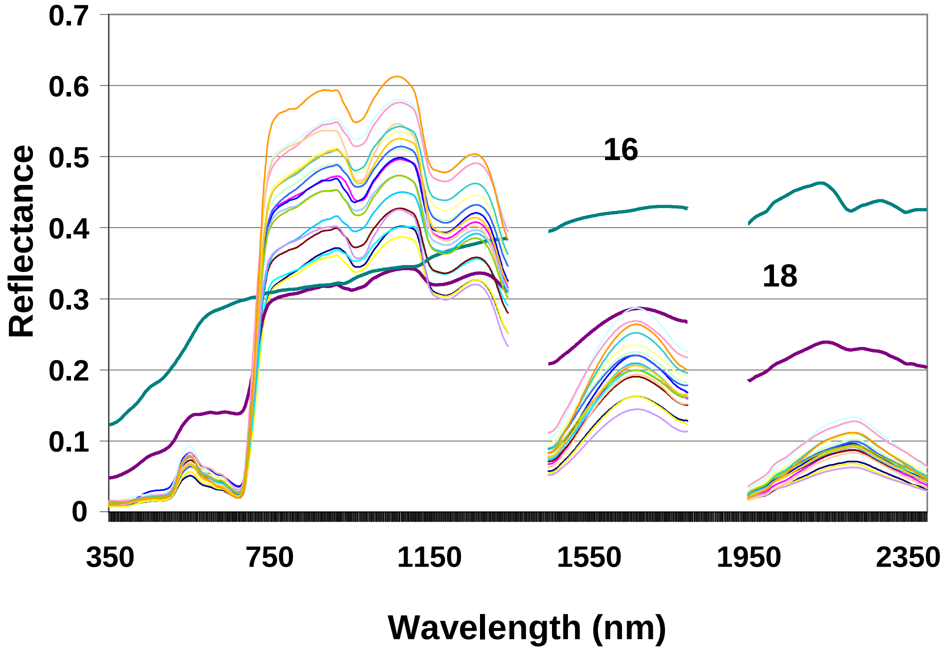
Centre for Geo-Information

Thesis Report GIRS-2009-14

Estimation of N content of natural vegetation using hyperspectral remote sensing data

Zhang Junwei

June 2009



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Estimation of N content of natural vegetation using hyperspectral remote sensing data

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A thesis submitted in partial fulfillment of the degree of Master of Science
at Wageningen University and Research Centre,
The Netherlands.

June 2009
Wageningen, The Netherlands

Thesis code number: GRS-80436
Wageningen University and Research Centre
Laboratory of Geo-Information Science and Remote Sensing
Thesis Report: GIRS-2009-14

Foreword

This report is my MSc thesis done as part of the Master of Science in Geo-Information Science (MGI) at the Wageningen University. The report is about estimation of N content of natural vegetation using hyperspectral remote sensing data.

I am deeply indebted to my supervisor Dr. Jan Clevers from the Wageningen University whose help, stimulating suggestions and encouragement helped me in all the time of research and writing of this thesis. I also would like to express my gratitude to all those who gave me the possibility to complete this thesis.

Junwei Zhang, June, 2009

Abstract

The position of the inflexion point in the red edge region (680-780nm) of the spectral reflectance signature, termed the red edge position (REP), is affected by biochemical and biophysical parameters and has been used as a means to estimate foliar nitrogen content and it provides a very sensitive indicator of, among other things, vegetation stress. The high spectral resolution of airborne imaging spectrometers now offers the potential for determining the REP of vegetation canopies at regional scales. However, the accurate estimation of the REP is dependent upon sensor band positions, widths and sensor type. Various techniques have been developed to minimize the error in estimating the REP, such as inverted Gaussian fitting and linear four-point interpolation in the region of the red edge. In this report, aim is to assess different Remote Sensing techniques for estimation of nitrogen content of vegetation in the Millingerwaard nature reserve using hyperspectral data and to test which one is best.

The feasibility of using information from the red edge position region of the spectrum was tested by estimating nitrogen content for one test site with different years (2004 and 2005). The site is a heterogeneous natural area in the floodplain Millingerwaard along the river Waal in the Netherlands. The spectral information in both two years was obtained with an ASD FieldSpec spectrometer. In addition, in 2004 HyMap airborne imaging spectrometer data were acquired and in 2005 AHS airborne imaging spectrometer data were obtained.

