Biotic controls over spectral indices of tundra vegetation and implications for regional scaling

by

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ABSTRACT

(--abstract needs revision--)

The use of remotely sensed data has become a desirable option for examining spatial and temporal dynamics of tundra vegetation at a variety of scales from landscape to regional to global. The key step in using remotely sensed data is correlating biophysical properties of vegetation to values of spectral measures. In this study seasonal field measurements of normalized difference vegetation index (NDVI), using a field spectroradiometer, and leaf area index (LAI), using a LI-COR LAI-2000 Plant Canopy Analyser, were compared with biomass data to investigate relationships between vegetation properties and spectral indices for four distinct tundra vegetation types at Ivotuk, Alaska (68.49 N, 155.74 W). NDVI, LAI, and biomass data were collected biweekly from four 100 m x 100 m grids, each representing a different vegetation type, during the 1999 growing season. The vegetation types examined in this study included Moist Acidic Tundra (MAT), Moist Non-acidic Tundra (MNT), Moss Tundra (MT), and Shrub Tundra (ST). NDVI showed the strongest relationship with the live foliar deciduous shrub component of biomass ($NDVI = 0.5955*(FolDecShrub)^{0.0584}$, $p < 0.05$, $r = 0.85$) when the data were examined across all tundra types. While the live foliar deciduous biomass represents approximately 10% of the total live biomass, it is the factor that may be exerting the greatest control over NDVI values for much of the tundra. Additionally, the non-linear relationship relating mean NDVI and mean deciduous live foliar biomass could lead to inconsistencies when using spectral indices to infer biomass at coarser scales, given that NDVI saturates with increasing biomass. LAI showed the strongest relationship with the overstory component (total excluding moss and lichen) of

biomass ($p < 0.05$, $r = 0.814$). A temporal effect was observed on the relationships examined in this study, with the strongest relationships occurring during the mid to late growing season. For example, NDVI and LAI were most strongly correlated in early August ($p < 0.05$, $r = 0.77$). The relationships between biophysical properties of differing vegetation types and spectral indices found in this field study can be extrapolated with the use of satellite data to provide valuable information regarding regional vegetation responses to climate change.

INTRODUCTION

The dynamics of tundra vegetation have become an important topic of research due to recent findings indicating that arctic systems are sensitive to climate change and that long term consequences are complex in nature (Oechel et al. 1993, Oechel et al. 1994, Chapin et al. 1995, Myneni et al. 1997, Arft et al. 1999, Epstein et al. 2000). Recent distinctions of tundra vegetation resulting from regional and local variations in substrate (Walker et al. 1994, Walker et al. 1998) and topography (Shaver et al. 1996) have heightened the importance of more completely understanding vegetation properties on the landscape scale. The sensitivity to climate change and local heterogeneity of tundra vegetation increase the importance of linking field measurements of ecological variables to regional estimates of these variables.

The use of remotely sensed data has become a desirable option for examining spatial and temporal dynamics of tundra vegetation at regional and local scales (Shippert et al. 1995, Walker et al. 1995, Stow et al. 1993, Hope et al. 1993, Jia et al. submitted). Remotely sensed data are non-destructive in nature and are often more financially and logistically feasible than field studies (Shippert et al. 1995). Another advantage of using remotely sensed data is that they capture actual rather than potential measures used to derive ecological variables (Shippert et al. 1995). The key step in using remotely sensed data is correlating biophysical properties of vegetation to values of spectral measures. This process has been fairly successful in temperate regions (Aase and Siddoway 1981, Asrar et al. 1985, Park and Deering 1982, Tucker et al. 1981). Recently, studies conducted in the tundra have focused on correlating differences in biomass among vegetation types to variations in normalized difference vegetation index (NDVI) (Shippert et al. 1995, Walker et al. 1995, Stow et al. 1993, Hope et al. 1993). NDVI was found to be greater in water track and moist hillslope acidic tundra communities compared to moist non-acidic tundra communities, due to a greater abundance of deciduous shrubs (Walker et al. 1995). Jia et al. (submitted) examined the difference between NDVI in moist acidic tundra and moist non-acidic tundra on a regional scale and found generally higher values of NDVI in the moist acidic tundra. Relationships have also been examined within plant community types. Hope et al. (1993) found that approximately 50 % of the variance in NDVI could be explained by the amount of photosynthetic biomass within several vegetation types.

Modeling of carbon dynamics or plant productivity is usually accomplished by making estimates from a simple set of vegetation properties which often includes biomass or LAI (Williams and Rastetter 1999, Williams et al. 2000). Obtaining values of biomass and LAI is not always logistically feasible. Therefore it is beneficial to be able to derive these variables from measures that can be obtained remotely, such as NDVI. Comparing field measurements of NDVI and LAI with detailed biomass data is not only important for relating ecological variables for use in modeling studies but also provides information as to what plant structure of tundra vegetation corresponds a certain measure of a spectral index. While several studies have successfully investigated relationships of spectral indices and biophysical properties in the Arctic (Stow et al. 1993, Hope et al. 1993, Walker et al. 1995, Shippert et al. 1995), the relationship between field NDVI and biomass or LAI has not been investigated at the level of detail of this study across an entire growing season.

The primary goal of our study was to examine relationships between spectral indices (such as NDVI and LAI) and biomass to determine what specific components of plant biomass are controlling the variance in spectral indices. We are considering LAI to be a spectral index because it is commonly determined by measuring differences in below and above canopy incoming solar radiation. Additionally, relationships between NDVI and LAI were investigated to assist in modeling efforts. Collecting biomass data simultaneously with field spectral data enabled us to avoid confounding effects of the atmosphere, and also provided the ability to target distinct local vegetation types (Hope et al. 1993).

