OBTAINING VOLUME ESTIMATES FROM CASI IMAGES OF A THINNING AND FERTILIZATION TRIAL

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ABSTRACT

The potential for estimating per hectare values of total stem volume from CASI images (pixel size ~ 60 x 60 cm) taken over a 49 year old thinning and fertilization trial with Douglas-fir at Shawnigan Lake, Vancouver Island, British Columbia was explored. Canopy structures, stem densities and volumes varied considerably among 42 square 20m trial plots which made the site ideal for testing the assumption that volume could be predicted from a vegetation index (NDVI) and the "uniformity" of the image as portrayed through spatial autocorrelations and variances of pixel values. A combination of NDVI, variances, and coefficients of spatial autocorrelation were used as predictors of plot total stem volume per hectare. Results were encouraging, the coefficient of determination was 0.60 and the mean standard error of prediction was 10%. Wavelet analyses did not suggest any tangible improvement in the predictions.

Keywords: CASI, volume, Douglas-fir, NDVI, LAI, spatial correlation, wavelet analysis.

RÉSUMÉ

ÉVALUATION DU VOLUME LIGNEUX D'UN SITE-TEST D'ÉLAIRCIE ET DE FERTILISATION À PARTIR D'IMAGES OBTENUES À L'AIDE DU SPECTROMÈTRE IMAGEUR AÉROPORTÉ COMPACT (CASI)

La présente étude porte sur le potentiel d'évaluation, au moyen d'images CASI (dimension des pixels ~ 60 cm x 60 cm), du volume total de tiges à l'hectare dans un site-test d'éclaircie et de fertilisation du Douglas vert exploité depuis 49 ans au lac Shawnigan sur l'Île de Vancouver, en Colombie-Britannique. Le site, découpé en 42 parcelles expérimentales carrées de 20 m présentant une grande diversité de structures de couverts forestiers, de densités et de volumes de tiges, constituait un lieu privilégié pour la vérification de l'hypothèse selon laquelle il est possible de prévoir le volume ligneux à partir d'un indice de végétation normalisé (NDVI) de même que pour la vérification de « l'uniformité » de l'image résultant d'autocorrélations spatiales et de variances des valeurs de pixels. On s'est servi d'une combinaison de NDVI, de variances et de coefficients d'autocorrélation spatiale comme prédicteurs du volume total de tiges à l'hectare dans les parcelles. Les résultats obtenus sont encourageants, puisque le coefficient de détermination a été établi à 0,60 et l'erreur-type moyenne de la prévision a été de l'ordre 10 %. Les analyses par ondelettes n'ont permis de dégager aucune amélioration tangible des prévisions.

INTRODUCTION

Estimates of the stem volume in forest stands are important to forest management for planning of harvest, thinning, and silvicultural activities (Clutter et al. 1983). Field estimates are usually derived from data of tree

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height, diameter and taper collected in forest inventory plots (Hamilton and Christie 1975, Loetch and Haller 1964, Max et al. 1996). The high costs associated with volume estimation has spurred the development of efficient sample and estimation procedures (for examples, Kohl and Kushwaha 1994, Max, Schreuder, Hazard, Oswald, Teply and Alegria 1996, Schreuder and Williams 1995) and a continuous search of alternate methods based on remote sensing technologies (Congalton and Biging 1992, Dralle and Rudemo 1996, Gholz et al. 1997, Holmgren et al. 1997, Katsch and Vanlaar 1994, Naesset 1997). Two approaches appear promising. One is through classification of attributes associated with species, site type, and age, followed by a prediction of volume given the classified attributes (Brandtberg 1997, Lachowski and Bowlin 1988, Ritchie et al. 1993, Saint-Onge and Cavayas 1995, Wilson 1996, Wulder et al. 1996). The second aims at estimating a proxy of volume such as crown size, biomass, leaf area index (LAI), height, stem number, or NDVI and then the prediction of volume through simple regressions (Katsch and Vanlaar 1994, Naesset 1997, Nelson et al. 1988, Nilsson 1996). This study reports on the relationships between stem volume and NDVI and other image features obtained from Compact Airborne Spectrographic Imager (CASI) images of an intensively studied trial with Douglas-fir (*Pseudotsuga menziesii,* Mirb.) on Vancouver island.

