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Use of MODIS NDVI at High Spatio-temporal Resolution to Define Vegetation Activity and Surface Exchange in the Landscape of the Haean Basin, South Korea

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Abstract: Landscape level simulation models are being developed to estimate land surface CO_2 exchange (as gross primary production GPP, ecosystem respiration Reco, and net ecosystem CO_2 exchange NEE) and latent heat exchange (vegetation transpiration T and evapotranspiration ET) in Haean Basin, South Korea. This study focuses on whether the Normalized Difference Vegetation Index (NDVI) from remote sensing may be used to help estimate seasonal timing in vegetation activity (crop and forest canopy phenology) and the magnitude of land surface exchange fluxes. Both aspects are extremely important for improving performance of the spatial simulation models. To eliminate systematic errors in NDVI, we used QC flags provided with MODIS data, and local polynomial smoothing. We have focused on “homogeneous” pixels defined from a field survey map of land use from 2009. Seasonal change of NDVI and phenology for specific land surface elements in the Haean Basin are illustrated. Additionally, examples of the relationship between canopy carboxylation capacity and NDVI at European field sites, and ways to extend these analyses to Haean Basin are discussed.

Keywords: *MODIS NDVI, phenology, carboxylation capacity, landscape gas exchange*

1. Introduction

Landscape level carbon and water balances and the agricultural yield of crops are determined by complex temporal and spatial variations in the behavior of different ecosystem types along topographic and climate gradients, as well as their response to management practices. To assess such phenomena at landscape scale, spatial simulation models are often applied that estimate land surface CO_2 exchange (as gross primary production GPP, ecosystem respiration Reco, and net ecosystem CO_2 exchange NEE) and latent heat exchange (vegetation transpiration T and evapotranspiration ET). Subsequently carbon gain is linked to crop growth and production, while water expenditures are a critical factor linked to the dynamics of runoff, soil water storage and ground water recharge.

Simulation models such as PIXGRO (Tenhunen et al. 2009) and SWAT (Neitsch et al. 2005) that are being applied in the Haean Basin will only simulate balances and agricultural yield with acceptable accuracy if they are supported by and adjusted to field observations and measurements of gas exchange fluxes, harvest data, land use and farming operations. Nevertheless, the extent to which direct observations may be carried out is limited. Thus, the work described here tries to determine how the parameterization of such models can be aided via the use of remotely sensed vegetation indices. Our interest is in using such indices independently as well as combining the information from remote sensing with other types of field studies. The work described below focuses on the one hand on seasonal timing in vegetation activity (crop and forest canopy phenology), and secondly on whether remote sensing may be used to help estimate the magnitude of land surface exchange fluxes. Both aspects are extremely important for improving the performance of the spatial simulation models.

The Normalized Difference Vegetation Index (NDVI) from MODIS allows monitoring of phenological events and seasonal changes in vegetation development (Myneni RB *et* al., 1997, Sakamoto T *et* al., 2005). The NDVI is derived from the red and near-infrared red reflectance ratio, which depends strongly on the amount of chlorophyll and other pigments exposed to the view of the satellite. We are investigating the patterns found in NDVI evaluated at the greatest spatial resolution provided by MODIS (250 m pixels) and high temporal resolution (daily) to determine what they can reveal about phenology in forests, dry land farm fields and rice paddies of the Haean Catchment. Such studies focus on topographic influences and climate trends. Additionally, we are trying to determine whether NDVI at high spatio-temporal resolution can be related to canopy photosynthetic capacity, carbon uptake and water use. This should be possible, since the seasonal changes in NDVI are correlated with the total chlorophyll containing aboveground biomass active in the photosynthetic process. With respect to water balance, strong correlations between photosynthetic carbon gain and water use have long been documented from both agronomical and ecophysiological perspectives.

