banksia sessilis* (Proteaceae) shrubs (high and low in their canopy), *Calothamnus quadrifidus* (Myrtaceae) and *Hibbertia hypericoides* (Dilleniaceae) respectively. These species are tall shrubs, medium shrubs and sub-shrubs and the most abundant members of these respective strata in the community. The vegetation is a tall shrubland (2-3m) over shallow limestone, a community type that occurs in small areas dispersed among the taller and more widespread Bankisa woodlands that dominate this area on deeper sands. The community includes areas of bare ground and small outcropping limestone. For the samples taken December 2018 and December 2019, a simple average of all the plant species sampled was first computed to obtain a single value of LFMC per site and date to compare to satellite estimates. This approach assumes that all plant species have equal contribution to the spectral signature that the satellite measures. However, this might not be true (e.g., in a closed forest the satellite will mainly receive a signal from the tree canopies that obscure the understory layers). Consequently, the percent cover of the different vegetation types in 25m radius of each plot was recorded on the 21st of May 2021 (Table 1) $\overline{LFMC}$ (*) of the LFMC of the different vegetation species on each site. Banksias upper and Banksias lower LFMC samples was averaged and weighted average was computed by Banksias spp. percent cover.

$$\overline{LFMC}^{*}(\%) = \frac{\sum_{i=1}^{n}(LFMC_{i} * LC_{i})}{\sum_{i=1}^{n}(LC_{i})} \quad \text{(Eq. 2)}$$

Where, $\overline{LFMC}^{*}$ is the weighted LFMC average, $LFMC_i$ is the LFMC values of the vegetation layer i and LC_i is the land cover percentage value for vegetation layer i or the weight (e.g., how much that LFMC measure counts for)

