Assessment of NDVI and NDWI spectral indices using MODIS time series analysis and development of a new spectral index based on MODIS shortwave infrared bands*

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ABSTRACT

We put forward a new spectral index, Shortwave Angle Normalized Index (SANI), based on the NIR and SWIR MODIS bands. The new index parameterizes the general shape of this part of the spectrum by measuring the angle at SWIR1 and the normalized index between NIR and SWIR2. Preliminary results show that it performs well in tracking moisture and discriminating between soil, vegetation and dry vegetation. We use Time Series Analysis to explore the temporal evolution of NDVI, NDWI and SANI and climatic data for the years 2000 to 2005. Our analyses show that SANI is synchronized with precipitation in grasslands but not in irrigated cropland where irrigation is a major source of moisture. NDVI does not follow precipitation closely in either of the two regions. SANI also shows an overall negative trend, which corresponds to the overall positive trend in precipitation levels from 2000 to 2005. Thus, this index seems to be a powerful tool for uncovering subtle sources of variability, inter-annual trends in environmental variables and dynamic relationships between soil and plant variables.

1 INTRODUCTION

In the last few decades, climate change has begun to affect the responses of natural and cultivated vegetation. Although ecosystem response to the climatic trends can be subtle and difficult to detect, changes can have a strong impact on ecosystem health at medium to longer time periods. It is crucial to assess such impacts in order to design effective management strategies. Long-term ecosystem variability can change abruptly due to land use or disturbance or slowly and cumulatively, as in the case of climate change. On the other hand, non-permanent inter-annual variability occurs with annual climate anomalies [1] or land management, e.g., crop rotation and it is important to be able to distinguish between small but significant trends versus natural inter-annual variability. Time series data acquired through remote sensing instruments can provide information about ecosystem dynamics at medium (decadal) time scales and at a frequency that makes it possible to study both abrupt and gradual change in response to short and longer term variability. Such information will allow assessment of multivariate relationships between climate and remote sensing variables as well as among those variables.

Spectral indices are one of the most common techniques used for analyzing remote sensing data [2]. Indices are based on combinations of a small number of bands that enhance specific spectral properties. In vegetated environments spectral indices focus on emphasizing vegetation characteristics. When working with multispectral data only a few bands can be used, therefore indices are usually indicators of general characteristics such as plant cover, greenness, or amount of exposed soil.

The most universal index, NDVI (Normalized Difference Vegetation Index) has been used extensively to monitor ecosystems; in both the spatial and temporal domains [3] because it is proven to be a good indicator of ecosystem parameters like biomass, LAI and FPAR [4] among others. While NDVI derived indices are based on plant pigment absorption there are other indices which try to discriminate vegetation parameters such as water content and the amount of non-photosynthetic vegetation. The NDWI, (Normalized Difference Water Index) is a good indicator of soil and vegetation water content [5]. There are also several indices that characterize non-photosynthetic vegetation, (NPV) [6]. Plants function within a constrained range of biochemical variation. For example, a healthy plant will have high pigment content and also high water and nitrogen contents. Thus indices used to measure these different characteristics are frequently physiologically correlated. Most indices are also constructed using red (R) and/or near-infrared (NIR) bands, which means that they are mathematically correlated.

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The principal advantage of indexes is their ease of use and potential to measure specific bands having known functional properties. Their disadvantage is a reduction in information content due to the decrease in the data dimensionality. Nevertheless, this becomes advantageous when significant information remains and is integrated in a framework for exploitation. For instance, the availability of R and NIR bands on the AVHRR sensor has made it possible to make the first temporal analyses spanning a long time period, showing for the first time, global responses to inter-annual and multi-decadal climate patterns [7].

The MODIS sensor has 7 bands in the optical domain which allow parameterization of the general shape of the reflectance spectrum, providing valuable information about vegetation greenness, moisture conditions, and presence of bare soil and dry vegetation. These data combined with the near-daily acquisition make it possible to use multidimensional schemes such that subtle changes in the spectral shape can be monitored over time for individual pixels and images can be monitored for spatial variation. At present, MODIS provides two vegetation indices; NDVI and EVI (Enhanced Vegetation Index) [8], both of them are based on the R and NIR bands. The use of the SWIR, which is not affected by the path radiance and is highly sensitive to moisture has been largely unexploited.