2. Materials and Methods

2.1. Study Site

Haean Catchment is a mountain basin in South Korea, located northeast of the city of Chuncheon in Yanggu County between longitude 128° 5' to 128° 11' E and latitude 38° 13' to 38° 20' N with a range in altitude from ca. 500 m to 1200 m. The total agricultural area in the basin is 44.7 km^2. The dry field highland agriculture for crops such as potato (15 % of cropland area), cabbage (15 %), radish (20 %) and bean (5 %) are carried out on the mountain slopes between 500 m and 750 m (Choi et al., 2010). The dry land farming area as opposed to wet paddy fields additionally include *Codonopsis pilosula* and ginseng, as well as relatively new plantings of fruit trees and miscellaneous specialty crops. Rice paddies cover ca. 25% of the cropland area in the Haean Catchment. The average annual air temperature is ca. 10.5°C at valley sites and ca. 7.5°C at the northern ridgeline. Average precipitation is estimated at 1200 mm with 50 % falling during the summer monsoon. The forest vegetation is diverse but dominated by oak species. The major tree species in forested slopes include *Quercus dentata*, *Q. mongolica*, *Q. serrata*, *Betula davurica*, and *Tilia amurensis*. Major species of the understory are *Q. mongolica*, *Weigela florida*, *Stephanadra incisa*, *Ulmus laciniata*, *Symplocos chinensis*, *Euonymus alatus*, *Acer pseudosieboldianum*, and *Corylus heterophylla*.

2.2. Daily MODIS NDVI for Selected Pixels

NDVI data from 2009 was obtained from daily gridded L2G (level-2) composite data at 250 m resolution that is embedded in the MODIS/terra surface reflectance products (MOD09GQ) obtained from the Warehouse Inventory Search Tool (WIST, https://wist.echo.nasa.gov/). MOD09GQ provides band 1 (620-670 nm) and band 2 (841-876 nm) in the Sinusoidal projection. The normalized difference vegetation index is calculated using surface reflectance in red and near-infra-red wave lengths as NDVI = $(\rho_{NIR}-\rho_{red})/(\rho_{NIR}+\rho_{red})$, where ρ is surface reflectance in near infra-red and red sensor bands, respectively (Running SW et al., 2004).

The original values of NDVI include frequency noise components due to clouds, water, snow, shadow, bidirectional effects, high solar or scan angles and transmission errors which are identified in a series of quality control indicators. In our initial studies reported here, we have determined a local polynomial regression fit to 9 day moving maxima for NDVI, where the maxima are estimated for broadly selected NDVI values according to the recorded QC flags. This polynomial was calculated locally to achieve the smallest estimated mean square error. Local polynomial smoothing allows fitting with combined linear and nonlinear regression data. Future steps in development of the analysis will include varying the quality of data included into the estimation of time series maximal NDVI values.

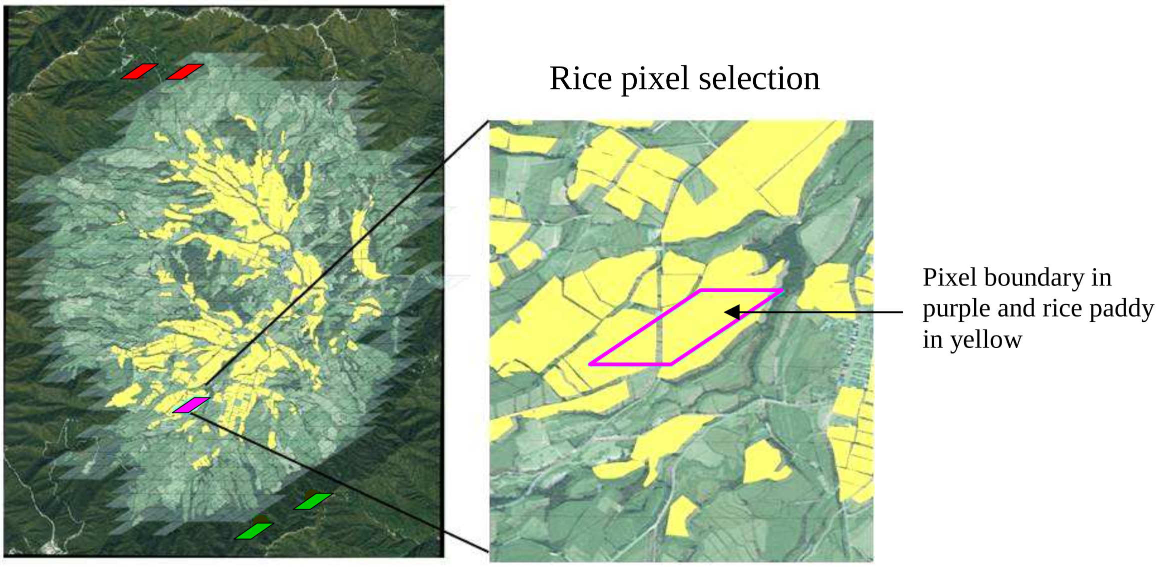

Figure 1. High resolution SPOT image of Haean Basin overlaid with MODIS pixel grid and with rice paddy land use determined in ground level studies (yellow). Enlarged image shows the detail of rice paddy land use in relation to one MODIS pixel (purple boundary). Pixels are analyzed where the land cover is more than 80% homogeneous with respect to rice paddy. Forest pixels shown in red (southeast facing) and green (northwest facing) are compared in Fig. 3 below.