MATERIAL AND METHODS

Field data came from the Shawnigan Lake Douglas-fir thinning and fertilization trial (Brix 1993) near Shawnigan Lake on Vancouver Island. (48°38' N, 123° 43' W). The trial was established within a fairly homogenous stand (50 ha) of mostly planted trees on a poor site (site index 25 m at age 50). Data from 42 square plots (36 from a randomized plot design with 12 treatments and three replications and six from subsidiary experiments) were used. Plot-size is 20 x 20 m. Field data reported here were collected in the winter of 94/95 when the trees were 49 years old (McWilliams and Therien 1996) and prorated, where appropriate, by one year to synchronize the field data to the laser scanner data. Prorating of heights, diameter, and volume was done via tree and trait specific relative growth rates estimated for the period between the last two measurements (McWilliams and Therien 1996). Diameter (*dbh*) was measured on all trial trees while heights (*ht*) were measured on an average of 15 trees per plot and predicted for the remaining by means of plot specific non-linear height-diameter regression models. Total stem volume (inside bark) was derived from measured *dbh*, and predicted *ht* in conjunction with local volume tables (Omule et al. 1987).

A biomass survey in 1988 and 1989 of 120 trees in 12 plots representing the range of treatments (for details see Brix 1993) provided data on needle dry weights. A total of 2214 branches were clipped, their vertical position noted, and the total needle dry weight determined after oven-drying to constant weight. A sub-sample of needles (~ 2 g) from the upper, middle and lower part of the crown was collected from each tree to determine specific leaf area (SLA) with a LICOR area meter. Total biomass and biomass per whorl were predicted by simple linear regressions, all with low standard errors of predictions (less than 5% on average per tree). Relationships obtained from this biomass survey were assumed to be valid for trees six years older in 1996. The vertical allocation of needle dry matter in the crown was described by a beta distribution with parameters determined from the height, diameter, and volume of a tree. Leaf area index (LAI) for each plot were derived by converting needle dry weight to one-sided needle areas through the relationship between SLA and the position of the needles in the canopy (distance to top, and height relative to the maximum tree height in the plot). Further details can be found in Magnussen and Boudewyn (1998).

CASI images of the trial area were acquired on September 27, 1996 at 19:50 G.M.T. The weather conditions were clear and the sun-angle was 39.4°. A composite and rectified image mosaic using channel(s) 1-8 (437.5-847.2 nm) was assembled for the area (Figure 1) with a pixel size of 60 cm. Full coverage was obtained for 27 plots, but only 21 plots had the full compliment of field data used in this study.

NDVI values were computed for each pixel as $NDVI = \frac{(\alpha_{nir} - \alpha_{vis})}{(\alpha_{nir} + \alpha_{vis})}$ where α_{nir} and α_{vis} represent surface reflectances averaged over ranges of wavelength in the visible (channel 5, λ~ 656.0 nm, "red") and near infrared (channel 8, λ~ 847.2 nm) regions of the CASI spectrum, respectively (Tucker 1979).

To explore the association between spatial autocorrelation of NDVI and plot mean values of basal area and volume we computed directional spatial autocorrelation coefficients (Cliff and Ord 1981) of NDVI-values in a plot. Coefficients were computed for first-order neighboring pixels (pixels sharing one common border), second-order neighbors (pixels separated by a first-order neighbor), and third-order neighboring pixels (pixels separated by a first- and a second-order neighbor pixel). Average values were computed as weighted means over the four cardinal directions (weight: sample size). According to (Carlson and Ripley 1997) one should expect the relationship between NDVI to be impacted by the homogeneity of the canopy structure. Spatial autocorrelations provides an measure of patchiness of the NDVI 'image'.