Several remote sensing studies have explored the relationships between temporal spectral profiles and seasonal dynamics to assess general trends and phenological parameters [9]. Benedetti [10] found a high correlation between NDVI and wheat phenology in Emilia Romagna, Italy, including an exponential increase in NDVI corresponding to maximum spring biomass. Runtunuwu [11] calculated the length of growing season as the period when the vegetation index exceeds a threshold. Although these and other studies have used time series data, analyses have rarely included specific statistical tests for time series. In time series analysis (TSA), a stochastic model is fitted to explain the data dynamics and predict future evolution. These statistical methodologies can uncover subtle relationships and trends contained in the temporal data that offer significant value for research on ecosystem response to climate change. Piwowar and Ledrew [12] proposed the use of the Auto Regressive-Moving Average (ARMA) model to analyze NDVI temporal data. ARMA has been used in ecology and recently also in remote sensing. These methods are appropriate for parameterizing temporal relationships and locating them in a spatial context.

The objective of this research was to assess the potential of three spectral indices to monitor the temporal variability of ecosystems and the relationships between climatic variables and ecosystem change, using two TSA techniques. We also investigated whether indexes not based on R and NIR can provide new information about phenological evolution. We tested two common indices, NDVI and NDWI, and a third index that we introduce in this paper, termed Shortwave Angle Normalized Index (SANI). We tested whether these indexes contain distinct information that can complement each other. In the first part we describe the new index, SANI and explore the spectral variability contained in MODIS bands over the year. In the second part we use TSA to examine the relationships among several indexes and the response of indexes to climatic variables.

1.1 The SANI Index

The SANI index is based on a combination of NIR, SWIR1 and SWIR2 MODIS bands. Whiting et al. [13] demonstrated that the SWIR region could be fitted by an inverted Gaussian function that was highly correlated with moisture content in soils. SANI emulates the general shape of this part of the spectrum as it would be shown by a hyperspectral sensor. To accomplish this we evaluate a triangle with three vertices at NIR, SWIR1 and SWIR2 in terms of the size of the angle at SWIR1 (α_{SWIR1}) and the inclination of the line that connects the NIR reflectance with SWIR2 ($\mathbf{L_{NS}}$) (see figures 1, a and b)

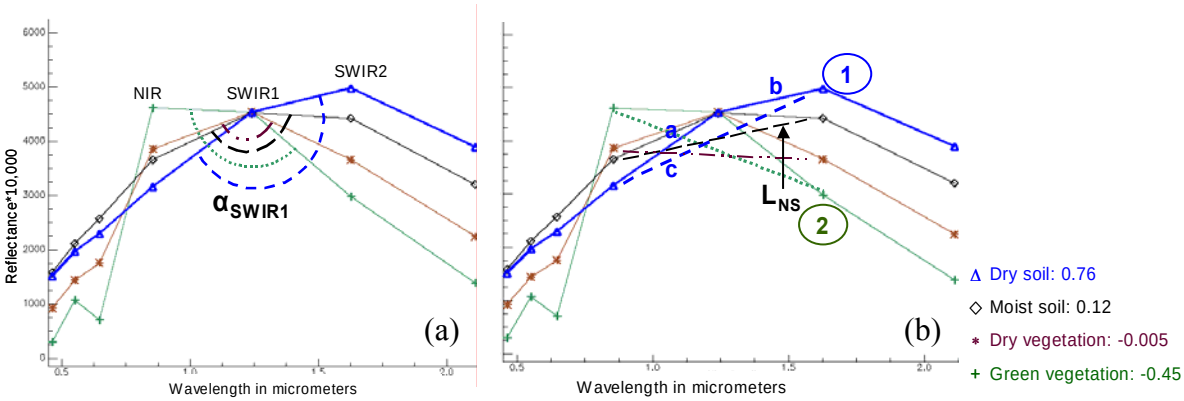

Figure 1. (a) Angle α_{SWIR1} formed at vertex, SWIR1 of the triangle formed by NIR-SWIR1-SWIR2 bands of MODIS and (b) Line L_{NS} that passes through NIR-SWIR2 with sides a, b and c of the triangle.