~~It is thought that~~ relationships between spectral measures and biophysical properties vary across the growing season (Hope et al. 1993), these methods allowed us to capture these variations from the onset of the growing season to the end. Therefore, a secondary goal of this study was to examine how relationships between spectral indices and biomass change over the growing season. Conducting field measurements across several vegetation types for an entire field season allowed for the examination of these relationships at a high level of detail. The general goal of establishing relationships between spectral indices and biophysical properties was to provide information regarding

Condense into one paragraph of goals should be closer to front of introduction even 1st ¶

local distinctions of tundra vegetation, which can then be extrapolated to coarser scales and be used in modeling studies.

METHODS

Ivotuk, Alaska (68.49 N, 155.74 W), located on the north slope of the Brooks Mountain Range, is characterized by a growing season length of 70-80 days and a mean July maximum temperature of 12° C. The study site was chosen because four tundra vegetation types, moist acidic tundra (MAT), moist non-acidic tundra (MNT), moss tundra (MT), and shrub tundra (ST) exist within a 2 km^2 area. The vegetation at the MAT site is comprised of *Eriophorum vaginatum, Sphagnum* mosses and prostrate shrubs. The MNT site, found on non-acidic soils, has a vegetative community dominated by *Carex bigelowii* and *Dryas integrifolia*. The MT site is comprised mostly of *Sphagnum* mosses, *Betula nana*, and lichens. The ST site, found in a well drained riparian region, is dominated by *Salix pulchra* and *Betula nana*. Ivotuk is also a key sampling location for the NSF Arctic Transitions in the Land-Atmosphere System study as part of a transect from Barrow to the Seward Peninsula.

Also, the airstrip provided one of the few easily accessable sites in Northwestern Alaska. A comparable point to Toolik along the Dalton Hiway

separate ¶

Intraseasonal trends of leaf area index (LAI) and normalized difference vegetation index (NDVI) were compared with biomass data to investigate relationships between vegetation properties and spectral indices for four distinct tundra vegetation types. LAI, NDVI, and biomass samples were collected bi-weekly from four 100 m x 100 m grids, each representing a different vegetation type, during the 1999 growing season. Field measurements were divided into seven sampling periods beginning June 5th and ending August 27th. LAI and NDVI measurements were taken at 20 random points within each grid; the same 20 points were used throughout the growing season. LAI was measured using a LI-COR LAI-2000 instrument. ***(--will insert technical description of LAI measurements--)*** At each of the 20 grid points one above canopy reading was taken and four below canopy readings were taken one 1 m north, east, south, and west of the point, to yield a mean LAI value.

NDVI was measured using an Analytical Spectral Devices FieldSpec spectroradiometer. The Visible/Near infrared spectrum is measured by a 512 channel silicon photodiode array and separated by a filter, which provides a spectral sampling interval of approximately 1.4 nm. After being separated and reflected onto independent detectors, incident photons are converted into electrons and finally digitized (ASD Field Spec User's Guide 1998). The reflectance data for the pertinent wavelength intervals were used to calculate NDVI using the formula:

Too much detail

$$NDVI = (NIR - Red)/(NIR + Red)$$

where NIR is the near infrared band reflectance (725 – 1060 nm) and Red is the red band reflectance (580 – 680 nm) of the vegetation. Four replicate measurements were taken 1 m north, east, south, and west of each grid point and averaged to give a mean NDVI value. The fiber optic sensor of the FieldSpec spectroradiometer was held approximately 1.5 m above the surface of the vegetation. A 25 ° field of view from the sensor yields a footprint of 0.35 m^2 when sensed at this height.

Biomass was collected from 10 randomly selected 20 cm x 50 cm plots within each grid, for a total of 1 m^2 per vegetation type for each of the first six sample periods. Biomass sampling occurred near, but not within, the footprints of LAI and NDVI measurements. On the fourth ~~4th~~ sample period (July 15 - 26), the quantity of biomass harvests was doubled for MAT and MT. On the 5th sample period (July 27 – Aug. 7), the quantity of biomass harvests was doubled for MNT and ST. Generally, vascular plants were clipped at the top of the moss surface. Mosses were clipped at the base of the green layer. Therefore when we refer to biomass, we are referring only to this aboveground fraction. Biomass samples were sorted into six main categories (byrophytes, horsetails, other forbs, graminoids, lichens, and shrubs). The graminiod and shrub samples were sorted further into subcategories. Graminoid biomass was divided into live and dead material. Shrub biomass was divided into evergreen and deciduous, which were then separated into woody, foliar live, and foliar dead components. Statistical analyses were performed on several levels of data aggregation. To investigate relationships across all vegetation types, data were grouped solely by vegetation type (individual measurements for each vegetation type across all sampling periods were combined, n = 4). Second, data were grouped by vegetation type and sample period (individual grid point measurements for each vegetation type were averaged for each sample period), to investigate relationships across all vegetation types (n = 24) and within vegetation types (n = 6). Finally, individual grid point measurements were compared to investigate how relationships varied throughout the growing season. Regression analyses were performed to establish relationships between spectral indices (such as NDVI and LAI) and total live biomass, between spectral indices and specific components of biomass, and between NDVI and LAI (SPSS 8.0). ? State specifically in a separate ~~paragraph~~ sentence what statistical approaches were used

Maybe consistent and call it "aboveground phytomass"

