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ASSESSMENT OF MODIS-EVI, MODIS-NDVI AND VEGETATION-NDVI COMPOSITE DATA USING AGRICULTURAL MEASUREMENTS: AN EXAMPLE AT CORN FIELDS IN WESTERN MEXICO

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Abstract. Although several types of satellite data provide temporal information of the land use at no cost, digital satellite data applications for agricultural studies are limited compared to applications for forest management. This study assessed the suitability of vegetation indices derived from the TERRA-Moderate Resolution Imaging Spectroradiometer (MODIS) sensor and SPOT-VEGETATION (VGT) sensor for identifying corn growth in western Mexico. Overall, the Normalized Difference Vegetation Index (NDVI) composites from the VGT sensor based on bi-directional compositing method produced vegetation information most closely resembling actual crop conditions. The NDVI composites from the MODIS sensor exhibited saturated signals starting 30 days after planting, but corresponded to green leaf senescence in April. The temporal NDVI composites from the VGT sensor based on the maximum value method had a maximum plateau for 80 days, which masked the important crop transformation from vegetative stage to reproductive stage. The Enhanced Vegetation Index (EVI) composites from the MODIS sensor reached a maximum plateau 40 days earlier than the occurrence of maximum leaf area index (LAI) and maximum intercepted fraction of photosynthetic active radiation (fPAR) derived from in-situ measurements. The results of this study showed that the 250-m resolution MODIS data did not provide more accurate vegetation information for corn growth description than the 500-m and 1000-m resolution MODIS data.

Keywords: MODIS, SPOT/VEGETATION, NDVI, EVI

1. Introduction

The Normalized Difference Vegetation Index (NDVI) values are almost linearly correlated to leaf area index (LAI) and the intercepted fraction of photosynthetic active radiation (fPAR) absorbed by the plant canopy (Kumar and Monteith, 1982; Asrar *et al.*, 1984; Gallo *et al.*, 1985). Moreover, the relationship between NDVI and LAI or fPAR is affected by changes in soil reflectance (Choudhury, 1987; Huete, 1988). Current crop modeling involves the utilization of few temporal NDVI values with coincident field measurements to predict grain yield (Báez-González *et al.*, 2002; Dabrowska-Zielinska *et al.*, 2002; Rasmussen, 1998). Few studies have thoroughly examined whether selected satellite data properly provided the crop growth information in the fields. Huete (1988) found that NDVI was sensitive to canopy background variations and exhibited saturated signals for high biomass conditions. Other vegetation indices (VI) such as Soil Adjusted Vegetation Index (SAVI) and Modified Soil Adjusted Vegetation Index (MSAVI) were developed to reduce or eliminate soil influence on solar reflectance values (Huete, 1988; Huete *et al.*, 1994; Qi *et al.*, 1994). The Enhanced Vegetation Index (EVI) suggested by Huete *et al.* (1994) was improved with increased sensitivity for biomass estimation in dense vegetation canopies through a de-coupling of the canopy background signal and a reduction in atmospheric and soil reflectance influence (Huete *et al.*, 2002).

The SPOT-VEGETATION (VGT) data are available in near real time as 10-day NDVI composites at a spatial resolution of 1000 m. The TERRA-Moderate Resolution Imaging Spectroradiometer (MODIS) data are available in real time as 16-day NDVI and EVI composites at spatial resolutions of 250, 500 and 1000 m. The MODIS-EVI was derived from the red (0.62–0.67 μm), near-infrared (0.841–0.876 μm) and blue (0.459–0.479 μm) reflectance data (Huete *et al.*, 1994). The MODIS-NDVI was derived from the red (0.62–0.67 μm) and near-infrared (0.841–0.876 μm) reflectance data, while the SPOT-NDVI was derived from the red (0.61–0.68 μm) and near-infrared (0.78–0.89 μm) reflectance data. NDVI data from these two sensors could not be compared without applying a spectral adjustment. Chen *et al.* (2002a) and Trishchenko *et al.* (2002) found that AVHRR-NDVI data from different NOAA satellites (e.g. NOAA-14 and NOAA-15) or any other satellite sensor could not be compared directly, and concluded that a proper comparison of spectral data from different satellites must account for the spectral response function of the channels. Huete *et al.* (2002) mentioned that MODIS-EVI and MODIS-NDVI data were highly correlated if there were no significant soil background and atmospheric aerosol variations in the data set. VI values vary between -1.0 and $+1.0$. The negative VI values indicate the presence of cloud, snow, or water, and the positive VI values are positively correlated to green vegetation.