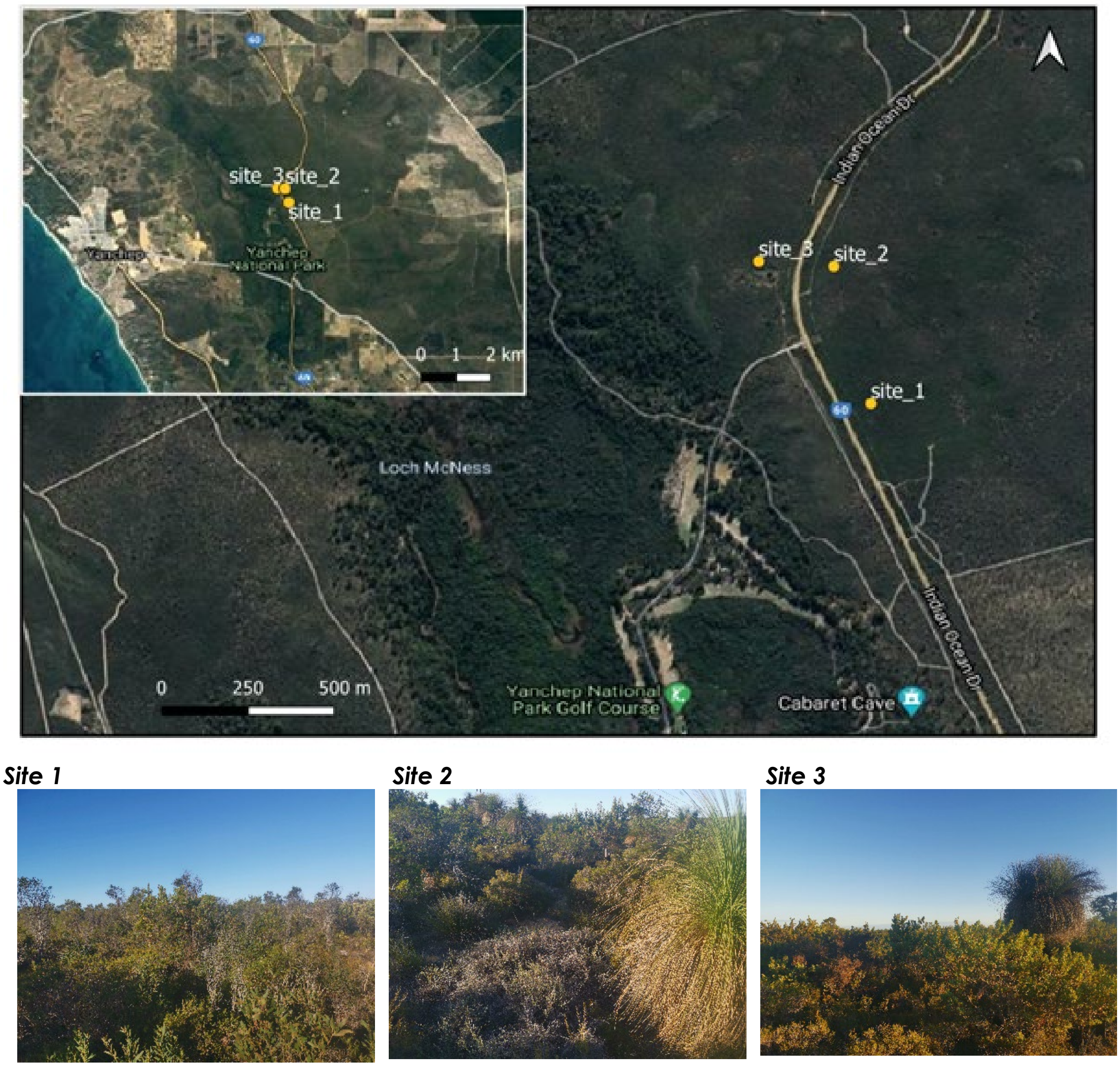


Figure 1. Map of study area (top) and pictures of the three field sites.

Table 1. Land cover types and percentages on study sites

Sites	Veg cover	Litter cover	Bare cover	Rock cover	Calothamnus	Hibbertia	Banksia
Site 1	80	5	13	2	25	3	15
Site 2	75	10	15	0	15	10	10
Site 3	84	5	10	1	5	20	25

All field sites have a vegetation cover > 75% with the remaining cover including litter, bare soil and rock cover (Table 1). However, the plant species sampled as representative of each site (Calothamnus quadrifidus, Hibbertia hypericoides and Banksia sessilis) only cover 43%, 35% and 50% of the 80%, 75% and 84% vegetation cover of site 1, site 2 and site 3, respectively. This may affect the accuracy of the Sentinel 2 estimates given the field measurements may not be fully representative of what the satellite sense.

Sentinel-2 LFMC

We used reflectance values from Sentinel 2 satellite imagery to calculate LFMC values (LFMC estimated) for the study sites using methods developed by Yebra et al. (2018).

Sentinel 2A and Sentinel 2B satellites were launched in June 2015 and March 2017, respectively, by the Copernicus program of European Space Agency (Revel et al. 2019). Sentinel 2 mission provides global coverage of images with 290 km field of view, 5 days revisit times (both satellites), 13 spectral bands in visible, near-infrared, and short-waive segments of the electromagnetic spectrum and 10, 20 and 60 m spatial resolution at different spectral bands (Gascon et al. 2017; Revel et al. 2019). Data were obtained from Digital Earth Australia (DEA) hosted at National Computing Infrastructure in Canberra, Australia (www.nci.org.au). DEA offers analysis ready data corrected for position, terrain, radiometry, atmosphere, and sun-sensor geometry (Dhu et al. 2017).

The methodology of the algorithm to estimate LFMC comprised of a physically based retrieval model to estimate LFMC from MODIS (Moderate Resolution Imaging Spectrometer) reflectance data using radiative transfer model inversion techniques. Accuracy of the original MODIS-based algorithm was evaluated with 360 field observations at 32 locations across Australia. Average accuracy of all land cover classes (grassland, shrubland, and forest) was RMSE=40% with explained variance of r^2=0.58 (Yebra et al. 2018).

The algorithm was proved to be sensor agnostic (Yebra et al. 2018) and therefore was adapted to calculate LFMC from Sentinel data (https://github.com/ANU-WALD/sentinel2_fmc).

Spatiotemporal collocation of Observed and Estimated LFMC is one of the more challenging aspects of a validation exercise (Loew et al. 2017). The objective is to select the closest matches both in time and in space.

Temporal collocation was achieved by matching each LFMC observation to the closest satellite LFMC estimate with a maximum distance of ±10 days. No auxiliary information was used to guarantee that the observations from the field and the satellite were measured under similar circumstances. For example, it could happen that the closest in time matching satellite LFMC estimation to a specific field LFMC observation was 9 days apart and have some precipitation or excessively hot dry weather in between that may affect the moisture conditions of the field observation.

Spatial collocation was achieved by computing the median LFMC on a 5 X 5m 25 m pixel kernel located at the center of each field site to reduce the potential noise due to georeferencing errors due to the satellite sounder having a sampling pattern that does not result in an exact overpass at the ground station.

Once the estimates and observations were matched, we evaluated the Sentinel-2 performance using the coefficient of correlation and the Root Mean Square Error (RMSE).

RESULTS

Relationship between observed (average of all vegetation layers) and estimated LFMC

91 LFMC observations out of 112 (3 sites x 38 field visit with site 1 missing 2 days of data) were matched to Sentinel-2 LFMC estimates to evaluate the Sentinel-2 performance. 21 field observations were lost mainly because of a lack of cloud free Sentinel-2 imagery within ±10 days given the field campaigns were originally scheduled for Landsat 8.

