# COMPARISONS OF MODIS VEGETATION INDEX PRODUCTS WITH BIOPHYSICAL AND FLUX TOWER MEASUREMENTS

**By**

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## Chapter II

## ABSTRACT

Vegetation indices (VI ) play an important role in studies of global climate and biogeochemical cycles, and are also positively related to many biophysical parameters and satellite products, such as leaf area index (LAI), gross primary production (GPP), land surface water index (LSWI) and land surface temperature (LST). In this study we found that VI's had strong relationships with some biophysical products, such as gross primary production, yet were less well correlated with biophysical structural parameters, such as leaf are index. The relationships between MODIS VI's and biophysical field measured LAI showed poor correlation at semi-arid land and broadleaf forest land cover type whereas cropland showed stronger correlations than the other vegetation types. In addition, the relationship between the enhanced vegetation index (EVI)-LAI and normalized difference vegetation index (NDVI)-LAI did not show significant differences. Comparisons of the relationships between the EVI and NDVI with tower-measured GPP from 11 flux towers in North America, showed that MODIS EVI had much stronger relationships with tower-GPP than did NDVI, and EVI was better correlated with the seasonal dynamics of GPP than was NDVI. In addition, there were no significant differences among the 1x1, 3x3 and 7x7 pixel sample sizes. The comparisons of VIs from the 3 MODIS products from which VI's are generated (Standard VI (MOD13)), Nadir Adjusted Surface Reflectance (NBAR (MOD43)), and Surface Reflectance (MOD09)), showed that MODIS NBAR-EVI (MOD43) was best correlated with GPP compared with the other VI products. In addition, the MODIS VI – tower GPP relationships were

significantly improved using NBAR-EVI over the more complex canopy structures, such as the broadleaf and needleleaf forests.

The relationship of tower-GPP with other MODIS products would be useful in more thorough characterization of some land cover types in which the VI's have encountered problems. The land surface temperature (LST) product were found useful for empirical estimations of GPP in needleleaf forests, but were not useful for the other land cover types, whereas the land surface water index (LSWI) was more sensitive to noise from snowmelt, ground water table levels, and wet soils than to the canopy moisture levels. Also the MODIS EVI was better correlated with LST than was NDVI. Finally, the cross- site comparisons of GPP and multi- products from MODIS showed that the relationships between EVI and GPP were the strongest while LST and GPP was the weakest. EVI may thus be useful in scaling across landscapes, including heterogeneous ones, for regional estimations of GPP, especially if BRDF effects have been taken into account (such as with the NBAR product). Thus, the relationships of EVI-GPP over space and time would potentially provide much useful information for studies of the global carbon cycle.

# I. INTRODUCTION

## *Introduction and Context of the problem*

The Moderate Resolution Imaging Spectroradiometer (MODIS), onboard NASA's Earth Observing System Terra platform, is designed for monitoring global vegetation biophysical and radiation budget parameters that influence carbon, water and surface energy fluxes. MODIS has been operating since 2000 and has generated many land data products, including vegetation indices (VI's). VI's play an important role in studies of global climate and biogeochemical cycles, and are also positively related to many biophysical products and the other spectral indices, such as leaf area index (LAI), land surface water index (LSWI) and land surface temperature (LST) etc.. In addition, VI's are utilized in several biogeochemical models that are intended for monitoring seasonal and spatial patterns in photosynthetic activity, or gross primary production (GPP).

Since VIs are very precise indices and strongly correlate with many biophysical characteristics. Many studies have investigated in these relationships with biophysical and biogeochemical products by using empirical-based approaches. Nevertheless, uncertainties in the MODIS VI's are present, resulting from variations in sun-sensor geometries, soil background, and canopy structural differences, as well as uncertainties due to corrections for atmospheric effects and also the chemical, water content, and structure dynamics of vegetation canopies, which vary with seasonal and environmental conditions.

Moreover, the relationship between VI's and biophysical products enable scaling-up from canopy stand levels to large areas and across many land cover types. As satellite data is increasingly being used to investigate climate change and forecast ecological change, it becomes important to validate and better characterize satellite data and investigate their relationships with sites with known surface conditions and biophysical quantities. Accordingly, validation of satellite products are difficult, as is characterizing their error and uncertainties. Thus, the improvement of VI's by minimizing noise and uncertainties would significantly improve the quality and accuracy of biophysical retrievals and render their use more valuable for global carbon cycle and climate change studies.

***Objectives***

The main objective of this study is to investigate the empirical relationships between MODIS EVI and MODIS NDVI with several biophysical products, including field-measured canopy properties, tower-based canopy fluxes, and satellite-derived vegetation products. We also investigated and compared the differences in the biophysical relationships derived from three different MODIS products that enable computation of VI's, namely the standard VI (MOD13), the nadir adjusted surface reflectance product (MOD43), and the surface reflectance (MOD09).

***Overview of dissertation***

MODIS VIs include the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). Whereas the NDVI is chlorophyll sensitive, the EVI is more responsive to canopy structural variations, including leaf area index (LAI), canopy type, plant physiognomy, and canopy architecture. Thus this study we compared the relationship between 2 VIs with biophysical parameters by separating into 3 chapters as the following:

In chapter II we investigated the relationships between EVI and NDVI, with field measured LAI and also evaluated how nadir-adjusted VI's improve upon the uncertainties generated from the standard VI's. In the chapter III, we explored the relationships and interannual variations of MODIS VI's and tower-GPP fluxes, compared the relationships between EVI and NDVI with tower GPP, and also explored the pixel sampling size variability in VI-GPP relationships in order to find the best spatial scale that coincide with flux tower footprints. Moreover, we made comparisons of VI's generated from the 3 different VI-products (MOD09, MOD13 and MOD43) to assess the best satellite- tower relationships. For chapter IV, we analyzed the seasonal dynamics and compared the relationships among multiple MODIS products that describe canopy states and processes, including the EVI, NDVI, Land Surface Water Index, and Land Surface Temperature products, with tower flux GPP measurements, and then compared their interrelationships to each other. We also investigated the global, cross-site relationships of the VI's and biophysical products.

# II. COMPARISON OF MODIS VEGETATION INDEX PRODUCTS WITH GROUND AND SATELLITE-BASED LAI

## *Introduction*

Vegetation indices (VIs) play important roles in studies of global climate and biogeochemical cycles, especially for the case of carbon, with about a quarter of atmospheric carbon dioxide potentially fixed as gross primary production by terrestrial vegetation annually (Myneni et al., 1997). Spectral transformations of two or more wavebands (especially visible and near-infrared wavelengths) are combined to formulate spectral vegetation indices, which allow measurement of spatial and temporal variations in terrestrial vegetation photosynthetic activity and canopy structure. VIs are computed without any bias or assumptions regarding land cover class, soil type, or climatic conditions (Huete at al., 2002) and thus provide a precise and continuous measure of seasonal, inter annual dynamics of vegetation structural, phenological, and biophysical parameters. Therefore, VIs are important parameters to various kinds of local, and global scale models, including agricultural and rangeland growth models, general circulation models, and biogeochemical models. They are also utilized in various operational applications such as famine early warning systems, land cover classification, health and epidemiology, drought detection, land degradation, deforestation, change detection and monitoring (http://tbrs.arizona.edu/cdrom/VI_Intro/VI_Introduction.html). In addition, VIs have also been shown to be well correlated with vegetation parameters such as green cover fraction, biomass, and the two key variables required in primary production and global climate studies namely leaf area index (LAI) and the fraction of absorbed photosynthetically active radiation (fAPAR). (Tucker, 1979; Asrar et al., 1989; Sellers, 1985). Since VIs are very precise indices and strongly correlated with many biophysical characteristics, many studies have investigated their relationships with biophysical parameters.

One of the most extensively applied relationships are between VIs and LAI. LAI is a key biophysical variable influencing vegetation photosynthesis, transpiration, and the energy balance of the land surface (Bonan, 1995; Running, 1990). Moreover, LAI is an important parameter in ecosystem process models and carbon and hydrologic cycle models (Gower et al., 1999). Consequently, the relationship of VI-LAI is potentially useful in measurement and monitoring of land surface characteristics especially, in the analysis of large-scale changes and for studying of global phenomena.

In early research, Jordan (1969) found a strong correlation between red and near-infrared transmittance ratio and LAI. Also, the ratio vegetation index (RVI) (Pearson and Miller, 1972), normalized difference vegetation indices (NDVI), and the perpendicular vegetation index (PVI) (Richardson and Wiegand, 1977) have been found to be well correlated with various vegetation variables such as green leaf area (Wiegand et al., 1979; Holben et al., 1980; Asrar et al., 1984, 1985; Hatfield et al., 1985; Clevers, 1989), the amount of leafy biomass or LAI (Tucker, 1979; Elvidge and Lyon, 1985), percent ground cover, amount of photosynthetically active tissue (Wiegand et al. 1984), and photosynthetic activity (Choudhury, 1987; Hatfield et al., 1984; Sellers, 1985; 1987). Many studies have established the relationships between LAI and remote sensing data (Badhwar et al., 1986; Peterson et al., 1987; Turner et al., 1999) by relying on empirical relationships between the ground-measured LAI and observed spectral responses (Curran et al., 1992; Peddle et al., 1999). In 1995, Myneni et al. used the empirical method to provide the theoretical interpretation of the relationship between vegetation indices and LAI. In addition, many researchers have applied empirical methods on various vegetation types, e.g., grasslands (Friedl et al., 1994), shrublands (Law & Waring, 1994), agroecosystems (Cohen et al., 2003), conifer forests (Chen & Cihlar, 1996; Cohen et al., 2003) and broadleaf forests (Fassnacht et al., 1997).

However, the retrieval of LAI using empirical approaches in establishing relationships between VIs and biophysical parameters, such as LAI, may be fail in the case where there are external influences associated with variable solar and viewing geometries, soil background, chlorophyll concentrations, or moisture conditions are different (Jacquemoud et al., 1995). Some researchers have found uncertainties between VI-LAI relationships, Sellers (1985) found that vegetation indices approach a saturation level asymptotically for a certain range of LAI and respond linearly to fAPAR. Baret and Guyot (1991) investigated the relationships between VI and LAI or photosynthetic active radiation by using the SAIL reflectance model and found the asymptotic trend of the VI-LAI when LAI became greater than 3. Moreover, many studies have concluded that the relationships of VI to LAI/fAPAR are dependent on canopy structure, land cover, leaf angle distribution, vegetation clumping, row orientation, spacing, and the optical properties of the canopy components (Asrar et al., 1992; Baret and Guyot, 1991; Choudhury, 1987; Goward and Huemmrich, 1992; Roujean and Breon, 1995). Different canopy types show drastic variations in canopy structure and reflectance properties, which can produce different VI values while having identical LAI or fAPAR values (Gao et al., 2000).

Also, many studies have been made on the uncertainties of VI in order to optimize and render them insensitive to variations in sun-surface-sensor geometries, atmosphere, calibration, and canopy background. As found in some studies, the darker soil substrates result in much higher normalized difference vegetation index (NDVI) [Eq. (1)] values in vegetated canopies while bright soil influences resulted in high perpendicular vegetation index (PVI) values (Huete et al., 1985; Elvidge et al., 1985; Roberts et al., 1990).

$$\mathrm{NDVI} = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \qquad \text{....(1)}$$

The atmospheric correction algorithm and bi-directional reflectance distribution function (BRDF) models help to improve the geometry problems and the soil adjusted vegetation index (SAVI) (Huete, 1988) helps to correct the brightness effect on VI from canopy background effect. The atmospheric resistance concepts were developed by Kaufman and Tanre (1992) by using the blue band for atmospheric correction to improve vegetation indices.  For instance to account for residual atmospheric contamination and variable soil background reflectance, the enhanced vegetation index (EVI) [Eq. (2)] was developed (Liu and Huete, 1995; Huete et al., 1997).

$$\mathrm{EVI} = 2.5 \times \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L} \qquad \text{....(2)}$$

The coefficients developed for the Moderate Resolution Imaging Spectroradiometer (MODIS) are L=1, $C_1$ =6, and $C_2$=7.5.

Remote sensing has played an important role in biosphere studies by measuring vegetation characteristics and their physical properties at global scales. The Moderate resolution imaging spectroradiometer (MODIS), onboard the Earth Observatory System (EOS) Terra platform was launched in December 1999 and began to provide MODIS Products since the year 2000. MODIS was designed to measure biological and physical processes on a global basis every 1 to 2 days with seven spectral bands and at spatial resolutions from 250 m, 500m and 1km. MODIS provides consistent spatial, and temporal comparisons of global vegetation conditions that can be used to monitor photosynthetic activity (Justice et al., 1998; Running et al., 1994). Whereas the NDVI is chlorophyll sensitive, the EVI is more responsive to canopy structural variations, including leaf area index (LAI), canopy type, plant physiognomy, and canopy architecture (Gao et al., 2000).

The NDVI, and EVI like most other remotely sensed measures, are not intrinsic physical quantities, but serve as surrogates and are correlated with certain physical properties such as LAI. The NDVI still has some limitations for example; attenuation by the atmospheric and by aerosols; the sensitivity of NDVI to LAI becomes increasingly weak with increasing LAI beyond between 2 and 3 (Carlson & Ripley, 1997) and soil brightness (Liu & Huete, 1995) as mentioned before.