The MODIS and VGT sensors have provided global reflectance on a daily basis since 1999 and 1998, respectively. However, the large swath angle makes the satellite observations strongly dependent on the sun-target-sensor geometry (Duchemin *et al.*, 2002). Daily spectral data from the MODIS and VGT sensors were improved by applying atmospheric correction, cloud removal, and bi-directional reflectance distribution function (BRDF) correction (Vermote *et al.*, 2002; Schaaf *et al.*, 2002; Duchemin and Maisongrande, 2002). The current compositing algorithms for the MODIS data include maximum value compositing (MVC) developed by Holben (1986) and view-angle-constrained MVC. The second algorithm was developed to prevent selection of off-nadir pixels, because the first algorithm was intended to choose off-nadir pixels for BRDF-corrected NDVI compositing (Huete *et al.*, 2002). Two types of 10-day composites are produced from VGT data. One is based on a revised MVC method with improved removal of clouds and aerosol, and the other one is Bi-Directional Compositing (BDC) developed by Duchemin *et al.* (2002). Published results showed that the patchworks and orbital track patterns resulted from the association of adjacent pixels from orbits with significantly different satellite zenith angles were visible on the MVC images, but they were removed on the BDC images (Duchemin *et al.*, 2002).

Corn, the most important crop in Mexico, is planted along the west coast of the country. Scientists in Mexico have applied cloud-free NOAA-14 and NOAA-16 Advanced Very High Resolution Radiometer (AVHRR)-NDVI composite data and field measurements to monitor and estimate corn yield in Mexico to ensure a secure national food supply (Báez-González *et al.*, 2002; Chen *et al.*, 2002b, 2003a). The involvement of satellite data for crop modeling was expected to obtain real-time crop growth conditions from satellite data, and reduce fieldwork associated with high labor costs. Hence, the accurate crop modeling depends on information from satellite data. Agricultural fields in Mexico varied in size from less than ten to several hundred hectares (ha). Data from the MODIS sensor with finer spatial resolutions such as 250 m and 500 m can be crucial for studying middle-sized agricultural fields. Little has been published on agricultural applications using MODIS and VGT data.

The first objective of this study was to record the temporal profiles for EVI and NDVI from MODIS and VGT sensors at various resolutions for a complete corn growth season in western Mexico. Temporal profiles would then be compared to actual corn growth stages observed in the fields to evaluate if satellite derived information corresponded to field changes. The other objective was to assess the correlation between EVI data and NDVI data from MODIS and VGT sensors as well as NDVI data from different sensors. For the long-term studies of crop growth monitoring and grain yield prediction, the intention of this work was to evaluate potential satellite data according to field information for national crop modeling in Mexico.

2. Study Sites and Methods

For this study, ten irrigated corn fields near the city of El Carrizo in the state of Sinaloa in western Mexico were selected from a series of field sites for the 2001 to 2002 corn growing season. This area planted with corn has a high density of homogeneous agriculture distributions (Figure 1). Corn development consists of the vegetative stage (include seedling emergence, leaf growth and tasseling) and the reproductive stage (include silking, the milk stage, the dough stage, the dent stage and maturity) (Iowa State University of Science and Technology Cooperative Extension Service, 1997). Irrigated corn fields in Western Mexico are mostly planted from the beginning of November to the end of December. Field measurements included LAI and fPAR derived from ACCUPAR (an instrument for accurate measurement of