An explorative Wavelet analysis with the same purpose as the spatial autocorrelation was carried out on the NDVI 'images' of each plot (Jawerth and Sweldens 1993). We used the father (Φ) and female (Ψ) Haar wavelets (Daubechies 1992) with scale factor J (J = 1, 2, and 3) in the analyses. The mean absolute deviation (MAD) of the wavelet coefficients $s^{k}_{J,m,n}$ of $\Phi^{k}(2^{-J}\cdot x-m, 2^{-J}\cdot y-n)$ and $d^{k}_{J,m,n}$ of $\Psi^{k}(2^{-J}\cdot x-m, 2^{-J}\cdot y-n)$ were computed for the two-directional smooth ($s^{h\otimes v}_{3,0,0}$), the vertical detail ($d^{v}_{J,0,0}$), the horizontal detail ($d^{h}_{J,0,0}$), and the diagonal detail ($d^{d}_{J,0,0}$). X and y are the row and column number of the pixels in the plot, respectively; m is the translation in the x- or y-direction. Throughout, m=0, and n=0. Superscript k is a direction indicator: k=h (horizontal), v (vertical) , h ⊕ v (horizontal x vertical), and d (diagonal). The mean absolute deviation of the these coefficients is a measure of image 'energy' in the various direction and resolutions.

Ordinary least squares regression models (Draper and Smith, 1981) to predict volume, basal area and leaf area index from NDVI statistics (means, variances, autocorrelation) and wavelet MAD-values were explored.

RESULTS AND DISCUSSION

Total stem volume per hectare in the 21 included plots varied from a low of 246 m^3 to a high of 573 m^3 with a median value of 449 m^3. Basal area varied accordingly from 32 $m^2\cdot ha^{-1}$ to 64 $m^2\cdot ha^{-1}$ (median: 54 $m^2\cdot ha^{-1}$). LAI values went from 2.0 to 4.6 (median: 3.5). Plot values of volume, basal area, and LAI represents a wide range of canopy structures, from very dense (~ 4000 stems $\cdot ha^{-1}$) with small crowns (length ~ 6 m) to fairly open (~ 800 stems $\cdot ha^{-1}$) with long lush crowns (length ~ 13 m). LAI values reported here compared favorably with LAI-values published elsewhere for for mono-specific coniferous stands in the northern hemisphere (Binkley and Reid 1984, Gholz, Curran, Kupiec and Smith 1997, Magnussen et al. 1986, Moir and Francis 1972) falls in the range of the Shawnigan plot values. A sample of the most promising exploratory correlations between volume, basal area, and LAI on one hand and a suite of statistics derived from the CASI images are presented in Table 1. Clearly, NDVI provides the strongest positive association with volume, basal area, and LAI. Low variability in the reflectance value of a channel was indicative of plots with above average values of volume, basal area and LAI. Variance of reflectance value register the spatial heterogeneity in the underlying feature space. Given the importance of spatial variation for the primary production processes (Ghent and Franson 1986, Hastings 1990, Legendre 1993, Liu and Burkhart 1994, Pacala and Deutschman 1995, Wulder, Franklin and Lavigne 1996) it is important to include aspects of feature variance in prediction of production of biomass and wood volume. Our wavelet analysis, although less convincing, produced similar results as the spatial autocorrelation, but did, otherwise not appear to offer the promised advantages of multi-scale resolution analysis as anticipated (Kolaczyk 1996, Raffy 1994b). Simple explorations of spatial covariances (Saint-Onge and Cavayas 1995, St-Onge and Cavayas 1997) has more appeal due to our ability to interpret the estimated image features.

Figure 3 shows in three scatter plots the relationship between $NDVI_{plot}$ and VOL, BA, and LAI. A fourth scatter plot illustrates the tight relationship between average plot LAI values and the total stem volume they contain. The biomass survey of the Shawnigan trial (Brix 1993) and subsequent analyses (Magnussen and Boudewyn, unpublished) supported the contention of a linear relationship between needle dry weight and stem volume. NDVI appears to be a consistent predictor of both VOL, BA and LAI throughout the observed range. Note, however, the very limited range of observed values, the difference between the highest and the lowest was a mere 0.03, or barely 4%. This short range makes predictions extremely sensitive to atmospheric attenuations of the NDVI values (Carlson and Ripley 1997). The frequently observed saturation of NDVI at LAI values above 3 did not materialize (Carlson and Ripley 1997, Leprieur et al. 1996, Liu and Huete 1995). A main contributor to the among-plot differences in NDVI-values is the effective crown area, F (Jupp and Walker 1997). F is the areas of crowns after discounting gaps and openess. NDVI was negatively correlated with F (-0.32). Figure 4 shows the within plot variation of NDVI values for the two plots with the highest and the two plots with the lowest mean.