RESULTS

Correlation of NDVI to Vegetation Properties

Mean total live biomass did not show a significant relationship with mean NDVI when data were grouped simply by vegetation type (n = 4). When the data were grouped by vegetation type and sample period, mean NDVI was significantly related to mean total live biomass ($R^2 = 0.42$, $p < 0.05$), as well as several components of biomass (Table 1). Aside from the forb component, all the biomass components that exhibited significant relationships with NDVI were comprised of either one or several subsets of shrub biomass. The photosynthetic component of total biomass (all live biomass excluding woody material) surprisingly showed no significant relationship with mean NDVI ($R^2 = 0.05$, $p = 0.30$). The biomass component that showed the strongest correlation to mean NDVI was the live foliar deciduous shrub biomass. A power curve provided the best fit for this relationship ($NDVI = 0.5987*FolDecShrub^{0.0559}$, $R^2 = 0.77$, n = 24, $p< 0.05$)(Fig. 1a). When examining the data within individual tundra types, mean NDVI was not significantly related to mean total live biomass. Similar to the composite data, mean NDVI showed the strongest relationship to the mean live foliar deciduous shrub component of biomass for MAT ($R^2 = 0.93$, $p < 0.05$), and ST ($R^2 = 0.87$, $p < 0.05$) (Fig. 1b). However, for MNT and MT the strongest relationship observed was between mean NDVI and mean live graminoid biomass ($p < 0.05$, $R^2 = 0.82$, $R^2 = 96$ respectively) (Fig. 1c).

Analysis of data grouped by vegetation type and sample period revealed a significant relationship between mean NDVI and mean LAI ($NDVI = 0.0487*LAI + 0.6001$, $R^2 = 0.23$, $p < 0.05$). Within vegetation types no significant relationships existed (n = 6).

Correlation of LAI to Biomass

The best relationship between LAI and biomass was observed between mean LAI and mean overstory (total biomass excluding moss and lichen) component of biomass ($R^2 = 0.90$, $p < 0.05$). This relationship occurred when the data were grouped only by vegetation type ($n = 4$). When the data were grouped by vegetation type and sample period, again mean LAI showed the strongest correlation to the mean overstory component of biomass ($R^2 = 0.66$, $p < 0.05$) (Fig. 2). Mean LAI was significantly related to mean total live biomass ($R^2 = 0.47$, $p < 0.05$), as well as several components of biomass (Table 2). The biomass components that exhibited significant relationships were comprised of either or both the woody and deciduous foliar shrub components of biomass. When examining data within vegetation types, LAI was significantly related to a few biomass components for which there was no reasonable biological explanation.

Seasonal Trends of Relationships

Seasonal trends indicating the strongest correlation occurs during mid to late growing season were evident in all three vegetation property comparisons. Analysis of seasonal trends was accomplished by comparison among all individual grid point samples. For relationships between NDVI or LAI and biomass several of the key biomass components demonstrated a peak in correlation coefficients during mid growing season. The relationships between NDVI and the deciduous live foliar ($R^2 = 0.69$) and total live ($R^2 = 0.59$) components of biomass were strongest with sampling conducted from July 2 to July 10 (Fig. 3a). The relationship between NDVI and the shrub live ($R^2 = 0.72$) component of biomass was strongest with sampling conducted from July 15 to July

Tense keep results in past Tense throughout

25. The relationships between LAI and the deciduous woody ($R^2 = 0.41$), shrub live ($R^2 = 0.50$), overstory ($R^2 = 0.50$), and total live ($R^2 = 0.25$) components of biomass were strongest with sampling conducted from July 15 to July 26 (Fig. 3b).

The relationship between NDVI and LAI became stronger as the growing season progressed (Fig. 3c), with a peak correlation for sampling conducted from Aug. 13 – 20 ($NDVI = 0.6647*(LAI)^{0.0534}$, $r = 0.77$, $p < 0.05$) (Fig. 4). The relationships were generally best described by linear functions, except for the last two sample periods during which power relationships demonstrated the best fit for the data.

Reanalysis of Relationships

Due to the presence of seasonal trends in the relationships, regression analyses were performed on data grouped by vegetation type and by sample period using only mid or late season data. The relationship between mean NDVI and mean total live biomass was improved when early and late season data was excluded from the regression. This relationship was best described by a moderately strong linear curve ($NDVI = 0.002*TotLive + 0.59$, $R^2 = 0.66$, $n = 12$, $p < 0.05$) (Fig. 5) for data collected in periods 2 through 4 (June 17 to July 26). The relationship between mean LAI and mean total live biomass or mean overstory biomass did not become significantly stronger when using only mid season data. The relationship between mean NDVI and mean LAI became only slightly stronger when early season data was excluded from analysis and was similar to the relationship observed when comparing individual grid point data for period 6 (Aug. 13 – Aug. 20).

DISCUSSION

As suggested by the findings of Hope et al (1993), the photosynthetic component of biomass was expected to have a significant influence on the variance of NDVI. However, our results did not reveal a significant relationship between NDVI and the photosynthetic component of biomass. Rather a subset of photosynthetic biomass, the live foliar deciduous shrub component of biomass, exerted the greatest control on NDVI. This is true across all vegetation types and within each vegetation type except for moist non-acidic tundra (MNT) and moss tundra (MT). For the MNT and MT live graminoid biomass had the most significant control on NDVI. The discrepancy as to which biomass component exhibits the greatest control on NDVI within a vegetation type can most likely be attributed to the quantity of shrub biomass. In the MNT and MT the live shrub biomass makes up only 11 % and 19 % of total live biomass respectively, which is significantly lower than in the MAT and ST sites where shrub biomass makes up 51 % and 63 % of total live biomass respectively. The relatively low quantity of shrub biomass found in the MNT and MT means that variations in other biomass components will have a greater effect on NDVI. In both cases the quantity of live graminoid biomass had most significant control NDVI within these vegetation types. The fact that the presence or absence of large amounts of shrub biomass determines the role of the relationships between NDVI and biomass components within a vegetation type supports the conclusion that quantities of shrub biomass are the most important factor controlling levels of NDVI across all vegetation types. A conclusion that is consistent with the results found in this study (relationship between mean NDVI and live foliar deciduous shrub biomass was strongest of all components of biomass when comparing across all vegetation types) (Fig.

1a) and with previous studies conducted on tundra vegetation (Hope et al. 1993, Walker et al. 1995).

