Generation of improved surface moisture information using angle-based drought index derived from Resourcesat-2 AWiFS for Haryana state, India

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ABSTRACT
The lack of availability of two shortwave-infrared (SWIR) bands in most of the satellite sensors restricts the utilization of shortwave angle slope index (SASI). The potential of Resourcesat-2 Advanced Wide-Field Sensor (AWiFS) with a single SWIR band was explored to generate surface moisture information comparable to SASI over Haryana, India. The fractional values of several vegetation indices, viz. normalized difference water index (NDWI), SASI and angle-based drought index (ABDI) derived from moderate resolution imaging spectroradiometer (MODIS) were compared. At different phenological stages, ABDI was found to be a better index than NDWI while representing SASI values using regression analysis and Mahalonobis distance measurement. A very high coefficient of regression value ($R^2 = 0.8$) was observed while analyzing the agreement between AWiFS-derived ABDI and MODIS-derived SASI for the year 2012. The regression parameters were deployed on AWiFS-derived ABDI to generate improved moisture images for the year 2013 and were compared with actual SASI images from MODIS data.

1. Introduction
Drought is a recurring and inevitable phenomenon, especially in arid and semi-arid regions of India. It can have a substantial impact on the ecosystem and agriculture of the affected region. The effects of drought can be minimized by an early drought warning system and its mitigation planning. Satellite remote sensing can provide information over large regions for measuring drought impacts. This offers a great advantage in monitoring the spread of drought on near-real-time basis, timely drought assessment and early drought warning, etc. (Liu et al. 2010). Normalized difference vegetation index (NDVI), an index for crop vigour and health monitoring, has been widely used for the operational drought monitoring (Thenkabail et al. 2004; Murthy et al. 2007). The response of NDVI with rainfall was utilized for predicting agricultural drought over parts of India (Dutta et al. 2013). Due to its high spatial resolution over meteorological data, the vegetation condition index (VCI) derived from time-series NDVI was also extensively utilized for drought-related studies over Indian region (Singh et al. 2010; Dutta et al. 2015).

Surface moisture is the key parameter for monitoring the status of crop sowing as well as crop stress condition. The drought indices developed using the shortwave infrared (SWIR) reflectance...
bands are sensitive to canopy moisture and background soil (Tucker & Chowdhary 1987; Lingli et al. 2008). This fact has been utilized for agricultural drought monitoring and assessment. Normalized difference water index (NDWI) is derived from two bands that include a moisture-sensitive SWIR band and insensitive NIR band (Gao 1996). Pigment-independent assessment of surface moisture can be carried out using the measurements at NIR-SWIR region (Serrano et al. 2000; Zarco-Tejada et al. 2003). The moisture-sensitive bands centred at 858.5, 1240, and 1640 nm of moderate resolution imaging spectroradiometer (MODIS) sensors have been used to retrieve the crop water content (Gao 1996; Fensholt & Sandholt 2003; Xiao et al. 2005). Based on the sensitivity of thermal band of AVHRR (advanced very high resolution radiometer) towards surface wetness, the temperature condition index (TCI) coupled with VCI was utilized as a tool to monitor both agricultural drought and surface wetness over Indian region (Singh et al. 2010). Of late, a combined deficit index (CDI) has been developed from rainfall and NDVI deficits based on the generalized lag-response behaviour of water supply and crop growth. However, this index has been found to be sensitive to only late-season agricultural drought (Vyas et al. 2015).

The SWIR-based indices developed for surface moisture studies are mainly normalized indices. The angle-based index, using the angle formed at any vertex in a multispectral broadband spectrum, was first conceptualized by Palacios-Orueta et al. (2006). The index examines the relationship between bands instead of absolute value of reflectance at any one of those bands, acting as coarse spectral fitting analogous to hyperspectral data. Consequently, on a similar line, Khanna et al. (2007) proposed shortwave angle slope index (SASI) to estimate the surface moisture and discriminate land cover. SASI has a unique characteristic of shifting its sign from positive to negative while changing from soil to vegetation background. This was identified as a good discriminator of soil, vegetation, and dry vegetation. SASI could track the surface moisture pattern and synchronized well with rainfall, whereas NDVI did not follow rainfall closely (Palacios-Orueta et al. 2006; Khanna et al. 2007). The index has already been studied by few of the researchers for its unique response to surface moisture changes.