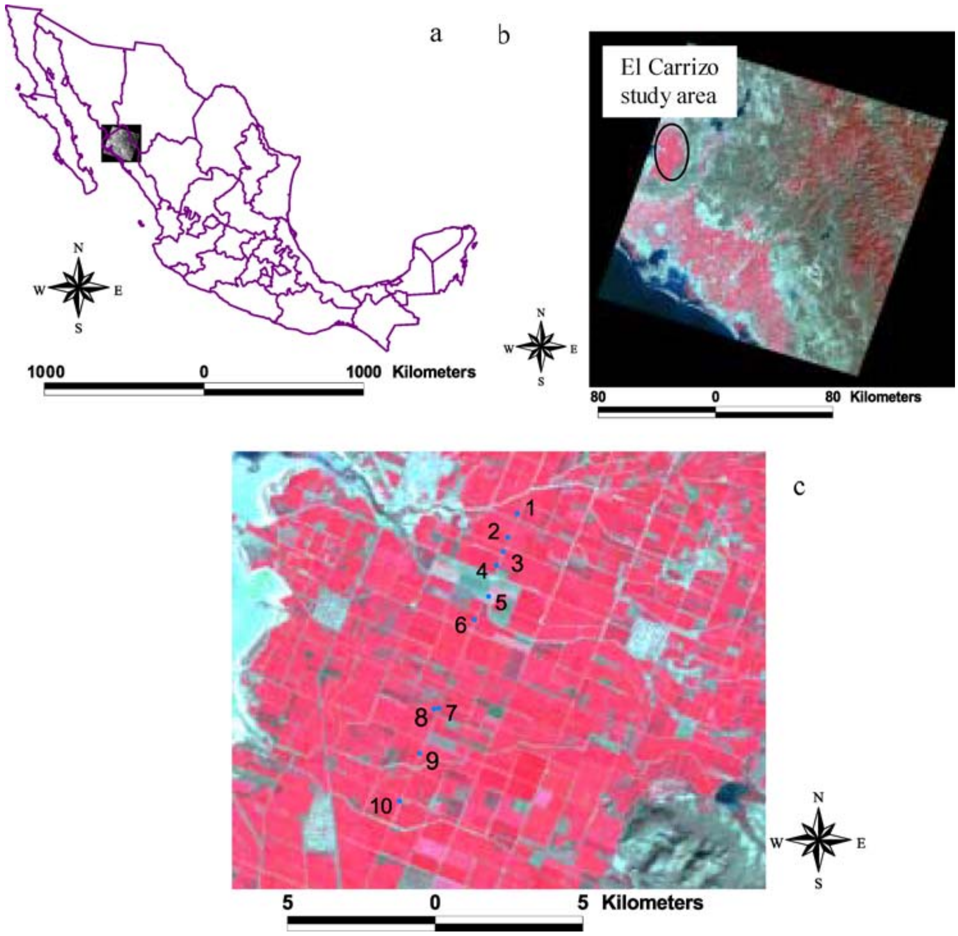

Figure 1. Irrigated corn fields in the El Carrizo study area in the state of Sinaloa in Western Mexico (a) on a Landsat-7 ETM+ image dated on February 8, 2002 as a false color composite of the green, red and near-infrared bands (b) and 10 sampled locations (c) (pixels in red color were agricultural fields planted with corn and pixels in other colors included fallow lands, urban areas, water bodies and agricultural fields for other crops).

PAR and LAI), GPS UTM coordinates and corn growth stage, which were collected once in February and twice in March (Table I). In this study, field data served as a reference to provide corn growth condition in the fields. They were not suitable for statistical analysis, because single sample point per field was not accurate enough to represent entire corn fields within pixels with a spatial resolution between 250 m and 1000 m.

The longitude and latitude of each sampled location were used to extract the NDVI and EVI values from the composite images. One series of 16-day NDVI and EVI composites from MODIS sensor at spatial resolutions of 250, 500 and 1000 m were downloaded from the Distribution Active Archive Center (DAAC)

TABLE I
Field measurements of corn collected in the 2001 to 2002 crop calendar year for the El Carrizo study area

Site	Planting date	Measuring date	Growth stage	Leaf area index	Fraction of photosynthetic active radiation
1	Nov. 30	Feb. 26	Leaf growth	3.13	0.90
		Mar. 11	Leaf growth	5.63	0.98
		Mar. 27	Tasseling	5.74	0.97
2	Dec. 1	Feb. 26	Leaf growth	2.86	0.88
		Mar. 11	Leaf growth	3.41	0.90
		Mar. 27	Tasseling	4.74	0.95
3	Nov. 12	Feb. 26	Leaf growth	2.36	0.81
		Mar. 11	Tasseling	3.69	0.94
		Mar. 27	Silking	5.56	0.97
4	Nov. 3	Feb. 26	Tasseling	4.53	0.94
		Mar. 11	Silking	5.18	0.97
		Mar. 27	milking	5.93	0.97
5	Nov. 24	Feb. 26	Leaf growth	3.45	0.88
		Mar. 11	Tasseling	4.47	0.95
		Mar. 27	Silking	5.8	0.97
6	Nov. 24	Feb. 26	Leaf growth	3.41	0.87
		Mar. 11	Tasseling	4.81	0.96
		Mar. 27	Silking	4.96	0.95
7	Nov. 25	Feb. 26	Leaf growth	3.04	0.84
		Mar. 11	Leaf growth	4.35	0.94
		Mar. 27	Silking	6.71	0.98
8	Nov. 22	Feb. 26	Leaf growth	3.66	0.89
		Mar. 11	Leaf growth	4.87	0.96
		Mar. 27	Silking	6.39	0.98
9	Nov. 17	Feb. 26	Leaf growth	3.62	0.88
		Mar. 11	Tasseling	5.19	0.97
		Mar. 27	Silking	5.47	0.96
10	Nov. 19	Feb. 26	Leaf growth	4.23	0.92
		Mar. 11	Tasseling	6.21	0.98
		Mar. 27	Silking	6.84	0.98

at NASA Goddard Space Flight Center (GSFC) for November 2001 to October 2002. Two types of 10-day NDVI composites from VGT sensor at a spatial resolution of 1000 m were downloaded from the SPOT VEGETATION Program website (http://free.vgt.vito.be) for the same period of time. The 10-day MVC synthesis of VGT-NDVI data was named VGT_S10, and the 10-day BDC synthesis of VGT-NDVI data was named VGT_D10. Downloaded images from the MODIS and VGT sensors were pre-processed and geo-referenced. Accurate geo-referencing is important for studies involving temporal and spatial observations. Individual image was controlled to have a shift less than 1 pixel. Most corn fields near El Carrizo had sizes greater than 0.5 km $\times$ 0.5 km (Figure 1), and the planting time as well as farming practice were very similar within the study area.