From the REP extracted using four different techniques, in case of 2004 data, they have similar R^2 just like in 2005. During estimation of nitrogen concentration, the lowest R^2 is for the maximum band depth (MBD) in interval 550 nm to 751 nm and the highest R^2 for the maximum band depth normalized to the area (BNA) in interval 550 nm to 751 nm. There are big R^2 differences between estimated nitrogen content in 2004 and 2005. The continuum removal technique showed a high correlation with foliar nitrogen concentration and nitrogen content for FieldSpec measurements in 2005. Two coarser resolution spectra (Hymap and ASD) offered little help during the research and the maximum first derivative technique has very bad results in comparison to the other three techniques.

Keyword(s): **Nitrogen content, Natural vegetation, Hyperspectral remote sensing, Red-edge indices, Continuum removal, Maximum first derivative spectrum, Linear four-point interpolation, Inverted Gaussian fitting**

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Abbreviations

ASD	Analytical spectral devices
AREA	Area absorption feature
AHS	Airborne Hyperspectral Scanner
BNA	Maximum Band depth normalized to area of absorption feature
DW	Dry weight
IG	Inverted Gaussian fitting
MBD	Maximum band depth
N	Nitrogen
REP	Red Edge Position

1. INTRODUCTION

This chapter gives a short introduction into the red edge position, nitrogen concentration of natural vegetation and study area. Next the problem definition is described, research objectives and questions are formulated and the set-up of the report is given.

1.1 Background

The impact of climate and climate change on the earth system is one of the current focal issues of scientific research. One of the challenges of the coming decades is the understanding of the role of terrestrial ecosystems and the changes they may undergo. Ecosystem productivity is one of its key characteristics. Canopy nitrogen (N) content is a key biophysical variable for determining photosynthesis and net primary production. Various indices have been developed for estimating N content. Most of these are based on the red-edge feature. The wavelength region of the red–NIR transition (680 to 780 nm) has been shown to have high information content for vegetation spectra. This region is referred to as the "red edge" region. It represents the region of abrupt change in leaf reflectance between 680 and 780 nm caused by the combined effects of strong chlorophyll absorption in the red wavelengths and high reflectance in the NIR wavelengths due to leaf internal scattering (Gates et al., 1965; Horler et al., 1983).
The position of the inflection point at the red edge is affected by biochemical and biophysical parameters and has been used often to estimate the chlorophyll and nitrogen content. Several studies have shown the discontinuity in the red edge, characterized by a double peak in the reflectance (Cho and Skidmore, 2006). Other studies use a continuum removal approach (Curran et al., 2001). This is a way of normalizing the reflectance spectra. From this continuum removed spectra the maximum band depth, the area under the curve, and the maximum band depth normalized to the area of the absorption feature can be calculated. All these measures can be used for estimating N content.

The spectral signature of living leaf material is dominated by chlorophyll, the cell structure and the water content, which influence the amount of reflected radiation in the VIS, NIR and SWIR regions of the electromagnetic spectrum. Imaging spectrometry offers new possibilities for estimating. However to date, the remote sensing of foliar chemical concentrations, other than chlorophyll and water, has not been very successful. The presence of water in living leaf tissue almost completely masks these biochemical absorption features. Clevers (1999) showed that imaging spectrometry might provide additional information at the red edge region, not covered by the information derived from a combination of a NIR and a VIS broad spectral band. He concluded that, concerning high spectral resolution data, this seems to be the major contribution of imaging spectrometry to applications in agriculture.

Plant nitrogen status is often related to chlorophyll content (Boochs et al., 1990; Yoder & Pettigrew Crosby, 1995). But such a relationship depends on the physiological status of the plant, e.g. changing from low to high positive correlations with increasing leaf age (Wenjiang et al., 2004). Nitrogen is used for the formation of components such as chlorophyll, the carbon fixing enzyme ribulose biphosphate carboxylase (Rubisco) and inert structural components in cell tissue (Jongschaap & Booij, 2004). Reflectance measurements in the visible and red edge wavelengths (400–700 nm) have been used to determine foliar nitrogen concentration (Sullivan et al., 2004). But the results rely on the close correlation between nitrogen and chlorophyll pigments (Haboudane et al., 2004; Hansen & Schjoerring, 2003; Yoder & Pettigrew-Crosby, 1995) because pigments (chlorophyll, carotenoids and xanthophylls) predominantly determine most spectral features between 400 and 700 nm (Yoder & Pettigrew-Crosby, 1995). Therefore, the estimation of foliar nitrogen concentration based on the red-edge position (REP) as the predictor (Lamb et al., 2002) indirectly depends on shifts in the REP mainly attributed to changes in chlorophyll concentration.

