CHARACTERISING HETEROGENEOUS VEGETATED SURFACES USING MULTIANGULAR SATELLITE DATA

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Abstract - Bidirectional Reflectance Distribution Functions (BRDF) seek to represent variations in surface reflectance resulting from changes in a satellite's view and illumination angles. BRDF representations have been widely used to assist in the characterisation of vegetation. The resulting BRDF represents a spatial integral of all the individual surface features present in a pixel. To fully understand the BRDF of specific materials, homogenous surfaces must be studied, but these surfaces are often of limited interest, for example dried salt lakes.

This paper describes the results of an alternate approach to the understanding of BRDF by examining a small area (single pixel) of a well defined homogenous surface, specifically a single species cropped field that varies from bare soil, through a growth cycle, to a closed canopy at harvest. This has enabled structural variations to be identified via their association with temporal changes. The implementation of the Ross Thick Li Sparse BRDF model using MODIS is a stable, mature data product with a 10 year history and is a ready data source. Using this dataset, temporal BRDF effects have been observed with respect to different wavelengths, the relationship with crop density and interpretation of the BRDF effects. A number of observed wavelengths/BRDF parameters demonstrate distinct relationships with known surface structures that cannot be resolved by reflectance data alone. This provides an insight into how BRDF effects can be used to characterise vegetation and also provides a basis for further techniques to resolve BRDF effects within more complex heterogeneous surfaces.

1. INTRODUCTION

BRDF effects cannot be directly derived from Landsat data due to the small variation in illumination and viewing angles and infrequent revisits of the sensor (F.Li et al., 2010). Sensors capable of determining BRDF effects tend to have moderate/lower spatial resolution, and as a consequence BRDF effects on studied surfaces will frequently be a spatial integral of the different surface features present in a pixel. To study BRDF effects of specific features, surfaces often need to be found that are temporally invariant and homogeneous at a given spatial scale. Suitable study sites may therefore be difficult to find and/or are of minimal interest and studies have tended to focus on the classification of large land area extents (Lovell and Graetz, 2001; Grant, 2000).

To assist with the characterisation of vegetation within satellite imagery, an alternative approach is to examine a single species cropped field that is sufficiently large in area, such that the pixel(s) studied will be fully contained within the field. Such a study site, managed as a single entity, may be considered homogeneous at each epoch, but heterogeneous across epochs, although containing just two well defined feature types in varying combinations: soil and crop. Temporal variation in BRDF effects may then be observed and compared with known changes in the field's crop cover in order identify how the BRDF effects can be related to vegetation structural characteristics.

Whilst a surface of a single species, homogeneous crop is very simplistic, the resulting BRDF effects are likely to be well contrasted and have smooth temporal variations. The techniques used for analysis of this simple surface may also be applicable to more complex vegetated surfaces.

Of particular interest are surface structural features that are not apparent in spectral reflectance data; for example, crop and soil cultivation activities and vegetation heights.

This study will use existing BRDF representations/available data sets. This is a pragmatic approach to data collection and processing and means that any results have broad and immediate application.

NASA's MODIS sensor provides a BRDF representation in the MCD43 product. This product is freely and readily available from the CSIRO as a re-projected map grid covering the Australian continent (Paget and King, 2008). Cropped areas managed as a single plot of at least 1km^2 in area are necessary to ensure that a MODIS 500m x 500m pixel will always be fully contained within the area of the cropped field. Although fields of this size are uncommon, two study sites have been identified that meet this criterion: cotton/wheat grown at Cubbie Station (Lat 28º 41'S, Long 148º 03'E) in Southern Queensland (Figure 1) and sugar cane grown near Ayr (Lat 19º 41'S, Long 147º 14'E) in Northern Queensland (Figure 2). This provides two very different crops and growing conditions in which to examine BRDF effects. Three adjacent fields at each site have been selected for this study.

Additionally, randomly chosen pixels have been selected from a dried salt lake in South Australia (i.e. Lake Frome: Lat 30° 43'S, Long 139° 46'E) for contrast/reference to the two cropped sites.

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Figure 1. Cotton/Wheat Fields, Cubbie Station, QLD. Designated by property management as fields 2, 3, & 7.

Figure 2. Sugar Cane Fields, Ayr QLD. Arbitrarily designated as fields 1, 2 & 3.