3. Results and Discussion

3.1. Satellite data vs. actual field measurements

Three field measurements were collected in one month from late February to the end of March. Corn was in the leaf growth step for the first 90 days (Table I). Báez-González *et al.* (2002) found that the transition from leaf growth to silking was a critical time for predicting crop yields. Field measurements showed that both LAI and fPAR values increased during leaf growth and reached a plateau when the corn was in the tasseling and silking steps starting in the middle of March (about 115 days after planting) (Table I). Most fPAR reached 0.9 or greater starting the beginning of March and lasted for one month, while LAI started peaking in the middle of March. In corn fields, the leaves at the bottom of corn plants started withering when the corn was silking, because the plants in the reproductive stage required large amounts of nutrients to support grain production. Hence, the LAI and fPAR values declined in April when leaves starting turning yellow. The maximum value occurrence of temporal profiles for EVI and NDVI data varied between satellite sensors. Overall, the NDVI temporal profiles from VGT_D10 data provided the best information related to crop growth in the fields. Temporal profiles from VGT_S10 and MODIS-NDVI data were only weakly related to measured crop growth changes. The MODIS-EVI data reached a maximum plateau much earlier than the LAI and fPAR measurements.

Most of the VGT_D10 data reached two peaks within one month. One peak was observed on February 10 (about 85 days after planting) during leaf growth. The other peak occurred on March 10 (about 115 days after planting), when the corn was at the end of the vegetative stage (Table I). The first peak had a NDVI value slightly greater than the second peak. The first peak on February 10 was unusual, since the corn plants in February were still producing new leaves. The second peak of NDVI values on March 10 corresponded to the maximum LAI and fPAR values starting at the end of February or the middle of March. However, the NDVI values declined after March 10, while the LAI and fPAR values peaked at the end of March. A similar study using NOAA-AVHRR data found that maximum LAI values from in-situ measurements of Northern Texas occurred 7-day earlier than maximum NDVI values (Chen *et al.*, 2003b). All NDVI values for VGT_D10 data declined rapidly after April 10 (about 145 days after planting), which corresponded to green leaf senescence in the fields.

The VGT_S10 data always had higher values than the VGT_D10 data when the NDVI values increased in the vegetative stage, but the difference was barely noticeable when the NDVI decreased in the reproductive stage (Figure 2). The NDVI temporal profiles for VGT_S10 data had a smooth transition from leaf growth to leaf senescence, and the maximum plateau extended from January 10 to March