The angle α_{SWIR1} is large in dry soils and in healthy photosynthetic vegetation (PV), it decreases in NPV and moist soils. The line L_{NS} tilts towards NIR when moisture content increases and towards SWIR2 as the moisture content decreases. As a consequence, the normalized ratio between SWIR2 and NIR is negative in vegetation and positive in soils and is intermediate with different levels of moisture. The extreme negative and positive slopes of L_{NS} are coincident with large α_{SWIR1} in healthy vegetation and dry soil respectively (positions 1 and 2 in figure 1b). Thus, by multiplying the angle, α_{SWIR1} and the normalized difference between NIR and SWIR2, the discrimination of soil, NPV, and PV is emphasized by assigning high positive values to dry soils and high negative values to healthy vegetation. In the case of NPV both, α_{SWIR1} and the normalized ratio are small, so that SANI is close to zero. For moist soils the normalized index is still positive but α_{SWIR1} is smaller with low positive values. It is expected that the main source of error in SANI will be discriminating between NPV and moist soils. Since the index is based on bands sensitive to moisture and not to photosynthetic activity we expect that it to show different dynamics than NDVI. Due to the construction of the index, it is observed that when NDVI is high SANI is low. For example, in healthy full cover vegetation, NDVI is highly positive and SANI is highly negative. We expect that SANI is efficient when discriminating soil and NPV at low NDVI values.

2 DATA AND METHODOLOGY

We used MODIS surface-reflectance (MOD09) 8-day composite images. Two-hundred forty-seven (247) images from February 2000 to July 2005 were downloaded from the MODIS website (http://redhook.gsfc.nasa.gov/) and re-projected to latitude and longitude using the MODIS reprojection tool. Time series data were compiled for each of the seven bands using IDL programming language. Three spectral indices, NDVI, NDWI, and SANI were computed from these bands. We downloaded daily climatic data from the California Irrigation Management Information System (CIMIS) network (http://www.cimis.water.ca.gov/cimis) and summarized them into 8-day values. For solar radiation we calculated the average and precipitation was summed for the 8-day period. Dynamic relationships were studied using TSA using both frequency and temporal domains. Fourier methods [14] are commonly used to measure periodicities and dynamic relationships. We applied Fourier Spectral Analysis (FSA) to search for hidden periodicities in each time series index and determine the dynamic relationships between index and climate variable periodicities. In the temporal domain, we tested the stationarity of the time series using the "Unit Root Test" [15]. All analyses were performed in SAS v8.2. The study areas were located in Central California and consisted of two distinct ecosystems, annual grasslands and summer-irrigated crops. The objective was to determine if we could observe dynamic relationships between indices and climatic variables by studying two distinct phenological cycles in the two land-cover types.

3 RESULTS AND DISCUSSION

3.1 Annual profiles of precipitation and spectral indexes

We describe the annual evolution of the NDVI, NDWI, SANI and precipitation during 2002 for annual grasslands located in the foothills of the Sierra Nevada Range and summer irrigated crops located in the San Joaquin Valley. To assess the functioning of the indexes we also explore typical spectral profiles from the annual grassland site.

3.1.1 Annual Grasslands

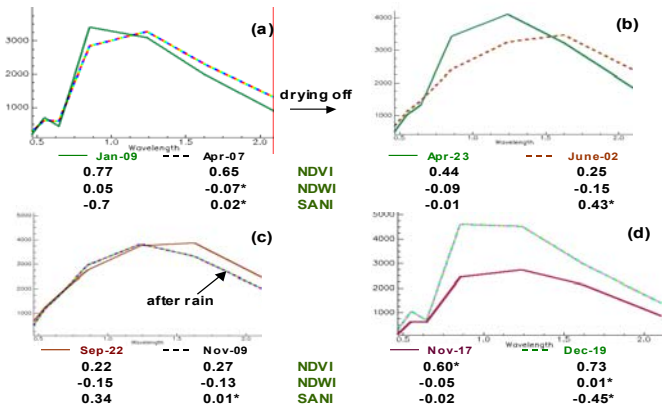

Figure 2: Spectral Profiles at different times of the year for the grassland pixel in the Sierra Nevada foothills. **(a)** January and April, **(b)** April and June, **(c)** September and November and **(d)** November and December