MODIS 250 m resolution provides the best currently available daily information on NDVI. Nevertheless, 250 m NDVI has different utility in determining vegetation activity patterns of forest, dry field farms and rice paddies due to fragmentation and the patterning in land use. Based on the field survey map of land use from 2009, homogeneity values for each MODIS pixel are obtained. For forests, an infinitely large number of pixels may be selected for analysis, although species composition of those pixels is unknown. In the case of rice paddies, many pixels with greater than 80% homogeneity occur, due to clustering of the paddies in the basin. Overlays of MODIS pixel projections and land use as shown in Fig. 1 allow selection of the “best pixels” in terms of homogeneity. However, in the case of dry land farm fields, only a small number of locations provide clear information about specific crops, e.g., growth of radish, potatoes, beans or cabbage. Part of the task in this work is to determine how the information from “best pixels” can be utilized in improving spatial simulation models.

2.3 Phenology and Heat Sum Estimations

From seasonal NDVI curves, the onset of green-up and onset of senescence indicated in DOY units can be detected using the method by Zhang et al. (2003), Bradley BA et al. (2007) and Sakamoto et al. (2005). In the case of forest and rice paddy locations, it is our intent to analyze spatial variation in these important phenological dates on the basis of heat sums calculated for the specific locations. Heat sums, or the accumulation of daily mean temperature in degrees exceeding a base reference temperature are strongly correlated with plant development (Neitsch SL *et* al., 2005). Heat-sums are calculated daily based on spatial extrapolation of climate data from 14 automatic weather stations installed in Haean Catchment. The analysis is not yet included in this preliminary report.

2.4 NDVI and Carboxylation Capacity ($Vc_{uptake1*}$)

CO_2 uptake capacity of vegetation depends on the amount of photosynthetically active biomass present, the physical arrangement of this biomass with respect to light interception, and the investment by plants in enzymatic components of the carbon fixation cycle which is often correlated with concentration of nitrogen (N) in plant organs. CO_2 uptake itself depends on momentary influences of radiation, temperature, CO_2 concentration in the air, and canopy conductance as influenced by species-specific traits along with availability of water to the root system. Owen et al. (2007) demonstrated via the analysis of eddy covariance-based monitoring of gas exchange of a wide variety of plant types that CO_2 uptake over the course of annual cycles could be understood in terms of a true “capacity” for uptake, and modifications that occur due to short-term fluctuations in environmental factors. The capacity ($Vc_{uptake1*}$ in the terminology of Owen et al. 2007) depends on the exposed photosynthetically-active biomass. Therefore, we investigate whether NDVI allows us to observe the seasonal course in $Vc_{uptake1*}$ and, thereby, to predict CO_2 uptake as well as water lost by the vegetation canopy. $Vc_{uptake1*}$ has been obtained for selected locations by inversion of a canopy gas exchange as described by Owen et al. (2007). For the same locations, daily values of NDVI were obtained according to the methods described in section 2.2.

3. Results

3.1 Seasonal Changes in NDVI and Phenology in Haean Basin

The seasonal change of NDVI for Haean Basin at 250 m resolution is illustrated in Fig. 2 with 8 selected days from day of year (DOY) 93 to DOY 299. The background reflectance during winter differs between leafless deciduous forest (NDVI ca. 0.3 to 0.4) and fallow fields (NDVI less than 0.3) and is influenced further by snow cover. The initial springtime changes in NDVI or onset of green-up are seen on DOY 124 with more advanced development in the forest areas southeast of the basin. Ten days later on DOY 133 when planting activity in general begins, the leaf flush in forests has occurred across the entire scene, including forest locations in the center and scattered within the basin. Subsequently in the period DOY 178 to 261, crop canopies develop to their maximum LAI, and early developing crops even begin to senesce (apparent in some dry field locations on the slopes). By DOY 293, senescence is apparent in the forested areas and crops have been harvested. At the end of October (DOY 299), the gradual return to the winter situation is seen.