2. METHOD

Cropping history since 2000 has been obtained from the respective property managers. NDVI derived from MODIS Nadir BRDF-Adjusted Reflectance (NBAR) has also been determined for each of the six fields for the same period.
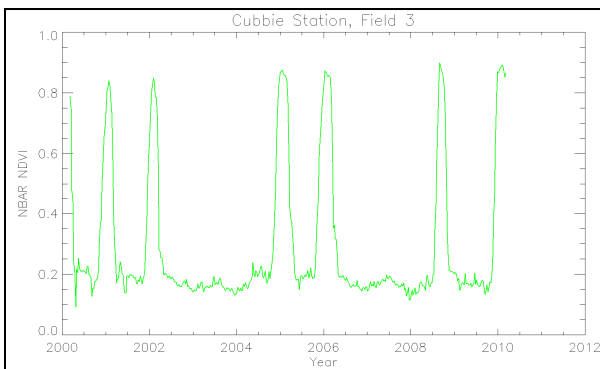

Figure 3. NBAR NDVI for Cubbie Station field # 3

Figure 3 demonstrates the distinct cropping cycles and fallow 'bare soil' periods. Very similar profiles are observed for the two other Cubbie fields which have the same cropping program, i.e. cotton grown in all cycles, except 2008 when the crop grown was wheat.
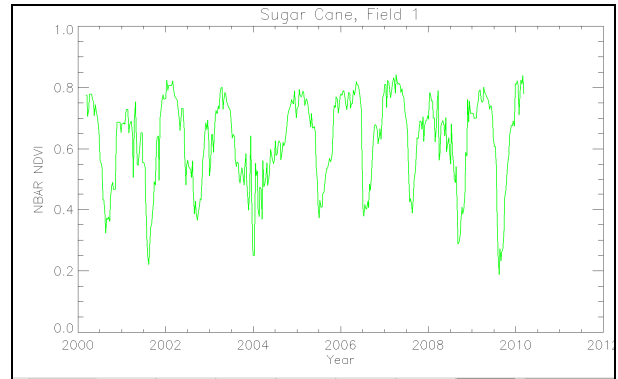

Figure 4. NBAR NDVI for sugar cane field #1.

The crop cycle for sugar cane is evident in Figure 4, although without the extended fallow periods because the crop is allowed to naturally re-grow from stubble after harvesting. Similar profiles are observed for the two other cane fields.

Large cropped fields have the benefit of generally being on flat topography which eliminates any slope and aspect considerations with BRDF representations. The fields on Cubbie Station have the additional benefit of being irrigated, thus minimising variations associated with weather events. The homogeneity within the fields at Cubbie Station has been partially verified with 30m resolution Landsat data for a small number of sample periods. A less detailed history for the sugar cane fields has been obtained from property managers and the fields appear less homogeneous at each epoch. For instance, staggered harvesting appears evident in 2008 (see Figure 4).

The MODIS MCD43B1 product provides BRDF parameters of the RossThickLiSparseReciprocal BRDF model at 500m resolution in eight-day intervals. The MODIS BRDF representation models the atmospherically corrected surface reflectance as a function of the sun and view directions. The MODIS BRDF representation provides weights for the isotropic, volumetric and geometric kernel functions. The weights are derived separately for each of the seven observed visible to mid-infrared bands. For pixels that fall within the cropped fields, the three weights for each of the seven MODIS bands for all epochs between February 2000 and March 2010 (462 epochs) have been extracted.

The MODIS BRDF parameters are derived on the assumption that the arrangement of surface scattering and shading elements is random with no preferred azimuth (Lucht et al., 2000). The cropped fields being studied are non random, i.e. growing in rows as with nearly all planted crops. BRDF effects may therefore vary as a consequence of the absolute viewing azimuth used in deriving the BRDF: that is variations in the distribution of raw observations that are viewed along the rows compared to across the rows. This implication has not specifically been considered within this analysis.

3. RESULTS

For all seven bands correlations between BRDF volumetric and geometric parameters were computed and also between the BRDF volumetric and geometric parameters and MODIS NBAR NDVI, which has been used as a measure of

vegetation/biomass. The strongest correlations were observed for the geometric weights in the red, NIR and MIR bands both between the BRDF parameters and also between these BRDF parameters and MODIS NBAR NDVI. Volumetric weights displayed lower correlations between bands and lower correlations with MODIS NBAR NDVI. Volatility within the time series of MODIS BRDF parameters limited any consistent interpretation.