The study area of this thesis is the floodplain Millingerwaard in the Netherlands along the river Waal. Millingerwaard is part of the nature reserve 'Gelderse Poort' with an area of 400 ha. Until 1991, the main agricultural function of that area was production grassland and arable land (e.g., maize). In 1991 the WWF was the initiator of a nature project. Begin of the nineties the agricultural function gradually changed into nature where only small-scale nature management was conducted. The old agricultural areas transformed into wild, uncultivated areas with forests, marshland, meadow, lakes, river dunes and beaches along the river Waal.

1.2 Problem definition

Accurate remotely sensed estimates of the foliar biochemical concentration of vegetation canopies can provide a valuable aid to the understanding of ecosystem functioning over a wide range of scales.

Various approaches have been developed for estimation nitrogen (N) concentration in plants. Recently, studies have shown that the red edge is less sensitive to soil background and atmospheric effects and can provide information, not available from a combination of near infrared an visible spectral bands (Clevers, 1999; Clevers et al., 2000). However, the accurate estimation of the REP is dependent upon sensor band positions and widths. Various techniques have been developed to minimize the error in estimating the REP, such as inverted Gaussian curve fitting technique and linear interpolation.

This thesis will present which techniques are suitable for extracting the REP for estimation of N content of natural vegetation.

1.3 Research objectives

The aim of this study is to assess different Remote Sensing techniques for estimation of nitrogen content of vegetation in the Millingerwaard nature reserve using hyperspectral data and test which one is best.

Techniques to be compared:
Continuum removal
Maximum first derivative spectrum
Inverted Gaussian fitting technique (IG)
Linear four-point interpolation technique

1.4 Research questions

1. Are red-edge based indices suitable for estimating N-content of the natural vegetation in the Millingerwaard?
2. Which spectral interval should be used to apply the continuum removal technique to the chlorophyll absorption region?
3. Which REP estimation technique is best for estimating N content?

1.5 Set-up of this report

This report is divided in seven chapters. First chapter is an introduction, with some background information; next the problem definition is formulated and the main objectives of the present study are presented. Second chapter describes some knowledge on red edge and basic principles of continuum removal. Third chapter describes the data and the methodologies followed in order to achieve the research objectives. The results are presented in chapter 4. Chapter 5 provides a discussion of the main results. In chapter 6 final conclusions are made. The recommendations for future research are given in chapter 7.

2 LITERATURE REVIEW

This chapter provides an overview on the basic principles of red edge position algorithms. The position of the red edge is mostly defined as the inflexion point (or maximum slope) of the red infrared slope, and accurate determination requires a number of spectral measurements in narrow bands in this region. Subsequently, the REP is defined by the maximum first derivative of the reflectance spectrum in the region of the red-edge. However, the limitation of this approach is that the maximum first derivatives of contiguous spectra have been well documented to occur within two principal spectral regions (around 700 and 725 nm) causing a bimodal distribution of REP data around 700 and 725 nm and discontinuity in the REP/chlorophyll relationship (Horler et al., 1983). Several other studies have revealed the existence of this double-peak feature in the first derivative of contiguous spectra. Boochs et al. (1990) identified two peaks in winter wheat at 723 and 735 nm. Clevers et al. (2004) used the analytical spectral devices (ASD) FieldSpec FR Spectroradiometer with a 1 nm spectral resolution and observed two peaks in canopy spectra of grass near 700 and 720 nm.

Experimental studies have shown that low leaf chlorophyll concentration is associated with REP values near 700 nm, while high chlorophyll concentration in combination with leaf internal scattering influence REP values near 725 nm (Boochs et al., 1990; Horler et al., 1980; Lamb et al., 2002). Model fitting techniques such as the simple linear four-point interpolation method (Guyot & Baret, 1988), the maximum first derivative (Dawson & Curran, 1998) and computational complex procedures including fitting inverted Guassian function (Bonham-Carter, 1988) to reflectance spectrum REP data have been used for determining the REP. Also, indicators based on the continuum removal method have been used for this purpose. Dawson & Curran (1998) presented a technique based upon a three- point Lagrangian interpolation technique for locating the REP in spectra that have been sampled coarsely. A problem with this method arises when the reflectance spectrum exhibits more than one maximum in its first derivative.

The thesis aims to extract the Red Edge Position form natural vegetation using hyperspectral remote sensing data for estimation of N concentration by different techniques and to compare results.

2.1 Red edge position algorithms

The position of the inflexion point in the red edge region (680 to 780 nm) of the spectral reflectance signature, termed the red edge position (REP), is affected by biochemical and biophysical parameters and has been used as a means to estimate foliar chlorophyll or nitrogen. In this report, four techniques will be used to locate the REP. In this section three of them will be described, which are derived directly from the reflectance values. The next section will describe indices derived after applying a continuum removal technique.