Examples of smoothed daily NDVI curves obtained for relatively homogeneous rice, forest and dry cropland pixels are illustrated in Figs. 3 and 4. The reproducibly characteristic curve for rice paddies exhibit an initial increase in NDVI associated with transplanting of the seedlings (at or just after the observation of field planting on DOY 135 to 140). This appears to be followed by an exponential increase in NDVI associated with the growth phase. According to time-series data of the spectral reflectance of paddy fields (Shibayama and Akiyama 1989), the maximum NDVI appears around the heading date. Subsequently, reproductive growth removes nitrogen from the canopy, senescence of leaves increases and NDVI decreases. In the case of forest, NDVI increases rapidly as leaves flush in the spring, increasing to maximum LAI within two weeks. The decrease with senescence in fall is slower. From the curves shown in Fig. 3, it is apparent that LAI remained almost constant throughout the summer during 2009.

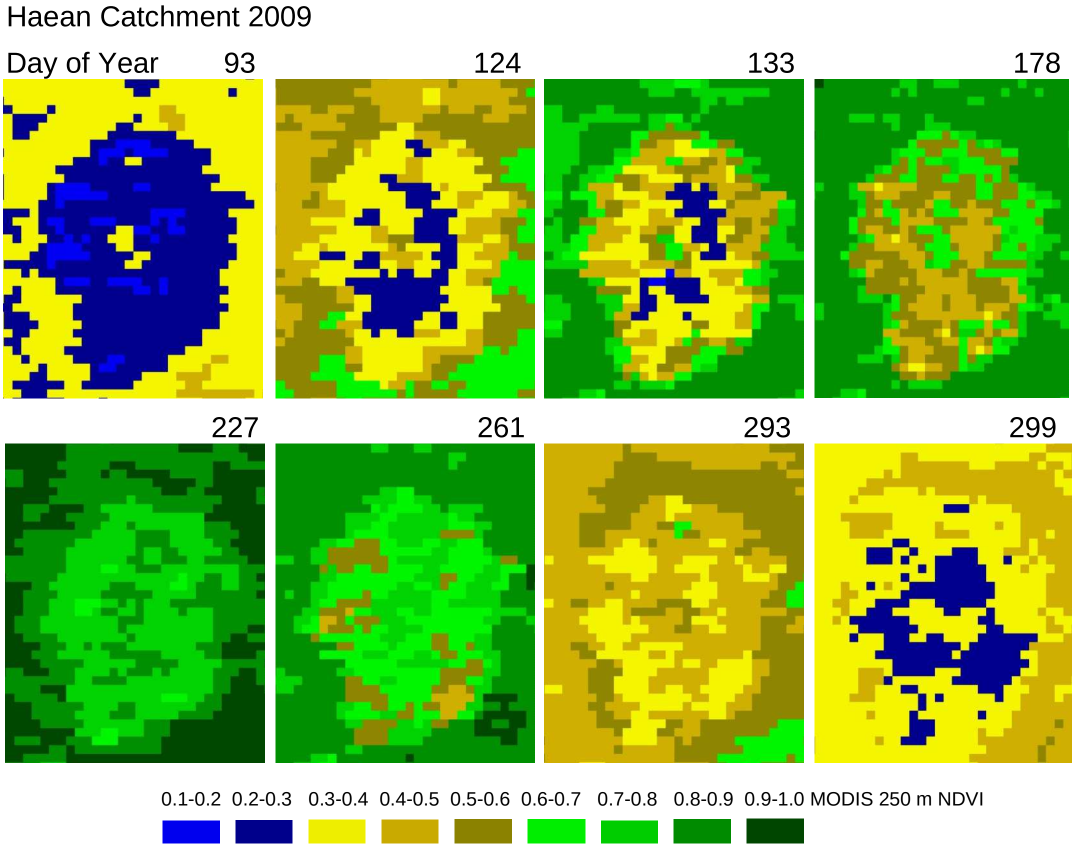

Figure 2. The annual cycle of change in NDVI in Haean Basin and adjacent forested areas illustrated for 2009.

