Relating Biomass and Land Surface Reflectance to Primary Terrain Attributes in a Small Catchment.

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Abstract Ground based biomass and satellite measures of land cover data were correlated with five primary terrain attributes yielding a range of responses with r^2 values up to 0.78. The primary terrain attributes were obtained using a grid-based Digital Elevation Model (DEM) and Terrain Analysis Program for Environmental Sciences -Grid version (TAPES-G). Drainage direction was calculated using the Rho8 algorithm and catchment area was computed using a multiple drainage direction technique with a slope weighting algorithm. The five primary terrain attributes selected were drainage area, slope, aspect, tangential curvature and flow path length. The land cover data were ground measured biomass, and Landsat Thematic Mapper (TMSAT) derived Red and Near Infrared (NIR) reflectance data. NDVI values were included in the landcover data and were calculated by the ratio of NIR to Red reflectance values. A cubic correlation between biomass and aspect produced a $r^2 = 0.74$ and a quadratic correlation of TMSAT red waveband to tangential curvature gave a $r^2 = 0.78$. The study concludes, that in this low relief catchment there is a strong association between primary terrain attributes and both observed biomass and reflectance data. The terrain attributes depended on the DEM providing an accurate representation of surface shape.

1. INTRODUCTION

Hydrologists, geomorphologists, agricultural scientists and native land cover management groups have an interest in spatial vegetation data. Water quality is inextricably linked to land surface characteristics, land use and its surface cover (Prowse 1995). Primary terrain attributes can link biomass to the surface hydrology. Terrain data can be accurately determined by a Digital Elevation Model (DEM) created from streamline, point and contour data.

Since terrain attribute data provides information about surface hydrology, such data may enable the prediction of spatial biomass, and the disaggregation of biomass data from lumped hydrologic models. The correlation between the biomass and terrain attributes can also facilitate the management of native vegetation or agricultural catchments by providing more spatial data about biomass especially in cleared low relief catchments which are common in Australia.

1.2 Spatial Modelling

Spatial models are becoming more common as research tools in many scientific applications where data collected from different locations needs to be modelled or interpolated to regions where data can not be directly sampled (Cressie 1991).

Spatial modelling in hydrology has increased since the mid-late eighties when remotely sensed data sets became more accessible (Moore *et al.*, 1991). Many hydrological models are now based on topography-based data. Topographic data allow the determination of drainage areas, area specific slopes (length and shape) and channel networks.

Vegetation has a role in process based hydrological modelling. For example, Chehbouni *et al.* (1994) considers vegetation-related information as critical for modelling hydrological processes. They also argued that remotely sensed spectral data provide a powerful means to characterise the vegetation status.

Landscape geometry can be determined from a DEM (Moore *et a*l. 1992) and once calibrated and geo-referenced to the surface, relationships between the topography and biomass can be determined. From correlations between terrain attributes and biomass, spatial coverage of biomass may be obtained or modelled outputs of averaged biomass data may be disaggregated.

Many plant growth models exist and most produce lumped or point values for biomass. Two models which can produce catchment-averaged biomass outputs are GROWEST (Nix, 1981) and SWRRB (Williams *et al.* 1985). GROWEST is derived from climate determinants for plant growth and development. The SWRRB hydrological model has a biomass component based on radiation and leaf area index (LAI).

1.2 Digital Terrain Models

DEMs can provide accurate representation of the surface shape and drainage structure if produced by a technique which overcomes inherent biases in source topographic data (Hutchinson 1997). Models such as the terrain analysis program for environmental sciences -grid version TAPES-G uses DEMs to obtain primary terrain attributes. The utility of terrain attributes depends critically on the accuracy of the landscape representation by the DEM. This is where Hutchinson (1988, 1989) has played an important role in delivering a suitably accurate DEM. DEMs can be calculated from digitised point, contour, stream data. This method includes a drainage enforcement algorithm which automatically calculates stream and ridge lines from contour data (Hutchinson 1988). This alleviates the problems associated with contour data representing drainage in low relief catchments. Once an accurate DEM is established TAPES-G can show the spatial variability of the dominant hydrological processes (Gallant and Wilson 1996) and allow more physically-based secondary attributes to be identified.