This study is focused on the evaluation and uncertainties in biophysical retrievals from MODIS VIs with an emphasis in the spatial domain. We analyzed the relationship of the two VI indices, EVI and NDVI, with LAI and also evaluated how nadir-based VI composites improve the uncertainties generated from regular VIs. In addition, we compared the satellite based with ground based cases for different land cover types in order to investigate suitable ways for validation purposes.

As satellite data is increasingly being used to investigate climate change and forecast ecological change, it becomes important to validate and better characterize satellite data and investigate their relationships with sites with known surface conditions and biophysical quantities. The validation of satellite products is a difficult task as is characterizing their error and uncertainties. Thus, the improvement of VI by minimizing noise and uncertainties would significantly improve the quality of biophysical estimation.

***Methodology***

***A. Study area, Sample design for field measurement, and Satellite data***

Five different land cover types were used in this study, with one study site, Walnut Gulch located in Arizona and four study sites from the Bigfoot (MODIS land validation project). These sites included Harvard forest (mixed broadleaf forest), Agro (agricultural cropland), Konza (tallgrass prairie) and Sevilleta (desert grassland). The site information and the detail of methodology for each site are described as the following;

***Walnut Gulch Experimental Watershed (WGEW) Study Site***

***Site Background***

Walnut Gulch is located in the transition zone between Sonoran and Chihuahuan desert in Southern Arizona, U.S.A. (31° 43′N, 110° 41′W) encompasses the 150 $km^2$. It is one of the most densely monitored semiarid rangeland watersheds in the world and has been a critical watershed toward improving the scientific understanding of semiarid ecosystems. The watershed is contained within the upper San Pedro River Basin in southwest Arizona. The study area lies inside this watershed and is composed by grass and shrub dominated by creosote bush (Larrea tridentata), tarbush (Flourensia cernua), Sandpaper bush (Mortania scabrella), and whitethorn (Acacia constricta) which covers about 2/3 of the watershed. The remaining 1/3 is grassland, dominated mainly by black grama (Bouteloua eriopoda), blue grama (Bouteloua gracilis), sideoats grama (Bouteloua curtipendula), lehmann lovegrass (Eragrostis lehmanniana) and tobosa grass (Hilaria jamesii). Figure 1 shows the study area at Walnut Gulch with 2 intensive study areas; the Lucky Hills (brush dominated) and Kendall (grass dominated).

LAI measurement for this study was the part of Soil Moisture Experiment 2004 (SMEX04) project. The project focuses on topography, vegetation, and strengthening the soil moisture components of the North American Monsoon Experiment (NAME). Field experiment provided the critical soil moisture products by using the new generation of satellite sensors.

***Sampling Design and Field measurement***

This site has a network of 88 rain gauges used to record rainfall over the watersheds. 51 rain gauge locations were selected for the LAI sampling measurement plots for this study. Each plot was designed to have subplot measurements by taking a reading every 5 meters on a 25-meter transect with 3 replications located 10 meters apart for each transect. The lay out for plot sampling is shown in figure 2. Plot location were determined using a Global Positioning System (GPS). The LAI was measured with LAI 2000 Plant Canopy Analyzer for each subplot and then averaged to provide a single value for each plot. The field measurements were performed during July 29$^{th}$ , 2004 to August

25th , 2004. The sampling sites were separated into two groups by using the land cover classification map as shown in figure 3 in order to separate into two dominant vegetation types, grass and shrub, for this study site. There are 6 subgroups for each vegetation type and 3-5 rain gauges were combined to form one subgroup. The resulting subgroups of shrubland and grassland are shown in table 1 and 2. The mean LAI field value of each subgroup was derived from the average of the combined rain gauges in that subgroup (table 1, 2).

***Satellite Data***

We downloaded the 16-day, 250m resolution Vegetation Indices (MOD13Q1), the 16-day, 1km resolution VI (MOD13A2) and the16-day, 1km resolution Nadir BRDF Adjusted Reflectances (MOD43B4) for 2 composites from the EROS Data Center, US Geological Survey (http://www.edc.usgs.gov/).The period covered the duration of the field sampling period (during July 29th -August 6th 2004 and August 14th –August 25th 2004). We extracted the vegetation indices and spectral reflectances for the 250-m and 1-km pixels based on geo-location (latitude and longitude) of the raingauge locations. Since each raingauge is approximately 1-km apart so either 250-m or 1-km resolution, there will be only one pixel that matches with one raingauge so each pixel did not overlap each other as shown in figure 4.

For MOD43B4 after extracted we received 7 spectral band values, then we calculated VI value from NDVI and EVI equation (1) and (2) respectively.

For MOD15A2, the leaf area indices are produced at 1km spatial resolution and for 8-day compositing period obtained from the same source and the same period of time as

VIs and NBAR products. Since MOD15 LAI products were available as 8-day composites thus we averaged two consecutive periods of these data in order to conform to 16-day VIs. Similar to the MODIS VI, we also extracted the 8-day LAI compositing data downloaded from the same source and the same period of time. The standard VI, NBAR, and LAI products were processed by using quality assurance method prior to analyses. After that we performed the relationship by using linear regression method (as the detail in 2.2 Regression method)

***Bigfoot Study Site***

***Site Background***

Bigfoot is MODIS land validation designed to provide ecological data in order to validate the data products derived from MODIS and related sensors. The validation data are provided by Bigfoot and include land cover, LAI, FPAR, and net primary production (NPP). The Bigfoot project is working at nine flux tower sites from Alaska to Brazil. Each site representative of one or two distinct biomes. Bigfoot collected field-based data over 25 $km^2$ (5x5 km) in size, and uses Landsat ETM+ image data and ecosystem process models to characterize 49 $km^2$ (7x7 km) around each tower (Cohen, et al., 2003). Each Bigfoot site is centered on an eddy flux tower measuring continuous water, energy, and carbon fluxes that relatively small footprint (~ 1 $km^2$) which is nearly equivalent to a single MODIS resolution cell. Thus, this flux tower can potentially be used to validate MODIS products. There are four representative sites selected from nine Bigfoot sites used for this study. These sites include a desert grassland, Sevilleta (SEVI), in New Mexico; a tall grass prairie, Konza (KONZ), in central Kansas; an

Agroecosystem (AGRO) site, consisting of a series of private farmlands of annually alternating corn and soybeans in west-central Illinois; and a temperate mixed forest, Harvard (HARV) dominated by a closed hardwood forest system with some small patches of conifer and mixed hardwood-conifer stands is located in Western Massachusetts (Cohen, et al., 2003).

The ground sample of each Bigfoot site was designed to measure a 5x5 km area with around 100 plots of 25x25 m size land cover types and each plot has neatly nesting at various increment up to 1 km. LAI were measured at five subplots per plot. Subplot measurements were averaged to provide a single value for each measured variable at each plot. Plot locations were determined using a real-time differential GPS. The accuracy of the system was <0.5 m in both the x and y directions (Cohen et al., 2003). About 60-80 plots are concentrated with in a 1 km cell center which is the location of eddy flux tower the rest of 100 plots are distributed randomly over the entire region outside the flux tower cell but within 5x5 km of Bigfoot footprint. (http://www.fsl.orst.edu/larse/bigfoot/ovr_dsgn.html). LAI is measured using standard direct and optical methods at each site (Gower et al., 1999). The direct measurement approaches include periodic area harvests for non-forest sites and application of allometric equations to tree diameter data for forest sites. LAI was also estimated indirectly using the Li-Cor LAI-2000 Plant Canopy Analyzers (http://www.fsl.orst.edu/larse/bigfoot/ovr_mthd.html). The LAI measurement used for this study were performed at different periods of time for each site as the following:

- AGRO site: The measurement were performed on May 24, 2000; July 24, 2000; August 11, 2000 and September 9, 2000. The site centers at latitude = 40.0066580, longitude = -88.2991535, MODIS tile h11v4.
- SEVI site: The measurements were performed on July 26, 2002; August 22, 2002; September 9, 2002; November 15, 2002; June 23, 2003; July 28, 2003; September 15, 2003; and November 21, 2003. The site centers at latitude = 34.350858, longitude = -106.689897, MODIS tile h9v5.
- KONZ site: The measurements were performed on June 7-8, 2000; August 25-26, 2000; and October 12-13, 2000. The site centers at latitude =39.089073, longitude = -106.689897, MODIS tile h10v5.
- HARV site: The measurements were performed on June 18, 2000; August 4, 2000, July 27, 2001; and August 24, 2002. The site centers at latitude = 42.528513, longitude = -72.172907, MODIS tile h12v4.

LAI ground sampling locations of each plot were converted from UTM coordinate to MODIS Sinusoidal Projection (SIN), using the MODIS tile calculator in order to acquire tile coordinate for line and sample of each plot and able to match with MODIS VI and LAI at the same pixel. We derived the mean LAI values per MODIS pixel by averaging from the plots located at the same line and sample of a MODIS pixel.

***Satellite data***

We also obtained the MOD13Q1, MOD13A2, MOD43B4 and MOD15A2 from the EROS Data Center, US Geological Survey (http://www.edc.usgs.gov/). For the Bigfoot study sites, each scene of MODIS reflectance spectra was extracted for the area approximately 5x5 km covering the whole plots for each Bigfoot site extracted pixel by pixel by using the same geographic coordinate as LAI ground sampling plots at the same period of time as ground sampling for each site. For MOD43B4 after extraction, we calculated the NDVI and EVI from equation (1) and (2) respectively.

Since MOD15 LAI products were available as 8-day composites we averaged two consecutive periods in order to match to the 16-day VIs. Similar to the MODIS VI, the MODIS LAI also were extracted pixel by pixel by using the same geographic coordinate as mentioned above. Then we performed the regression analysis.

### *B. Regression Method*

Empirical methods are important tools for scaling field-measured biophysical variables to remote sensing data. Regression analysis, and Pearson coefficient of correlation ($R^2$) have been extensively used to derive empirical relationships between VI and LAI. The methodology normally employed is to use the biophysical property variable, LAI as the dependent variables and the spectral indices as the independent variable. This allows for comparisons of the potential ability of different VIs to estimate LAI. The performance of the VIs to estimate a biophysical property variable was determined by the selection of the simplest model that explained the most variation in the dependent variable and appeared to be sensitive over the range of the dependent variable. The relationships between field- based LAI and MODIS VI (250m, 1km) from MOD13Q1, MOD13A2 and MOD43B4 were applied for all MODIS pixels located over field plot locations. And the relationship method was also applied to MODIS LAI (1km) from MOD15A2 and MODIS VI using the same as products mentioned before. In addition, we undertook error analysis procedures to identify uncertainties in the LAI estimations from the regression models. We analyzed an intercomparison considering the coefficient of determination ($R^2$), the standard error (SE), and the level of significance (p).

***Results and Discussion***

***A. Walnut Gulch Study Site***

***1) Relationship between MODIS VI (MOD13Q1, MOD13A2 and MOD43B4) and Field LAI***

The regression plots with results performed from the Pearson coefficient of correlation analysis method are shown for field LAI - MODIS EVI and field LAI-MODIS NDVI in Fig. 5. For each case, there were three different models which showed the relationship between field measured LAI and MODIS VI for 250 m (MOD13Q1), 1km (MOD13A2), and 1 km (MOD43B4), and the results were separated into shrubland (figure5 (a), and (b)) and grassland (figure 5 (c), and (d)). The $R^2$ values for all models were relatively poor or with no relationship between MODIS VI and field LAI at the Walnut Gulch site.

In separating the vegetation into the two dominant ecosystems, grass and shrub, we found that the correlations and regression slopes between field LAI- MODIS EVI and field LAI- MODIS NDVI with the three different products and two different resolutions showed a significant difference between shrub and grassland. The $R^2$ values from both land cover types ranged from 0.01 to 0.42 with the $R^2$ values of the shrubland much lower than that for grassland. The MODIS EVI- field LAI showed a slight correlation using the MOD13A2 product ($R^2 = 0.30$), while NDVI showed relatively low correlation with field LAI for all VI-products as shown in figure 5 (a) and (b). The strongest correlations were from field LAI- MODIS VI (MOD13Q1), at 250 m resolution, which showed $R^2$ of EVI = 0.37 and NDVI = 0.42 as shown in figure 5 (c), and (d). However, the p-values were relatively high (p=0.08 and 0.09 for EVI and NDVI respectively based on 95% confidential interval) and a sample size was relatively small since each sample was estimated the mean of 6 subgroups averaged from 3-5 raingauges of 28 raingauges located in shurbland area (table 1) and also for 23 raingauges located in grassland area (table 2). The summary of statistical analysis results are shown in table 3. Therefore, we could not conclude that the VI at grassland were significantly correlated with LAI even $R^2$ show slightly better than $R^2$ at grassland.