Noise and correlation between BRDF parameters has been identified in previous studies as an issue making the interpretation of individual parameters difficult (Gao et al., 2003). Notwithstanding this, the combined MODIS BRDF model has been shown to be accurate (Schaaf et al., 2002). Using the MODIS BRDF representation, NDVI has been calculated for a range of viewing angles (nadir to 1.25 radians), whilst fixing illumination angles and relative azimuths. For periods of low vegetation densities or bare soil, NDVI was observed to generally increase with increases in viewing angles. As crop density increase, the NDVI variation at higher viewing angles is less and in the mature growth stages, NDVI tends to flatten and then decrease with higher view angles. This later effect has been previously been observed (Tian et al., 2010; Sandmeier et al., 1998).
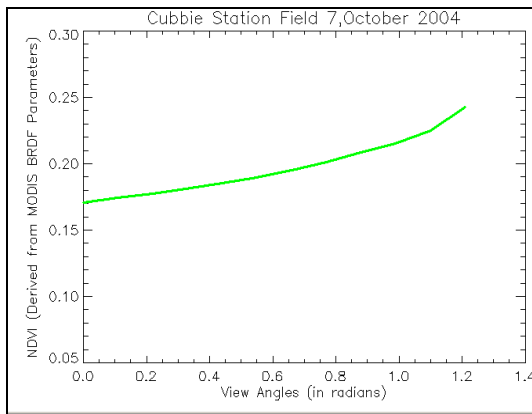

Figure 5. Low density crop cover showing the derived NDVI increasing with higher view angles.
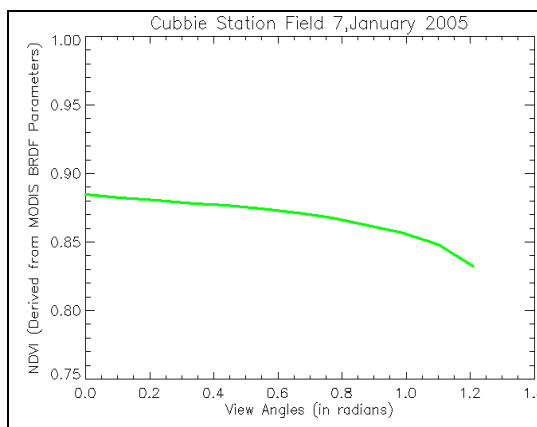

Figure 6. High density crop cover showing the derived NDVI decreasing with higher view angles.

The pattern of NDVI increasing with higher viewing angles at low crop densities and decreasing with higher viewing angles at higher crop densities was particularly evident for the three

cotton fields. Volatility is apparent, particularly in the mature sugar cane crop at higher viewing angles, remaining flat or even increasing at higher viewing angles and crop densities.
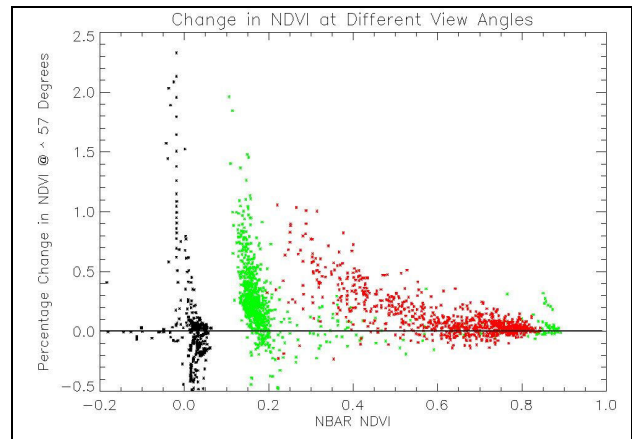

Figure 7. The percentage difference in NDVI at a viewing angle of 1 radian (57°) from the NDVI at zero (NBAR). Red is sugar cane, green is cotton and black is Lake Frome.

In order to quantifiably interpret the variations in NDVI with respect to changes in viewing angles a geometric optical model is proposed. Such a model may be considered a reverse engineering and re-expression of the BRDF effects into an alternate and more readily interpretable set of parameters. Such a model may also be thought of as a mixing model, where the end members are soil and crop and the determination of the component quantities is based upon both spectral and angular effects.