The surface wetness was tracked and the rice transplantation pattern was extracted using SASI over Hirakud irrigation command area, India (Murthy et al. 2012). It was observed that SASI was able to show a better separability of rice classes, sown at different time, compared to NDVI and NDWI. Das et al (2013a) utilized SASI for characterization of surface dryness/wetness over three different meteorological sub-divisions of India for monitoring and assessment of early season agricultural drought. SASI was found to be a better indicator than NDVI to discriminate early season agricultural drought among different years. An integrated SASI approach was also proposed and successfully utilized to categorize different dryness/wetness conditions during the crop sowing season (Das et al 2013a). The synchronization among significant increase in rainfall amount, increase in crop sown area and change in the sign of SASI from positive to negative values was observed by Das et al (2013b). Based on that information, soil- and crop-specific SASI thresholds were developed to convert the SASI image into information on area favourable for crop sowing for Andhra Pradesh state, India. This methodology has been operationally adopted by the National Agricultural Drought Assessment and Monitoring System (NADAMS) for in-season agricultural drought monitoring for Indian region since 2010 (www.bhuvan.nrsc.gov.in).

In spite of its advantages, the SASI has remained under-utilized because of its requirement of two SWIR bands for computation. Due to non-availability of two SWIR bands in many of the medium resolution remote sensing sensors namely SPOT, Resourcesat Advanced Wide-Field Sensor (AWiFS), and NOAA AVHRR, the potential of the index was not fully utilized. A new angle-based drought index (ABDI) which parameterizes the shape of the broadband spectrum of the SWIR and NIR bands was proposed by Liu et al. (2010). The response of ABDI towards daily precipitation was analyzed over eastern Sichuan Basin of China, and it was found to be effective in agricultural drought monitoring. In the present study, the potential of the new ABDI was compared with traditional normalized difference water index for extracting similar information of SASI at different crop
phenological stages for agricultural drought monitoring. Furthermore, Resoucesat-2 AWiFS data with single SWIR band available was utilized to generate improved surface moisture information comparable to SASI (SASIAWIFS) at a better spatial resolution and the product was validated using actual SASI product derived from MODIS (SASIMODIS).

2. Study area

Haryana is a landlocked state in northern India (Figure 1), majority of it being an agricultural plain, with the southern and western edge being more dry and arid. It is located between 27°39’ and 30°35’N latitude and between 74°28’ and 77°36’E longitude. The altitude of Haryana varies between 200 and 1200 m above sea level. With a total geographical area of 4.42 M ha, Haryana accounts for 1.37% of India’s total geographical area.

The climate of Haryana varies from arid to semi-arid with an average rainfall of 455 mm. Around 70% of the total rainfall is received during the months from July to September and the remaining during December to February. There are two agro-climatic zones in the state. The north western part is suitable for rice, wheat, vegetables and temperate fruits, whereas the south western part is suitable for high-quality agricultural produce, tropical fruits, exotic vegetables and herbal and medicinal plants. The cultivable area is 3.8 M ha, which is 86% of the geographical area of the state. Out of this, 3.62 M ha, i.e. 96.2% of the area, is under cultivation. About 75% of the area is irrigated through tubewells and an extensive system of canals. Wheat and rice are the major crops, and Haryana is the second largest contributor to India’s central pool of food grains.

3. Methodology

MODIS 8-day composite surface-reflectance data (MOD09A1) were downloaded from ftp://e4ftl01uecs.nasa.gov/MOLT/MOD09A1.005 for 2012 and 2013 (January—December). The images were re-projected to Lambert Conformal Conic projection from sinusoidal projection. Cloud masking was carried out using the MODIS blue band reflectance value (Das et al. 2013a, 2013b). Five vegetation indices images, i.e. NDVI, NDWI, SASI, ABDI-1 and ABDI-2 were generated. The equations