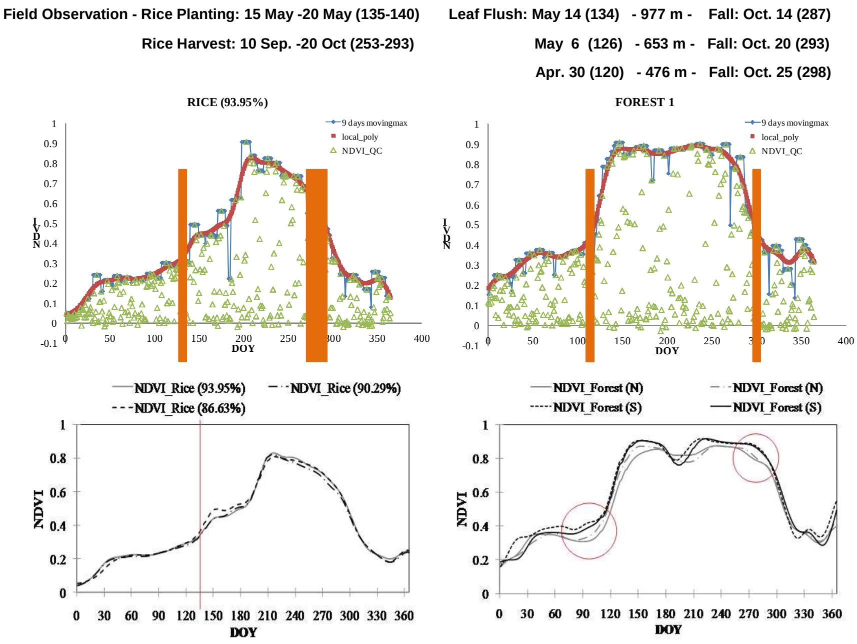

Figure 3. Upper Panels: Examples of smoothed daily NDVI curves obtained for a selected rice pixel and forest pixel. The green triangles indicate individual NDVI values from initial screening, the blue filled rectangles are 9 day moving maxima. The red line represents NDVI pattern after applying the local polynomial regression procedure. DOY is day of year. Lower Panels: The NDVI curves in several rice pixels (left) and forest pixels (right). The red line in rice denotes the green-up onset (planting date). The forest curves showed different green-up onset and senescence between locations in the southern forest and northern forest (the red circles). General field observations on planting, harvest and green-up are given at the top of the figure.

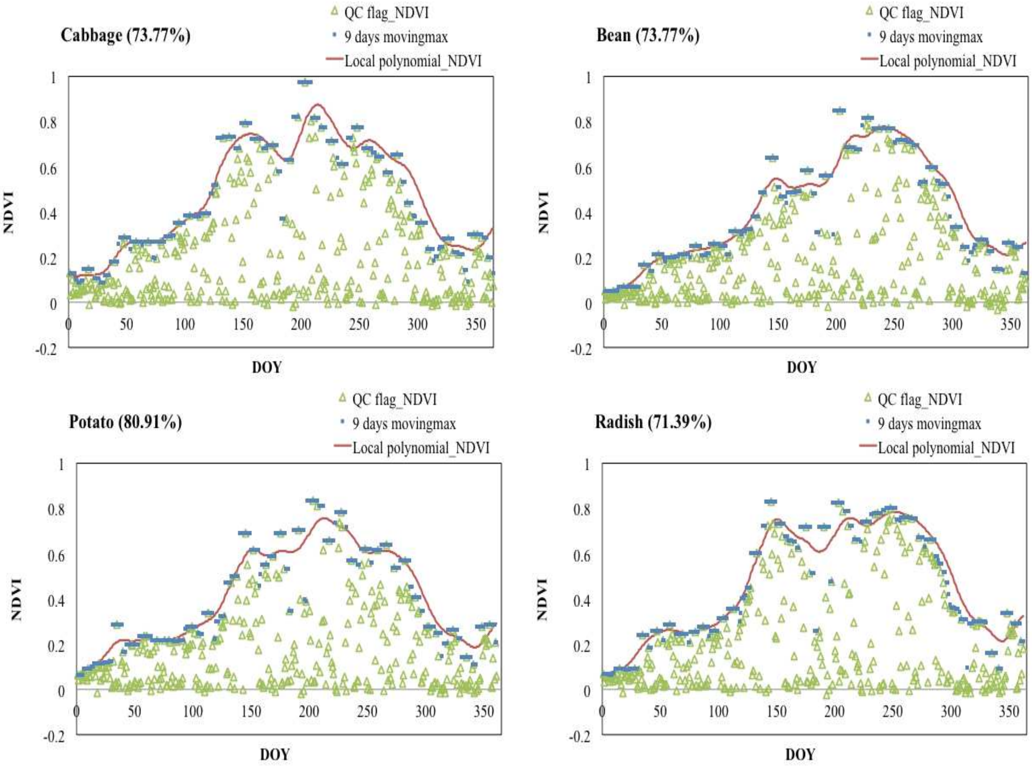

Figure 4. Examples of smoothed daily NDVI curves obtained for the most homogeneous 250 m resolution cabbage, bean, potato and radish pixels in 2009. The green triangles indicate individual NDVI values from initial screening, the blue filled rectangles are 9 day moving maxima, and the red line the local polynomial fit according to procedures described above.