Terrain attributes determined by a DEM can be divided into two types viz. primary and secondary or compound attributes. Primary terrain attributes consist of a topographic factors such as drainage area, slope, aspect, tangential curvature and flow path length. In this study they have been correlated individually with biomass and reflectance data. Primary attributes have been applied to this catchment to understand the influence of these minor topographic features have on biomass. Slope and aspect in even seemingly flat landscapes, which are common in Australia, may influence the rate of biomass or plant growth. Minor changes in the surface geometry may affect the interaction between surface hydrology and biomass. Tangential curvature is useful for determining flow convergence and divergence and can therefore indicate where water is available for uptake by vegetation.

Secondary or compound terrain attributes combine the primary terrain attributes and may be used to represent some hydrologic processes more directly. Topographic wetness index is a secondary terrain attribute defined by ln(a/tanB) where a is the upslope area draining past a certain point per unit of slope, and B is the local surface slope angle. Zheng *et al.* 1996 compared the available soil water capacity estimated from topography using ln(a/tanB) to the available water capacity calculated from soil series information and found a strong linear relationship.

1.3 Remotely sensed data

The type and resolution of a remote sensor determines its use and sensitivity to the surface parameters being measured. Spatial resolution is determined by the optical aperture of the sensor and the sampling rate. Remote sensors integrate the response of the landscape elements within an area.

Use of remotely sensed data also requires an understanding of the view angle over the surface and its interactions with solar zenith angles (Jackson *et al.* 1990). Off-nadir position and view angle can affect the bidirectional reflectance factors. Canopy spectra and seasonality due to wet and dry seasons may also influence the reflectance values (Qi *et al.* 1994).

Calibrations of biomass to remotely sensed data can allow direct correlations between remotely sensed reflectance data and terrain attributes data. Remotely sensed NDVI data are important as they minimise the effects of season, sun angle and soil background on reflectance when measuring vegetation (Smith 1997). Previous studies in this experimental catchment by Cusack *et al.* (1997ab) concluded that correlation of biomass to LAI gave $r^2 = 0.78$ Biomass to TMSAT NDVI also produced an exponential regression with $r^2 = 0.62$. Given such correlations between remotely sensed data and biomass, improvements of these correlations should be pursued by including terrain attribute data.

TAPES-G is a useful tool to represent topography-driven surface hydrology. However, the satellite data is a single 'snapshot' of the surface reflectance of biomass and the antecedent soil moisture are not known. Caution needs to be taken as temporal variation in both the climate and biomass has not been taken into account.

Recent research by Running and Thorton (1996) uses estimates of the relationship between meteorological variables and elevation for each grid cell to generate interpolated temperature and precipitation based on daily observations. They are also exploring the potential for incorporating remotely sensed thermal infrared data as a way to restrain the regressions of observed meteorological variables against elevation.

This paper examines the correlation between biomass, reflectance data and primary terrain attributes. The study also identifies the type of correlations, and their implications in a small catchment. The need for secondary terrain analysis is also demonstrated.

2. CLIMATIC CONDITIONS OF SITE

The site is a 27 km^2 in the Southern Tablelands in New South Wales, Australia. The meteorological data from 1 to 22 February (satellite overpass) and 1 to 21 March (biomass samples collected) 1993 were examined to determine the type and significance of their correlations. Table 1 shows a weather data summary for the days of the biomass sampling (21 March 1993) and the satellite overpass (22 February 1993). The difference in the satellite overpass and biomass collection dates occurred because 22 February 1993 was the closest day with clear sky conditions to the biomass sampling date: cloud free conditions are important for accurate determination of reflectance data.

The climate data was collected from ground-based meteorological stations and the biomass data was collected using electric clippers and a 0.25m^2 quadrat. All biomass samples were dried and weighed and notes on the vegetation height, composition of weeds and general site conditions were recorded.

Table 1. Climate data for acquisition of biomass data and the satellite data overpass.

Climatic Variable	22 Feb 1993	21 March 1993
Mean air temp. ° C	10.9	13.4
Max surface temp. ° C	NA	23.0
Min surface temp. ° C	NA	6.8
Vapour pressure mb	6.72	11.98
Solar radiation MJ/m^2	24.01	17.65
Mean wind speed kph	21.38	9.17
Rainfall mm	0.6	0.4
Runoff mm	0.01	0.01

3. SOILS AND GEOLOGY

The typical soil profile in this region consists of sandy/silty A horizon and a B horizon of heavy clay which is usually clay and mottled. Northcote *et al* (1975) defined these soils as "mottled-yellow duplex soils". An intensive study by Guerra (1995) described the soils as derived from

Lockyersleigh Adamellite, an acidic granite intrusive that outcrops in the northern end of the catchment and near the centre lower third of the catchment). According to Guerra (1995) other parts of the catchment are derived from Ordovician-Silurian and Devonian sediments. The north eastern parts of the catchment are characterised by stony loam texture with rocky outcrops .