The relationship between VI and LAI for at Walnut Gulch is very complex with discontinuous canopies than for homogeneous canopies because more parameters are involved. This creates problems for VI-LAI empirical studies in semi-arid regions. Since the vegetation canopies are generally sparse and characterized by low LAI vegetation. Moreover, this region is dry and the soil is bright so there are canopy background "brightness" effects on the VI values. Nevertheless, this problem could be handled within the VI equation itself. Although the EVI includes a soil adjustment factor in the equation, from the spatial analysis made in this study, one could not conclude that EVI was able to improve the relationship between MODIS VI and field-based LAI.

When we grouped plots located in the shrub or grassland classes, the VI-LAI correlations were increased. The average value from many plots should give more accuracy than only one plot against one MODIS pixel. The field LAI- MODIS VI relationships over the shrubland may have a low $R^2$ because of the limited LAI sampling period, as shown in figure 6 (a), in which the range of characteristic LAI and VI values did not change much, compared with grassland where characteristic LAI and VI values over both dates showed more variability, as shown in figure 6 (b). There were several reasons could cause low correlation between VI and LAI such as there were not so much variation in spatial domain, satellite data may be too noisy and satellite data may be measures many canopy properties simultaneously (LAI, chlorophyll, cover, etc.), and hence is not so correlated to just 1 property, like LAI. In addition, there were uncertainties from LAI measurements could cause by persons who performed the measurement because filed LAI is difficult to measure accurately especially for arid land and the accuracy of the equipment itself as well. However, these results indicate that the dominant factor influencing the spatial distribution of LAI across the landscape in Walnut Gulch is variability within land cover types as opposed to differences between the two dominant vegetation types. Because of the strong spatial heterogeneity and the sparse level of vegetation observed in the field LAI measurements for this semi-arid region, it was difficult to quantify the relation between field measurements and satellite retrievals.

Therefore, either the number of point measurements within pixel resolution should be increased, or a region-by-region comparison should be attempted.

***2) Comparison between VI (MOD13A2 and MOD43B4) with MODIS LAI and Field LAI***

We found the overall relationships between MODIS VI's (MOD13A2) with either MODIS LAI or field LAI had little to no correlations and we could not conclude that the relationships between MODIS NBAR VI's (MOD43B4) with either field LAI or MODIS LAI were improved (figure 7). For the grassland case, both VI from MOD13A2 and MOD43B4 were highly correlated with MODIS LAI (from 0.86-0.91) even though they were slightly correlated with field-based LAI (from 0.24-0.33) and a comparison of regression lines for both EVI and NDVI did not show significant differences for this site, however the relationship showed the same trend for both field and satellite based although satellite based LAI was extremely over predicted, the results were shown as figure 8. The summary results and statistical analysis results are shown as table 4 and 5.

We can conclude that the MODIS LAI product considerably overestimated LAI at grassland and seemed to be same (no correlation) at shrubland. The MODIS VI's were more correlated with field-LAI measures than with the MODIS LAI product in the shrubland site, however, not in the grassland site.

***B. BigFoot Study Site***

***1) In Site relationship between Field-Based LAI and MODIS VI***

The 4 BigFoot sites (figure 9) of this study represent a diverse group of vegetation types. The relationship between field-based LAI and MODIS VI were highly variable by land cover types. Over all results for both forest and non-forested sites, we found that Pearson coefficient of correlation ($R^2$) models for individual sampling dates were either poor or with no correlation for every individual sampling date that LAI had been measured. However, when the data from several measurement dates were combined, the relationship increased for most of the land cover types except for the Harvard Forest site (Harv). In addition, the strongest correlations were found for both NBAR-EVI and NBAR-NDVI generated from MOD43B4 ($R^2$=0.88) when compared among the other MODIS VI products. The overall comparisons of regression models for the two VIs from three different products showed there was no evidence that the slopes and intercepts were significantly different from each other. The details for each of the sites are discussed below.

For the Agro site, the vegetation is fairly homogeneous, with no woody material, minimal leaf clumping, and intermediate soil brightness. The scatter-plot of corn and soybean from the 3 measurement days in May, July and August 2000 revealed that these two crops represented different populations and were best to analyze separately. After we separated the 2 crops, corn and soybean, the $R^2$ of corn were stronger for all VI relationships while the $R^2$ of soybean increased only for the 250m VI from MOD13Q1 and there were not significant differences between EVI and NDVI. The results of combining corn and soybean are shown as figure 10 (a) for EVI and (b) for NDVI and the separated results between the two crops are shown in figure 10 (c) and (d) for corn and figure 10 (e) and (f) for soybean. However, from the statistical analysis we found that standard errors for all VI-based were relatively high (for corn ~0.67-0.83, for soybean

~0.83-1.25) even p-values were very low (for corn p <0.001, for soybean p <0.05), the statistical results were shown as table 6 and 7 for corn and soybean respectively. Since the scatter-plots were separated into two groups because the 3 ground measurements were performed during different seasonal periods of the crop cycle as shown in figure 12 (a) for the first measurement were performed during the beginning of growing season, the second measurement were performed during the peak of growing season and the third measurement were performed during the drying down period. Thus, this might cause the two distinct groups of data for low LAI value and high LAI value. As we know, different vegetation types vary in canopy structure such as leaf angle distribution, vegetation clumping, row orientation, spacing and optical properties of canopy components (leaf, stem, etc.). Therefore, it is better to separate the vegetation types when making empirical relationships with VI.

For the Harvard Forest site, even after combing measurement data from several days, the correlations were still poor for all VI products. In addition, standard error and p-value were relatively high as shown in table 8. The low correlation in this case is possibly due to the fact that the LAI of these stands may attain large values which saturates the NDVI and EVI, thus for this study neither NDVI-LAI or EVI-LAI showed good correlations (figure11 (a) and 11 (b)). The cause of these results also may be from the measurement period at the Harvard site, which occurred during the peak of the growing season when LAI remained constant for a while after reaching the maximum values of the year. The sampling dates of LAI is shown in figure 12 (b). Thus, there were difficulties to distinguish the difference between each sampling period because they almost had the same LAI value during this period of time. In addition, most forest LAI values are strongly dependent on the understory leaf area index. So this might have some effect on the LAI measurement as well.

For the Konza site, the grassland canopies exhibit vertical and lateral homogeneity, and green cover fraction is almost 1.0, and in addition, soils are intermediate in brightness. Thus, this site has less effect from canopy background noise. Spatial analysis of the individual sampling dates did not show good correlations, however when several samplings were combined the correlation results showed better trends in the relationship between MODIS VI and field LAI values and the relationship between NBAR NDVI and field-LAI was slightly better than the other relationships, as shown in figure 11 (c) and (d), so view angle was most likely an important influence on MODIS VI's at this grassland site. Moreover, this site LAI was not too large (approximately 3-4), so there was no asymptotic effect and the periods of LAI measurements were during the different growing periods as shown in figure 12 (c), the LAI measurements were performed during growing season (on May 24, 00; June 10, 01 and Aug13, 01) and drying season (on Sep 25, 00 and Oct 12, 00), thus the spectral characteristics were obviously different. However, this site showed slight to intermediate correlation between VI-LAI for all VI-based and the correlations varied from 0.26-0.54. Even there were relatively low p-value but standard error still very high as shown in table 9.

For the Sevilleta site, there were slight trends in the relationships of MODIS VI and field LAI for both EVI and NDVI, even though the periods of LAI measurement were different as shown in figure 12 (d). Because the vegetation cover for this site is desert shrub, the canopies exhibit lateral heterogeneity, low to intermediate vegetation ground cover, small leaves, woody material, and bright backgrounds, and thus there are many uncertainties caused by soil-noise and sparse canopies. The correlations at this site were relatively low for all MODIS VI products and there were no significant differences between EVI and NDVI and among the three different VI products. The results of this land cover type are shown as figure 11 (e) and (f) and the statistical analysis were shown as table 10.

***2) In Site Comparison between LAI (MODIS and Field-based) and MODIS VI (MOD13A2 and MOD43B4)***

For the Agro site, the relationship between MODIS LAI and ground based LAI with MODIS VI retrieved from MOD13A2 and MOD43B4 showed similar trends, however the relationship of MODIS VI and MODIS LAI was stronger than the MODIS VI - field LAI, and there were no significant differences between the 2 VI products as shown in figure 13 (a) and (b) for MOD13A2 and figure 13 (c) and (d) for MOD43B4. The cropland canopies exhibit lateral heterogeneity and ground cover is pretty high, and soils are dark soil background (Knyazikhin et al., 1998). From their characteristics, there are not much effect from view angle and soil background, therefore we did not find differences between VI from MOD13A2 and MOD43B4 and also differences between EVI and NDVI.

For the Harvard site, there were no relationships between MODIS LAI or from field LAI with MODIS VI's, as shown in figure 14 (a) and (b). We also could not find the significant differences between MOD13A2 and MOD43B4 as shown in figure 14 (c) and (d). Since VI from MOD43B4 should improve the relationship for complex canopy structure, however the LAI measurement were performed during the same season as mention before. Moreover, EVI did not improve the relationship because this land cover type is very dense and homogeneity so did not effect by soil background.

For the Konza site, the vegetation at this site is quite homogeneous and we found that the correlation from both field based and MODIS based were almost the same especially for VI generated from NBAR product ($R^2$ = 0.37 and 0.46 for EVI and 0.43 and 0.43 for NDVI) as shown in figure 15 (a) and (b) for MOD13A2 and figure 15 (c) and (d) for MOD43B4. At this site a variety of surface reflectance was dominated by the presence of standing litter which had a disproportionately strong effect on canopy reflectance in grasslands and a change in a litter biomass plays a stronger role in driving reflectance variability than a change in LAI (Asner, 1998). A small increase in litter has a strong effect on NDVI (van Leeuwan and Huete, 1996). The litter in biomass affected the relationships between VI-LAI, thus the grassland had a lower correlation than cropland and because this land cover type is homogeneous, there were no effects from soil background. Consequently, the EVI did not show a better correlation than NDVI for this land cover type. In addition, removal of BRDF effects in the NBAR VI products did little to improve the relationships for this land cover type, most likely because the grassland exhibited vertical and lateral homogeneity, minimal leaf clumping therefore, the view angle does have much effects over this land cover type.

For the Sevilleta site, we found that there were relatively low correlations between MODIS VI and field LAI for both VI products, and there were no significant differences between EVI and NDVI as well. However, the MODIS VI and MODIS LAI showed better correlations and there were no significant differences between EVI and NDVI between the 2 products, as shown in figure 16 (a), and (b) for MOD13A2 and figure 16 (c) and (d) for MOD43B4.

***3) Cross site relationships between LAI and VI with MODIS-LAI and Field-LAI***

When we averaged the field measured LAI values from each sampling period data and then combine all sites together, we found the mean values of field LAI and MODIS LAI were strongly correlated with the mean value of MODIS EVI and MODIS NDVI across all different land cover types (figure 17, 18). For all the regression models, the $R^2$ values between MODIS VI- field LAI of all models varied from 0.70 to 0.75. In addition, all models could be fitted to the field LAI data within the confidence level of 95%. The correlation analysis showed significant coefficients ($p < 0.05$) and the standard errors ranged from 0.12 to 0.17 as shown in table 6. The strongest correlations ($R^2 = 0.75$) were found in both VI-based using the MODIS (MOD13) and MODIS (MOD43B4) with field LAI (figure 17 (a), (b) and 18 (a), (b) respectively). However, between EVI and NDVI derived from 2 VI-based, the correlations of MODIS EVI (0.74) and MODIS NDVI (0.75) were not significantly different. Whereas the correlations between MODIS VI (MOD13A2 and MOD43B4) with MODIS LAI (figure 17 (c), (d) and 18 (c), (d) respectively) were slightly lower than with field LAI. The correlations of MODIS EVI and MODIS NDVI were identical (0.70).

***Conclusions***

The spatial variations in MODIS VI- LAI relationships were clearly revealed in our results. The overall analyses showed that the pixel by pixel correlation between field-based LAI and MODIS VI were relatively low or with no correlation for most land cover types in which the vegetation was too dense, like broadleaf forests, or too sparse, like shrublands in semi-arid regions. The regression models were highly site-specific and there was no uniform relationship between MODIS vegetation indices and field measured LAI for the individual sites. For the land cover types with LAI values less than 4, the NDVI had no influence from saturation and background effects. At the Agro site (LAI<4), the relationships were the strongest, compared with the other sites, while in more dense canopies, such as Harvard Forest site (LAI > 4), because when the surface reflectance change but LAI change remain the same. Thus, there were mostly low or no correlations for this land cover type and other forests sites, that may be strongly dependent on the understory leaf area index as well. Moreover, this study found that the background effect from soil also influenced the relationship of MODIS VI with field LAI and the EVI might help improving relationship. In addition, the VI retrieved from the MODIS NBAR product would be more useful for improving the relationship of MODIS VI- field LAI than the other MODIS VI products except for semi-arid region. From this study, we found that the disadvantages associated with the empirical approaches in establishing a correlation between satellite VI and field LAI tends to be site-specific. Yet in situ calibration measurements of LAI over regional or global scales are impractical. Furthermore, empirical relationships are valid only under the conditions concerning the sparse and dense vegetation and also a variety of canopy structures. Since different canopy types exhibit drastic variations in canopy structure and reflectance properties which can produce different VI values while having identical LAI values. Even though, the empirical study between VI-LAI did not show good results for the spatial scale study and for specific land cover types. However, the across sites relationships estimated from mean values of MODIS VI's and field LAI's across all the individual sites were very high and would be useful for regional-scale or global studies.