The results from our study suggest that the quantity of overstory biomass has the strongest influence on LAI. In examining which biomass components were significantly related to LAI, it is evident that woody and deciduous foliar shrub material have the largest impact on LAI. While obviously foliar biomass is expected to control values of LAI, the fact that woody material plays such a significant role is most likely due in part to the method of measurement and in part to the fact that woody biomass and foliar material are covariates. Although strong relationships where observed between LAI and several biomass components across all vegetation types, when examining within individual vegetation types no significant relationships were found. The variability in LAI within a vegetation type is within the range of measurement error, and therefore no significant trends were observed. However, when investigating the relationship across all vegetation types the variance in LAI is greater than the range of measurement error, and thus the significant relationship was observed.

The high variability of NDVI and LAI observed within a vegetation type resulted in the absence of a strong correlation between NDVI and LAI within any of the individual vegetation types. While a significant relationship was observed across all vegetation types and all sampling periods, the strongest correlation occurred when comparing data taken late in the growing season. The relationship continued to become stronger as the growing season progressed, until peaking at the second to last sampling period (Aug. 13 – 20). This seasonal trend suggests that the relative abundance of material that is contributing differently to values of either LAI or NDVI, may not be in balance early in the growing season and fluctuates across the growing season. For example, early in the growing season the relative amount of woody material is greater than peak season at, which would increase values of LAI while having no effect on NDVI.

Additionally, late in the growing season the relationship between NDVI and LAI becomes non-linear. The non-linear nature of relationships of NDVI to biophysical properties could be explained by the fact that as vegetation density increases late in the growing season, the ability for chlorophyll to absorb more incident red light saturates (Shippert et al. 1995). Therefore, late in the growing season, patches or sites with dense biomass reach a point where the NDVI is no longer sensitive to increases of biomass or LAI. ***(--will insert saturation biomass values--)*** A temporal effect was also observed when comparing NDVI and LAI to biomass. The strongest relationships were observed in July, during mid growing season, when plant growth had reached sufficient levels to influence spectral indices, yet before there was substantial plant tissue senescence.

incomplete sentence

Implications for modeling

The seasonality of these relationships suggests that they are not stable over the growing season (Hope et al. 1993), and when estimating biophysical properties of vegetation from spectral data it is best to do so during mid growing season. Calculating LAI or biomass from the relationships found in this study using NDVI values obtained at times other than mid growing season could lead to increases in error. The power relationships observed in our results are consistent with past researchers who have found non-linear relationships between NDVI and biophysical properties (Hope et al 1993, Shippert et al. 1995). Consequences of non-linear relationships would yield inconsistencies when using spectral indices to infer biomass or LAI at coarser scales. With non-linear relationships, at high levels of NDVI there is a relatively larger variability of LAI or biomass thus decreasing the predictability of these ecological variables. Small errors in NDVI lead to large errors in the saturating variable being predicted.

not necessarily only if the NDVI was within the range of saturation ($\gtrsim 0.7$) It seems at coarser scales this is less of a problem rather than more of a problem because of mixing with elements w/ low NDVI

NDVI showed significant relationships with both total live biomass and LAI, which would be important when using satellite data to infer regional estimates of these biophysical properties. However, only approximately 40% of the variance of NDVI was explained by total live biomass. Shrub biomass, especially the live foliar deciduous biomass, is the major factor affecting NDVI across all vegetation types. The live foliar deciduous shrub component represents less than 10% of the total biomass but explains almost 80% of the variance of NDVI. Therefore, while NDVI is still useful in estimating levels of total biomass it is significantly affected by the presence of shrub foliar biomass. The relationships established in this study, which are based on local distinctions of tundra vegetation, provide a means for deriving ecological variables from spectral indices for use in modeling studies and on regional scales.

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TABLE LEGENDS

Table 1. Significance level of linear regressions and R^2 values of relationships between specific biomass components and NDVI across all vegetation types for data grouped by vegetation type and sampling period.

Table 2. Significance level of linear regressions and R^2 values of relationships between specific biomass components and LAI across all vegetation types for data grouped by vegetation type and sampling period.

FIGURE LEGENDS

Figure 1a. The relationship between mean live foliar deciduous biomass and mean NDVI for data grouped by vegetation type and sampling period.

Figure 1b. The relationship between mean live foliar deciduous biomass and mean NDVI for moist acidic tundra and shrub tundra for data grouped by sampling period.

Figure 1c. The relationship between mean live graminoid biomass and mean NDVI for moist non-acidic tundra and moss tundra for data grouped by sampling period.

Figure 2. The relationship between mean overstory biomass and mean LAI for data grouped by vegetation type and sample period.

Figure 3a. Pearson's Correlation Coefficients for linear correlations of several biomass components and NDVI over the 1999 growing season.

Figure 3b. Pearson's Correlation Coefficients for linear correlations of several biomass components and LAI over the 1999 growing season.

Figure 3c. Pearson's Correlation Coefficients for correlations of NDVI and LAI over the 1999 growing season.

Figure 4. The relation ship between LAI and NDVI for ungrouped data taken during sample period #6 (August 13 – 20)

Figure5. The relationship between mean total live biomass and mean NDVI for data grouped by vegetation type and sampling period. The data is for sampling conducted from June 17 to July 26.

Table 1.

NDVI v. Biomass

Biomass Component	P value	R^2
Live graminoid	0.469	0.02
Dead graminiod	0.837	0.00
Total graminiod	0.941	0.00
Moss	0.804	0.00
Lichen	0.721	0.01
Horsetail	0.407	0.03
Forb	**0.009**	**0.27**
Woody deciduous shrub	**0.007**	**0.29**
Live foliar deciduous shrub	**0.000**	**0.66**
Dead foliar deciduous shrub	0.425	0.03
Total foliar deciduous shurb	**0.001**	**0.40**
Woody evergreen shrub	0.773	0.00
Live foliar evergreen shrub	0.765	0.00
Dead foliar evergreen shrub	0.065	0.15
Total live foliar shrub	**0.002**	**0.36**
Total foliar shrub	**0.000**	**0.51**
Total live shrub	**0.001**	**0.42**
Total dead shrub	0.663	0.01
Total shrub	**0.002**	**0.37**
Photosynthetic biomass	0.297	0.05
Total live biomass	**0.001**	**0.42**
Total dead biomass	0.662	0.01
Total biomass	**0.001**	**0.42**

* Significant relationship, $p \leq .05$?