In annual grasslands at this latitude (37 N) with a Mediterranean climate, maximum moisture and photosynthetic activity happen during fall, winter and beginning of spring due to precipitation patterns. The grasslands become dry by mid-spring and by late spring soils become the dominant spectral component of the pixel until the following fall. Figures 2 a, b, c, and d, show the evolution of the spectral profiles from January to December 2002. The asterisks in the index values indicate a significant change from the previous date. The reflectance profiles show a transition from full green cover in January to bare soil in September. In January the spectral shape corresponds to fully green vegetation so NDVI is high (0.77) and NDWI is low but positive (0.05). The NIR reflectance is much larger than SWIR2 and therefore SANI is highly negative (-0.7). By mid-April the spectral profile approaches the typical NPV shape. The decrease in moisture is captured by NDWI, which becomes negative (-0.07) but is even more evident in SANI which increases to -0.02. On the other hand NDVI decreases only slightly (0.65). In contrast, during the rest of April there is a significant decrease in NDVI, while NDWI and SANI barely change. It appears that the drop in moisture is reflected by the rapid change of NDWI and SANI early in the month and the corresponding gradual decrease in green vegetation is evident by the lagged decrease of NDVI. By the beginning of June, the spectral profile is typical of dry soil; NDVI has decreased at a constant rate while SANI has increased significantly, becoming positive. This sign change indicates that the surface residue component is decreasing and soils represent the largest fraction of the pixel. Throughout the summer, reflectance profiles have the typical shape of dry soil, with low NDVI and NDWI and high SANI. By mid-November, after the first week of rains, SANI has decreased markedly due to soil moisture but NDVI and NDWI do not change significantly until late in November when vegetation starts growing due to the available moisture. There is a sharp increase in NDVI (0.33) and SANI becomes negative due to the presence of green vegetation. By mid-December, the pixel is again dominated by green vegetation, NDWI becomes slightly positive (0.01), NDVI increases to 0. 73, and SANI decreases to -0.45.

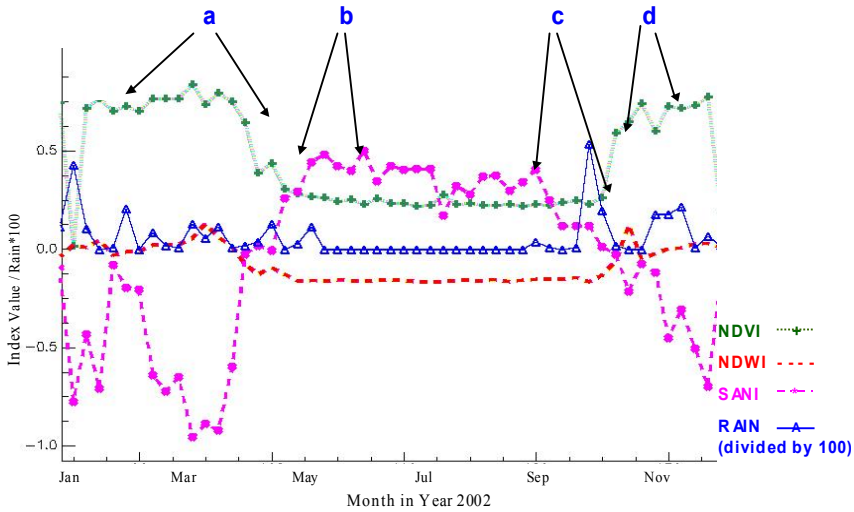

Figure 3: Annual Profile of NDVI, NDWI, SANI and precipitation in the year 2002 for Annual Grasslands

Figure 3 shows the annual evolution of the indices and precipitation for this site. The letters on the graph indicate the spectral profile of dates shown in figures 2.a, b, c, and d. NDVI has continuous high values during fall, winter and early spring and low values in summer. NDWI shows the same trend as NDVI, but with the inflection points happening earlier in spring (March) and later in autumn (October), so that it has a longer period of low values. Also, at the inflection points this index changes sign, so that a threshold at zero could be used as an indicator of the beginning of the dry season. SANI is highly negative during the growing period and highly positive during summer due to the dominance of dry soil. It fluctuates more than NDVI and NDWI during the whole year especially in winter due to its higher dynamic range and its quick response to soil moisture, so that declines in index values are coupled to rain events. At the end of the wet period there is a three week plateau with near zero values due the presence of NPV which is consistently observed in all grassland pixels.