Figure 1: The location of Study area in Walnut Gulch, Arizona. The 2 intensive study areas are Lucky Hills (brush dominated) and Kendall (grass dominated) (http://ars.usda.gov)

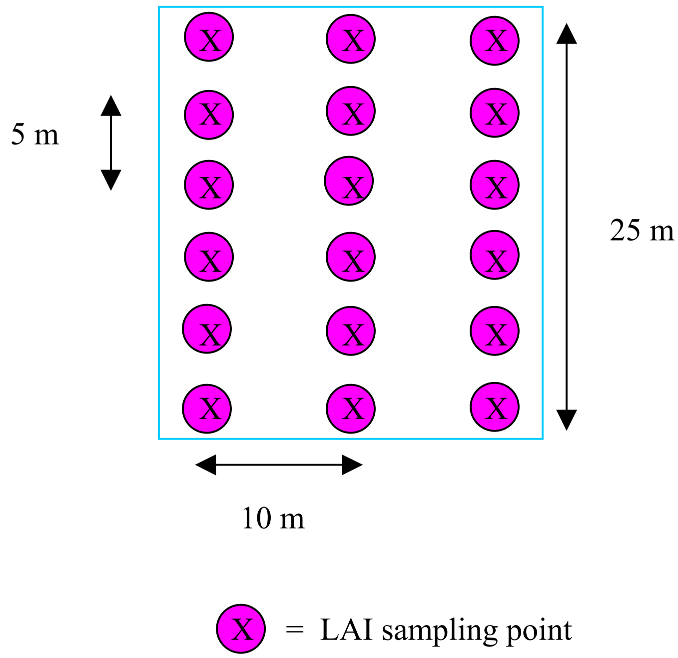



Figure 2. Layout of LAI sampling at Walnut Gulch Water Shade Experiment scheme

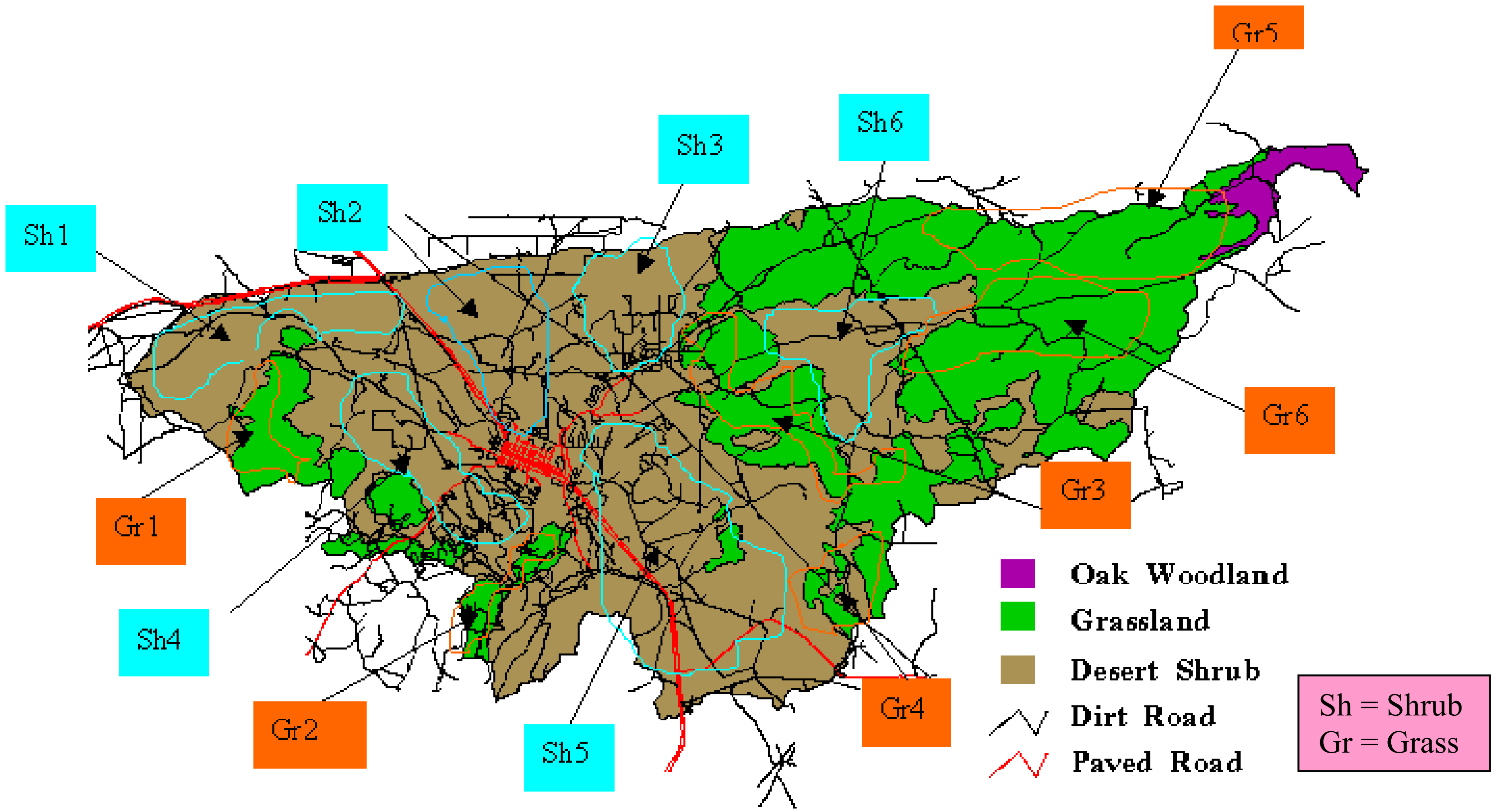



Figure 3: Shrub and Grassland were divided into 6 subgroups, each subgroup composed of 3-5 raingauges by using land classification map from USDA. LAI sampling were performed at these raingauge during July 29th -August 6th 2004 and August 14th –August 25th 2004.

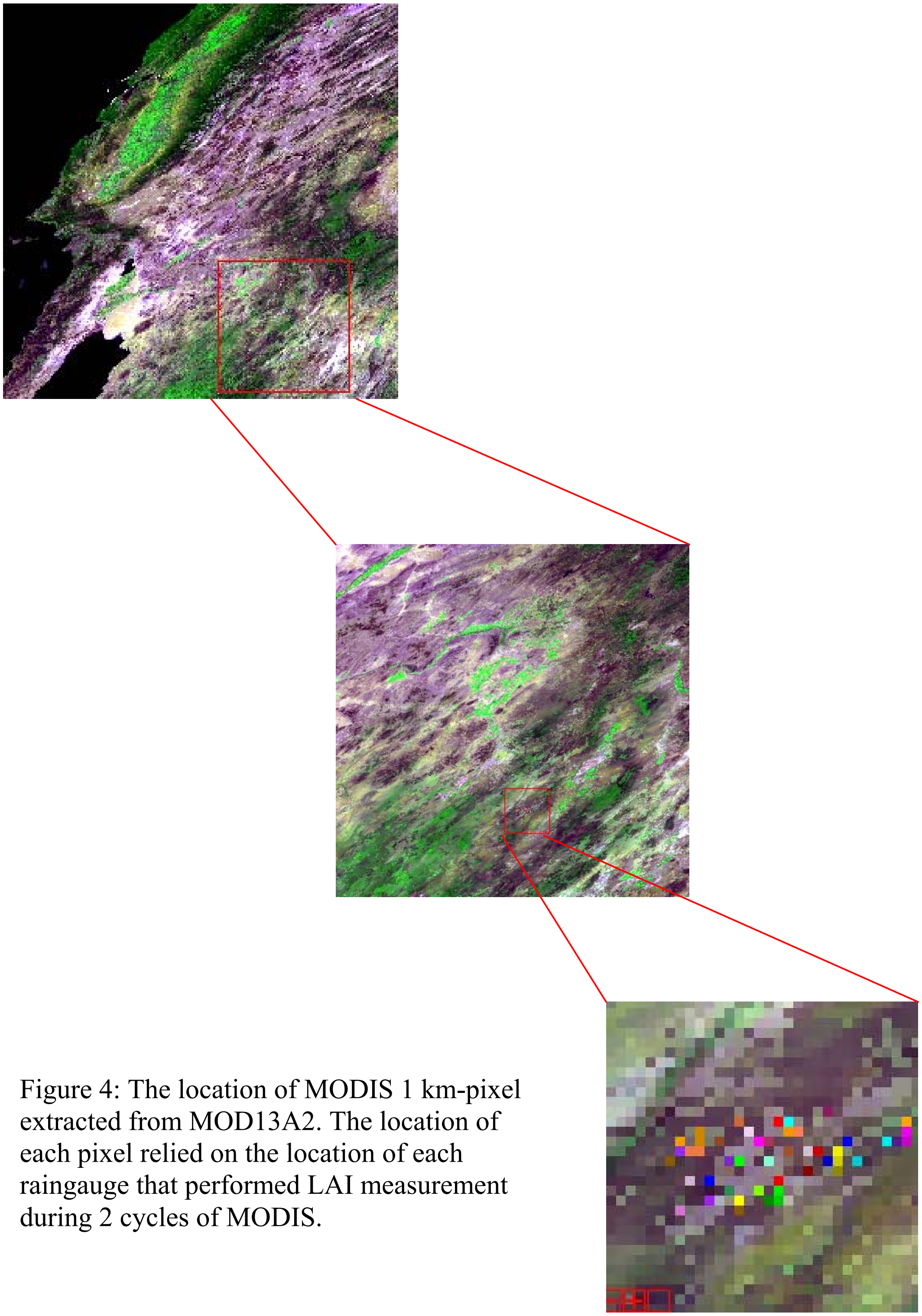


Figure 4: The location of MODIS 1 km-pixel extracted from MOD13A2. The location of each pixel relied on the location of each raingauge that performed LAI measurement during 2 cycles of MODIS.