** Strongest correlation, $p \leq .01$?

LAI vs. Biomass

Table 2.

need R^2 values

Biomass Component	P value	R
Live graminoid	0.313	0.220
Dead graminiod	0.361	0.200
Total graminiod	0.330	0.213
Moss	***0.036**	**-0.439**
Lichen	0.515	-0.143
Horsetail	***0.000**	**-0.728**
Forb	0.643	0.102
Woody deciduous shrub	***0.001**	**0.627**
Live foliar deciduous shrub	***0.003**	**0.585**
Dead foliar deciduous shrub	0.124	0.330
Total foliar deciduous shurb	***0.003**	**0.586**
Woody evergreen shrub	0.278	0.236
Live foliar evergreen shrub	0.876	0.035
Dead foliar evergreen shrub	***0.024**	**-0.468**
Total live foliar shrub	***0.020**	**0.483**
Total foliar shrub	***0.008**	**0.535**
Total live shrub	***0.000**	**0.730**
Total dead shrub	0.998	-0.001
Total shrub	***0.000**	**0.697**
Overstory biomass	***0.000**	****0.814**
Total live biomass	***0.022**	**0.474**
Total dead biomass	0.275	0.238
Total biomass	***0.005**	**0.569**

* Significant relationship

** Strongest correlation

Figure 1a.

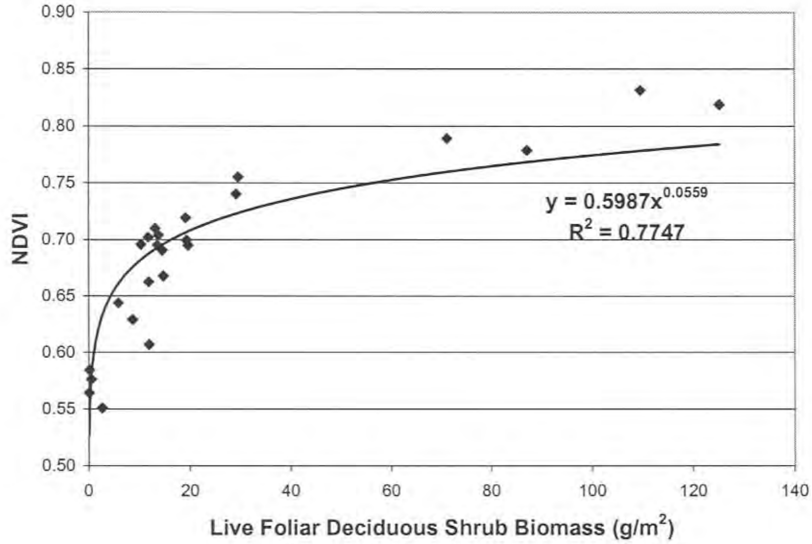


Figure 1b.

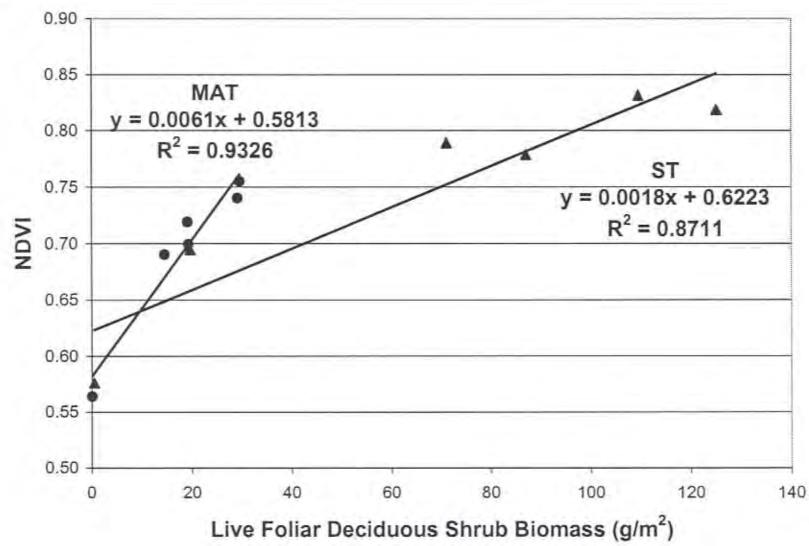
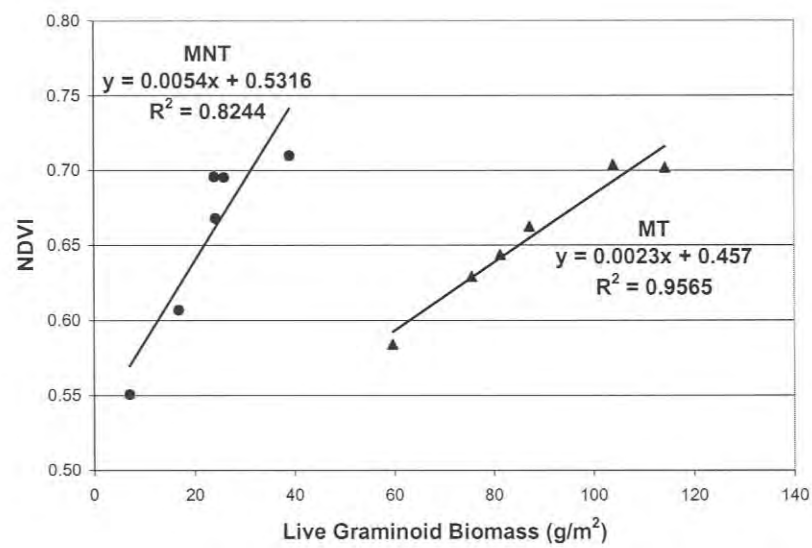


Figure 1c.