Maximum first derivative spectrum

The REP is defined by the wavelength of the maximum first derivative of the reflectance spectrum in the region of the red edge. The first derivative was calculated using a first-difference transformation of the reflectance spectrum (Dawson & Curran, 1998)

$$\mathbf{FDR}\ (\lambda_i) = (\mathbf{R}\ \lambda_{(j+1)} - \mathbf{R}\ \lambda_j) / \Delta\lambda \qquad \mathbf{(1)}$$

Where FDR is the first derivative reflectance at a wavelength i, midpoint between wavebands j and j+1, R λ(j) is the reflectance at the waveband j, R λ(j+1) is the reflectance at the waveband j+1, and Δλ is the difference in wavelengths between j and j+1.

Linear four-point interpolation technique

The linear four-point interpolation method (Guyot & Baret, 1988) assumes that the reflectance curve at the red edge can be simplified to a straight line centred near the midpoint between the reflectance in the NIR at about 780 nm and the reflectance minimum of the chlorophyll absorption feature at about 670 nm. These authors estimated the reflectance value at the inflexion point and applied a linear interpolation procedure for the measurements at 700 and 740 nm estimating the wavelength corresponding to the estimated reflectance value at the inflexion point. It uses four wavebands (670, 700, 740 and 780 nm), and the REP is determined by using a two-step calculation procedure, which can be described in the following way:

(1) Calculation of the reflectance at the inflexion point (R_{re})

$$R_{re} = (R_{670} + R_{780}) / 2 \qquad \mathbf{(2)}$$

Where R is the reflectance.

(2) Calculation of the red edge wavelength or red edge position (REP):

$$REP = 700 + 40\ ((R_{re} - R_{700}) / (R_{740} - R_{700})) \qquad \mathbf{(3)}$$

R_{670}, R_{700}, R_{740} and R_{780} are the reflectance values at 670, 700, 740 and 780 nm wavelength, respectively, and the constants 700 and 40 result from interpolation in the 700-740 nm interval.

Inverted Gaussian fitting technique

An inverted Gaussian (IG) model (Bonham-Carter, 1988; Dawson & Curran, 1998; Miller et al., 1990) can be fitted to the spectral reflectance in the 660-780 nm band range. Accordingly, the IG model represents the red edge by the reflectance equation:

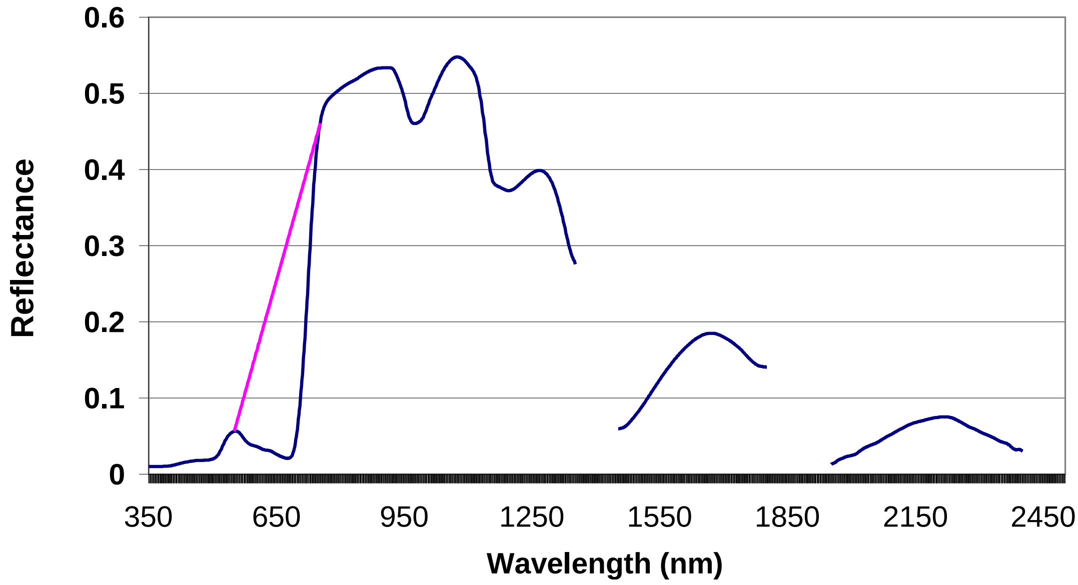
$$\mathbf{R(\lambda) = R_s - (R_s - R_o) \exp(-(\lambda_0 - \lambda)^2 / 2\sigma^2)} \qquad \textbf{(4)}$$