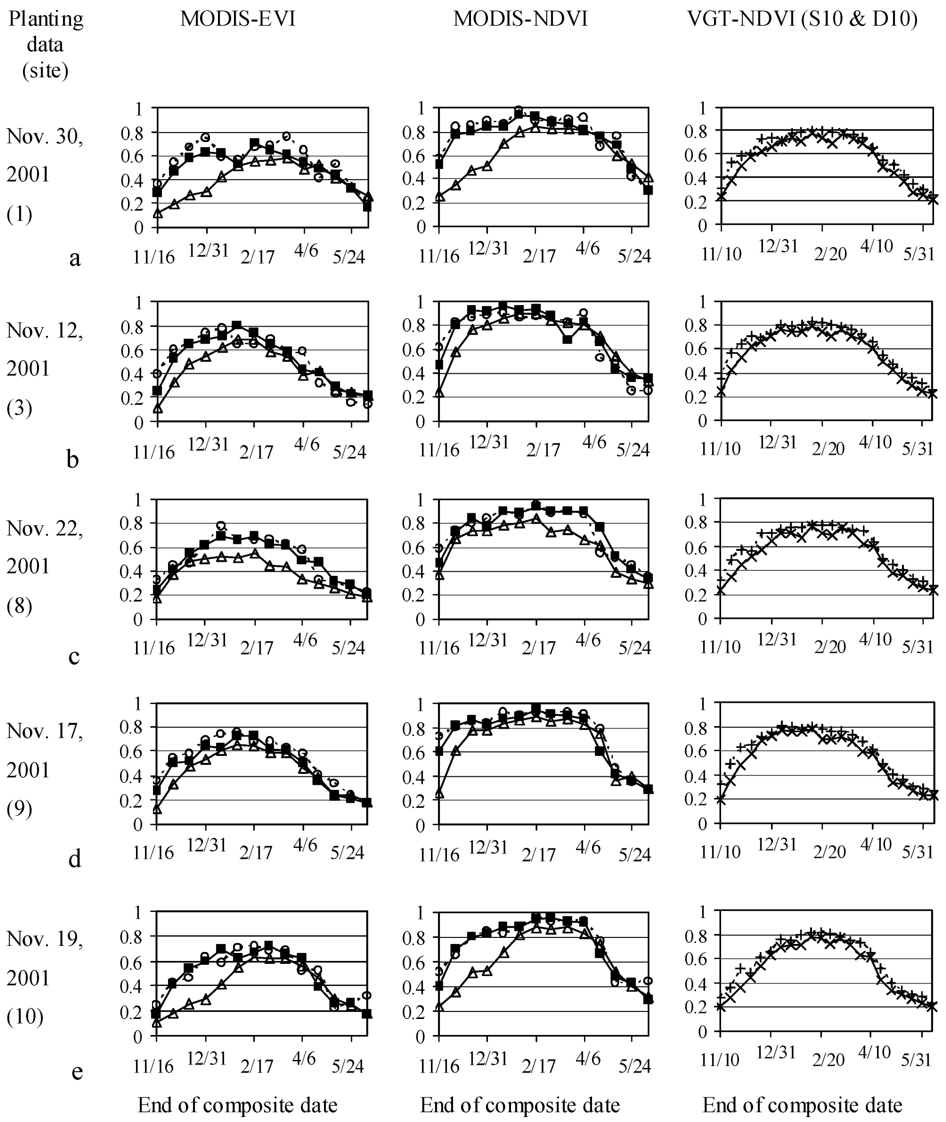

Figure 2. Temporal profiles of 16-day MODIS-EVI and MODIS-NDVI composite data at 250-m (○), 500-m (■) and 1000-m (△) resolutions as well as 10-day VGT_S10 (+) and VGT_D10 (x) composite data for irrigated corn fields at 5 out of 10 sampled locations in the El Carrizo study area of Western Mexico from the end of 2001 to the middle of 2002.

31 (55 days to 135 days after planting). The greater NDVI values and 80-day maximum plateau of VGT_S10 data could be caused by large satellite angles. Larger satellite angles, observing more than one pixel on the ground, generated greater NDVI values, which was most likely being selected for 10-day composites. Cihlar and Huang (1994) found that atmospheric correction may introduce a systematic bias towards the selection of off-nadir pixels for the maximum value composites. The results of that study showed that the BDC compositing method of taking the average of NDVI values effectively reduced the data noise caused by satellite zenith angle and other sources. The maximum values of the VGT_S10 data occurred either on February 10 (about 85 days after planting) or February 20 (about 95 days after planting) when the corn was in the leaf growth stage, similar to results with VGT_D10 data. The VGT_S10 data indicated green leaf senescence in the fields starting in April.

The performances of MODIS-EVI data varied between spatial resolutions (Figure 2). The maximum EVI values for the temporal profiles of EVI data from 250-m pixels (MODIS_EVI_250m) occurred randomly from the middle of January to the end of March. Most of the maximum EVI values for the temporal profiles of EVI data from 500-m pixels (MODIS_EVI_500 m) and 1000-m pixels (MODIS_EVI_1000 m) reached a maximum plateau from the end of January to the middle of February. Both MODIS_EVI_500 m and MODIS_EVI_1000 m data had maximum EVI values around February 17 (about 90 days after planting). A similar behavior was observed for VGT-NDVI data. It is unclear whether the February peak was caused by satellite data noise, by the physical configuration of crop rows or by other atmospheric or weather factors. The MODIS-EVI values decreased slightly when corn plants were growing from the end of February to the middle of March (Figure 2); meanwhile the LAI and fPAR values continuously increased (Table I). Several published results assumed that VIs derived from satellite data corresponded closely to LAI and fPAR measurements. However, this study revealed that there was a time difference between maximum LAI and fPAR values and maximum NDVI or maximum EVI data (Table II). Further work is needed to identify critical growth stages to apply VI values for corn yield prediction. The EVI values declined starting in April, about 10 day earlier than for the VGT-NDVI data. Moreover, the decrease in EVI data was more rapid than in VGT-NDVI data.

Both MODIS_EVI_250 m and MODIS_EVI_500 m data had similar EVI values but varied inconsistently over time. The MODIS_EVI_1000 m data had EVI values less than the MODIS_EVI_250 m and MODIS_EVI_500 m data in the vegetative stage, but all EVI values were very similar when the corn was in the reproductive stage. The reason of MODIS_EVI_250 m and MODIS_EVI_500 m data having greater EVI values was that the finer resolution pixels had less proportion of non-agricultural coverage. On the whole, the MODIS_EVI_250 m temporal profiles were not as smooth as the MODIS_EVI_500 m and MODIS_EVI_1000 m temporal profiles. This behavior may be related to the farming practices or presence of cloud shadows that differed between fields.

TABLE II
Periods of time when leaf area index (LAI), the fraction of photosynthetic active radiation (fPAR) and vegetation indices reached the maximum values for the El Carrizo study area