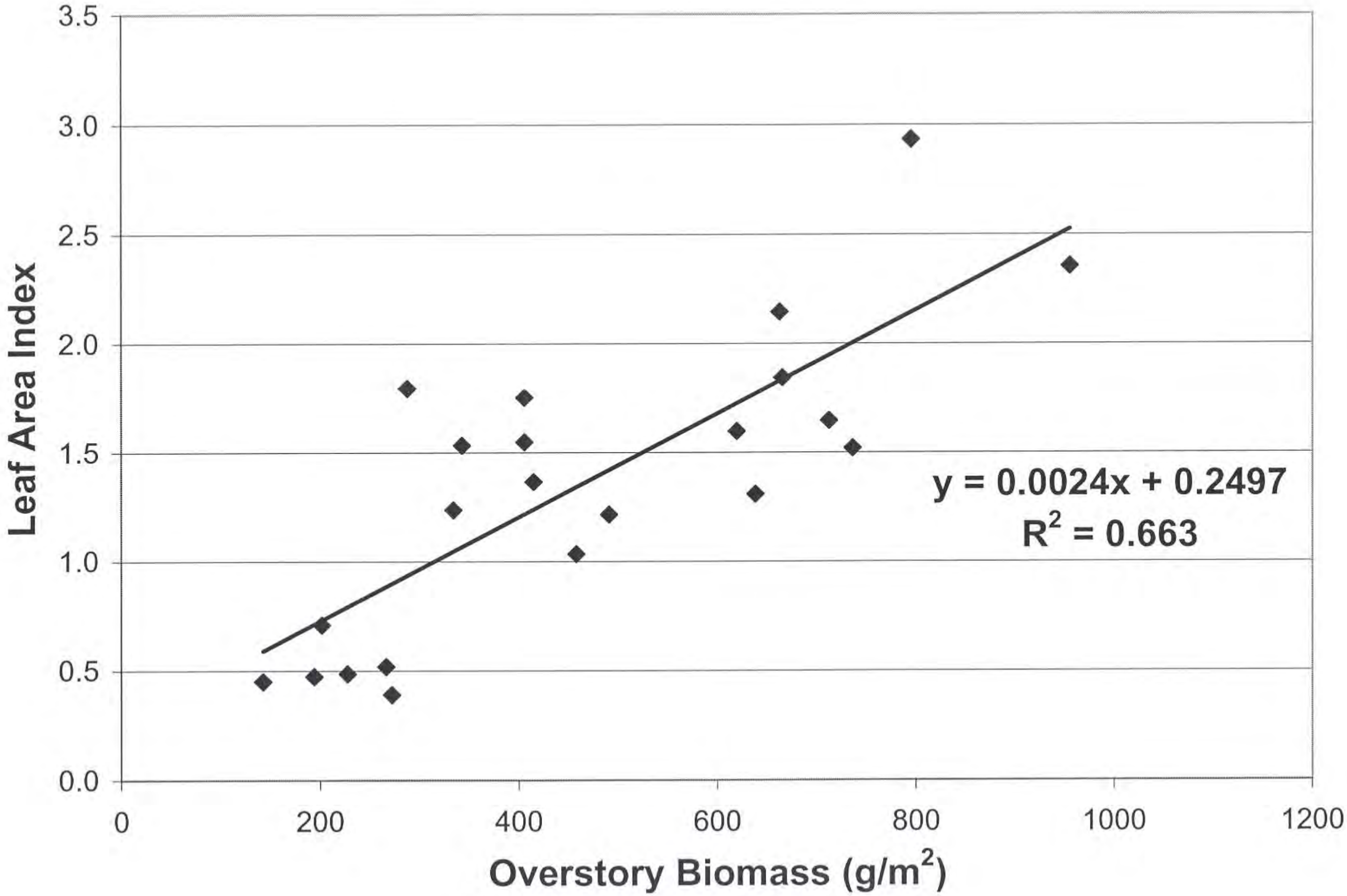

Leaf Area Index
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
1200
Overstory Biomass (g/m²)
y = 0.0024x + 0.2497
R² = 0.663

Figure 2.

Figure 3a.

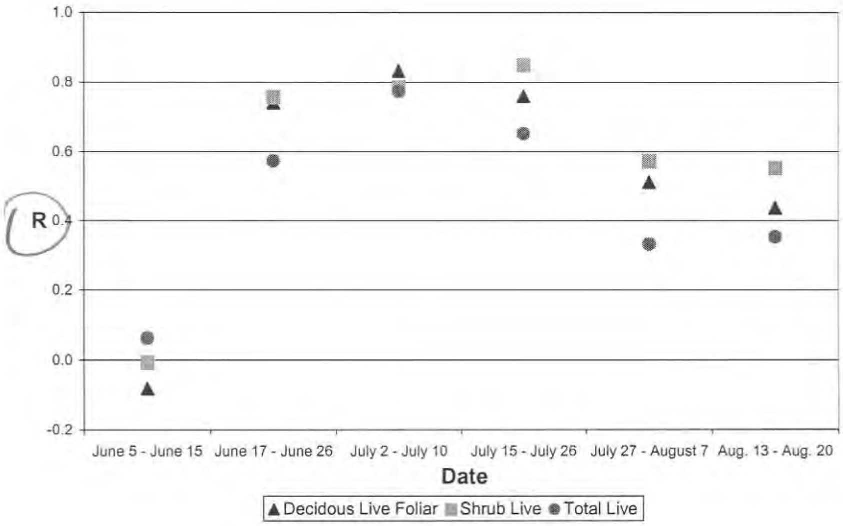


Figure 3b.