Seasonal patterns of LFMC variability were clearly identified by the satellite estimates (Fig. 2). Winter months had higher LFMC values (min = 82.1%, max = 167.9%, mean = 118.5%) and summer months lower LFMC values (min = 55.6%, max = 149.5%, mean= 92.4%). The lowest LFMC values were depicted in the 2019-2020 fire season (specially on site 2) when a devastating black summer bushfire hit Yanchep. It should be noted that these study sites were not affected by the Yanchep bushfire that occurred in that season, so the LFMC values displayed here are not affected by the bushfire.

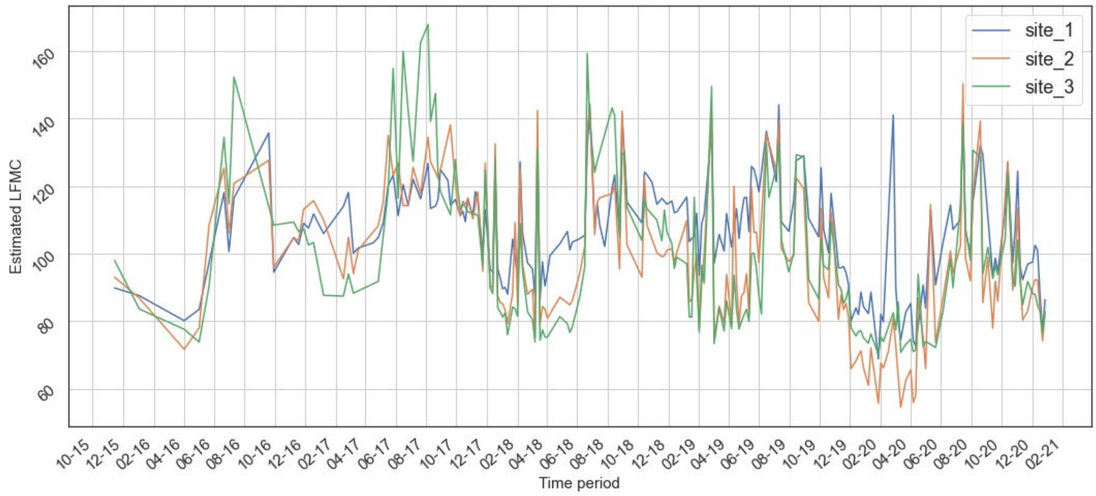


Figure 2. Time - series of LFMC values calculated from Sentinel 2 imagery on the 3 study sites.

When comparing these dynamics with the ground measurements we can see that although estimated and observed LFMC follow similar patterns, estimated LFMC is biased towards underestimating LFMC.

Figure 3. Line plot of average observed and estimate LFMC over time for different study sites. Note that there are data gaps in the LFMC observations as field data was not collected between 2018-04-27 and 2018-12-18 and in the satellite estimates mainly because of cloud coverage.

Overall, the variability of observed LFMC values for site 1 and site 2 were similar (between 90% - 180%, median ≈ 120%), however, a larger range was observed in site 3 (between 37% - 171%, median ≈ 120%) (Figure 4). The range of estimated LFMC values were comparable (between 80% - 130%) across the three different sites, although site one presented a smaller range of variation than site 2 and 3. Box plots also show that estimated LFMC are lower than observed LFMC.

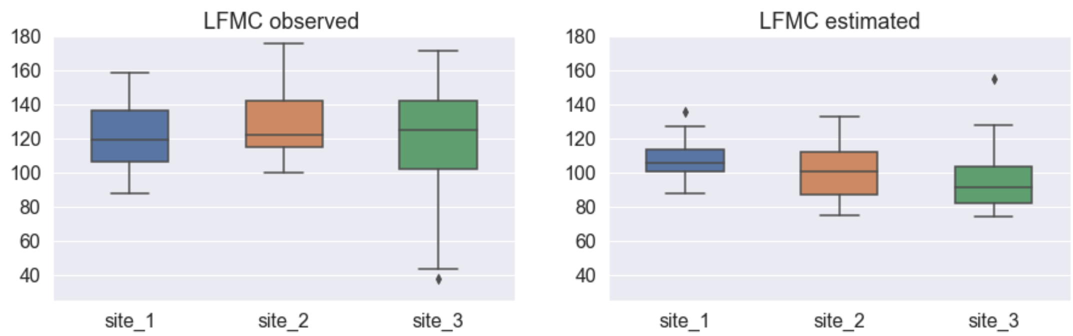


Figure 4. Distribution of average observed and estimated LFMC values for different study sites

There is a significant relationship ($P < 0.05$) between the observed and estimated LFMC for all three sites with RMSE ranging between 22% and 37% (Figure 5). This relationship is stronger for site 2 and site 3 ($R^2 = 0.22$, and $R^2 = 0.17$, respectively) compared to site 1 ($R^2 = 0.11$), which shows that the seasonal changes in LFMC are better tracked in site 2 and 3 than in 1. However in absolute terms LFMC is better estimated in site 1 (RMSE=22.41%), followed by site 2 (RMSE =32.71%) and 3 (RMSE=37.27%).