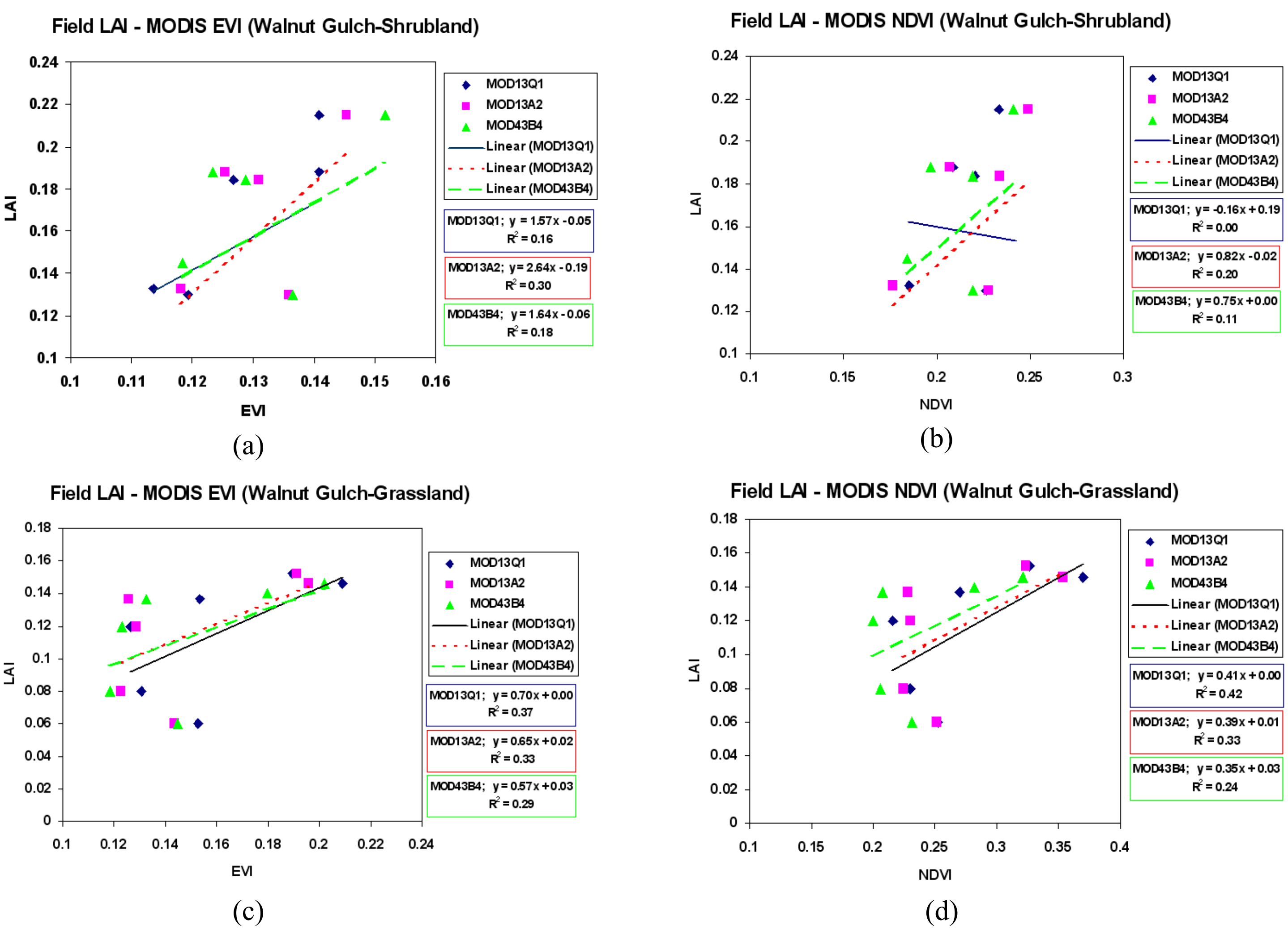
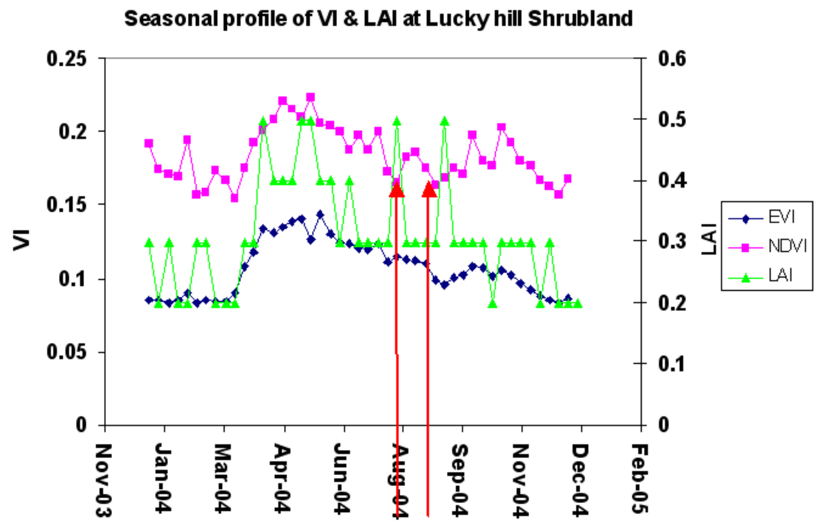
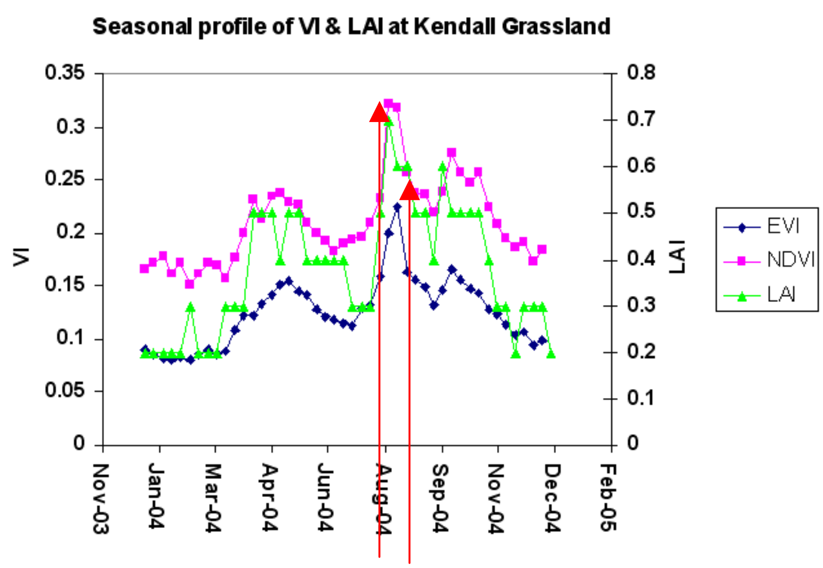



Figure 5: The comparison among 3 VI-based from MODIS with Field LAI; (a) and (b) are for shrubland (c) and (d) are for grassland




(a)




(b)

Figure 6: The graph showed seasonal profile of shrubland (a) at Lucky hill and grassland (b) at Kendall for 2004. The red arrows indicated the Field LAI was conducted during July 29th -August 6th 2004 and August 14th –August 25th 2004) for both land cover types.

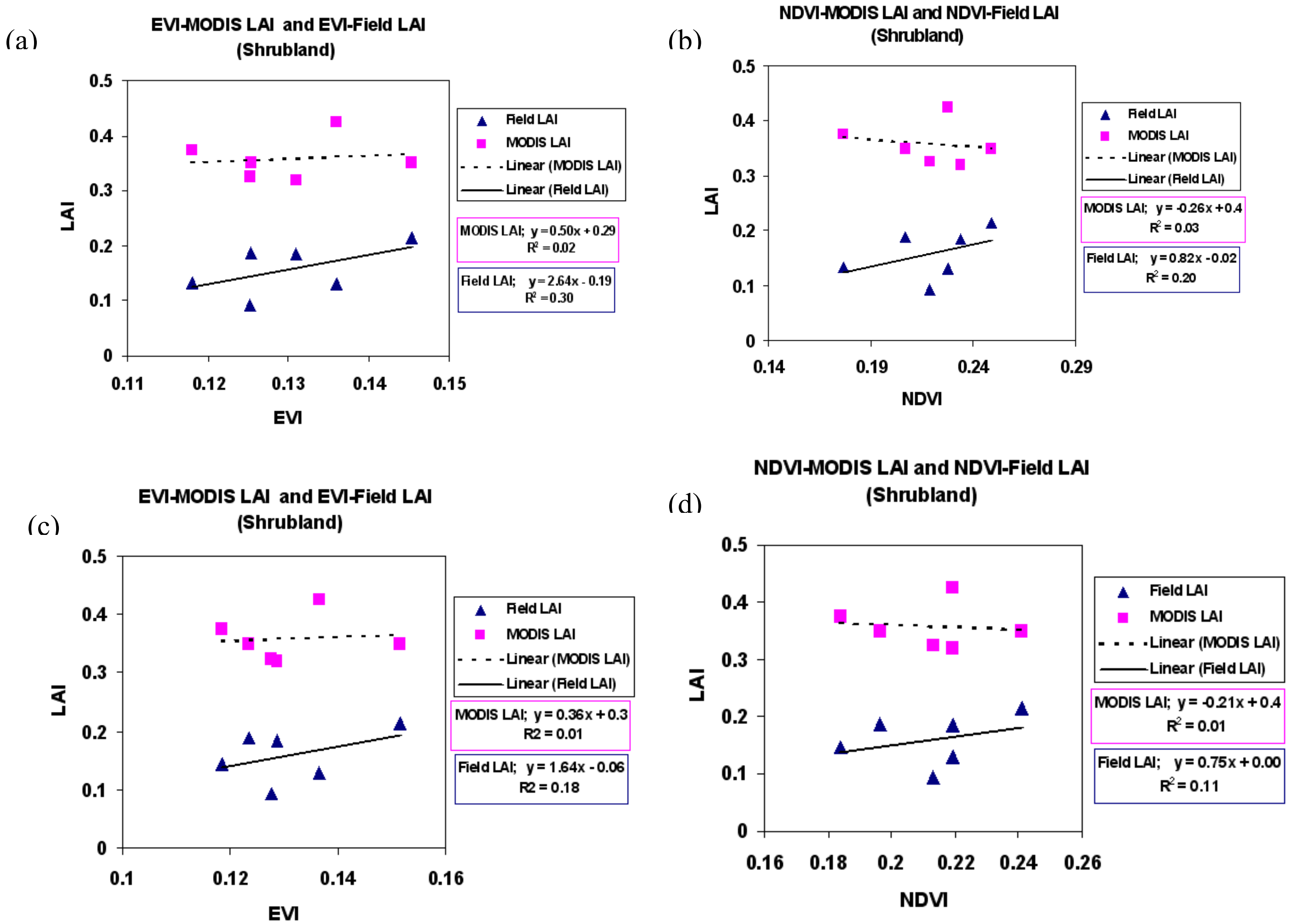



Figure 7: The comparison between LAI field-based and LAI MODIS with VI from MOD13A2 (a and b) and from MOD43B4 (c and d) for Shrubland

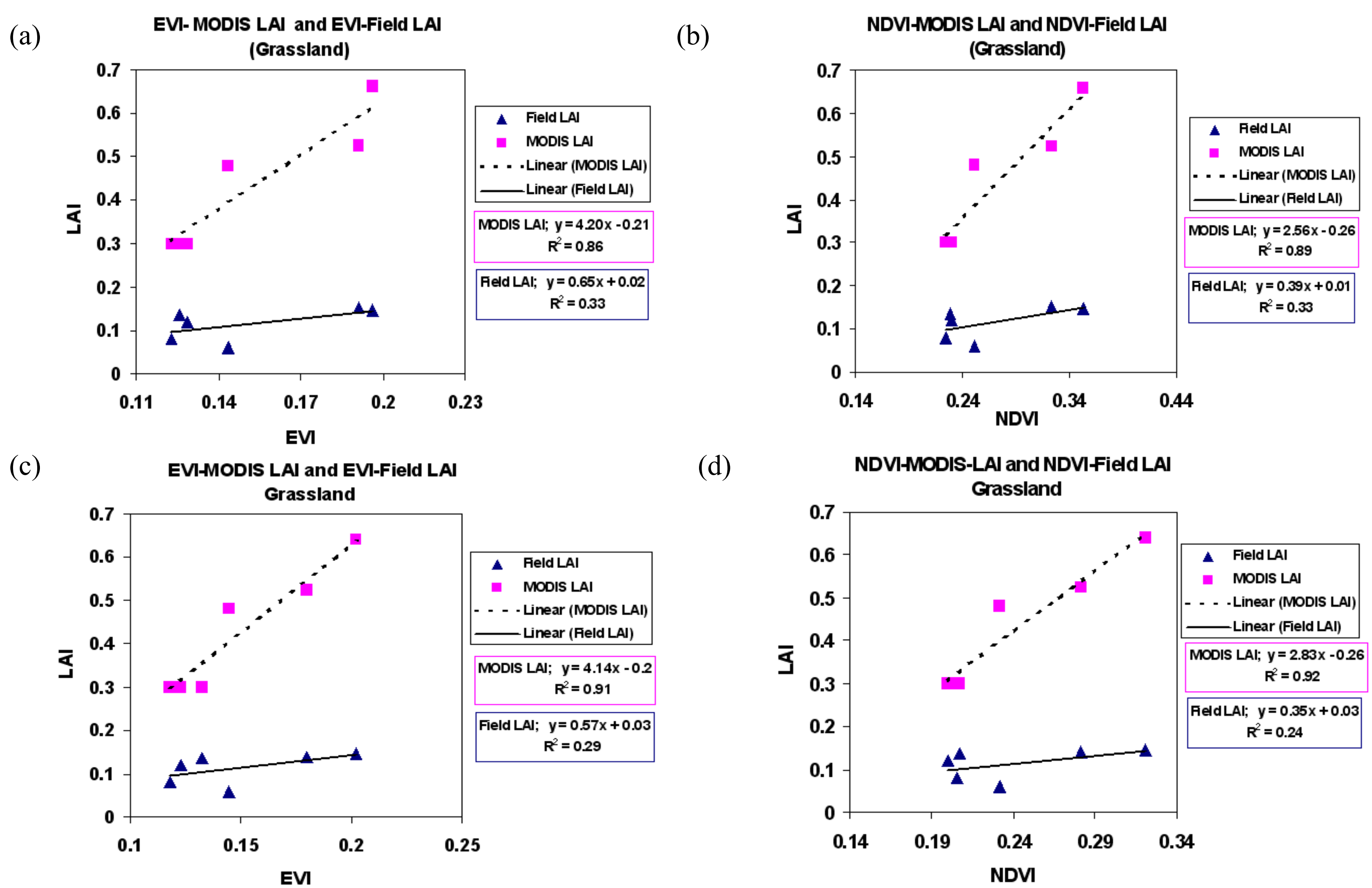



Figure 8: The comparison between LAI field-based and LAI MODIS with VI from MOD13A2 (a and b) and from MOD43B4 (c and d) for grassland