is this ? R or ρ

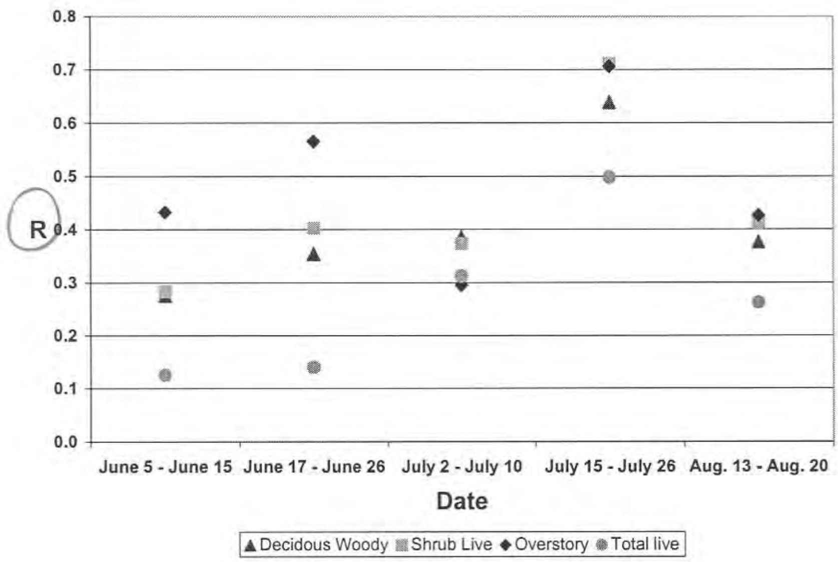
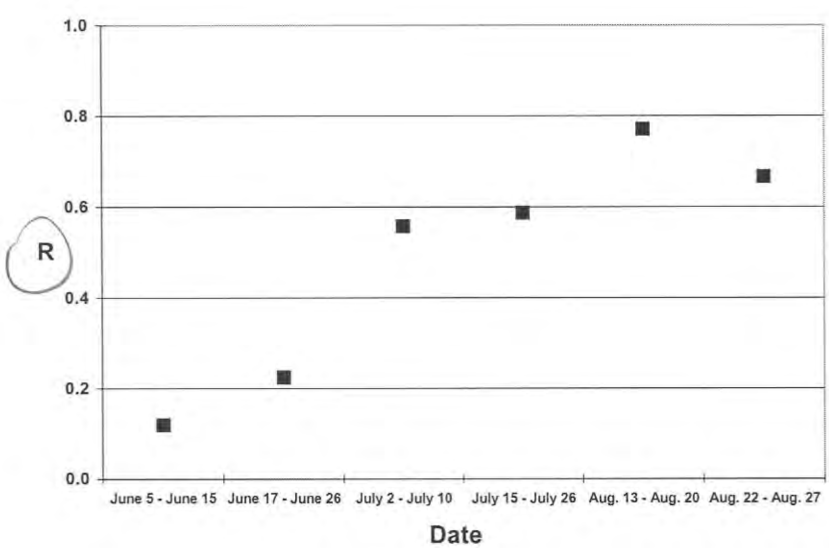


Figure 3c.