4. MODELLING ATTRIBUTES AND RESULTS

The DEM was calculated using the Australian National University interpolation program (ANUDEM) (Hutchinson 1989) from digitised point, contour and stream data derived from a 1:25,000 map sheet. UTM position co-ordinates were stipulated, and a 30 m DEM resolution was generated by the ANUDEM program (Hutchinson 1996).

The terrain analysis program for environmental sciences - grid version (TAPES-G) used in this study was originally developed by Professor Ian Moore. It calculates fourteen primary terrain attributes from a DEM. These 14 attributes were then correlated to biomass, TMSAT NDVI, red and NIR wavebands. Five terrain attributes were selected from their correlations to biomass and reflectance data. They were drainage area, slope, aspect, tangent curvature and flow path length. The calculation of these attributes is described in detail by Moore *et al.* (1992).

Drainage area is the upslope contributing area or the area draining out of each cell. The maximum slope as a ratio can be calculated from finite differences and the D8 approach calculates the gradient as the steepest slope to one of the eight nearest neighbours. Aspect was defined in the direction of the steepest downwards slope and measured in degrees clockwise from north. Tangential curvature is the curvature of the line formed by intersection of surface with plane normal to flow line. Flow path length is the longest flow path from the catchment divide or edge of the DEM to the cell.

The modelling specifications are shown in Table 2 and the statistically analysed results are shown in Table 3.

Table 2: Summary of TAPES-G inputs using outputs from the DEM

Grid cell size	30 m
DEM (depressionless	x, y and z values
Critical area	ln(a/tanB) (m^2)
Drainage directions	Rho8 algorithms
Catchment area	multiple drainage directions method using a slope weighting algorithm
Output slope	finite difference algorithm

Table 3 TMSAT and surface biomass correlated with five hydrologic terrain variables.

Variables below include constant	Drainage Area m^2 r^2 values	Slope (%) r^2 values	Aspect degrees $(^0)$ r^2 values
Biomass	L = 0.05 Q = 0.05 E = 0.06 C = 0.07	L = 0.28 Q = 0.29 E = 0.49 C = 0.33	L = 0.07 Q = 0.67 E = 0.02 C = 0.74
TMSAT Red	L = 0.01 Q = 0.02 E = 0.01 C = 0.05	L = 0.21 Q = 0.21 E = 0.21 C = 0.40	L = 0.04 Q = 0.52 E = 0.03 C = 0.54
TMSAT NDVI	L = 0.06 Q = 0.58 E = 0.07 C = 0.58	L = 0.17 Q = 0.30 E = 0.19 C = 0.38	L = 0.41 Q = 0.42 E = 0.41 C = 0.58
TMSAT NIR	L = 0.02 Q = 0.29 E = 0.02 C = 0.32	L = 0.02 Q = 0.07 E = 0.02 C = 0.63	L = 0.14 Q = 0.56 E = 0.14 C = 0.61

Variables below include a constant	Tangential Curvature 1/(100 m) r^2 values	Flow Path Length (m) r^2 values
Biomass	L = 0.00 Q = 0.23 E = 0.01 C = 0.24	L = 0.19 Q = 0.27 E = 0.11 C = 0.42
TMSAT Red	L = 0.69 Q = 0.78 E = 0.70 C = 0.69	L = 0.17 Q = 0.39 E = 0.15 C = 0.43
TMSAT NDV	L = 0.11 Q = 0.17 E = 0.09 C = 0.27	L = 0.11 Q = 0.63 E = 0.13 C = 0.65
TMSAT NIR	L = 0.01 Q = 0.34 E = 0.02 C = 0.34	L = 0.02 Q = 0.03 E = 0.02 C = 0.03

Table 3 shows r^2 values for Linear (L), Quadratic (R), Exponential (E) and (C) Cubic regressions. The dependent variables are biomass, TMSAT red, NDVI or NIR and the independent variables are the five terrain attributes.