When pooling all sites together we also observe a significant relationship between observed and estimated LFMC ($P < 0.001$, $R^2 = 0.15$) and a RMSE=31.43% which is comparable with the errors reported in the literature (Yebra et al 2013).

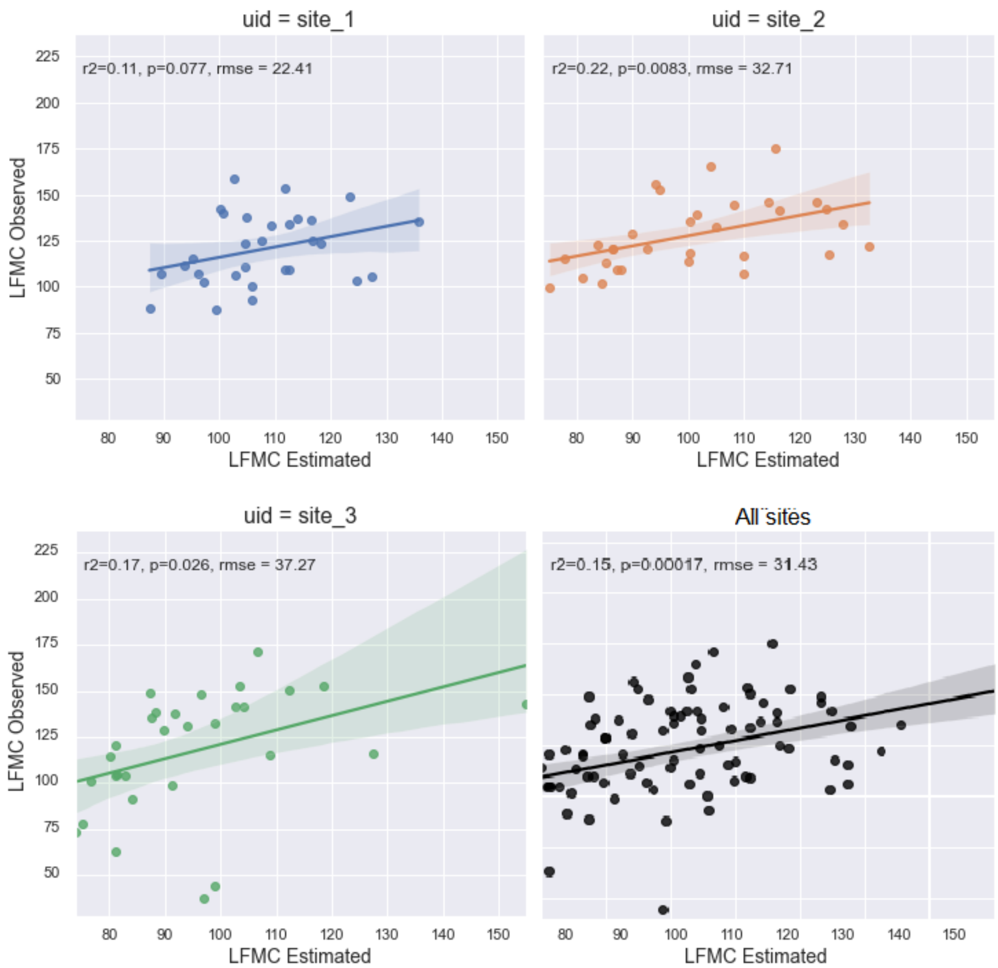
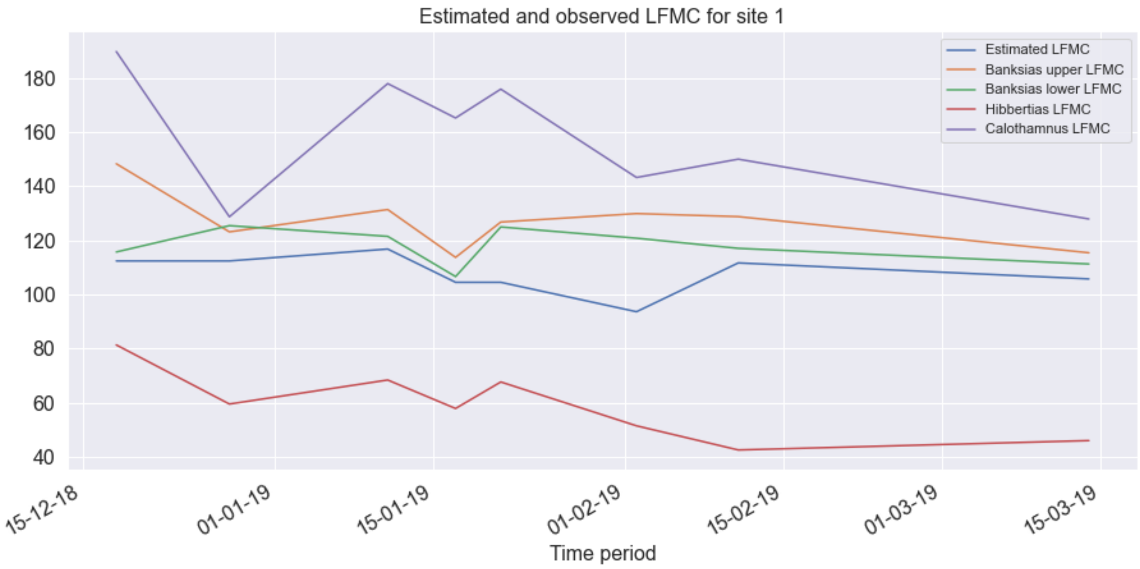