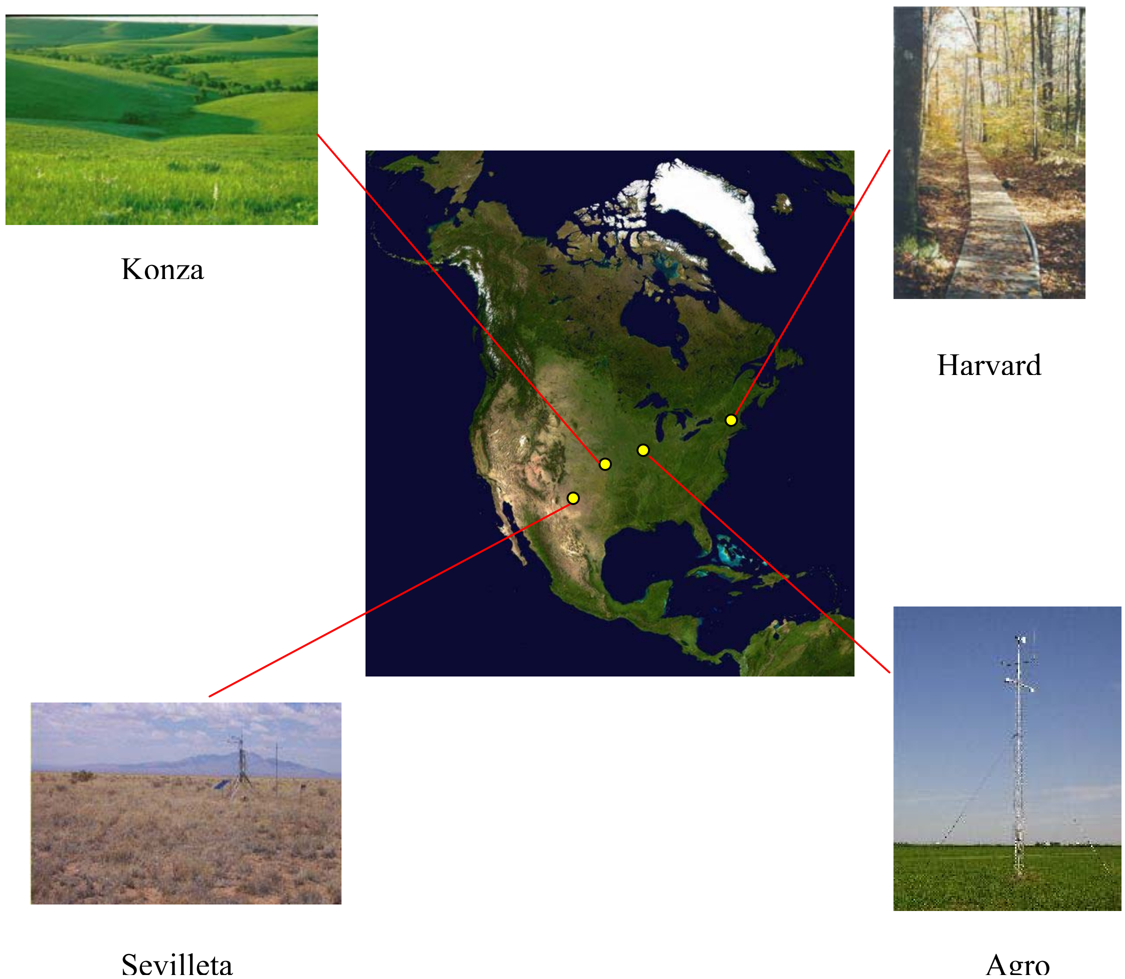



Figure 9: BigFoot study sites composed of Konza (tallgrass prairie), Sevilleta (desert grassland), Agro (agricultural cropland), and Harvard forest (mixed broadleaf forest).

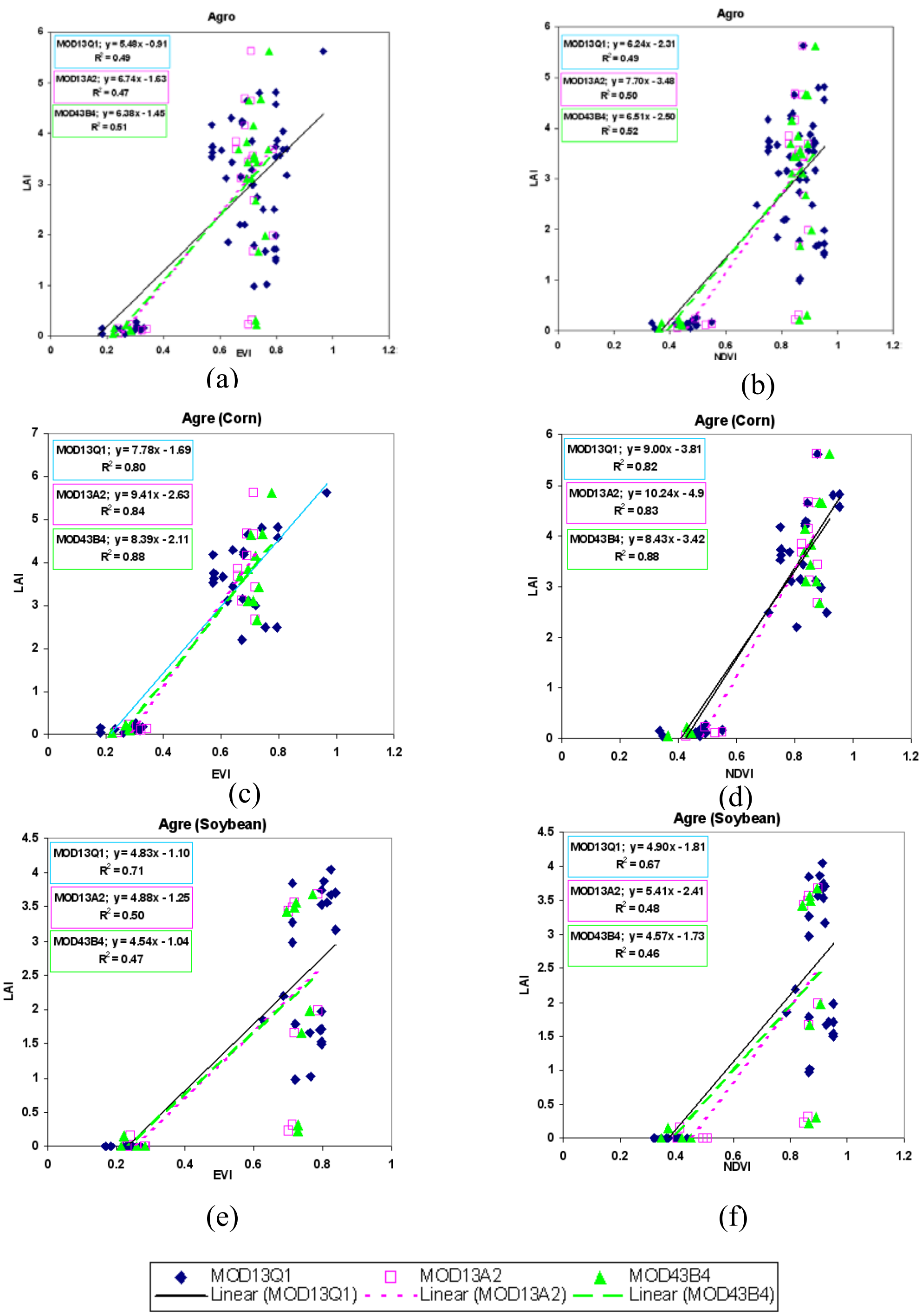



Figure 10: The comparison of 3 VI-based with Field LAI for Agro site; (a) EVI-Field LAI for mixed corn and soybean, (b) NDVI-Field LAI for mixed corn and soybean, (c) EVI-Field LAI for corn, (d) NDVI-Field LAI for corn, (e) EVI-Field LAI for soybean, and (f) NDVI-Field LAI for soybean

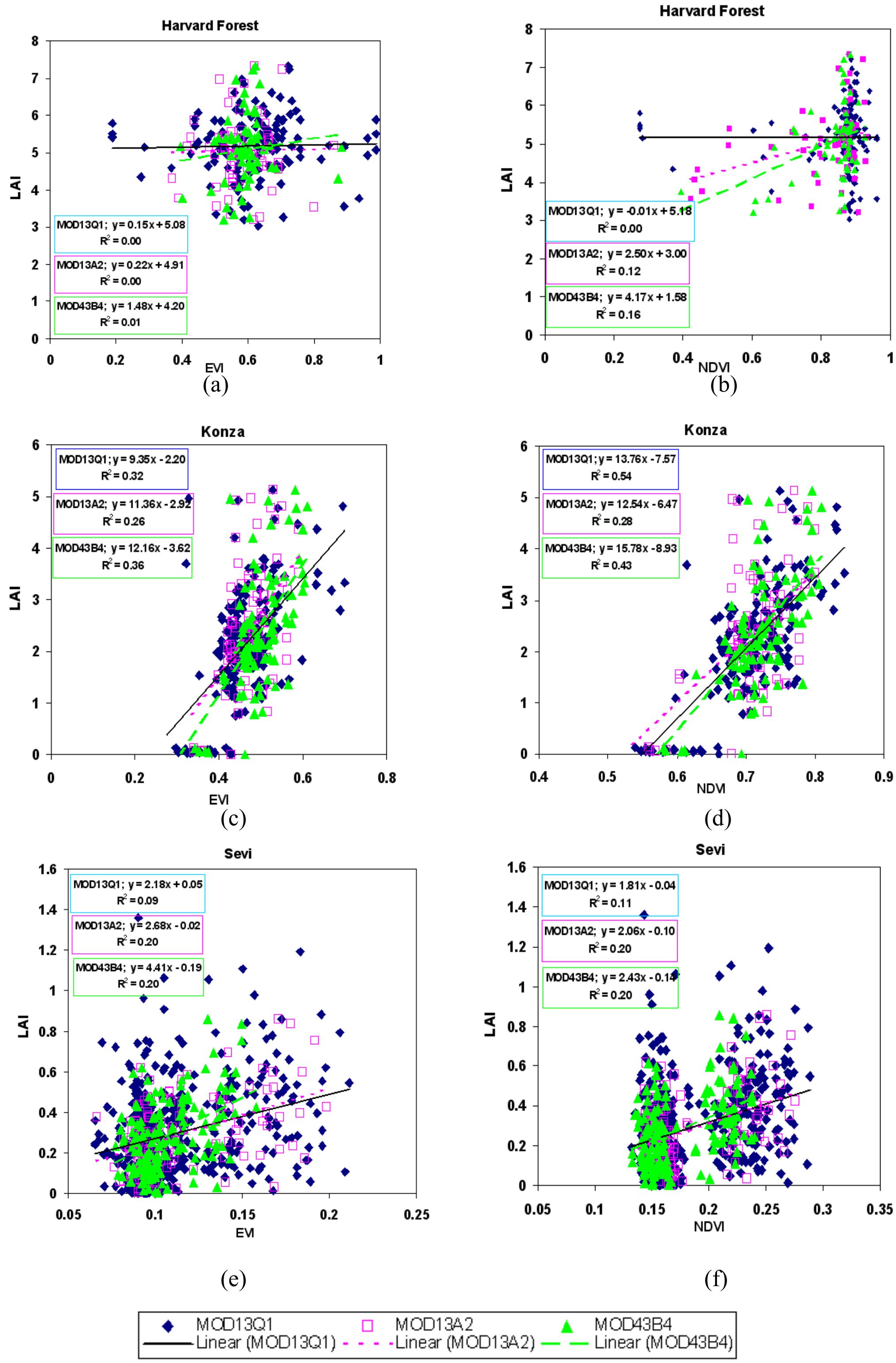



Figure 11: Comparison between 3 modes of EVI and NDVI with Field LAI for Harvard forest (a) and (b), Konza (c) and (d), and Sevilleta (e) and (f).

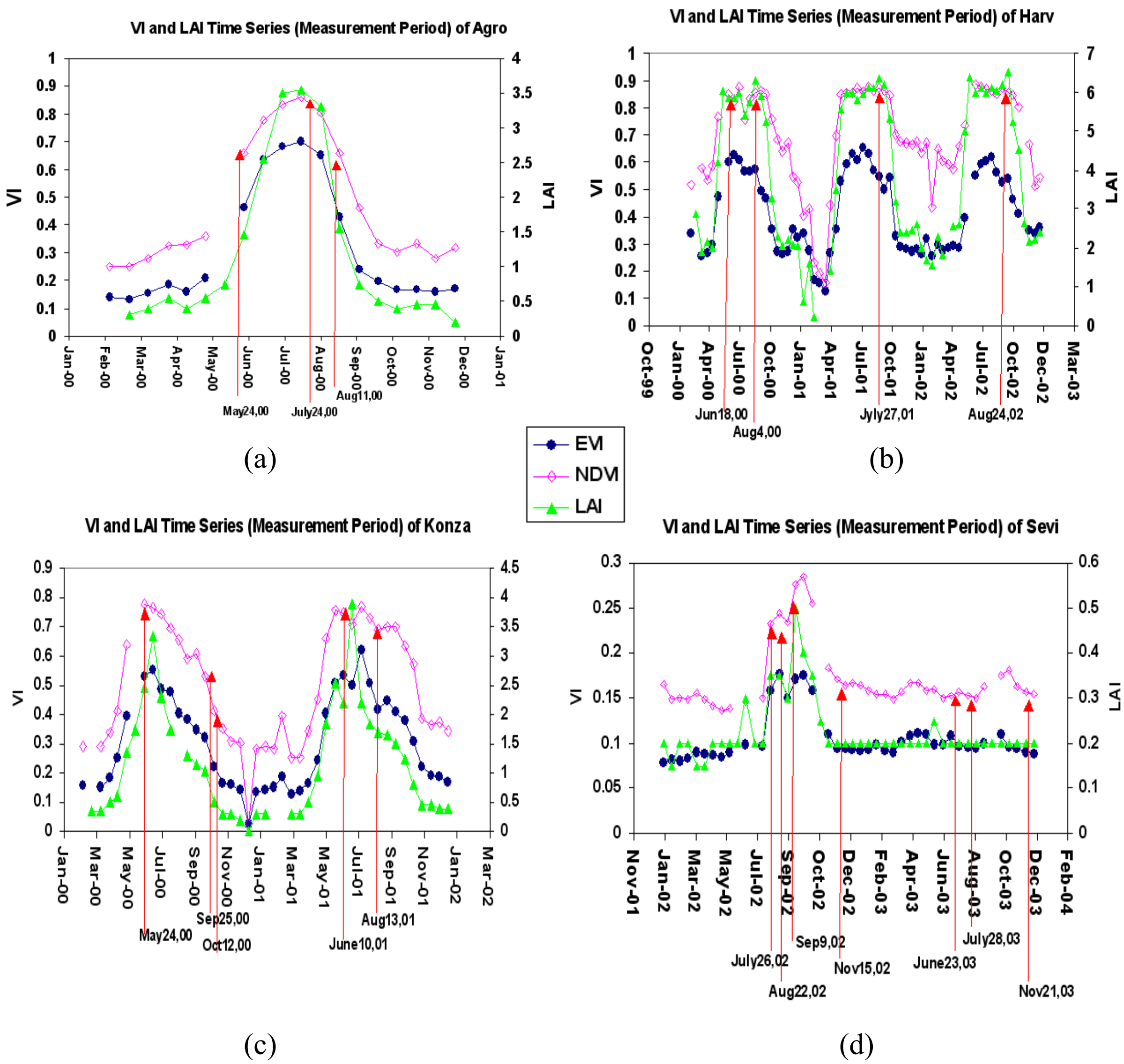



Figure 12: The Field-based LAI were performed for different period of time as shown for each site; Agro (a), Harvard forest (b), Konza (c), and (d) Sevilleta.