The equations for Table 3 are:

Linear	$Y = b_0 + b_1 T$
Quadratic	$Y = b_0 + b_1 T + b_2 T^2$
Exponential	$Y = b_0 \exp(b_1 T)$
Cubic	$Y = b_0 + b_1 T + b_2 T^2 + b_3$

Where:

Y = dependent variables: biomass (kg/ha), TMSAT NDVI, red and NIR wavebands
b_0 , b_1 , b_2 , b_3 = regression coefficients
T = independent variables, terrain attributes

These equations were chosen to examine a range of responses that may exist between biomass and surface hydrology derived from the topography.

5. RESULTS

Figure 1a through to Figure 4 display selected relationships between the land surface and terrain attributes.

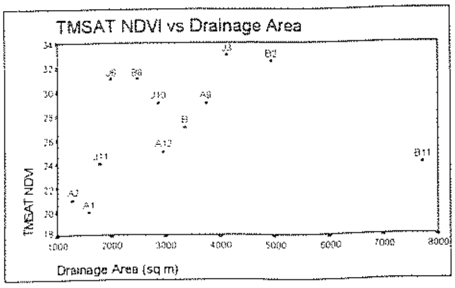

Figure 1a: NDVI vs Drainage area.

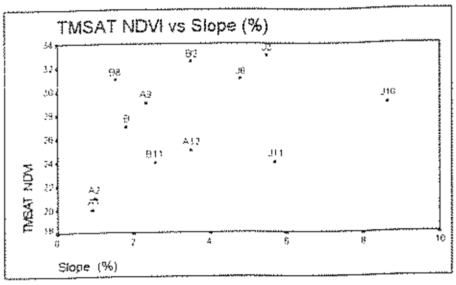

Figure 1b: NDVI vs Slope

Figure 1a shows increasing NDVI with increasing drainage area up to a drainage area between approximately 5000 and 7000 sq m. This quadratic correlation ($r^2 = 0.60$) suggests that NDVI eventually decreases with increasing drainage area at some critical point between these values. Site B11 with a large upslope contributing area influences the quadratic curve by showing a different trend or indicating some saturation point where increasing drainage area actually decreases NDVI. In reality, some annual species of grass and pasture may survive with zero drainage area and rely totally on intermittent rainfall to sustain photosynthesis and produce chlorophyll.

Figure 1b has a general trend of increasing NDVI for increasing slope values. An increasing slope allows higher intensity of solar radiation for the production of 'green' biomass. NDVI and biomass correlations with slope show different trends. Further analysis using composite attributes may explain some of these differences. Sites J10 and J11 in Fig 1b show less greenness than would be expected from their slope and this is possibly due to their proximity to the open woodlands which do not reflect the same intensity of greenness as the surrounding grassland. In addition, the woodland canopy may also be providing some topographic shading on these sites.

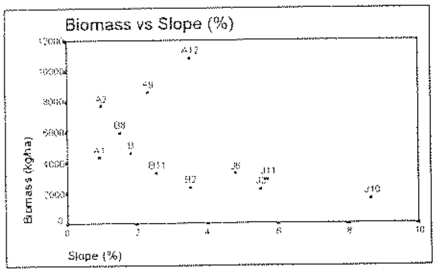

Figure 2: Biomass vs Slope

Figure 2 shows a complex relationship where most sites (except sites A12 and A9) show decreasing biomass with increasing slope. The interaction between aspect and slope could be influencing biomass even though the gradient within this catchment is slight. Sites A9 is on a western slope and A12 is close to north (Fig 3a and 3b).

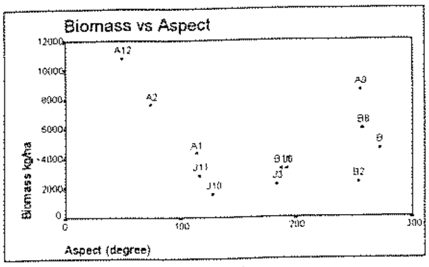

Figure 3a: Biomass vs Aspect.