A geometric optical model using a derived vegetation index such as NDVI in proposed to reduce the number of model parameters and enables results in terms of a readily understood scalar quantity. Furthermore, the stronger correlation between BRDF NIR and Red geometric parameters with NDVI provides support for use of a vegetation index combined with a geometric optical model.

3.1 Geometric Optical Model

A surface pixel on the study sites may be considered to be a mix of soil components (lower NDVI) and crop canopy components (higher NDVI). The NDVI values for end-member states are obtained from observations of bare soil prior to planting and the mature crop canopy prior to harvest respectively. If a pixel is defined as having a unit-less area of 1 (that is 1 x 1), prisms of vegetation may be considered on the surface having dimensions d x d x (h x d), where 'd' is a unit-less value between 0 and 1 representing the length and width of the vegetation prism in the horizontal plane and 'h' is a unit-less height–to-width ratio. The use of prism shaped objects to represent vegetation has been considered in past BRDF models (Roujean et el., 1992).

Larger viewing angles will bring the vertical surface of higher NDVI vegetation into view and obscure an area of lower NDVI soil. Thus for greater viewing angles, higher values of NDVI should result.
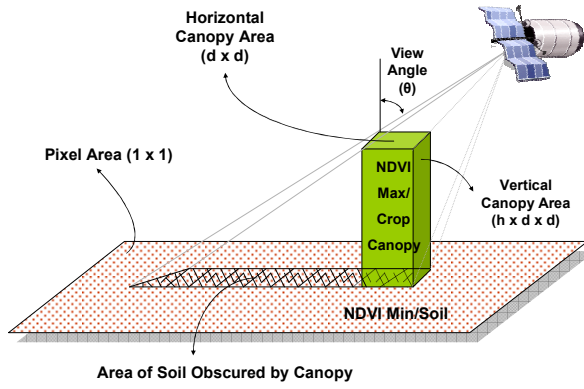
Figure 8. A single 'prism' of vegetation (i.e. of higher NDVI) is depicted on a flat surface of soil having a lower NDVI.

Using the geometry of these surfaces an expression for changes in NDVI as a function of viewing angle, (i.e. NDVI (θ)) can be described as the sum of the horizontal and vertical surface components:

$$NDVI_{Total}(\theta) = NDVI_{horizontal}(\theta) + NDVI_{vertical}(\theta) \quad (1)$$

$$NDVI_{horizontal}(\theta) = D\,NDVI_{max}(\theta) + (1-D)\,NDVI_{min}(\theta) \quad (2)$$

$$NDVI_{vertical}(\theta) = h\,D\,Tan(\theta)\,[\,NDVI_{max}(\theta) - NDVI_{min}(\theta)] \quad (3)$$

Where: h = the height-to-width ratio of vegetation.
$D = d^2$ and represents the density of vegetation cover with a range $0 \leq D \leq 1$, with value 0 being for all soil and no vegetation and 1 being for complete vegetation coverage and no soil.
θ = the viewing angle.

Equation 2 is the linear combination of soil and canopy NDVIs on the horizontal plane for the case when only the horizontal vegetation surfaces are present (h=0). Equation 3 is the additional contribution that the vertical plane of canopy makes to the observed NDVI as a function of the viewing angle including the additional soil obscuration relative to the h=0 case. Total/observed NDVI (equation 1), as a function of viewing angle is therefore the sum of equations 2 and 3. This development assumes that the vegetation prisms do not overlap from the satellite viewpoint and neglects shadows. If viewed at zenith (i.e. $\theta = 0$) or the vegetation has no vertical profile (i.e. h = 0), then equation 3 becomes zero. Increases in NDVI as a consequence of higher viewing angles will be greatest when:

- the NDVI difference between canopy and soil is greatest, and/or
- the height-to-width ratio of the vegetation is large (that is larger values of h), and/or
- higher vegetation densities are present (that is larger values of D).

Values for the model parameters h and D may be determined by numerical methods that provide a best fit (lowest root mean squared error (RMSE)) between the model and NDVI as derived from the MODIS BRDF parameters across a range of viewing angles (0 to 1.25 radians). For the results to be consistent across epochs, solar angular variation effects have been removed from the MODIS BRDF derived NDVI. In applying this model NDVI derived from the MODIS BRDF representation effectively become 'observations'. The model's approach seeks to replace the wavelength-specific isometric, volumetric and geometric parameters within the MODIS BRDF model with the alternate parameter set of : NDVI $_{max}$, NDVI $_{min}$ vegetation density (D) and a height-to-width ratio (h) which offer more direct interpretation of vegetation structure.