3.1.2 Summer-Irrigated Cropland

For the summer irrigated crops (Figure 4) the indexes follow opposite trends. The cropping practices define the temporal evolution, so that phenological periods are distinct. Irrigation provides enough moisture throughout the year that water is not limiting. During summer there is full vegetation cover, while in winter soil is the main component, except for some greenness due to weeds. There are two distinct short periods, one in spring when green cover is incomplete and one at the end of summer when NPV is present before harvesting. As expected, NDVI is highest during the growing season and lowest but still positive during winter. NDWI is negative except for a short

period in the middle of the growing season (56 days). SANI has the highest dynamic range being negative during summer (i.e., active crop growth) and positive during winter when soil is bare or has minor weed cover. From the end of January to June, NDVI and NDWI are nearly constant while SANI is more variable due to varying soil moisture. SANI decreases sharply in May, which is the beginning of the crop irrigation. Both NDVI and SANI rapidly change at the beginning of the growing season. These indexes reach maximum and minimum values respectively in mid-July.

NDVI and SANI change at the end of the growing season at a slower rate than at the beginning. While at the beginning of the growing period, green cover is growing over bare soil, at the end, green cover is changing to NPV. NDVI keeps decreasing monotonically until November but SANI shows an inflection point in mid-September forming a plateau with near zero values until the end of the month. These low SANI values can be due to either moist soil or presence of NPV. Since this is cropland, we can assume that at the end of the growing season, these values indicate NPV, not high moisture content. This plateau lasts while the dry crop canopy stays on the field. NDWI on the other hand reaches negative values 21 days before SANI when the crop starts to dry out. This indicates that NDWI can be a good indicator of mild desiccation, signifying the early stages of the dry season.

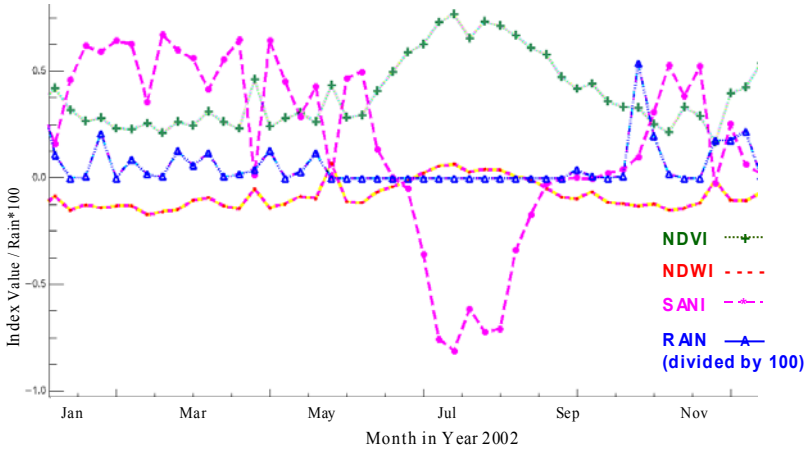

Figure 4: Annual Profile of NDVI, NDWI, SANI and precipitation in the year 2002 for Summer-Irrigated Cropland

3.2 Time Series Analysis for the 5-year period

To analyze the dynamic relationships among indexes and climatic variables we applied TSA to data from February 2000 to July 2005. Figures 5 and 8 show the time series of precipitation, solar radiation, NDVI and SANI for the annual grasslands and the summer-irrigated crop, respectively.