			MODIS-EVI			MODIS-NDVI			VGT_S10	VGT_D10
Site	LAI	fPAR	250 m	500 m	1000 m	250 m	500 m	1000 m	1000 m	1000 m
1	3/11-3/27	2/26-3/27	12/31 & 3/21	2/17	2/1-3/21	2/1	2/1-3/21	2/1-4/22	12/20-3/31	2/10 & 3/10
2	3/27	3/11-3/27	1/16-2/1	2/1	2/1-2/17	12/2-4/6	12/2-4/6	12/18-4/6	1/10-3/31	1/10 & 2/10 & 3/10
3	3/27	3/11-3/27	1/16	2/1	2/1-2/17	12/2-4/6	12/18-3/5	12/18-4/6	1/10-3/31	1/10 & 2/10 & 3/10
4	3/11-3/27	2/26-3/27	12/31 & 3/5	2/17	2/1-2/17	12/31-4/6	12/18-4/6	12/18-3/21	12/31-3/31	2/10 & 3/10
5	3/27	3/11-3/27	1/16	1/16 & 2/17	12/1-3/21	2/1-4/6	11/16-4/22	12/18-4/22	2/28	3/10
6	3/11-3/27	3/11-3/27	3/5	12/31-2/17	2/1-2/17	1/16-4/6	12/2-4/6	12/18-4/6	12/20-3/31	2/10 & 3/10
7	3/27	3/11-3/27	2/17-3/21	1/16-3/21	12/18-2/17	12/31-4/6	12/2-4/6	12/2-2/17	12/20-3/31	2/10 & 3/10
8	3/27	3/11-3/27	1/16	1/16-2/17	12/18-2/17	1/16-4/6	12/18-4/6	12/2-2/17	12/20-3/31	2/10 & 3/10
9	3/11-3/27	3/11-3/27	12/31-2/1	2/1-2/17	1/16-2/17	1/16-4/6	12/2-4/6	12/18-4/22	12/20-3/20	1/10 & 2/10
10	3/11-3/27	2/26-3/27	2/1-3/21	1/16 & 3/5	2/17-3/21	12/18-4/6	12/2-4/6	2/1-4/6	1/10-3/31	2/10 & 3/10

The acts of MODIS-NDVI data also varied between spatial resolutions, but they all rapidly decreased starting in April when leaves were senescing (Figure 2). For most temporal profiles of MODIS-NDVI data from 1000-m pixels (MODIS_NDVI_1000m), NDVI values dramatically increased during the first month after planting (Figure 2). The increase was restricted in the temporal profiles of NDVI data from 500-m pixels (MODIS_NDVI_500m) and 250-m pixels (MODIS_NDVI_250m), because unusually high NDVI values were observed shortly after planting. Unexpectedly high NDVI values at the beginning of planting can be attributed to soil reflectance that can be especially high in the near-infrared channel. The MODIS_NDVI_250 m pixels had maximum VI values during planting and before emergence because of a homogeneous barren soil for the sampled pixel, while the MODIS_NDVI_1000 m pixels might include tractor pathways and non-agricultural areas in addition to barren soil. The results of this study showed that the soil reflectance affected the MODIS-NDVI data more than the MODIS-EVI and VGT-NDVI data.

The MODIS-NDVI difference between spatial resolutions was minimized after all the corn leaves emerged. The NDVI values were saturated after the middle of December 2001 (30 days after planting), and did not decrease until leaf senescence in April. The saturated phenomenon lasted for about 100 days, when the corn was progressing through the vegetative stage and into the reproductive stage. Most saturated values occurred during the vegetative stage because of the increasing density of corn canopies. No significantly saturated signals were observed in the MODIS-EVI and VGT-NDVI data. The deficiencies of soil reflectance and saturated signals made the MODIS-NDVI data useless for crop growth studies. Hence, the MODIS-NDVI data were not further analyzed in this study. The results of this study indicated that NDVI saturation was related to the spectral ranges of red and near-infrared channels.

3.2. MODIS-EVI AND VGT-NDVI DATA

The linear correlations were pursued for the VGT-NDVI and MODIS-EVI data for the three major crop stages of planting, tasseling and silking. The high correlations between the VGT_S10 and VGT_D10 data were expected because of the same data source and spatial resolution, but the results showed that r^2 values varied between corn stages (Table III). The r^2 values of MODIS-EVI data varied between spatial resolutions and crop growth steps, and the highest r^2 value 0.75 was observed between the MODIS_EVI_250 m and MODIS_EVI_500 m data in the planting step (Table IV). Most MODIS-EVI data had low correlations ($r^2 < 0.4$) between different resolutions, though the MODIS_EVI_500 m and MODIS_EVI_1000 m data were derived based on the MODIS_EVI_250 m data. Similar low correlations were observed between the VGT-NDVI and MODIS_EVI_1000 m data (Table III). The r^2 values for the MODIS_EVI_1000 m data correlated to the VGT_D10 data were 0.58 in the planting stage, less than 0.15 at both tasseling

TABLE III

Summary of statistical correlations between the VGT-NDVI and MODIS_EVI_1000 m data at different steps of corn growth

		VGT_D10 1000 m			VGT_S10 1000 m		
		Planting	Tasseling	Silking	Planting	Tasseling	Silking
VGT_S10	1000 m	0.58	0.94	0.25			
MODIS-EVI	1000 m	0.58	0.051	<0.01	0.41	0.12	< 0.01

TABLE IV

Summary of statistical correlations between the MODIS-EVI data for three spatial resolutions at different steps of corn growth