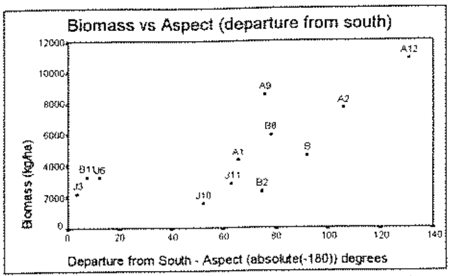

Figure 3b. Biomass vs Departure from South

Figures 3a and 3b describe two ways to examine the effect of aspect on biomass. Figure 3a shows a quadratic regression between proximity to north and biomass. The ground biomass data is highly variable but has an $r^2 = 0.74$ whereas the TMSAT reflectance data has a cubic fit but with less statistical significance $r^2 = 0.58$ (Table 3).

Figure 3b shows biomass as a function of aspect interpreted as 'departure from south'

Y = Biomass (kg/ha)
X = Aspect (absolute value -180 degrees)
as departure from south (degrees)

Figure 3b shows a linear fit between biomass and departure from south. Site A9 does not fit the curve as well due to its north west aspect (Fig 3a), and its divergent location as indicated by the flow path length. The combination of these factors produced a higher biomass at site A9.

B11 has a relatively high biomass due to its proximity to south, but as Figure 1a indicates its NDVI value is low and therefore it contains a high percent of brown biomass. This is confirmed by previous field work where B11 contained 43% 'brown' biomass (Cusack *et al.* 1997a).

Figure 3b produced a linear correlation with an $r^2 = 0.70$, whereas Fig 3a had a cubic fit with $r^2 = 0.74$. This difference confirms the asymptotic nature of the cubic fit where the western slopes (at approximately 250 degrees) had a positive effect on biomass production due to the diurnal cycle radiation load and associated positive sensible heat flux. The significance of showing both linear and cubic fits for aspect was to demonstrate the impact of western slopes on biomass values.

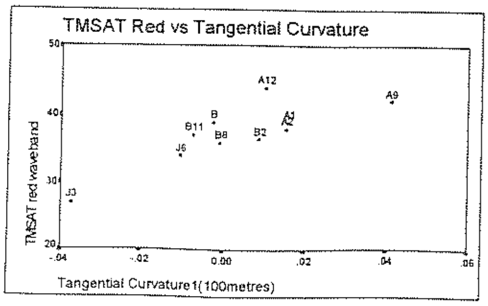

Figure 4: TMSAT red waveband vs tangential curvature.

Table 4: Statistical significance levels for Fig 4.

Linear $r^2 = 0.69$ Significant $F = 0.003$
Quadratic $r^2 = 0.78$ Significant $F = 0.005$
Exponential $r^2 = 0.70$ Significant $F = 0.002$
Cubic $r^2 = 0.78$ Significant $F = 0.020$

Tangential curvature is useful for studying flow convergences and divergences. Sites J3 is a convergent site whereas site A9 is divergent. This graph shows with an increase in tangential curvature and subsequent flow divergence, where the biomass appears as more "brown". TMSAT red wavebands reflect 'brown' biomass, and this correlation with tangential curvature suggests that with more divergent flow the biomass is becoming 'drier' and giving increased red reflectance indicating brown, dry biomass.

Sites J10 and J11 have been excluded from Figure 4 as the TMSAT red waveband reflects 'brown' biomass which is only relates to grassland and pasture as the woodland sites do not change colour (from green to brown) to the same degree.

6. DISCUSSION

Primary terrain attributes were correlated to biomass and remotely sensed reflectance data. The association between slopes and NDVI as well as between drainage area and NDVI showed that primary terrain attributes were correlated to NDVI for the climatic conditions of this study. NDVI also appeared to be correlated to flow path length, and in dry (non-rainfall periods) the flow path length could be critical to the NDVI value.

Figure 1b and Fig 2 show that an increase in slope produced an increase in NDVI and a decrease in biomass respectively. These opposite effects need to be examined more fully to understand what dominant processes/s are responsible for these results. Further examination using secondary terrain attributes (such as radiation and wetness index) could give greater insight into the dominant forces or environmental conditions responsible for the spatial variability in biomass.

In low relief catchments it is often assumed that terrain attributes such as aspect and slope do not have a significant effect on biomass. However, this study shows that even minor changes in the terrain can have an impact on landcover in grasses and pastures. This is confirmed by the fact that biomass was correlated to slope and aspect. Some correlations between biomass and aspect were as high as $r^2 = 0.74$ with significant $F = 0.002$.