Examples of the NDVI curves for cabbage, bean, potato and radish are shown in Fig. 4. Due to the lower degree of homogeneity, these curves may be influenced by surrounding vegetation. The interpretation of dry land crop NDVI is only beginning at the present time.

3.2 Linking NDVI with Canopy Carboxylation Capacity

The seasonal changes in GPP, LAI, $Vc_{uptake1*}$ and NDVI for rice paddy fields at El Saler, Spain are shown for 2007 and 2008 in Fig. 5. Flux and harvest data are from the CarboEurope studies of Carrera et al. (personnal communication). Daily GPP increased strongly together with LAI increase after planting in both 2007 and 2008. The seasonal pattern in GPP in these two years and during the period 2004 through 2008 was very consistent, both in magnitude of CO_2 uptake and timing in the changes in flux rates. Nevertheless, small variations occurred in plant development and gas exchange as revealed in Fig. 5. Extrapolated LAI based on multiple harvests at El saler (Fig. 5, upper right panel) had maximum values of near 6 on ca. DOY 220 in 2007 and ca. DOY 210 in 2008.

Canopy model inversions that estimate the parameter $Vc_{uptake1*}$ and also the smoothed NDVI curves do not show the differences in development 2007 and 2008, possibly due to the sensitivities of these to vegetation/environmental factor interactions and compensatory effects. NDVI is clearly related to the time course of green-up or changes in LAI (Fig. 5, lower right panel).

The relationship of carboxylation capacity, $Vc_{uptake1*}$, to NDVI and rice canopy development at El Saler, Spain in 2008 is illustrated in Fig. 6. Seasonal changes may be separated into two phases. During initial growth and canopy expansion (vegetative phase), the upper regression line in Fig. 6 (left panel) is found; while after the maximum in GPP, LAI and flowering (senescent phase or phase with translocation to the developing grain), a second relationship is valid (lower regression line in left panel). When LAI is adjusted in the model inversions for leaf N content (apparent enzymatic capacity for carboxylation), e.g. LAI as a measure of chlorophyll containing biomass but multiplied by leaf N content (enzymatic capacity), a single relationship is valid for the entire summer.

It appears that the key physiological parameter $Vc_{uptake1*}$ can be broadly related to NDVI, as seen in preliminary data obtained in analysis of GPP fluxes from 5 European crops (Fig.7). Thus, NDVI may be used to estimate carboxylation capacity and flux rates, or may aid the modeling of dry crop growth and production in landscapes by defining appropriate relationships between aboveground biomass and gas exchange rates.

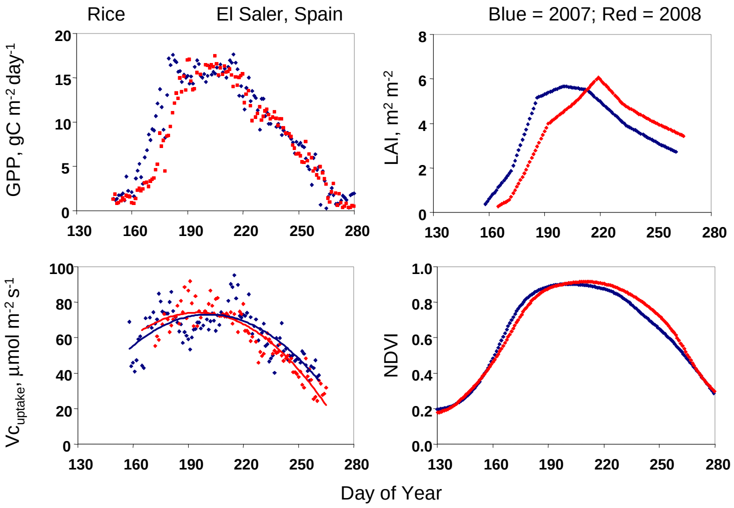

Figure 5. Seasonal changes in GPP from eddy covariance measurement, in LAI based on extrapolation from multiple harvests, in the carboxylation capacity $Vc_{uptake*1}$ from model inversions, and in NDVI from MODIS satellite data at El Saler, Spain in 2007 and 2008.