Prediction of stem volume, basal area, and LAI from NDVI, spatial autocorrelation, and variance of reflectance value was attempted by exploring a multitude of linear regressions. The most promising combination of predictors in terms of residual standard deviation, low colinearity (Fox and Monette 1992) and Bayes information criteria, (BIC, Ledwina 1994). Equation (1) gives the chosen regression model (all predictors are sample estimates on a per plot basis)

Eq. (1) $$VOL_{plot} = \overline{VOL}_{plot} + 1230.6 \cdot NDVI_{plot} - 2.054\sqrt{\sigma^2_{channel3 reflectance}} - 2932 \cdot \rho_1 \cdot \rho_3$$

where ρ_i is the average ith-order correlation coefficient of within plot pixel values of NDVI. The expected prediction error of equation (1) is 10% (r^2=0.61, $F_{regression}$ = 9.22, P < 0.001). Figure 5 depicts the field estimates of stem volume plotted against the predicted values (the solid line is the line of perfect predictions). No consistent pattern emerged when the five plots with residuals > 9% of the predicted value were scrutinized. They represent both lightly and heavily thinned plots, they include three different fertilizer regimes and the average crown size, density, and number of overtopped trees did not deviate in any systematic way from the remaining plots. Note the order of magnitude differences in the regression coefficients which is a cause of concern (Myers 1986) in terms of the robustness of the predictions. As formulated, the predictions will be very sensitive to errors in the predictors (Fuller 1987).

CONCLUSIONS

The results of this study were in many aspects “typical”; they illustrate that high resolution scenes contains enough information to discriminate effectively between areas with high and low values of LAI, volume and other canopy proxies of biomass (Gholz, Curran, Kupiec and Smith 1997, Gougeon 1995, Naesset 1997, Saint-Onge and Cavayas 1995). Yet the real challenge for wider applications in forest inventories lies in making these model-based predictions applicable outside the scene from which they were derived, our results are strongly scale dependent (Raffy 1994a) and we expect that minor changes in atmospheric conditions will modify the derived relationship.

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NDVI plot image attribute	VOL ($m^3 \cdot ha^{-1}$)	BA ($m^2 \cdot ha^{-1}$)	LAI
mean NDVI of plot	0.79**	0.56**	0.83 **
variance of channel 3 (λ~ 500 µm)	-0.58**	-0.52**	-0.59 **
variance of channel 6 (λ~ 700 µm)	-0.71**	-0.47**	-0.75**
third-order spatial autocorrelation of NDVI	-0.41 n.s.	-0.43*	-0.33 n.s.
fourth-order spatial autocorrelation of NDVI	-0.34 n.s.	-0.27 n.s.	-0.29 n.s.
MAD of wavelet coefficients, horizontal detail	-0.45*	-0.45*	-0.42 n.s.
MAD of wavelet coefficients, vertical detail	-0.21 n.s.	-0.52**	-0.10 n.s.

Table 1. Product moment correlations between volume (VOL), basal area (BA), and leaf area index (LAI) and various image attributes.