Where Rs is the maximum or “shoulder” reflectance, Ro and λo are the minimum spectral reflectance and corresponding wavelength, and σ is the Gaussian function variance. The REP is then defined as:

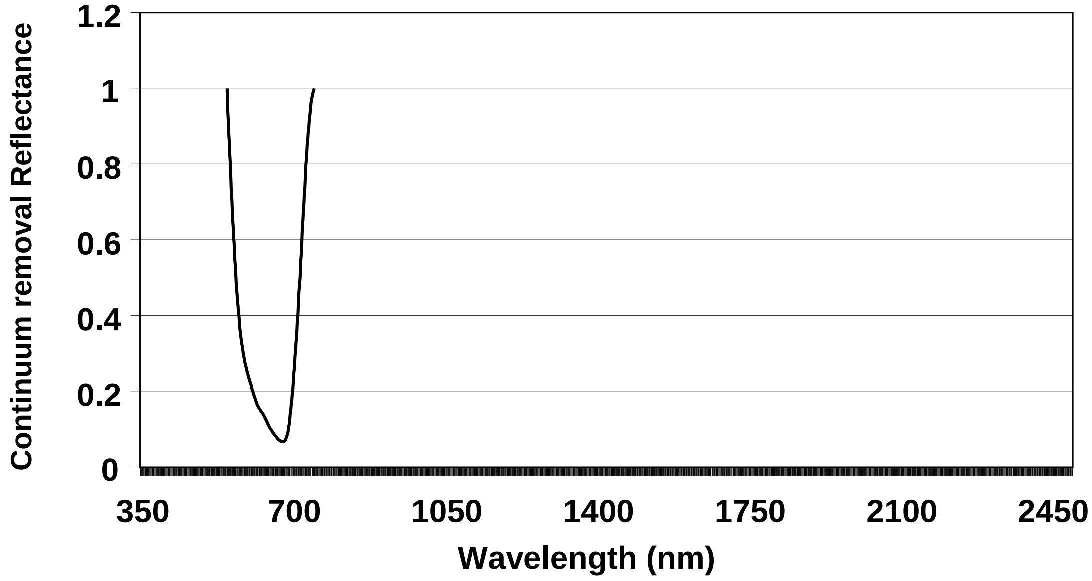
$$\mathbf{REP = \lambda_0 + \sigma} \qquad \textbf{(5)}$$

2.2 Continuum removal

The continuum is simply an estimate of the other absorptions present in the spectrum, not including the one of interest.
Once the continuum line is established, the continuum-removed spectra are calculated by dividing the original reflectance values by the corresponding values of the continuum line.



(a)



(b)

Figure 1. Example spectrum of a FieldSpec measurement at the floodplain Millingerwaard 2005

(a) Reflectance spectrum with continuum line

(b) Continuum removed reflectance spectrum

Band Depth (BD)

Band depths within absorption features were normalized to the continuum line. The normalized band depths (BD) within the continuum-removed absorption band are calculated by dividing the band depth of each channel by the band-depth at the band center (R_i):

$$\mathbf{BD = 1 - R / R_i} \qquad \textbf{(6)}$$

Variations of BD with wavelength describe the shape of the absorption feature.
BD is the band depth, R the reflectance of the sample at the waveband of interest, and R_i the reflectance of the continuum line at the waveband of interest. For estimating nitrogen the maximum band depth (MBD) will be used as an indicator.

Area absorption feature (A)

$$\mathbf{A = \sum_{\lambda_1}^{\lambda_2} (1 - R / R_i)} \qquad \textbf{(7)}$$

A is the area of the absorption feature. λ_1 and λ_2 are the begin and end wavelengths of the absorption feature.

Maximum Band depth normalized to area of absorption feature (BNA)

This measures the maximum depth of the waveband of interest from the continuum line, relative to the area of the absorption feature.

$$\mathbf{BNA = (1 - (R / R_i)) / A} \qquad \textbf{(8)}$$

BNA is the maximum band depth normalized to the area and A the area of the absorption feature.

3 MATERIAL AND METHODOLOGY

3.1 Introduction

This chapter describes the research methodology, the description of the study area is given and available data is described.