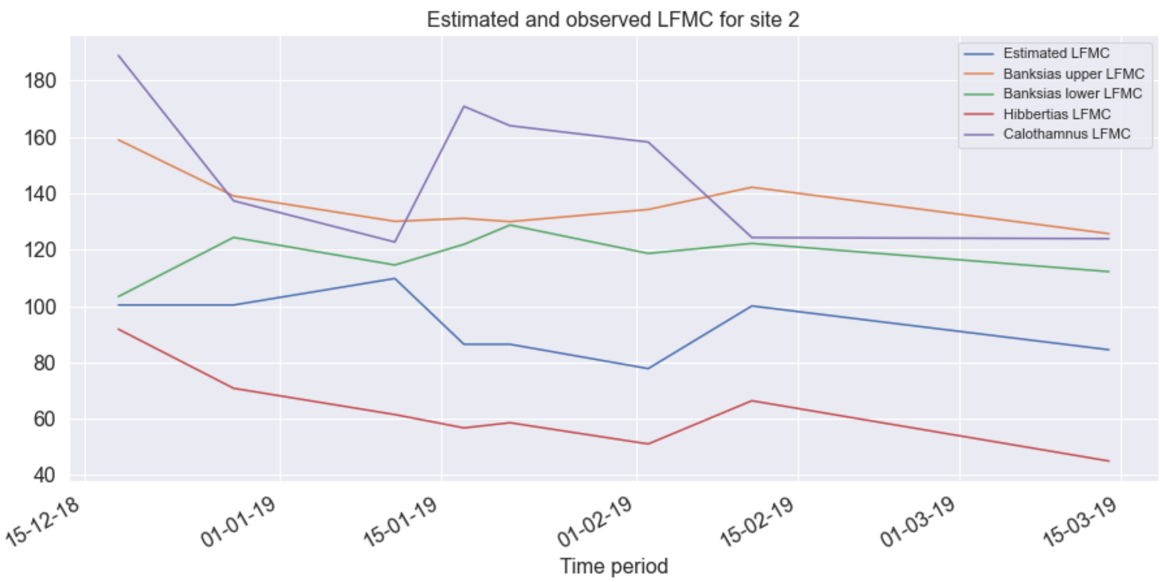
Figure 5. Linear relationship between observed (average value for each sampled vegetation layer) LFMC and estimated LFMC for different sites and across all sites.

Relationship between the observed and estimated LFMC for difference plant species

108 observations out of 120 (10 days, 4 vegetation types, 3 sites) were matched to Sentinel 2 estimated LFMC. 12 LFMC observations (1day x 4 vegetations types x 3 sites) were lost due to lack of a cloud free satellite imagery on the 2019-01-04.

Except for Hibbertias, observed LFMC were underestimated by the Sentinel-2 LFMC product (Figure 6). Observed and estimated LFMC for Sites 1 and 2 follow similar seasonal pattern for most vegetation layers. However, big variation in observed LFMC for Banksia upper, Banksia lower and Calothamnus occurred between January and February 2019 in site 3 which was not detected by the sentinel-2 product not observed in 1 and site 2.


Estimated and observed LFMC for site 1
Estimated LFMC
Banksias upper LFMC
Banksias lower LFMC
Hibbertias LFMC
Calothamnus LFMC
180
160
140
120
100
80
60
40
15-12-18
01-01-19
15-01-19
01-02-19
15-02-19
01-03-19
15-03-19
Time period


Estimated and observed LFMC for site 2
Estimated LFMC
Banksias upper LFMC
Banksias lower LFMC
Hibbertias LFMC
Calothamnus LFMC
180
160
140
120
100
80
60
40
15-12-18
01-01-19
15-01-19
01-02-19
15-02-19
01-03-19
15-03-19
Time period