Figure 1. India with state boundaries (a), and Haryana state with district boundaries (b).
used are as follows:

\[ NDVI = \frac{R_{\text{NIR}} - R_{\text{red}}}{R_{\text{NIR}} + R_{\text{red}}}, \]  
\[ NDWI = \frac{R_{\text{NIR}} - R_{\text{SWIR}}}{R_{\text{NIR}} + R_{\text{SWIR}}}, \]

\[ SASI = \beta_{\text{SWIR1}} \times \text{Slope} \quad \text{(radians)}, \]  
\[ \beta_{\text{SWIR1}} = \cos^{-1}\left[\frac{(a^2 + b^2 - c^2)/(2 \times a \times b)}{\lambda_{\text{SWIR1}}}\right], \]  
\[ \text{Slope} = \left(\frac{R_{\text{SWIR2}} - R_{\text{NIR}}}{R_{\text{NIR}} + R_{\text{SWIR}}}\right), \]

where \(a, b, \) and \(c\) are Euclidian distances between vertices NIR and SWIR-1, SWIR-1 and SWIR-2, and NIR and SWIR-2, respectively (Khanna et al. 2007).

\[ ABDI = R_{\text{NIR}} \times \tan^{-1}\left(\frac{R_{\text{NIR}} - R_{\text{SWIR}}}{\lambda_{\text{SWIR}} - \lambda_{\text{NIR}}}\right), \]

where \(\lambda\) is the wavelength of specific wavebands. For calculation of ABDI-1, the SWIR-1 band of MODIS centred at 1240 nm was used, whereas SWIR-2 band (centred at 1640 nm) was utilized for computation of ABDI-2. For vegetation, the value of ABDI is positive, and the value of green vegetation is larger than that of dry vegetation. For soils, the value of ABDI is negative, and the value of dry soil is lower than that of wet soil (Liu et al., 2010).

The agricultural area mask obtained from land use—land cover layer generated under Natural Resource Census at 1:250,000 scales at National Remote Sensing Centre (NRSC) (www.nrsc.gov.in) was applied on the vegetation indices (VI) images to ensure that the analysis is contained to agricultural areas. For each district of the Haryana state, the mean VI values over agricultural area were extracted at every 8-day interval using district vector. The mean values were used to generate the seasonal VI profiles for both the years, i.e. 2012 and 2013. The schematic diagram of the overall methodology is given in Figure 2.

The district-wise mean values of the vegetation indices were normalized by converting to their fractional values for inter-comparison, as the dynamics ranges of NDWI, SASI and ABDI were different. The fractional values of NDVI were utilized to extract the phenological information for all the districts of Haryana, separately. The fractional NDVI values with less than 10% of the peak value during the starting and end of a season was considered as dry phase. The stage with fractional value more than 50% during the peak crop growth was considered as peak vegetative phase. The growth periods between dry and peak growth phase were named as early vegetative phase and senescence phase during greening and browning period of the crop season, respectively (Figure 3).

A regression analysis, along with Mahalonobis distance measurement, was carried out for inter-comparison of the three surface moisture indices under four different phenological stages. The index with maximum resemblance with SASI value was selected based on the regression and distance analysis and the same was computed using reflectance bands of Resourcesat-2 AWiFS data for both 2012 and 2013. The district mean values of AWiFS-derived vegetation index at monthly level were extracted using Haryana district vector and the values were regressed with district mean SASI\(_{\text{MODIS}}\) values for the year 2012. The scatterplot was analyzed and the linear model parameters were deployed on the AWiFS-derived vegetation index of 2013, to generate AWiFS-derived SASI-like surface moisture (SASI\(_{\text{AWiFS}}\)) images, the improved surface moisture maps comparable to SASI. The output, i.e. AWiFS-derived SASI-like surface moisture maps were compared with MODIS-derived SASI maps for the year 2013. This was done to verify whether AWiFS-based index could provide similar spatial surface moisture information as SASI.
Download of MODIS data (09A1) during 2012 & 2013

Re-projection      Resample                Cloud masking

Computation of NDVI, NDWI, SASI, ABDI-1 and ABDI-2

Masking of non-agricultural area using LULC map

District level mean vegetation index values at 8-day interval

Normalization of values using fractional vegetation indices

Seasonal profiles of vegetation indices for each district

Crop phenology using fractional NDVI profiles

Inter-comparison of NDWI, SASI, ABDI-1 and ABDI-2 at four different crop phenological stages

Selection of index with maximum resemblance with SASI

Generation of AWiFS based index & its relation with SASI

Generation of SASI like index from AWiFS (SASI_{AWiFS}) using linear regression parameters & its comparison with actual SASI derived from MODIS (SASI_{MODIS})

Figure 2. Schematic diagram of the methodology.