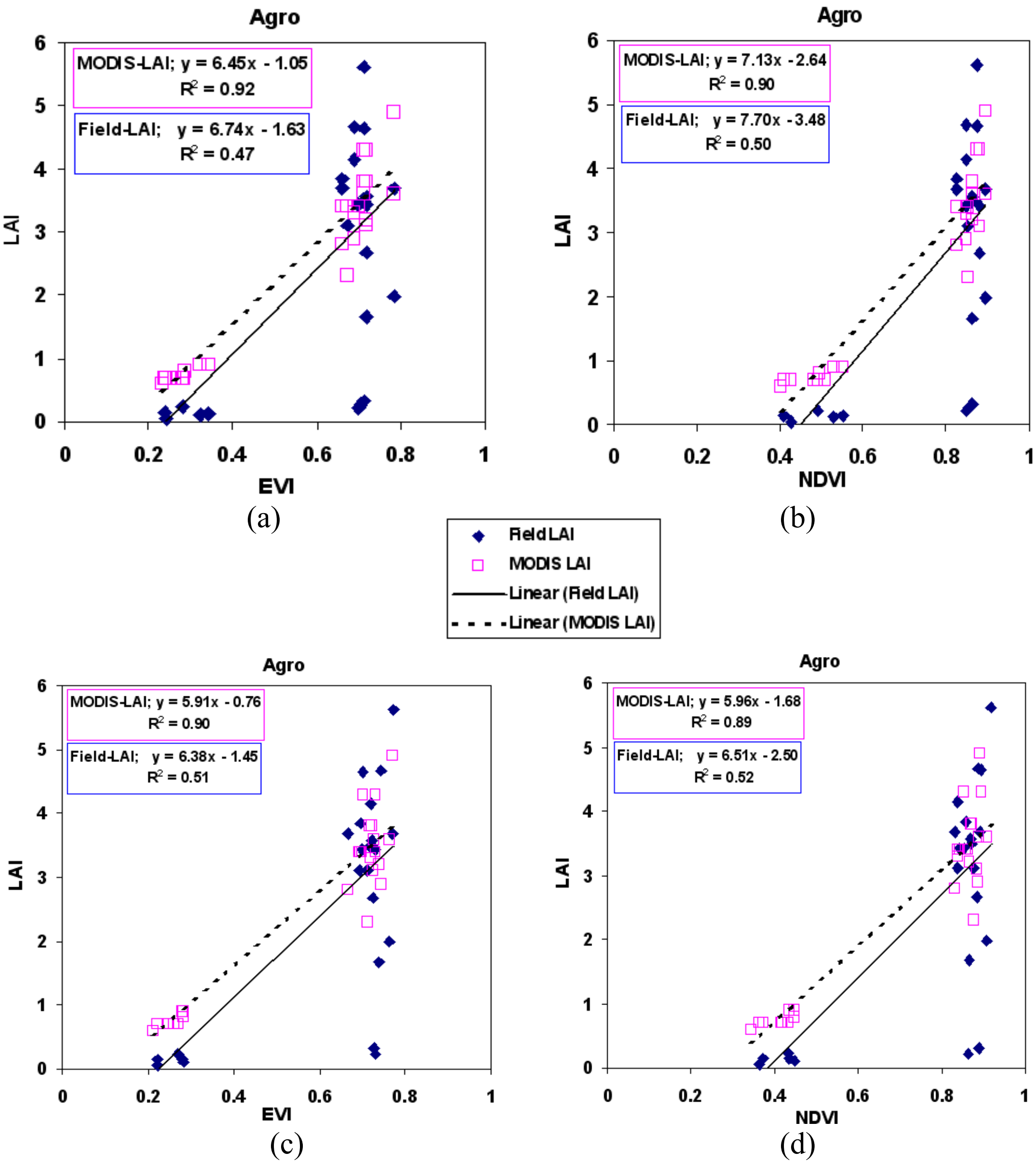



Figure 13: The comparison of the relationship between VI-Field LAI and VI-MODIS LAI (a) EVI and (b) NDVI from MOD13A2; (c) EVI and (d) NDVI from MOD43B4 for Agro site.

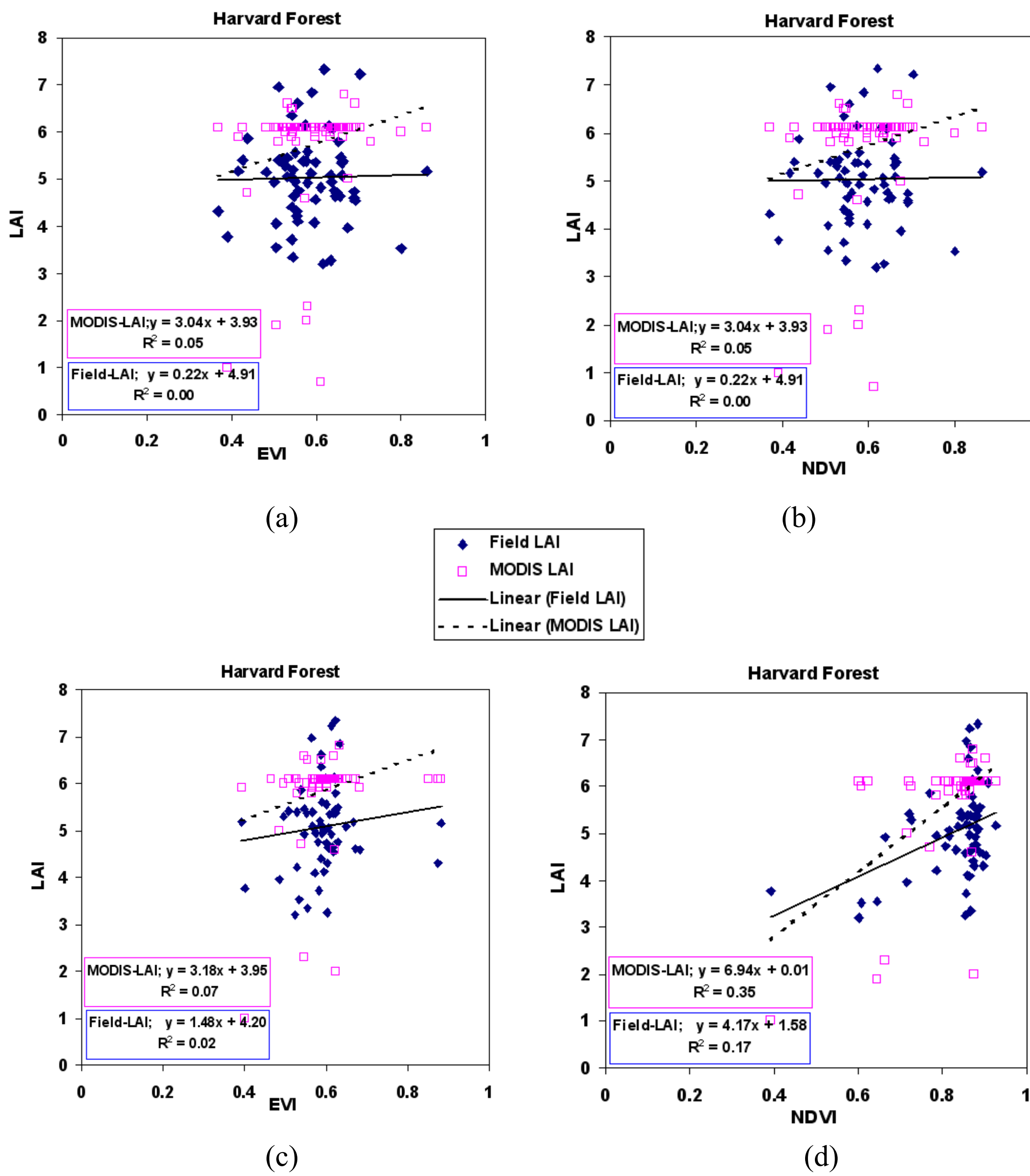



Figure 14: The comparison of the relationship between VI-Field LAI and VI-MODIS LAI (a) EVI and (b) NDVI from MOD13A2; (c) EVI and (d) NDVI from MOD43B4 for Harvard forest site.