In applying this model, a representative characteristic profile for NDVI $_{min}$ (θ) being bare soil and NDVI $_{max}$ (θ) being crop canopy must first be determined. This acknowledges that NDVI of soil and crop canopy are not constant but vary with viewing angle. Applying the model separately to sample periods of bare soil and mature canopy enables the development of an expression for the NDVI profile of soil and crop canopy of the form:

$$NDVI_{max/canopy}(\theta) = A - B\,Tan(\theta) \quad (4)$$

$$NDVI_{min/soil}(\theta) = A + B\,Tan(\theta) \quad (5)$$

Resolved values for A and B in equations 4 and 5 provide the characteristic profiles for soil and canopy that can be substituted into the final model. For bare soil, B will be positive and for a mature crop canopy B will generally be negative and was generally found to be of a smaller magnitude. The characteristic NDVI profiles for soil and vegetation canopy should be uniquely defined and vary according to the amount of vegetation mass, stubble, leaf littler and weeds present in the soil layer and vary for the mature canopy for different crops varieties. Difference in the NDVI profiles of soil and mature crop canopy were observed:

- Cane fields had higher NDVI minimum values and more significant increases with viewing angles than cotton. This might reasonably be attributed to the stubble (residual plant material) remaining in the fields after harvest.
- For the mature canopy, cane had a lower NDVI response and a flatter (or possibly increasing) profile with respect to viewing angles where cotton had a clearer decreasing profile.
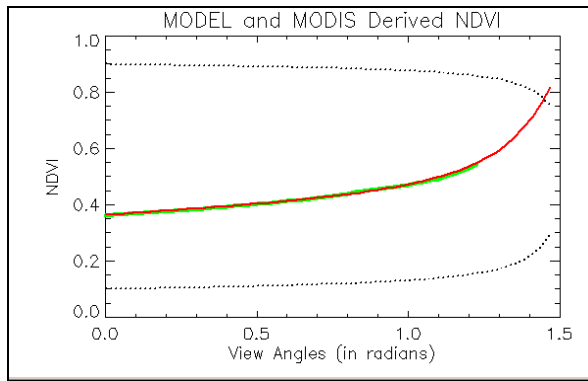
Figure 9. The derived model for Cubbie Station field # 7, approximately seven weeks after cotton was planted, at which time the plants were approximately 30cm high having been planted in rows 1m apart. The lower dashed black line is the characteristic profile for bare soil on field # 7 (average of several observations) and the upper dashed black line is the characteristic profile for mature cotton (average of several observation periods). The green line is NDVI derived from the MODIS BRDF parameters for the pixel/field with viewing angles ranging from 0 to 1.25 radians. The red line is NDVI predicted by the model having resolved values for h and D. Both the characteristic profiles for soil and canopy and the model have been extrapolated to viewing angles of 1.4 radians to provide a better visual representation of their respective shapes.

This model provides a strong fit to MODIS derived NDVI for all periods if positive or negative values for the height-to-width ratios (h) are allowed. As there are no interpretable explanations for negative height-to-width ratios, only positive values for h have been allowed, i.e. $0 \leq h \leq 5$ (being an arbitrary maximum). This is a similar consideration to that applied in the MODIS BRDF representation whereby only positive values for the parametric weights are allowed based on logical considerations (Lucht et al., 2000). The tendency for negative values for h will exist when there is low density vegetation and NDVI decreases or for high density vegetation where NDVI increases with higher viewing angles, in other words where the trend is opposite of that expected by the model. Where this occurs, the model yields a poor fit and h (being restricted to positive values only) will most likely tend to zero.
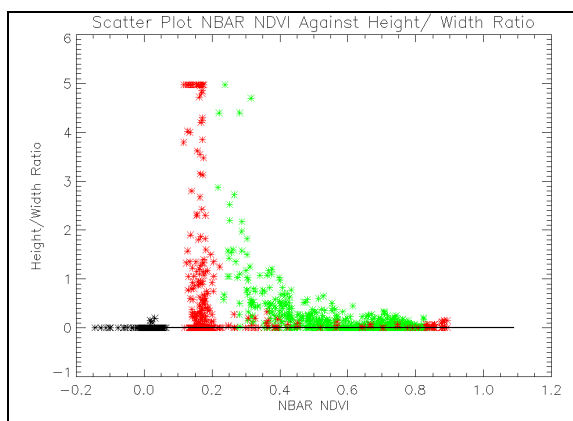