Figure 3. A representative curve showing four different phenological stages of a crop season.
4. Results and discussion

4.1. Seasonal profiles of surface moisture indices

The seasonal profiles for absolute values of NDWI, SASI, ABDI-1 and ABDI-2 for one district of Haryana state can be seen in Figure 4(a). Figure 4(b) represents the profiles of these indices after conversion to their respective fractional values. All the moisture indices were able to capture the seasonality of the crop in both the years. It can be seen from Figure 4(a) that the sign of the SASI values is opposite to that of the other three moisture indices, i.e. NDWI, ABDI-1 and ABDI-2. During peak vegetative stage, the value of SASI is around $-0.8$, whereas the values are $0.6$, $0.9$ and $1.2$ for NDWI, ABDI-1 and ABDI-2, respectively. Similarly, at the valley of dry phases, the values were around $0.2$, $-0.05$, $-0.3$ and $-0.2$ for SASI, NDWI, ABDI-1 and ABDI-2, respectively. It was interesting to observe that there was a difference between the absolute values of ABDI-1 and ABDI-2 throughout the seasons, whereas it was almost negligible after conversion to their fractional values, as seen in Figure 4(b). In all the seasons, the profile of NDWI was different from the other three indices, i.e. SASI, ABDI-1 and ABDI-2, during the early phase of crop season.

4.2. Inter-comparison of surface moisture indices under different crop phenological stages

A linear regression analysis was carried out among the fractional values of surface moisture indices to find the best index having maximum resemblance with SASI. Similarly, Mahalonobis distance...
was also computed to study the similarity and dissimilarity among the indices. From Figure 5(a), it can be observed that ABDI-1 showed maximum similarity with SASI, followed by ABDI-2, during dry phase. The fractional NDWI values were distributed parallel to the 1:1 line, representing similar values to that of fractional SASI but with a bias. The distance measurements corroborated the above findings (Table 1(a)), where it was found that ABDI-1 and SASI had no significant difference at 5% level of significance. The values of fractional ABDI-1 and ABDI-2 are different from NDWI with high-distance values, whereas ABDI-1 and ABDI-2 were found to be highly similar to each other with very low Mahalonobis distance value (Figure 5(a) and Table 1(a)).

Figure 5. Inter-comparison of different fractional surface moisture indices at four phenological stages, i.e. dry (a), early vegetative (b), peak vegetative (c) and senescence (d) stages of crop.

|       | SASI | NDWI | ABDI-1 | ABDI-2 |
|-------|------|------|--------|--------|
| (a)   |      |      |        |        |
| SASI  |      |      |        |        |
| NDWI  | 1.932|      |        |        |
| ABDI-1| 0.029*| 2.901|        |        |
| ABDI-2| 0.349| 4.269| 0.267*|        |
| (b)   |      |      |        |        |
| SASI  |      |      |        |        |
| NDWI  | 6.407|      |        |        |
| ABDI-1| 0.844| 10.482|        |        |
| ABDI-2| 2.462| 15.139| 0.233*|        |
| (c)   |      |      |        |        |
| SASI  |      |      |        |        |
| NDWI  | 1.712|      |        |        |
| ABDI-1| 1.894| 6.875 |        |        |
| ABDI-2| 1.399| 5.931 | 0.037**|        |
| (d)   |      |      |        |        |
| SASI  |      |      |        |        |
| NDWI  | 0.703|      |        |        |
| ABDI-1| 3.981| 6.076 |        |        |
| ABDI-2| 4.755| 6.874 | 0.015**|        |

**At 5% level of significance; *at 1% level of significance.
During the early vegetative phase, similar observations were seen where fractional SASI had maximum resemblance with fractional ABDI-1, followed by ABDI-2 (Figure 5(b)). Unlike dry phase, NDWI is not following the 1:1 line, representing higher dissimilarity with SASI. The results were in agreement with the findings of Table 1(b). The Mahalonobis distance showed that there is no significant difference between ABDI-1 and ABDI-2 at 1% level of significance, whereas both ABDI-1 and ABDI-2 are highly dissimilar to NDWI.

A different kind of observation was made during peak vegetative stage, where ABDI-2 showed maximum resemblance with SASI. The fractional ABDI-2 was distributed parallel to the 1:1 line with a bias (Figure 5(c)). Similar to the other two phenological stages, NDWI was found to be highly dissimilar to both the ABDIs, whereas ABDI-1 and ABDI-2 were found to be significantly similar to each other at 5% level of significance (Table 1(c)).