3.2.1 Annual Grasslands

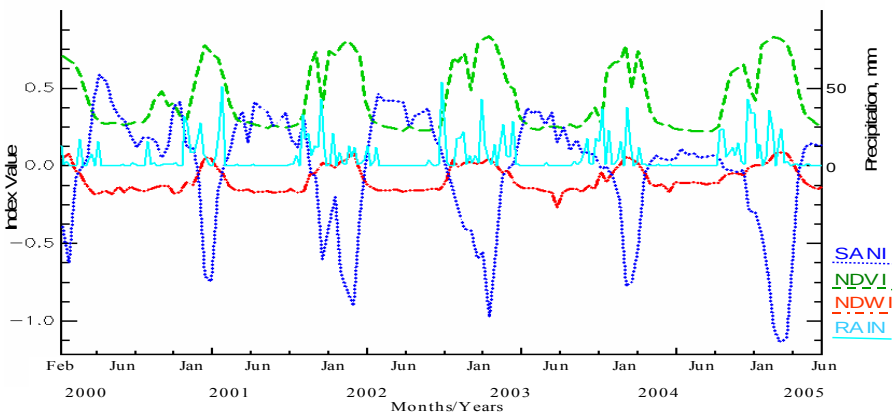

Figure 5: Five year time series of precipitation, NDVI, NDWI and SANI for annual grasslands

A Fourier Spectral Analysis was performed on both indexes at the two study sites**.** Figure 6a shows the periodogram for NDVI and SANI in the annual grasslands. Time series of both indexes exhibit a highly significant and dominant

peak at period 49.4 (fundamental frequency). This period corresponds, in terms of Fourier frequencies, to the annual cycle of 46 8-day periods. The SANI periodogram shows significantly higher values than NDVI in all frequencies, and especially in the fundamental frequency. This indicates that the sum of squares explained by the SANI model in terms of the variance (13.18) is higher than that explained by NDVI (2.44). The first difference periodograms suggest the same result.

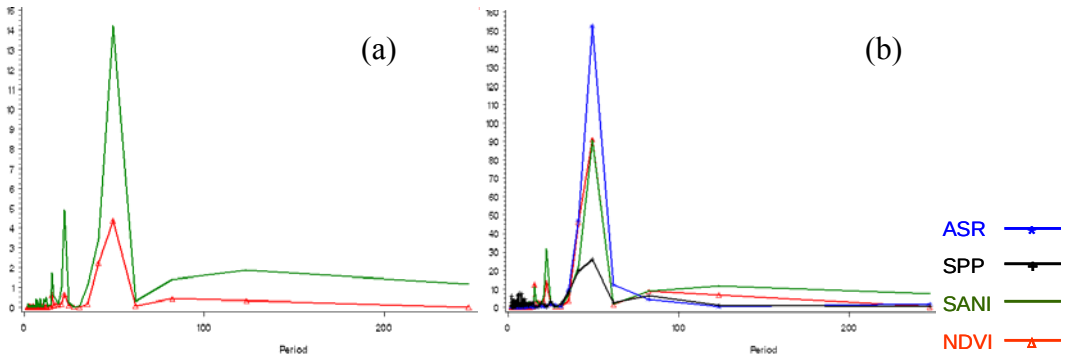

Figure 6: (a) Periodograms for NDVI and SANI five-year time series and (b) Periodograms for standardized values of time series of SPP, NDVI, NDWI and SANI.

In annual grasslands, SANI reaches its minimum value at the Fourier period 27.44 and begins its increasing trend in the next period 30.88, while NDVI reaches its minimum value at Fourier period 30.88 and begins its increasing trend with a lag at period 35.29. The SANI trend precedes NDVI, which is verified by the analysis of first differences of both series. Comparison of periodograms obtained from standardized values of NDVI, SANI, annual solar radiation (ASR) and cumulative precipitation (SPP) as shown in Figure 6b, reveals that the increasing trend for SANI and SPP begins at period 30.88 while for NDVI and ASR that trend begins at period 35.29. Thus SANI closely follows precipitation while NDVI closely follows the dominant annual cycle. Ecologically, by the end of the dry summer, the grasslands are almost bare soil. The first rains bring moisture to the soil, which are tracked efficiently and immediately by SANI. The moisture initiates vegetation growth, which is followed by slowly increasing NDVI. Thus it is observed that NDVI and ASR are simultaneous and lag behind SPP and SANI.