3.2 Study area

The study area of this thesis is the floodplain Millingerwaard in the Netherlands along the river Waal. Millingerwaard is part of the nature reserve 'Gelderse poort', with an area of 400 ha. Before the 1990s, the main agricultural function of the floodplain was production grassland and arable land (e.g., maize). In the period 1990-1993, the agricultural function gradually changed into nature. Only small-scale nature management was carried out: fences between parcels were removed and cattle for natural grazing were introduced.
The Millingerwaard was one of the first nature rehabilitation projects for the river floodplains in the Netherlands. It therefore serves as an example project for other floodplain rehabilitation projects. For 1994, 1998, 2002 vegetation maps are available, while the network of vegetation quadrates is monitored yearly. That monitoring focuses mainly on species composition. Information on biochemical and biophysical vegetation parameters are only limited available (Clevers & Kooistra, 2008).

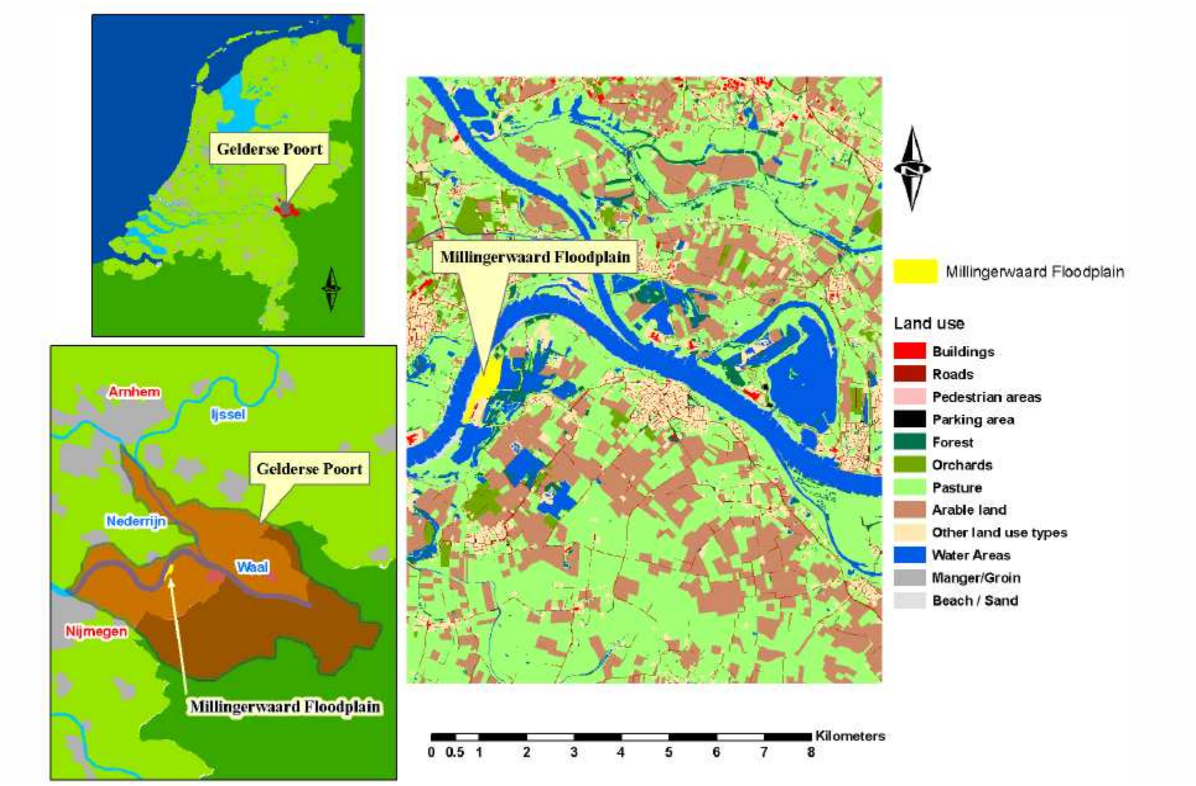


Figure 2. Location and current land use for the floodplain Millingerwaard along the River Rhine in the Netherlands.

3.3 Data

In this chapter the description of the available data is given. The chapter is written using the report on HyEco'04 – an airborne imaging spectroscopy campaign in the floodplain Millingerwaard (Kooistra et al., 2005) and AHS2005 – an airborne imaging spectroscopy campaign in the floodplain Millingerwaard (Clevers & Kooistra, 2008).

3.3.1 Remote Sensing data

HyMap sensor

Imaging spectrometer data for the Millingerwaard were acquired on July 28^{th} and August 2^{nd}, 2004, with the HyMap sensor (Integrated Spectronics, Australia). Due to the cloud clover, only the image from July 28th was further analyzed. A complete spectrum over the range of 450-2480 nm is recorded with a bandwidth of 15-20 nm by 4 spectrographic modules. Each module provides 32 spectral channels giving a total of 128 spectral measurements for each pixel. However, the delivered data contains 126 bands because 2 were deleted during the pre-processing. The ground resolution of the images is 5 m (Kooistra et al., 2005).