During senescence, the fractional values of NDWI were found to be much closer to fractional SASI values than both the ABDIs (Figure 5(d)). The observations were in corroboration with the findings of distance measurements. The similarity between NDWI and SASI is much higher than ABDI-1 and ABDI-2 (Table 1(d)). Similar to other phenological stages, in senescence stage also, ABDI-1 and ABDI-2 differ insignificantly from each other at 5% level of significance.

Few major inferences can be drawn out of the regression as well as distance measurement analysis — (1) in all the phenological stages, ABDI-1 and ABDI-2 were found to differ insignificantly. Hence, any of the two SWIR bands, specifically SWIR bands available in Resourcesat AWiFS sensor (1280 nm), is adequate to generate ABDI, (2) ABDI was found to have more resemblance with SASI in all the pheno-phases, except senescence. Since the information on surface moisture availability during early crop sowing period is more important than the senescence period, ABDI can be a proxy indicator of SASI during most of the crop growing stages, (3) Being an angle index, the values of ABDI were found to be different from normalized surface moisture index, i.e. NDWI, throughout the crop growing season.

### 4.3. Relationships between ABDI and SASI

The relationship between the district-level monthly mean ABDI derived from AWiFS and SASIMO-DIS were studied for the year 2012. The data of the entire year was analyzed to consider the maximum working range of both the vegetation indices, i.e. ABDI and SASI. The scatterplot followed the 1:1 line with a very high coefficient of regression and low bias (Figure 6). The high positive values of

$$y = -0.855x + 0.162$$

$$R^2 = 0.81$$

(n = 228)

**Figure 6.** Relationships between AWiFS-derived angle-based drought index and MODIS-derived shortwave angle slope index.
SASI characterize dry soils, and high negative values represent healthy vegetation (Khanna et al. 2007). SASI starts decreasing when soil moisture becomes sufficient for crop planting and begins to increase after soil moisture starts to drop (Liu et al. 2011). It was interesting to note that as the SASI values became negative, ABDI values were increasing in positive direction, representing a good soil or vegetation condition. On the contrary, positive values of SASI were coinciding with negative or very low positive ABDI values, indicating dry soil condition. ABDI closely followed the trend of SASI and could act as a proxy to SASI in detecting surface moisture condition throughout the crop season.

4.4. Generation of SASI-like index and its validation

The linear regression parameters derived from ABDI and SASI relationships were applied on the AWiFS-derived ABDI images of Haryana state for the year 2013. The spatial distribution of SASI_{AWiFS} was compared with SASI_{MODIS} for the corresponding 8-day composite period (Figure 7). The three dates, i.e. January, April and October, were chosen to represent different crop growing stages. January image represents mid-to-peak vegetative condition, whereas maturity to senescence period is captured by October image. During April, there is hardly any crop representing a dry soil condition. In all the three months, a good agreement was found between SASI_{AWiFS} and SASI_{MODIS} images. The high- and low-value patches in SASI_{AWiFS} images were in corroboration with the SASI_{MODIS} images. The minute variations found between SASI_{AWiFS} and SASI_{MODIS} images may be attributed due to the different footprint of these sensors and non-synchronized acquisition.

5. Conclusion

SASI is derived from NIR along with two SWIR bands of MODIS data and proved to be superior to other available moisture indices for early season agricultural drought monitoring. In the present
study, information similar to that derived from SASI was extracted from a single SWIR band with better spatial resolution. The normalized values of several vegetation indices could capture the seasonality across space and time over different districts of Haryana state. ABDI was found to be a better and closer representation of SASI during most of the crop phenological stages than normalized difference water index. ABDI derived from SWIR-1 and SWIR-2 showed no significant difference. Hence, either of the two SWIR bands of MODIS could generate ABDI image with similar effectiveness to reproduce surface moisture products comparable to SASI. A very good agreement was found between ABDI derived from AWiFS sensor and SASI obtained from MODIS. Furthermore, their linear regressed parameters were applied on AWiFS-derived ABDI images of another year to retrieve improved surface moisture index images. This was verified with actual SASI images for different parts of the crop phenological stages. Hence, it can be inferred that sensors with single SWIR band can also be effectively utilized to extract surface moisture information similar to that derived from SASI, for improved and better monitoring of agricultural drought condition.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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