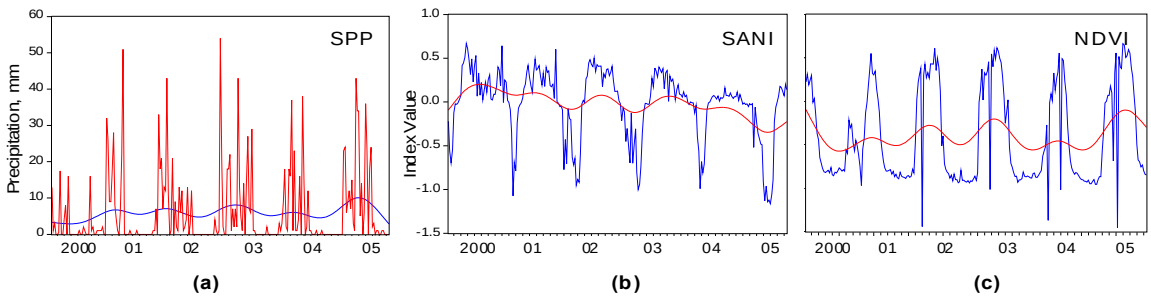

Figure 7: Hodrick-Prescott trends overlaid on the five-year time series of (a) precipitation, (b) SANI and (c) NDVI

Periodograms of SANI, NDVI, ASR and SPP (levels and standardized values) also suggest the presence of long-term trends, particularly in SANI. A stationarity test [15] (Table 2) was applied to investigate the presence of a stochastic trend (unit root) in the time series. The test rejected the presence of a stochastic trend in NDVI (-4.192 < -3.459) but could not reject it for SANI (-0.586 > -2.576). The estimated coefficients of the test indicate a negative stochastic trend in SANI, which is also observed in its time series plot (figure 7b). As precipitation increases, soil and vegetation moisture increases leading to a decrease in SANI. Thus a trend in increasing precipitation from 2001 to 2005 (figure 7a) will manifest itself as a decreasing trend in SANI. This is the pattern observed (figure 7b). However, no such trend is evident for NDVI as shown in figures 7c. The trend line is overlaid on the time series after applying an adaptation of the Hodrick-Prescott filter [16].

3.2.2 Summer-Irrigated Cropland

Figure 9a shows the periodograms for NDVI and SANI in the irrigated summer crop. General trends are similar to those found in grasslands but some significant differences occur in the dynamics of SANI and NDVI. The periodograms of the standardized values of ASR, SPP, NDVI and SANI (Figure 9b), indicate that the last three variables essentially follow the dominant annual cycle. However, SPP, NDVI and SANI begin the increasing trend

at the same Fourier period (30.88). This fact seems to indicate that precipitation influences the start of the cycles in both indexes. Since in irrigated croplands (especially summer crops) water is not a limiting factor both SANI and NDVI are simultaneous (Figure 9b).

Table 1: Augmented Dickey-Fuller (*ADF*) test values for three spectral indices measured in two California sites with the null hypothesis (H_0): the variable has a unit root. k is the number of lags included in the test regression. The AIC2 rule was used to choose the optimal lag length for all tests [17]. Number of observations, N=247.

Site	NDVI	k	SANI	k
Annual Grassland	-4.192*	9	-0.586	45
Irrigated Summer Crop	-4.548*	8	-5.792*	33

* Reject H_0 at the 1% critical value.