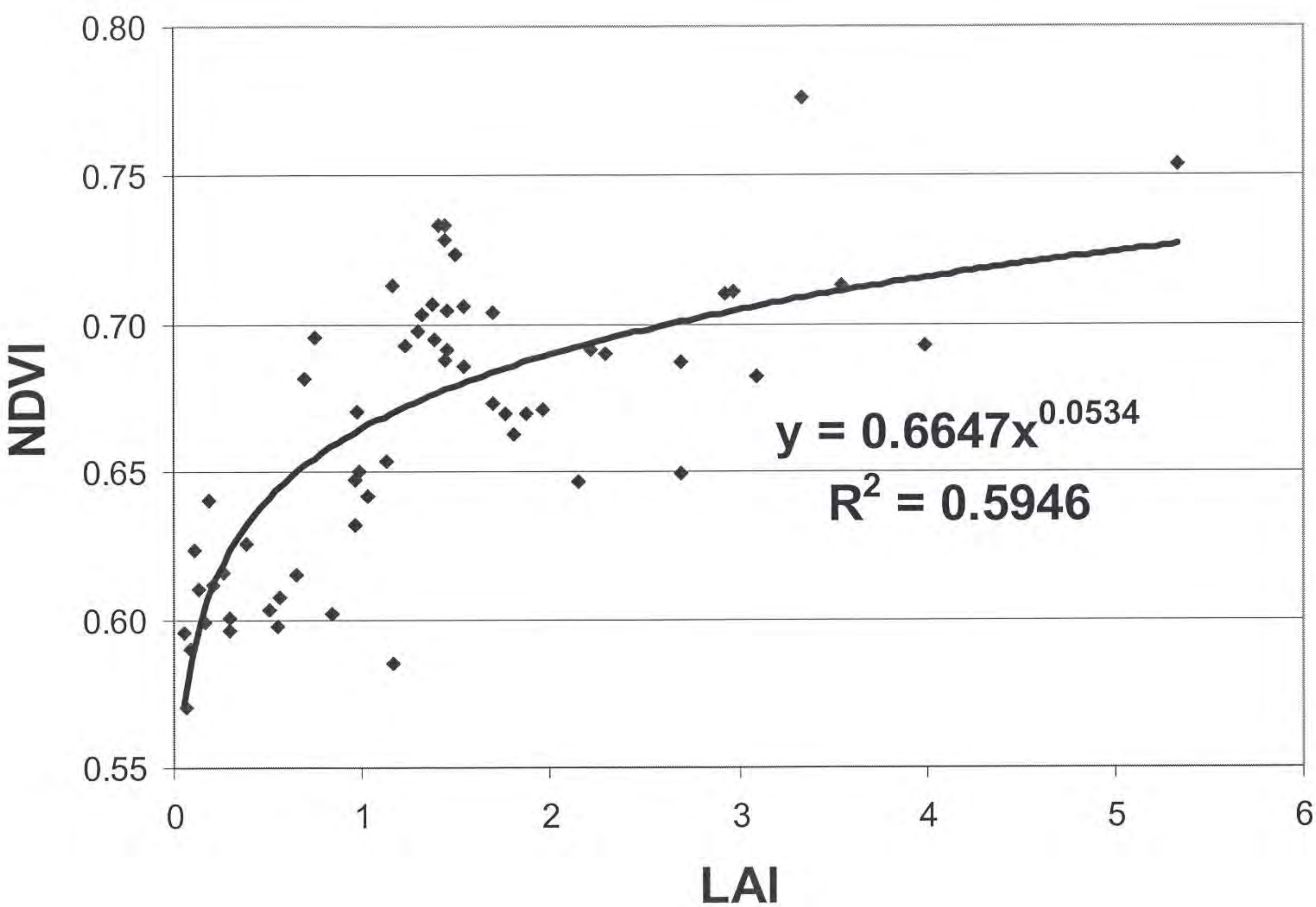

0.80
0.75
0.70
0.65
0.60
0.55
NDVI
0
1
2
3
4
5
6
LAI
$y = 0.6647x^{0.0534}$
$R^2 = 0.5946$

Figure 4.

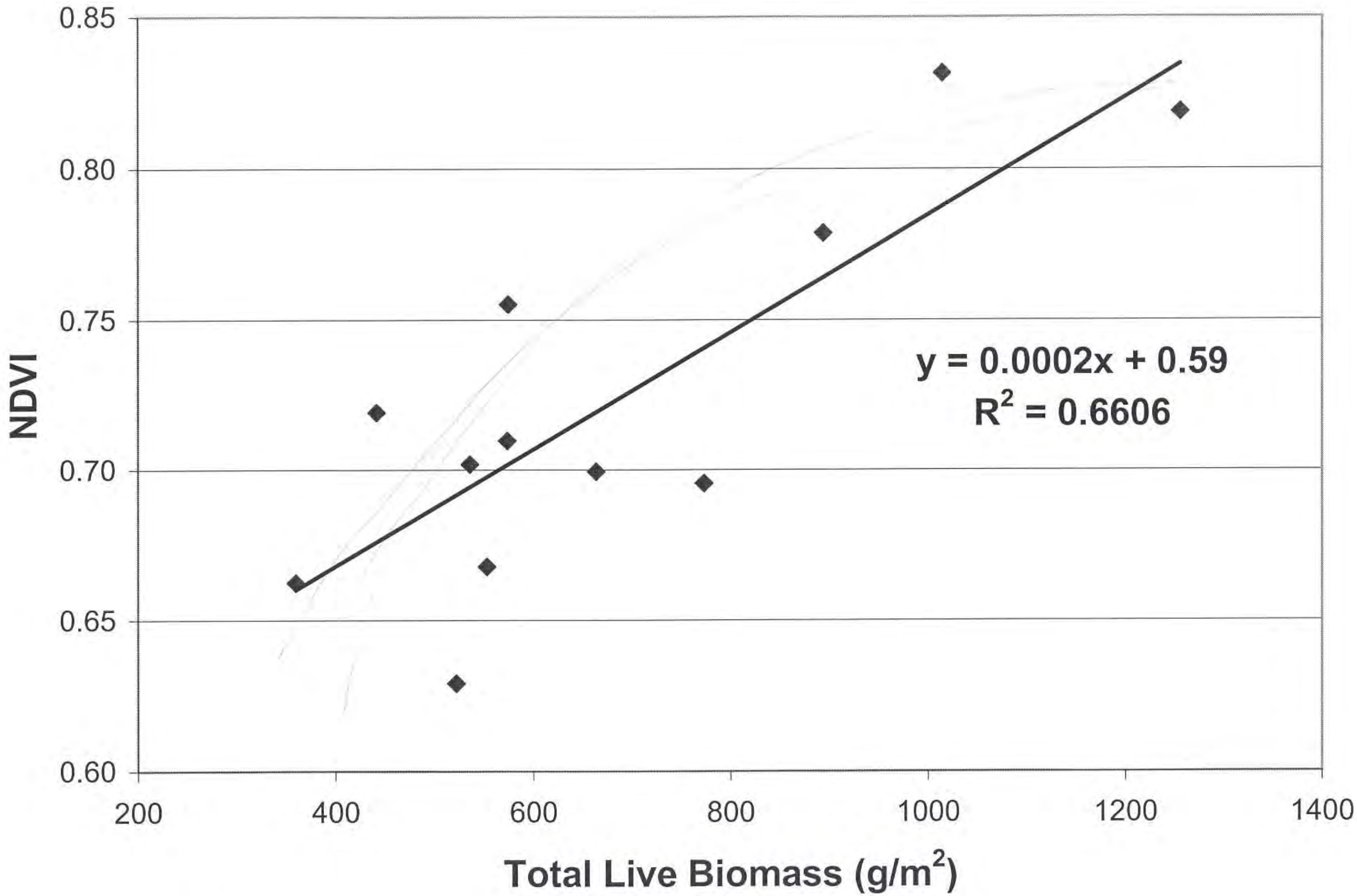

0.85
0.80
0.75
0.70
0.65
0.60
NDVI
200
400
600
800
1000
1200
1400
Total Live Biomass (g/m2)
y = 0.0002x + 0.59
R2 = 0.6606

Figure 5.