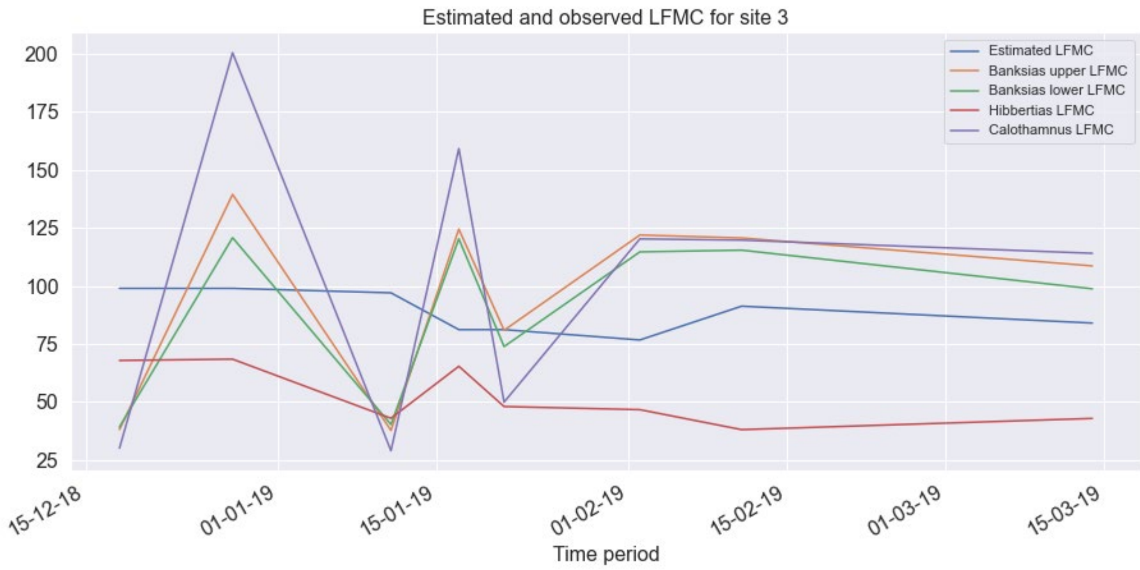


Figure 6. Observed and estimated LFMC change by different vegetation types and sites.

Observed Banksias lower and Banksias upper layers have similar LFMC values (median ≈ 125%) and the closest to estimated LFMC (median ≈ 100%). Banksias upper (newer) have slightly higher values tha lower (older) what fits expectations. Hibbertias presented lower LFMC (median ≈ 60%) while Calothamnus higher LFMC (median ≈ 140%) (Figure 7). All vegetation layers have outliers in their observed LFMC that are not captured by the Estimated LFMC (Fig 8).

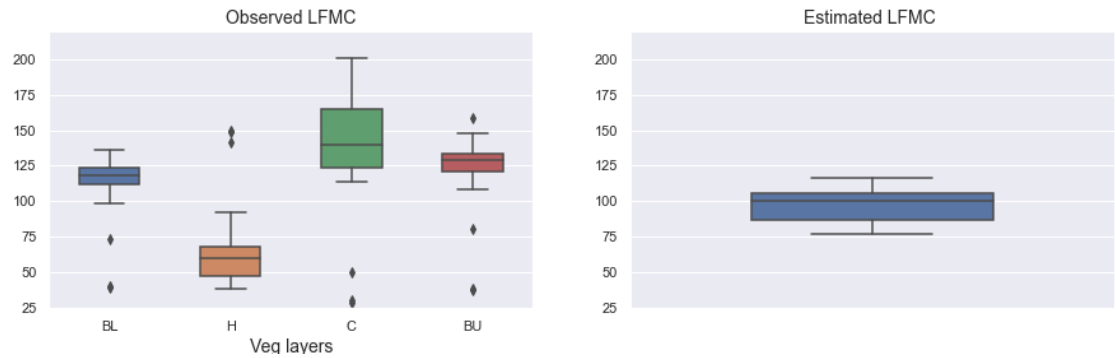


Figure 7. Distribution of LFMC values across different vegetation types and estimated LFMC (BL - Banksias Lower, BU - Banksias Upper, H - Hibbertias, C - Calothamnus).

There is a significant relationship between Hibbertias LFMC and estimated LFMC (Figure 8). All other vegetation nor the simple average of all vegetation layers (Figure 9) show a significant correlation.