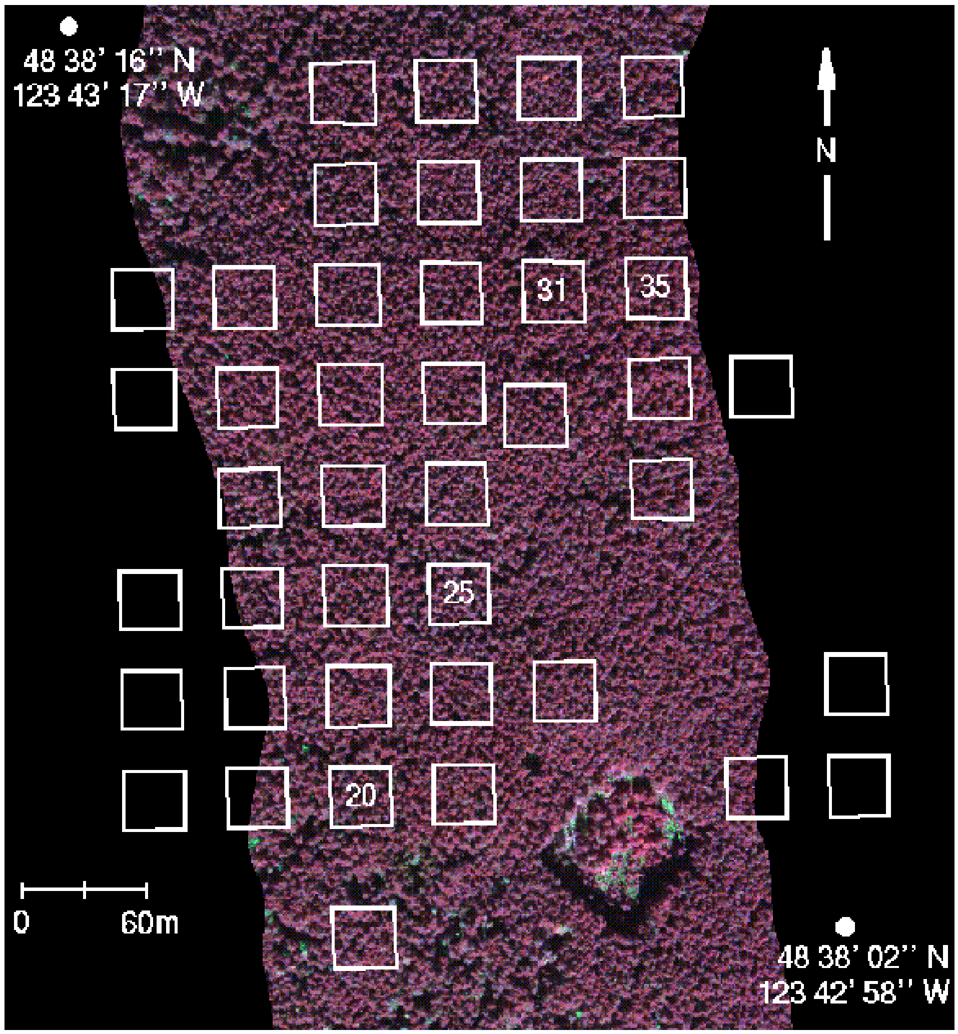

Figure 1. Overview of the Shawnigan trial area north of Victoria, Vancouver Island, British Columbia. Plots shown in close-up view in Figure 2 are numbered.