Figure 10. The height-to-width ratio (h) derived for Lake Frome (black), cotton on Cubbie Station (red) and sugar cane

(green) plotted against NBAR NDVI on the x-axis. Epochs shown are from mid-2002 to mid 2008. The large number of points shown for Cubbie Station/cotton with NDVI less than 0.2 is a reflection of the extended fallow periods between cropping.

For very low densities (low NDVI) the height-to-width ratio appears greater and volatile. For increased densities (high NDVI) the height-to-width ratio tends to zero. The model's determination of the height-to-width ratio of vegetation on Lake Frome is as expected, i.e. extremely low NDVI with no discernable vertical vegetation structure.

4. DISCUSSION

Whilst one objective of this model was to have directly interpretable values for height-to-width ratio (h) this appears not readily realisable.

Cotton plants grow to about 1.2m high and are planted in rows 1m apart with uniform growth in both horizontal and vertical directions towards mature crop state. Therefore, height-to-width ratios of 1 might be expected broadly across the growing cycle. Sugar cane grows much higher than cotton, reaching up to 3-4m at maturity, although with perhaps less definition around plant widths, however larger height-to-width ratios for cane might reasonably be expected, i.e. h > 1.

Even if the height-to-width ratio is not readily translatable into an absolute crop height, it still may be useful in distinguishing vegetation structure in a relative sense. A different height-to-width profile between cotton and sugar is evident in figure 10. The height-to-width ratio may be used to distinguish different crop types/structures by their profile shapes across a range of NDVI values during the growth cycle. Alternatively, at specific periods when the same NDVI response is observed, different height-to-width ratios may be apparent, for instance NBAR NDVI of 0.4 shows cane with a consistently greater height-to-width ratio compared with cotton which has a value close to zero. This approach for interpretation is similar to that used for the Structural Scattering Index (SSI) (Gao et al., 2003). To explore this, a variety of different vegetation covers will be necessary in addition to the two crop types used for this study.

Values for density (D) are very strongly associated with NDVI and also associated with the height-to-width ratio. Whilst this is expected, correlation between the parameters is not ideal for purpose of interpretation. Strong correlations between the parameters being one of the difficulties encountered in prior studies when seeking to interpret MODIS BRDF parameters.

The results showing higher NDVI at higher viewing angles for low density vegetation cover are expected: a greater amount of higher NDVI vegetation will be visible that obscures lower NDVI soil. The range of densities over which the model is applicable to resolve the height-to-width ratio is perhaps limited. Very low densities (resolved values for D < 0.1) tend to produce large and highly variable height-to-width ratios and higher densities (resolved values for D > 0.5) produce height-to-width ratios tending to zero. This later effect could be interpreted as that of a closed canopy where soil is no longer seen and the crop appear uniform from all viewing angles. This just leaves a small window of crop densities that the model may

be valid, for instance 30% densities coverage (D=0.3) may be ideal.

It is difficult to explain volatility within the data that produces a relationship between NDVI and viewing angle that is the inverse to that expected, that is where a negative height-to-width ratio produces best fit between the model and MODIS BRDF derived NDVI.

5. CONCLUSION

This paper provides some preliminary insights into the utility of specific study sites and analysis techniques for investigating the relation of vegetation structure to BRDF effects. The line of investigation discussed within this paper is in its early stages and is suggestive of further investigation:

- The model proposed needs further characterisation: for example sensitivity to the NDVI profile of end-members.
- The proposed model is quite simplistic, with opportunity for improved definition.
- Selection of additional sites with other surface types to model in order to determine if different height-to-width profiles can characterise or distinguish vegetation types.
- Determine the impact that the crop row orientation has on the MODIS BRDF representation and subsequent analysis.
- NDVI profiles of end-members (i.e. soil and canopy) across viewing angles had distinguishing characteristics that were not explored in this study.

6. ACKNOWLEDGEMENTS

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