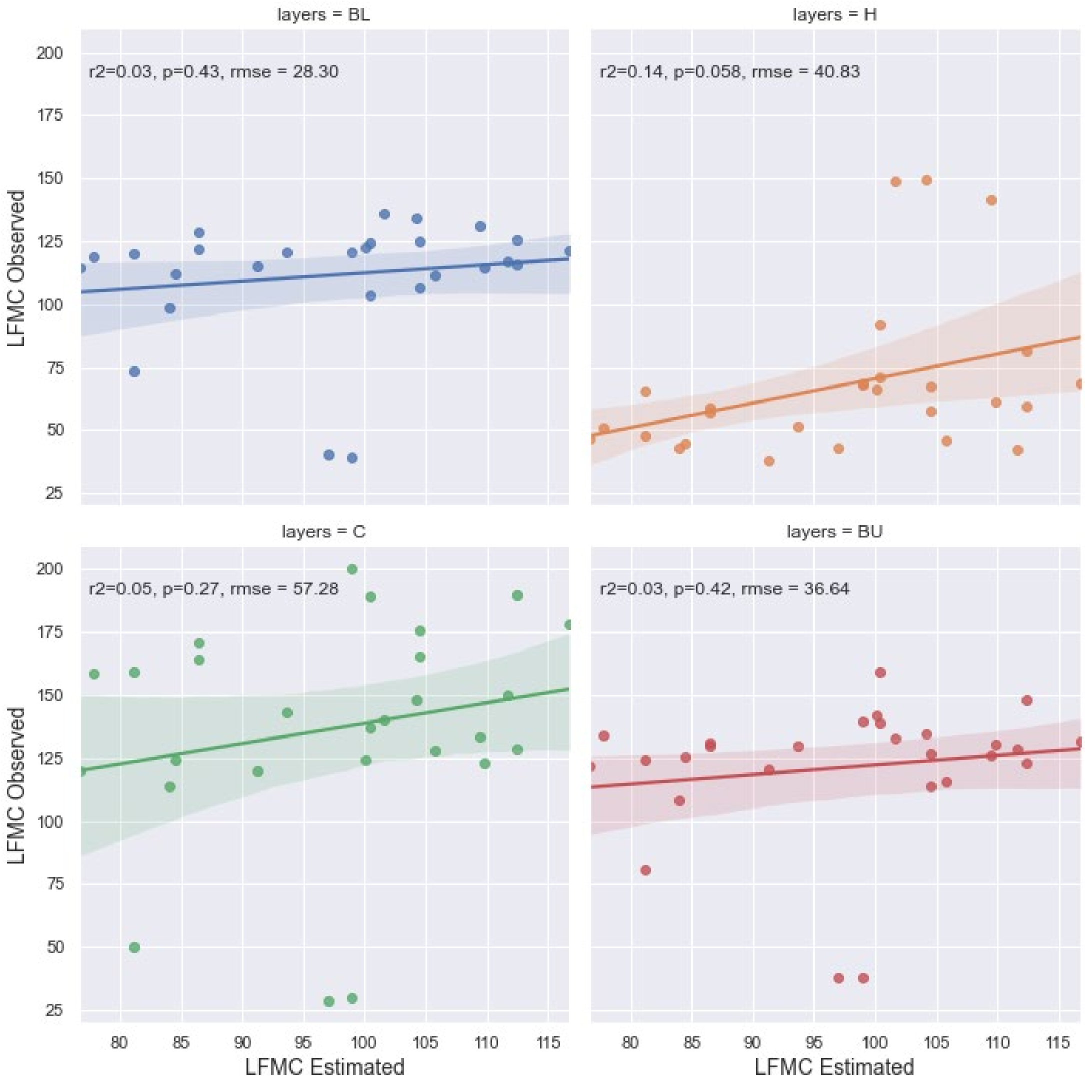


Figure 8. Relationship between observed and estimated LFMC by different vegetation layers (BL - Banksias Lower, BU - Banksias Upper, H - Hibbertias, C - Calothamnus).

However, we found a significant relationship between the $\overline{LFMC}^*$ (LFMC average weighted by the vegetation cover of each type) and estimated LFMC (R^2=0.25, $p<0.01$) (Figure 9). From the scatter plots we can see that observed LFMC has two outliers (Observed LFMC ≈ 31.46%). These outliers were removed using the interquartile score outlier method (Rousseeuw and Hubert 2011) resulting in a significant improvement in the Sentinel 2 model LFMC estimates (from r^2 = 0.25, RMSE=31.46% with outliers to r^2 = 0.45, RMSE=28.98% without outliers)

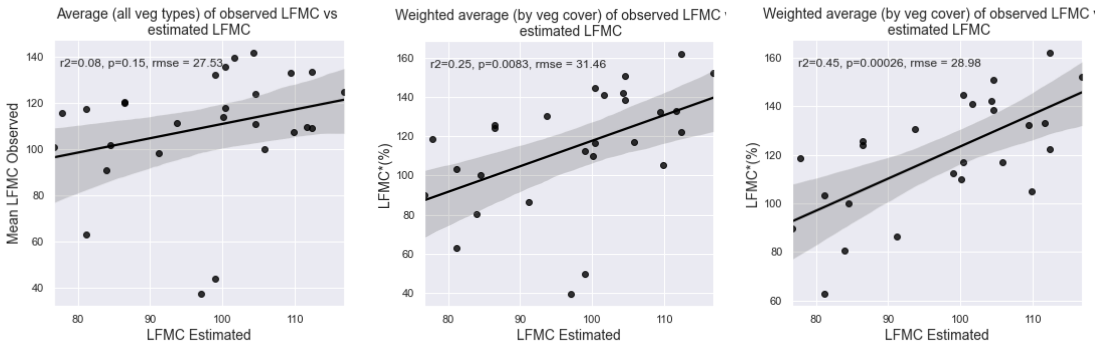


Figure 9. Relationship between the simple (left) weighted (central) and weighted without outliers (right) LFMC average of observed LFMC for different vegetation layers and estimated LFMC.