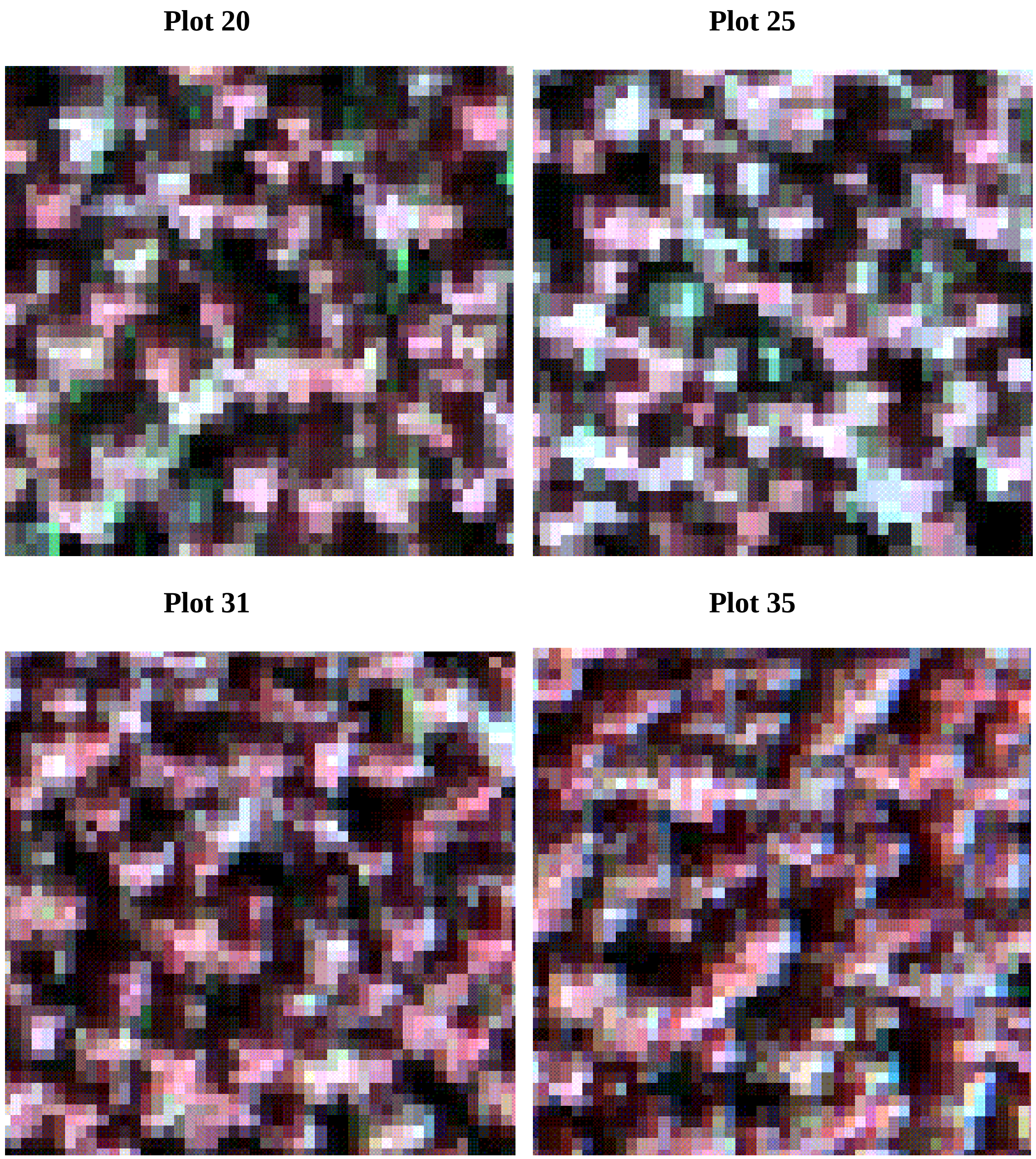

Figure 2. CASI close-up images of four plots, two with top ranking NDVI values (20 and 35) and two with lowest ranking NDVI values (25 and 31).