The relation between biomass and slope may indicate a number of physical processes (Fig 2). The increased slope could reduce runoff and therefore biomass could decrease with slope due to lack of surface moisture. Sites A however, may indicate increasing slope producing increasing solar radiation and therefore increasing biomass assuming there is sufficient rainfall or soil moisture. In summary, biomass vs slope could show 3 different curves where, the A sites are radiation driven, B sites becoming water saturated and the J sites in the woodlands area represent a different biome.

Aspect has two specific uses; it identifies increases in solar intensity due to its proximity to north and in combination with slope it can give more complex accurate spatial disaggregation of solar radiation. Figure 3a shows high biomass values for northerly aspect.

As previously stated, minor undulations in the landscape are easy to ignore. However, even small depressions, inclines and geometric polygons in the terrain seem to effect the potential productivity of the vegetative cover in this small catchment. However, direct comparison between topography and remotely sensed data can only be represented provided the DEM has sufficiently fine resolution (Hutchinson 1996).

The correlation of TMSAT red waveband to tangential curvature ($r^2 = 0.78$), is an example of surface shape influencing the remotely sensed signal. Given tangential curvature combines plan curvature and slope, it is important to understand plan curvature. Plan curvature is obtained by using a horizontal plane and measuring the convergence and divergence thereby showing the concentration of water in the landscape (Gallant and Wilson 1996). Tangential curvature is particularly useful in low relief catchments where the slope parameter accounted for small changes to the surface shape and thereby gave higher correlations with reflectance data. Plan curvature produced $r^2 = 0.75$ (quadratic fit) with TMSAT red but the correlations were considerably lower than tangential curvature using exponential and linear regressions (Table 4).

Tangential curvature is negative in valleys where water converges and positive on ridges where water divergs. Sites J3, J6, B11 and B show negative curvature with sites J3 and J6 having the steeper slope and sites B11 and B possibly low flat ground. The remaining sites are positioned on ridges, (confirmed by flow path length), have divergent flow and therefore reflected red wavebands indicating 'brown' biomass.

The climatic determinants for biomass are possibly best examined at a monthly timescale, given vegetative growth rates and therefore the difference in the data acquisition dates did not impede the outcomes of this study (Table 1). Both biomass and satellite vegetative information can be correlated to primary terrain attributes given the prevailing monthly climatic conditions of this study. However, the climatic impacts on the correlation between vegetation and the primary terrain attributes during a summer/winter seasonality would be a worthwhile comparison. The type of curve-fitting can vary with different remote sensors and at different times of the year.

This paper has shown it is possible to correlate biomass using TMSAT to five primary terrain attribute data under present climatic conditions in this catchment. However, the accuracy of this correlation is dependent on the accuracy of the DEM (Hutchinson 1996) and the prevailing climatic conditions. Given the difficulties in determining the spatial distribution rainfall, the temporal sensitivity of dependent hydro-ecological processes (such as biomass) should be carefully considered (Hutchinson 1995a). Therefore, temporal predictions of biomass have not been considered in this study. Further research is necessary to determine which correlations are best to use for the spatial distribution of biomass.

The use of TAPES-G made it possible to identify the key primary terrain attributes, as well as identify the type and accuracy of their correlation to land cover data. TAPES-G also indicated which secondary terrain attributes need further investigation.

7. CONCLUSION

This study concludes that there is a correlation between landcover (biomass and remotely sensed reflectance data) and primary terrain attributes. The correlations vary with some curve estimations producing r^2 values up to 0.78 (e.g. TMSAT red to tangential curvature). Tangential curvature is a particularly useful terrain parameter in low relief catchments due to its sensitivity to minor changes in curvature. Secondary terrain attributes and landcover data could be determined to provide important additional information for the spatial disaggregation of localised or lumped biomass data.

In view of the correlations between biomass and slope and aspect further analysis between solar radiation (a secondary terrain attribute) and NDVI could yield worthwhile results. Similarly, secondary terrain attributes such as the wetness index could be related to biomass values.

From a climatological perspective the comparison between biomass or reflectance data with terrain attributes in a different season could indicate the degree of spatial variability of landcover between seasons.

All correlations within this study are dependent on the initial DEM resolution and accuracy. The DEM accuracy determines the usefulness of TAPES-G outputs and therefore the validity of the correlations with ground and satellite data. The implications of this study are that primary terrain attributes do have impacts on biomass in low relief catchments and sufficient accuracy in the DEM is therefore essential. Further analysis correlating secondary terrain attributes will reported elsewhere.

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