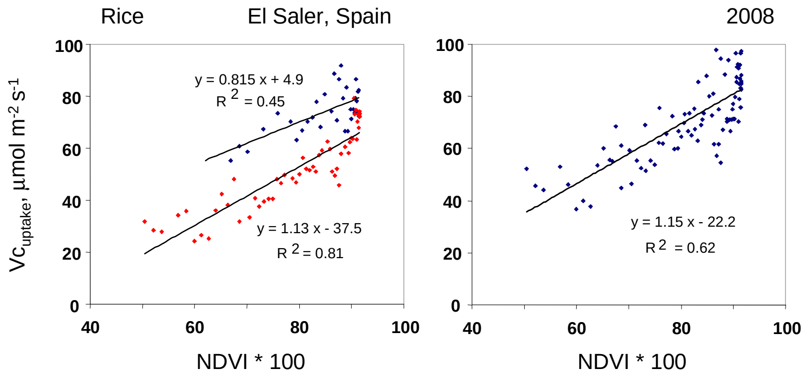

Figure 6. Correlations of the parameter $Vc_{uptake1*}$ *with NDVI at El Saler with rice canopy in 2008 using daily estimates of NDVI and extrapolated daily estimates of LAI from multiple harvests. Left panel shows the two relationships that are found during "vegetative" (canopy expansion) and "senescent" (post-flowering) phases when LAI is assumed to have the same efficiency in carboxylation. Right panel demonstrates that a single relationship is found when canopy efficiency in carboxylation is adjusted for seasonal change in leaf N content and presumably leaf enzymatic complement for carboxylation.*

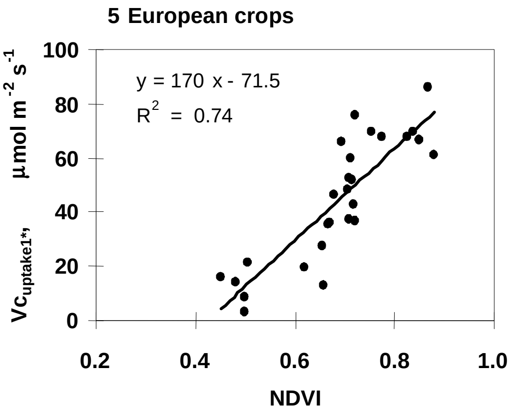

Figure 7. Correlations of the parameter $Vc_{uptake1*}$ *with NDVI using data from the specific times when crop canopy characteristics were measured at Klingenberg 2005 (rapeseed) and 2006 (winter wheat), Gebesee 2006 (sugar beet), El Saler-Sueca in 2007 (rice), and Lonzee in 2006 (potato).*

4. Discussion and Conclusions

Seasonal changes in surface reflectance are strongly linked to land surface function with respect to gas exchange, growth and production of the vegetation, and vegetation water use. This study focuses on understanding CO_2 and H_2O exchange, biomass development and yield of forest and crop canopy ecosystems, using field data together with vegetation indices such as MODIS NDVI. At the highest resolution possible with MODIS (ca. 250 m pixels), we attempt to obtain a picture of change in vegetation state as revealed via surface reflectance for specific crops and for forests located in particular landscape situations. The studies require careful analysis of the MODIS data, taking into account a variety of statistical problems and quality controls. These considerations are still under study. In the future, they would profit from simultaneous observations of reflectance with ground-based instrumentation.

Nevertheless, our effort is oriented to building true and robust relationships between remotely-sensed information and land surface processes, including changes in structure and physiology. Both are important to understand. Thus, the research is focused 1) on the relationship between NDVI and phenological patterns, 2) on the relationship between LAI (or aboveground biomass) and carboxylation capacity, and 3) on the relationship between NDVI and carboxylation capacity. The results to date demonstrate that reasonable linkages in the rice and forest pixels at Haean Basin may be established. Deriving the relationships for additional dryland crops remains a challenge that is currently being confronted. In part, we hope to overcome these difficulties through information gained at crop sites investigated in network carbon balance projects at European and Asian sites (cf. Bastiaanssen et al., 2000).

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