		MODIS-EVI 500 m			MODIS-EVI 1000 m		
		Planting	Tasseling	Silking	Planting	Tasseling	Silking
MODIS-EVI	250 m	0.75	0.37	0.26	0.31	0.03	0.24
MODIS-EVI	500 m				0.33	0.17	0.45

and silking steps. Similar results occurred between the MODIS_EVI_1000 m data and the VGT_S10 data. The r^2 values were 0.41 in the planting step, less than 0.15 at both tasseling and silking steps. Overall, vegetation information derived from the same sensor or various sensors was barely correlated except the VGT_D10 and VGT_S10 data having a high r^2 value of 0.94 in the tasseling step. Hence, users should be aware of the physical characteristics of satellite data and should examine data appropriateness before applying satellite-based vegetation information for studies.

The MODIS-EVI data are only available as 16-day composite images to minimize the inclusion of pixels with cloud contamination and extreme satellite view angles. For crops with growing seasons of four to five months in Mexico, 16-day composites sometimes fail to indicate the precise crop growth stage or to provide crop condition as a weekly or 10-day composite might. The VGT 10-day composite data provided an improved solution for the study of high density and large-sized agricultural fields near El Carrizo. For example, the MODIS-EVI data presented a major decrease between March 22 and April 6, while the VGT-NDVI data showed a major decrease between April 1 and April 10.

Although the cloud contamination had in principle been removed by the maximum value compositing (MVC) method, visible cloud shadows frequently appeared in the composite data. Chen *et al.* (2003a,b) suggested that pixel-by-pixel cloud detection as well as satellite and solar angle restrictions be applied to the individual scenes before producing composite data. The resulting daily cloud-free data could be used to construct short-time-period composite images valuable for indicating the precise crop growth stage as well as detecting subtle but critical environment changes.

4. Conclusions

The VGT_D10 data provided the most reliable information on corn growth stage in the fields, although the time differences between maximum LAI and fPAR values and NDVI values were about 15 days. The temporal profiles of MODIS-NDVI data had saturated NDVI values from December to March, which only decreased during corn leaf senescence. The MODIS-NDVI was influenced by soil background reflectance and densities of corn leaf canopies. The NDVI values from VGT_S10 data did not present observable saturated phenomenon, but had an 80-day maximum plateau possibly caused by maximum value composites selecting NDVI values from large satellite angles. The MODIS-EVI had a maximum plateau 40 days earlier than the LAI/fPAR from in-situ measurements. All VI values rapidly declined in April when the green leaves started withering and turning yellow. The MODIS-EVI value difference between 250-m and 500-m or 1000-m resolution data was attributable to the proportion of corn fields within a pixel. The MODIS_EVI_250 m data did not appear to provide more accurate information for detecting the change of corn growth. Further studies are needed to determine which factors caused the MODIS_EVI_250 m composite data to be noisier than the coarse resolution data.

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References

Asrar, G., Fuchs, M., Kanemasu, E. T. and Hatfield, J. L.: 1984, 'Estimating absorbed photosynthetically active radiation and leaf area index from spectral reflectance in wheat', *Agronomy Journal* **76**, 300–306.

Báez-González, A. D., Chen, P. Y., Tiscareño-López, M. and Srinivasan, R.: 2002, 'Using satellite and field data with crop growth modeling to monitor and estimate corn yield in Mexico', *Crop Science* **42**, 1943–1949.

Baret, F. and Guyot, G.: 1991, 'Potentials and limits of vegetation indices for lai and apar assessment', *Remote Sensing Environment* **35**, 161–173.

Chen, P. Y., Srinivasan, R. and Fedosejevs, G.: 2003a, 'An automated cloud detection method for daily NOAA-16 AVHRR data over texas and Mexico', *Journal of Geophysical Research-Atmosphere* **108**(D23), 1–9.

Chen, P. Y., Srinivasan, R., Fedosejevs, G., Báez-González, A. D. and Gong, P.: 2002a, 'Assessment of NDVI composite using merged NOAA-14 and NOAA-15 AVHRR sata', *Geographic Information Sciences* **8**, 31–38.

Chen, P. Y., Srinivasan, R., Fedosejevs, G. and Kiniry, J. R.: 2003b, 'Evaluating different NDVI composite techniques using NOAA-14 AVHRR data', *International Journal of Remote Sensing* **24**, 3403–3412.

Chen, P. Y., Srinivasan, R., Fedosejevs, G. and Narasimhan, B.: 2002b, 'An automated cloud detection method for daily NOAA-14 AVHRR Data for texas, USA', *International Journal of Remote Sensing* **23**, 2939–2950.

Choudhury, B. J.: 1987, 'Relationship between vegetation indices, radiation absorption, and net photosynthesis evaluated by sensitivity analysis', *Remote Sensing of Environment* **22**, 209–233.

Cihlar, J. and Huang, F.: 1994, 'Effect of atmospheric correction and viewing angle restriction on AVHRR data composites', *Canadian Journal of Remote Sensing* **20**, 132–137.