AHS sensor

On 19 June 2005 a flight with the AHS sensor was performed by the Remote Sensing Laboratory of the Instituto Nacional de Técnica Aerospacial (INTA) in Spain. The AHS sensor (Airborne Hyperspectral Scanner) is an airborne imaging 80-band line scanner radiometer based on the whiskbroom technique. It can be considered a powerful tool for applications in which high spectral, radiometric and spatial detail is required while keeping a wide spectral coverage.

All remote sensing images have been automatically corrected and spectral values for polygons matching the field plots already have been extracted.

3.3.2 FieldSpec Pro FR spectroradiometer

On 28 July 2004 a field campaign with the FieldSpec Pro FR spectroradiometer was performed to characterize vegetation and reference targets. The spectral range of that devise is 350-2500 nm. For the spectral characterization of both reference targets and vegetation canopy the same experimental set-up was used. First, an area of 5m x 5m was selected with relatively homogenous vegetation coverage. About 10 measurements per object were performed, whereby each measurement is the average of 50 readings at the same spot. Sampling was carried out from the outside of the sampling area to the centre. A subarea of 1 x 1 m in the centre was left untouched and located with a pole. This area was used later for vegetation description and sampling. Spectral sampling was conducted by holding the ASD fibre probe in nadir position (zenith = 0; azimuth = 0) and with a distance of ~100 cm above the ground (GFOV = ~44 cm).

Most reflectance spectra show the typical vegetation curve, except for three spectra (2, 16 and 18) that deviate. Plot 2 has a very short grass cover (either mowed or grazed) having a relatively high reflectance in the NIR and SWIR. Plot 16 and 18 have a relatively low vegetation coverage and are located on or near the sandy beach area: pioneer vegetation (Kooistra et al., 2006; Schaepman et al., 2007). As a result, 19 plots remained for further analysis.

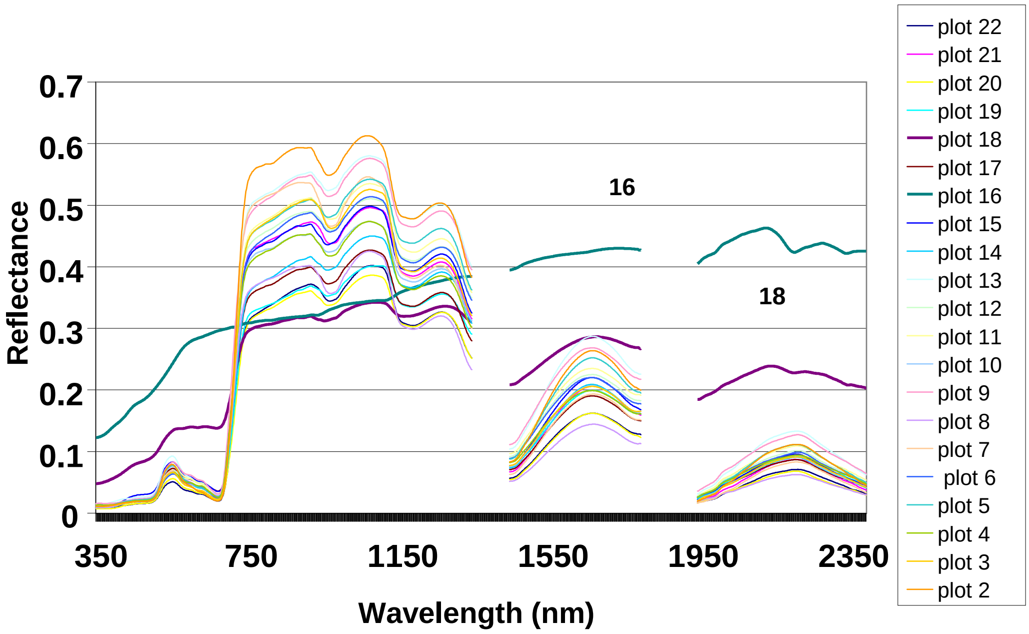


Figure 3. Overview of all measurements performed on 28 July 2004 over the vegetation plots after removing the noisy measurements.