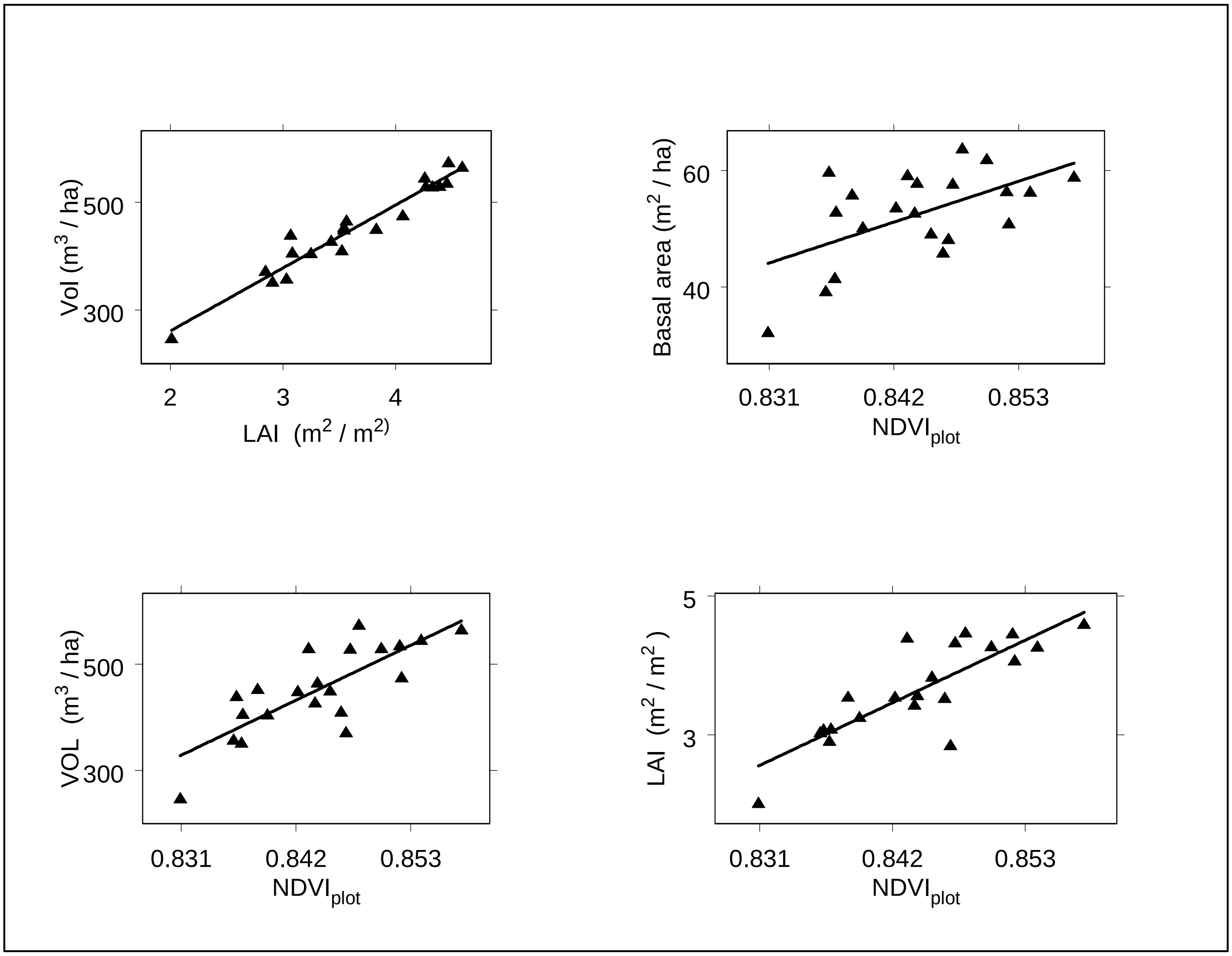

Figure 3. Scatter plots of plot mean values of volume, basal area, leaf area index, and NDVI..