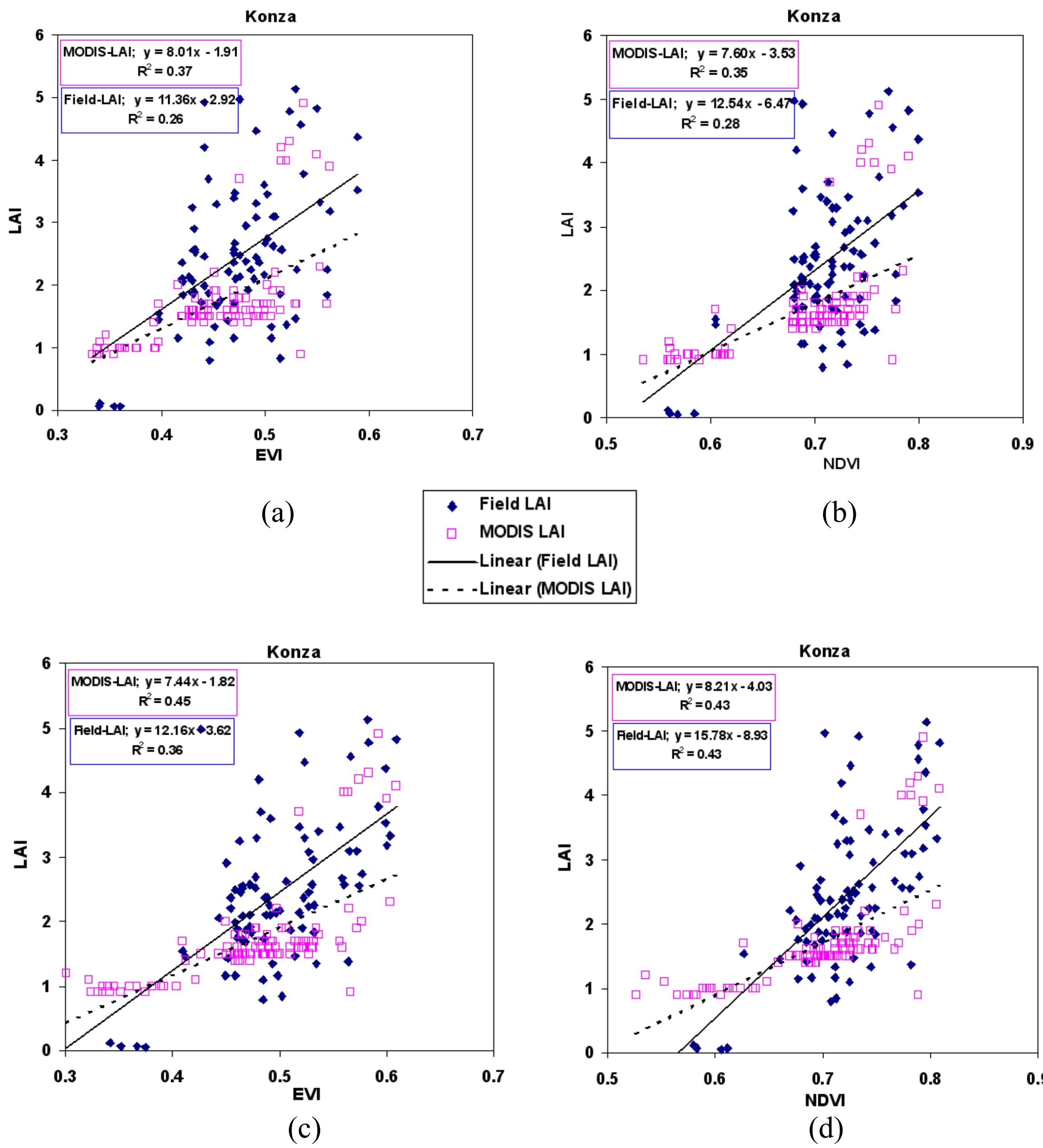
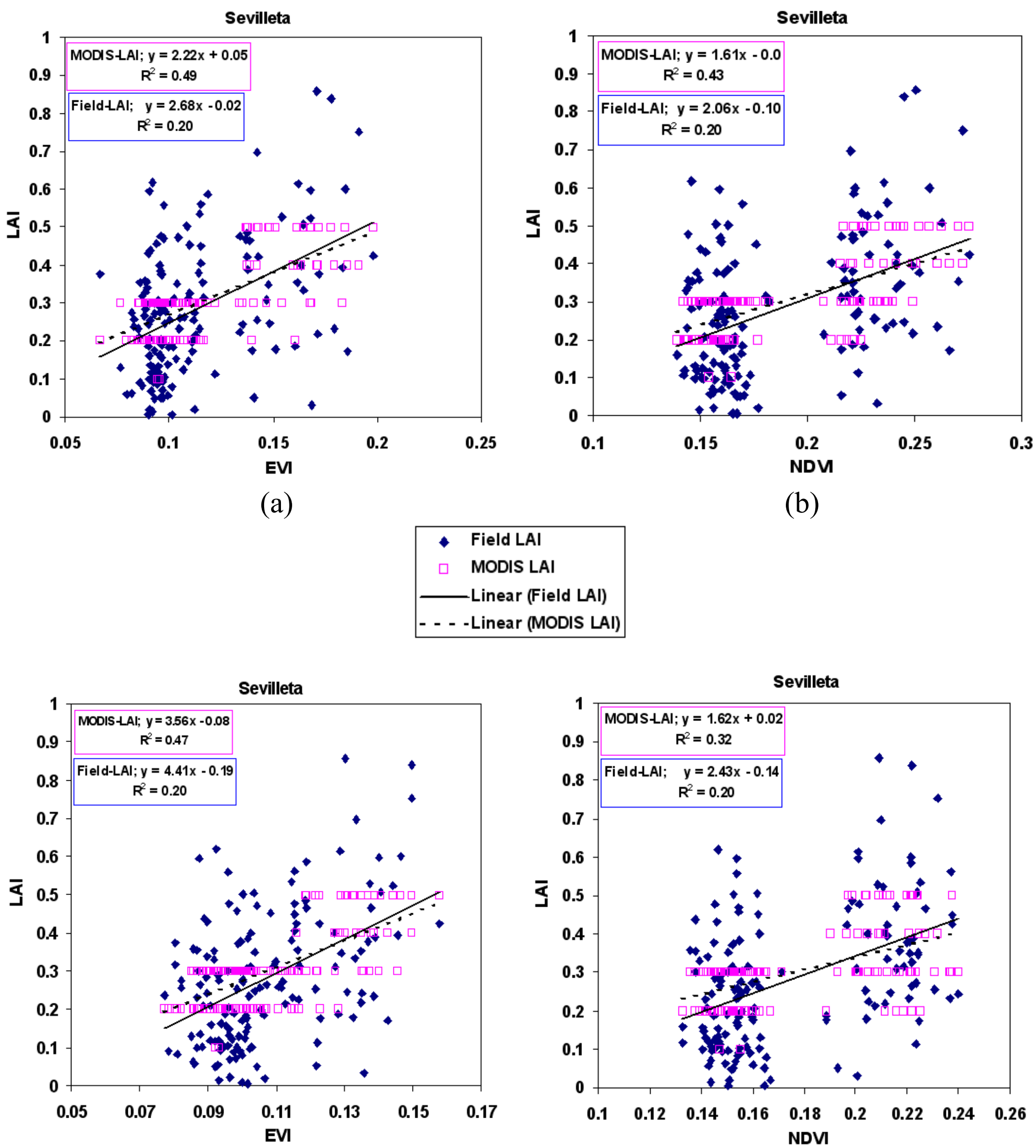



Figure 15: The comparison of the relationship between VI-Field LAI and VI-MODIS LAI (a) EVI and (b) NDVI from MOD13A2; (c) EVI and (d) NDVI from MOD43B4 for Konza site.




(a) (b)

(c) (d)

Figure 16: The comparison of the relationship between VI-Field LAI and VI-MODIS LAI (a) EVI and (b) NDVI from MOD13A2; (c) EVI and (d) NDVI from MOD43B4 for Sevilleta site.

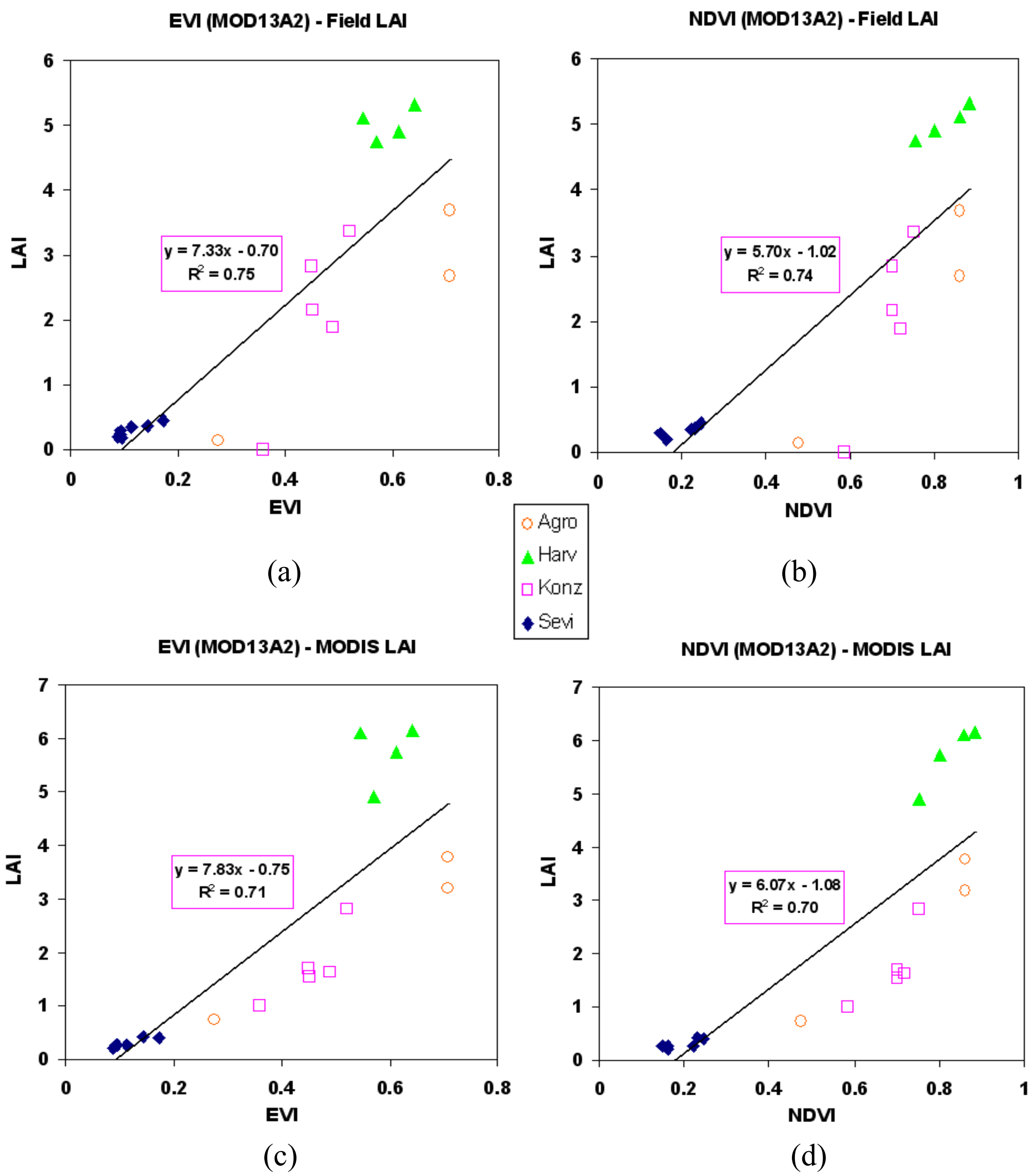



Figure 17: The relationship of combined 4 sites, each site using the mean value averaged from each sampling period. All VI derived from MOD13A2, each figure represents as (a) EVI –Field LAI, (b) NDVI-Field LAI, (c) EVI-MODIS LAI, and (d) NDVI MODIS LAI . There were not significantly different between EVI and NDVI from MOD13 and between field LAI and MODIS LAI

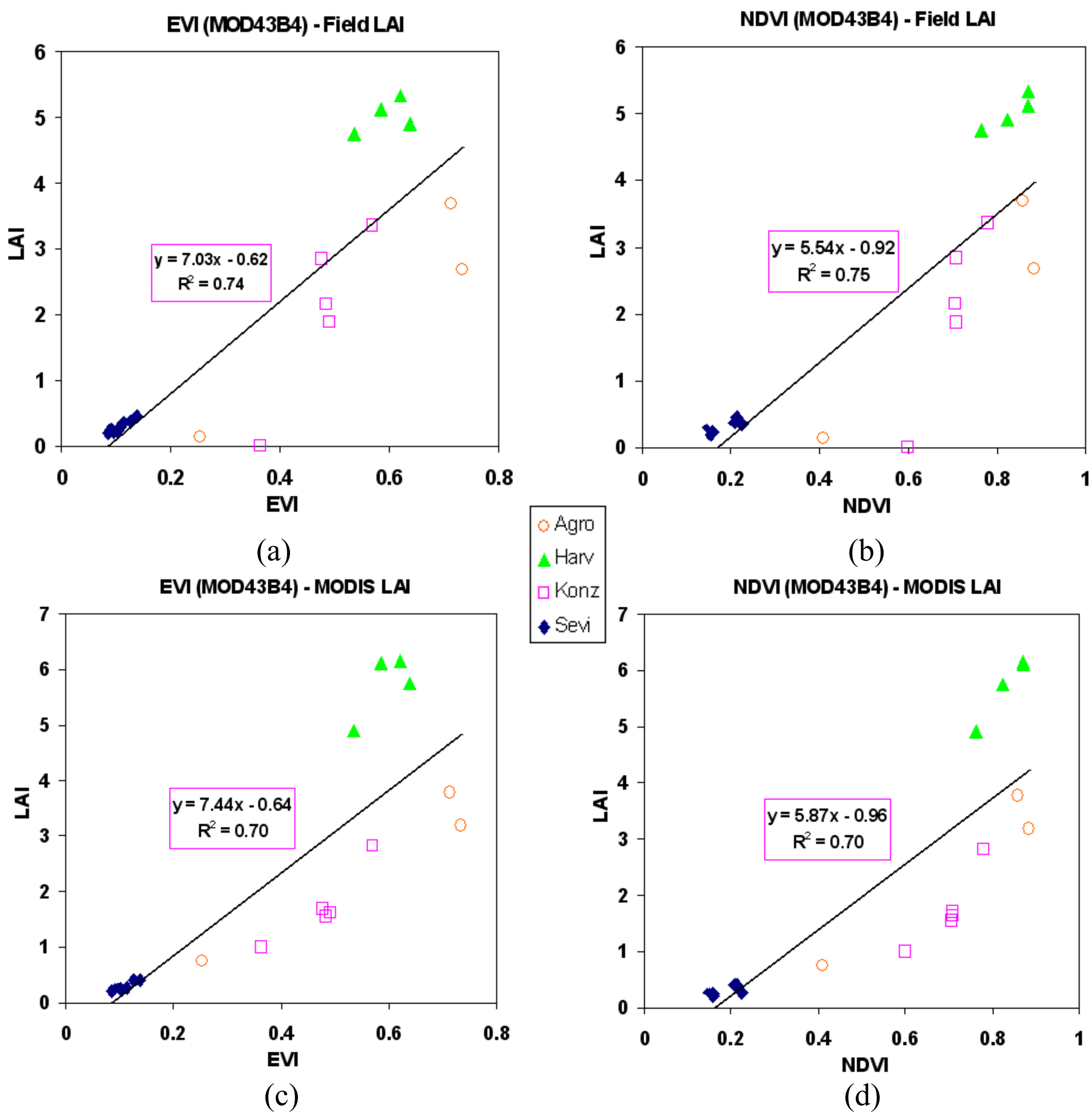



Figure 18: The relationship of combined 4 sites, each site using the mean value averaged from each sampling period. All VI derived from MOD43B4 each figure represents as (a) EVI –Field LAI, (b) NDVI-Field LAI, (c) EVI-MODIS LAI , and (d) NDVI MODIS LAI . There were not significantly different between EVI and NDVI from MOD13 and between field LAI and MODIS LAI