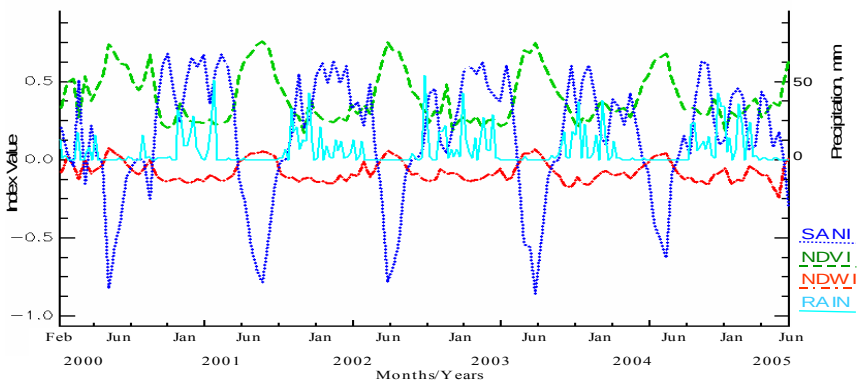

Figure 8: Five year time series of precipitation, NDVI, NDWI and SANI for summer-irrigated cropland

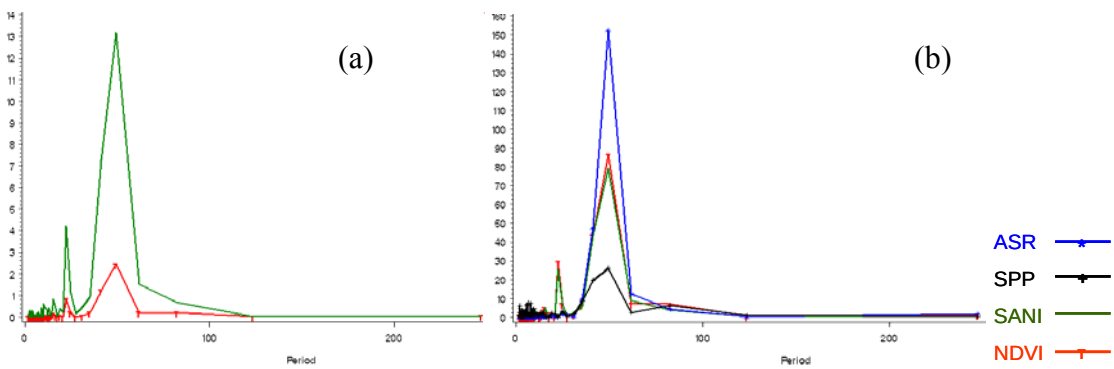

Figure 9: (a) Periodogram for NDVI and SANI five-year time series and (b) Periodograms for standardized values of time series of SPP, NDVI, NDWI and SANI.

Periodograms of SANI, NDVI, ASR and SPP (levels and standardized values) suggest the lack of long-term trends in these series (figures 9 a and b). The Dickey-Fuller test rejects the presence of stochastic trends in both indexes (for NDVI the test value was -4.548<-3.459 and for SANI the test value was -5.792<-3.462, Table 1) and confirms the previous result. As NDVI and SANI both are largely independent of precipitation in summer-irrigated crops, it is expected that the long-term trend of increasing precipitation will not manifest itself in either time-series index. Thus the rejection of trends, especially in the SANI time series only strengthens the argument that SANI is a good indicator of moisture evolution patterns for different land-cover types. The temporal evolution of three indexes has been analyzed from both the spectral perspective and with TSA. Results show that although the main temporal evolution of these indexes follow similar patterns they show differences that provide useful information about ecological functioning and potential for discrimination. The dynamic relationships of these indexes with climatologic time series, as well as variability among them, have been evaluated. SANI is demonstrated to be a good indicator of NPV and soil. It has been shown to be a better indicator of moisture than photosynthetic activity. Its major drawback is that it can confuse wet soil and NPV, which can affect the estimate of soil cover in certain

periods of the year. Nonetheless, if the type of vegetation is known (e.g. cropland, grassland, etc.), the temporal context be used to improve discrimination between these two elements.

4 CONCLUSIONS

While these are preliminary results we observe that SANI is the more sensitive at tracking moisture. This index shows a temporal profile distinct from the other indexes, having higher dynamic range and quicker response time to precipitation. In addition, SANI shows good potential for deriving clear thresholds that discriminate land cover classes. It seems to be a good indicator of NPV and soil. TSA like Fourier spectral analysis and trend detection are proven to be powerful tools for uncovering subtle variations and analyzing dynamic relationships. Future research will explore validating the new index as an indicator of moisture in soils and vegetation.

ACKNOWLEDGEMENTS

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