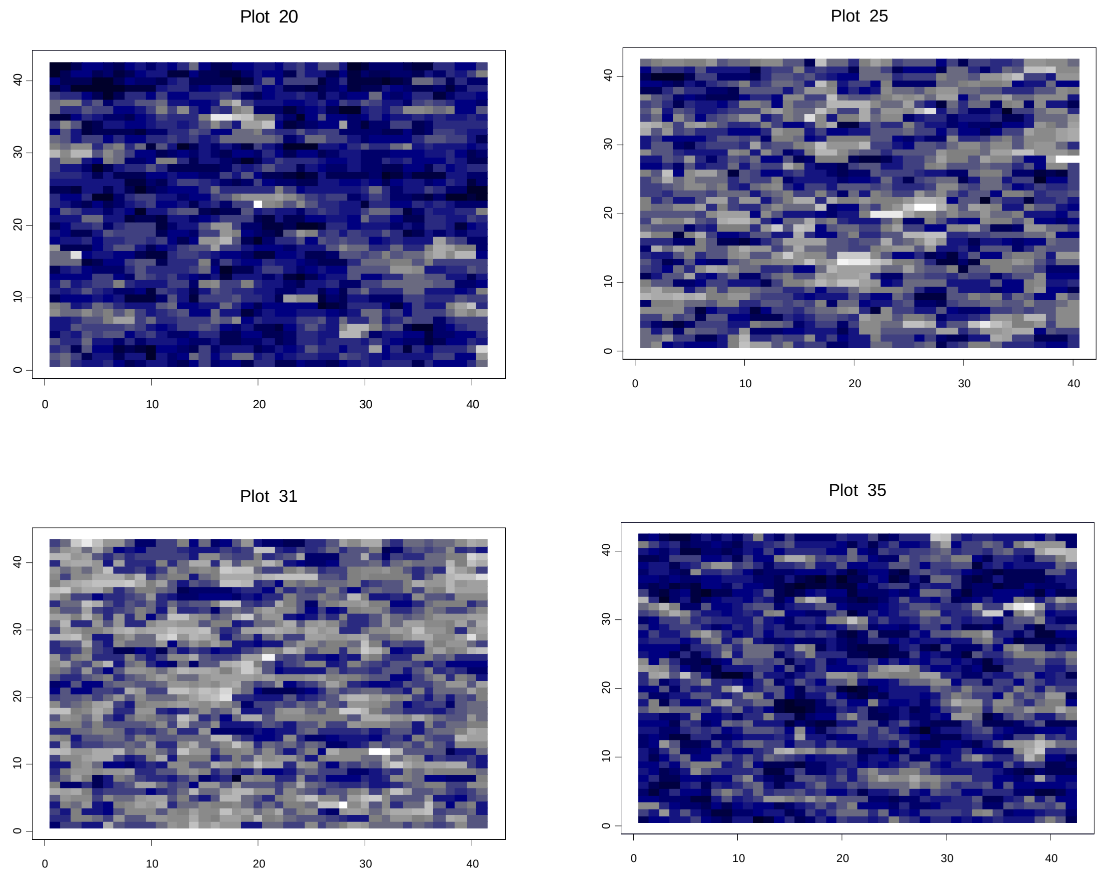

Figure 4. Four plots with contrasting NDVI values (clockwise starting in upper left corner: high, low, low, high).

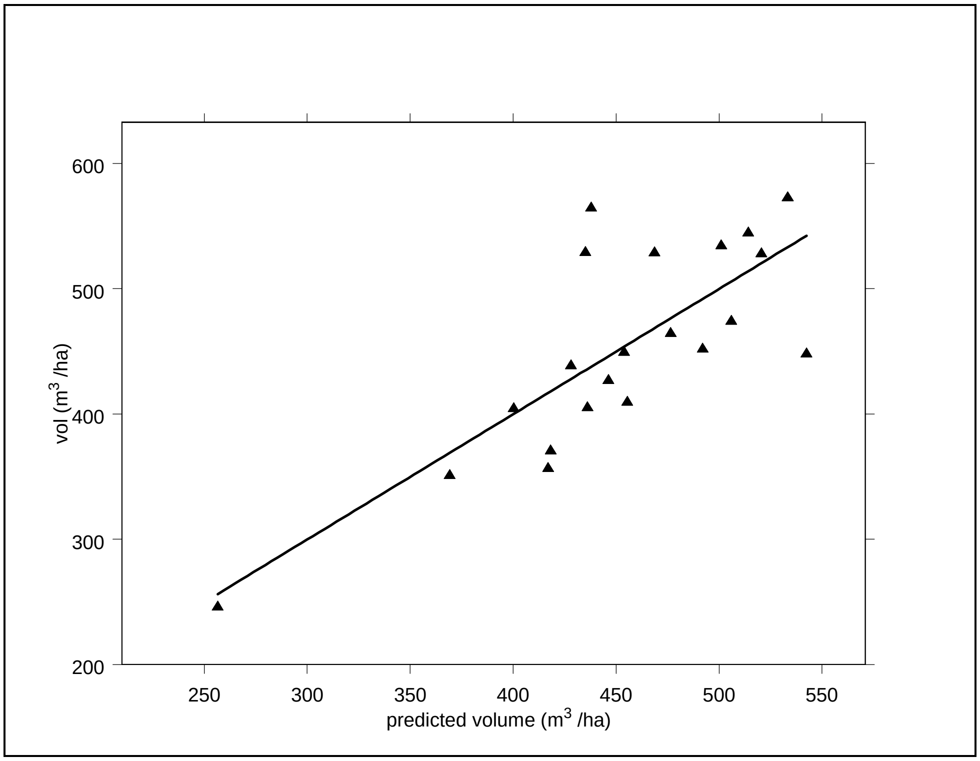

Figure 5. Estimated plot mean values of stem volume against predicted stem volume (from equation 1).