Dabrowska-Zielinska, K., Kogan, F., Ciolkosz, A., Gruszczynska, M. and Kowalik, W.: 2002, 'Modeling of crop growth conditions and crop yield in poland using AVHRR-based indices', *International Journal of Remote Sensing* **23**, 1109–1123.

Duchemin, B., Berthelot, B., Dedieu, G., Leroy, M. and Maisongrande, P.: 2002, 'Normalisation of directional effects in 10-day global syntheses derived from VEGETATION/SPOT: II. validation of an operational method on actual data sets', *Remote Sensing of Environment* **81**, 101–113.

Duchemin, B. and Maisongrande, P.: 2002, 'Normalisation of directional effects in 10-day global syntheses derived from VEGETATION/SPOT: I. investigation of concepts based on simulation', *Remote Sensing of Environment* **81**, 90–100.

Gallo, K. P., Daughtry, C. S., and Bauer, M. E.: 1985, 'Spectral estimation of absorbed photosynthetically active radiation in corn canopies', *Remote Sensing of Environment* **17**, 221–232.

Hatfield, J. L., Asrar, G. and Kanemasu, E. T.: 1984, 'Intercepted photosynthetically active radiation estimated by spectral reflectance', *Remote Sensing of Environment* **14**, 65–75.

Holben, B. N.: 1986, 'Characteristics of maximum values composite images from temporal AVHRR data', *International Journal of Remote Sensing* **7**, 1417–1434.

Huete, A. R.: 1988, 'A soil-adjusted vegetation index (SAVI)', *Remote Sensing of Environment* **25**, 295–309.

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X. and Ferreira, L. G.: 2002, 'Overview of the radiometric and biophysical performance of the MODIS Vegetation indices', *Remote Sensing of Environment* **83**, 195–213.

Huete, A., Justice, C. and Liu, H.: 1994, 'Development of vegetation and soil indices for MODIS-EOS', *Remote Sensing of Environment* **49**, 224–234.

Iowa State University of Science and Technology Cooperative Extension Service: 1997, 'How a corn plant develops', Special Report No. 48, Ames, Iowa.

Justice, C. O., Townshend, J. R. G., Vermote, E. F., Masuoka, E., Wolfe, R. E., Saleous, N., Roy, D. P. and Morisette, J. T.: 2002, 'An overview of MODIS land data processing and product status', *Remote Sensing of Environment* **83**, 3–15.

Kumar, M. and Monteith, J. L.: 1981, 'Remote sensing of crop growth', in: H. Smith (eds), *Plants and the Daylight Spectrum*, Academic Press, London, England, pp. 133–144.

Lobell, D. B., Hicke, J. A., Asner, G. P., Field, C. B., Tucker, C. J. and Loss, S. O.: 2002, 'Satellite estimates of productivity and light use efficiency in united states agriculture, 1982–1998', *Global Change Biology* **8**, 722–735.

Prince, S. D.: 1991, 'A model of regional primary production for use with coarse resolution satellite data', *International Journal of Remote Sensing* **12**, 1313–1330.

Qi, J., Chehbouni, A., Huete, A. R., Kerr, Y. H. and Sorooshian, S.: 1994, 'A modified soil adjusted vegetation index', *Remote Sensing of the Environment* **48**, 119–126.

Rasmussen, M. S.: 1998, 'Developing simple, operational, consistent NDVI-vegetation models by applying environmental and climatic information. Part II: Crop yield assessment', *International Journal of Remote Sensing* **19**, 119–139.

Ruimy, A., Saugier, B. and Dedieu, G.: 1994, 'Methodology for the estimation of terrestrial net primary production from remotely sensed data', *Journal of Geophysical Research* **99**, 5263–5283.

Schaaf, C. B., Gao, F., Strahler, A. H., Lucht, W., Li, X., Tsang, T., Strugnell, N. C., Zhang, X., Jin, Y., Muller, J. P., Lewis, P., Barnsley, M., Hobson, P., Disney, M., Roberts, G., Dunderdale, M., Doll, C., D'entremont, R. P., Hu, B., Liang, S., Privette, J. L. and Roy, D.: 2002, 'First operational brdf, albedo nadir reflectance products from MODIS', *Remote Sensing of Environment* **83**, 135–148.

Trishchenko, A. P., Cihlar, J. and Li, Z.: 2002, 'Effects of spectral response function on surface reflectance and NDVI measured with moderate resolution satellite sensors', *Remote Sensing of Environment* **81**, 1–18.

Vermote, E. F., El Saleous, N. Z. and Justice, C. O.: 2002, 'Atmospheric correction of MODIS data in the visible to middle infrared: First results', *Remote Sensing of Environment* **83**, 97–111.

Wiegand, C. L. and Richardson, A. J.: 1990, 'Use of spectral vegetation indices to infer leaf area, evapotranspiration and yield: II. Results', *Agronomy Journal* **82**, 630–636.