UTILISATION AND IMPACT

Given the tight timeframes of the project, there has not been time for uptake of the project work. However, the work demonstrated the good performance of the LFMC Sentinel-2 algorithm given the limitations of the field data used as ground truth.

The work also has given some indications on how field data collection can be improved including the consideration of species composition and variation in fractional cover of the dominant vegetation strata in the coastal shrublands. This will inform better data collection in the future.

Future adoption of the Sentinel-2 LFMC product is important as the level of moisture stress in woody vegetation, particularly shrublands has a significant effect on the level of bushfire hazard they possess and their difficulty of suppression.

The enhancement in spatial resolution that the Sentinel-2 products brings will allows the identification of local LFMC gradients in the landscape that are currently not identifiable using the 500 m pixel resolution of the MODIS product currently underpinning AFMS. This delivers the opportunity to apply the intelligence directly to bushfire suppression operations and prescribed burning operations. Emergency services personnel can use the high resolution spatially- explicit data to better inform fire behavior models and to better plan and execute prescribed burning operations. The system opens the possibility of conducting burns outside the normal burning windows but at a time when the LFMC is at ideal level

CONCLUSION

In this research, we used field measured LFMC to validate Sentinel 2 based LFMC estimates. Field measured LFMC was represented using a simple average of the LFMC of different plant species co-occurring in each field site, a weighted (by vegetation cover) average and the LFMC of individual layers.

Our statistical analysis found a significant relationship between estimated LFMC and the LFMC of Hibbertias species (although the RMSE high 40.8%) but did not find a significant relationship with the LFMC of Banksias (upper and lower) or Calothamnus LFMC. The strongest correlation was found with $\overline{LFMC}^{*}$ (using the by percent cover of each vegetation layer as weight) and then the simple average of sampled vegetation types. This indicates that Sentinel 2 tracks and integrated LFMC of dominant vegetation species rather than LFMC of individual species. We would like to note that the species that were collected on the field were not necessary the most representative of the plots and the field sites had other species that were not sampled but still occupied >50% of the vegetation cover of the site. Therefore, the influence that those species have in the moisture conditions of the sites captured by the satellite were not accounted for. Additionally, litter, rock and bare sand will also influence the Sentinel-2 signal given the vegetation cover in any of the three sites was 100%.

Field data was collected since August 2016 but given Sentinel 2B was launched in March 2017, a substantial proportion of field data only overlaps with Sentinel 2A imagery, thus reducing the number of images available to be matched to field observations. To prevent the loss of lot of field observations, we used ±10 days delta for matching estimated and observed LFMC. Depending on the vegetation species, vegetation response to temperature and rainfall can vary significantly within those 10 days making the field observations and the satellite estimates non comparable. A smaller time difference between satellite imagery acquisition and field data collection may result in stronger relationships and lower RMSE. The European Space Agency provides Sentinel 2 data acquisition dates in advance. This information can be used to plan field data collection to match with Sentinel 2 overpass on sampling sites. Considering that there is Sentinel 2A and 2B data available now, better time match can be achieved between observed and estimated LFMC which may improve the quality of the field data to be used to evaluate the performance of the Sentinel LFMC model.

We also demonstrated that the r^2 and RMSE between weighted averages of observed LFMC and estimated LFMC significantly increased and decreased, respectively, after removing 2 outliers in the observations. A few outliers can have such a significant impact on the results of regression analysis when there is a small number of observations (in this case, n=26). Impact of erroneous observations on statistical analysis can be avoided by collecting more samples and we encourage the DFES and DBCAto continue the splendid work they are doing on collecting this valuable field database.

TEAM MEMBERS

RESEARCH TEAM

Marta Yebra

Associate Professor at the ANU Fenner School of Environment & Society and the School of Engineering and Project Leader. Marta's research combines field measurements with on-ground sensor networks, airborne and satellite observations and high-performance computing technology and modelling to monitor, quantify and forecast vegetation and landscape processes, with applications in natural resources management, natural hazards, and ecosystem function at local, regional and global scale.

Shukhrat Shokirov

Postdoctoral research fellow at the ANU Fenner School of Environment & Society. Shukhrat uses active and passive remote sensing to estimate vegetation structure and composition for ecosystem habitat quality assessments and bushfire mapping and management. His current research involves evaluating Sentinel 2 based life fuel moisture content maps with field data.

END-USERS

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
DFES	Jackson Parker Agnes Kristina	Project scoping, discussion results
DBCA	Ben Miller	Project scoping, discussion results

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