June 19th, 2005, a field campaign with an ASD FieldSpec Pro FR spectroradiometer was performed at the Millingerwaard site. In total 14 plots were defined. For every plot 12 measurements were performed according to the VALERI sampling scheme, whereby each measurement was the average of 15 readings at the same spot. Measurement height was about 1 m above the vegetation. A Spectralon white reference panel was used for calibration.

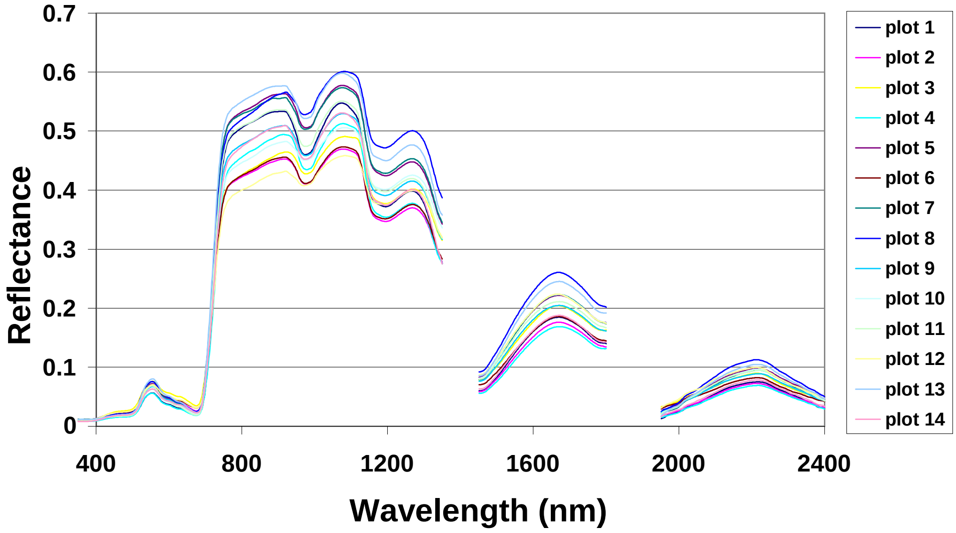


Figure 4. Overview of all measurements performed on June 19th 2005 over the vegetation plots after removing the noisy measurements.

3.3.3 Ground measurements

Main objective of the project was to explore the use of hyperspectral sensors to retrieve biophysical and biochemical vegetation parameters. To support the hyperspectral AHS images, HyMap images and Fieldspec radiometer data, ground data collection was performed. These data are the basis for validation of the imaging spectroscopy derived products in a later stage of the project.

Vegetation description

Vegetation descriptions were made according to the method of Braun-Blanquet (1951). Abundance per species was estimated optically as percentage soil covered by living biomass in vertical projection, and scored on a nine-point scale. All bryophytes and lichens, and also vascular species that were not readily recognizable in the field, were collected for later identification. Taraxacum species were taken together as T. vulgare, and Rubus species were taken together as R. fruticosus, except R. caesius. No subspecific taxa were used. Nomenclature follows van der Meijden et al. (1990), Touw & Rubers (1989), and Brand et al. (1988) for vascular species, mosses and lichens, respectively. No distinction in layers (e.g. by using pseudo-species) was made. Syntaxonomic nomenclature follows Schaminée et al. (1995, 1996, 1998).

Biomass

In 2004 vegetation sampling was taken from 50 cm * 50 cm subplots with relatively homogenous vegetation, located at three corners of each main plot. Biomass was clipped at 0.5 cm above the ground level and stored in paper bags. The collected material was air-dried, first 5 days at room temperature in open bags, and subsequently for 24 h at 70 degrees Celsius and then weighted.

In case of 2005, vegetation biomass was sampled in three subplots with a relatively homogeneous (vegetation) cover measuring 0.5 x 0.5 m, located within the Valeri-plots. Biomass was clipped at 0.5 cm above the ground level and stored in paper bags. The collected material was weighted for fresh biomass, then it was dried for 24 h at 70ºC, and weighed again.

Biochemistry

Sampled vegetation material for the 21 vegetation plots in 2004 and the 14 vegetation plots in 2005 were chemically analyzed for N, P, K, and Ca (mmol/kg).

3.4 Methodology

3.4.1 Introduction

The conceptual model of the methodology is show in the Figure 5.
In general the research is divided into 3 steps:
Step 1 will be the overview of the ground collected and airborne spectral data both of 2004 and 2005. To check if there are some error data.
Step 2 will be the calculation of the REP by different indices and estimation both of nitrogen concentration and nitrogen content.
Step 3 will be the comparison of all results form different techniques and validation by RMSEP (section 3.5).

3.4.2 Flow Chart of the Methodology

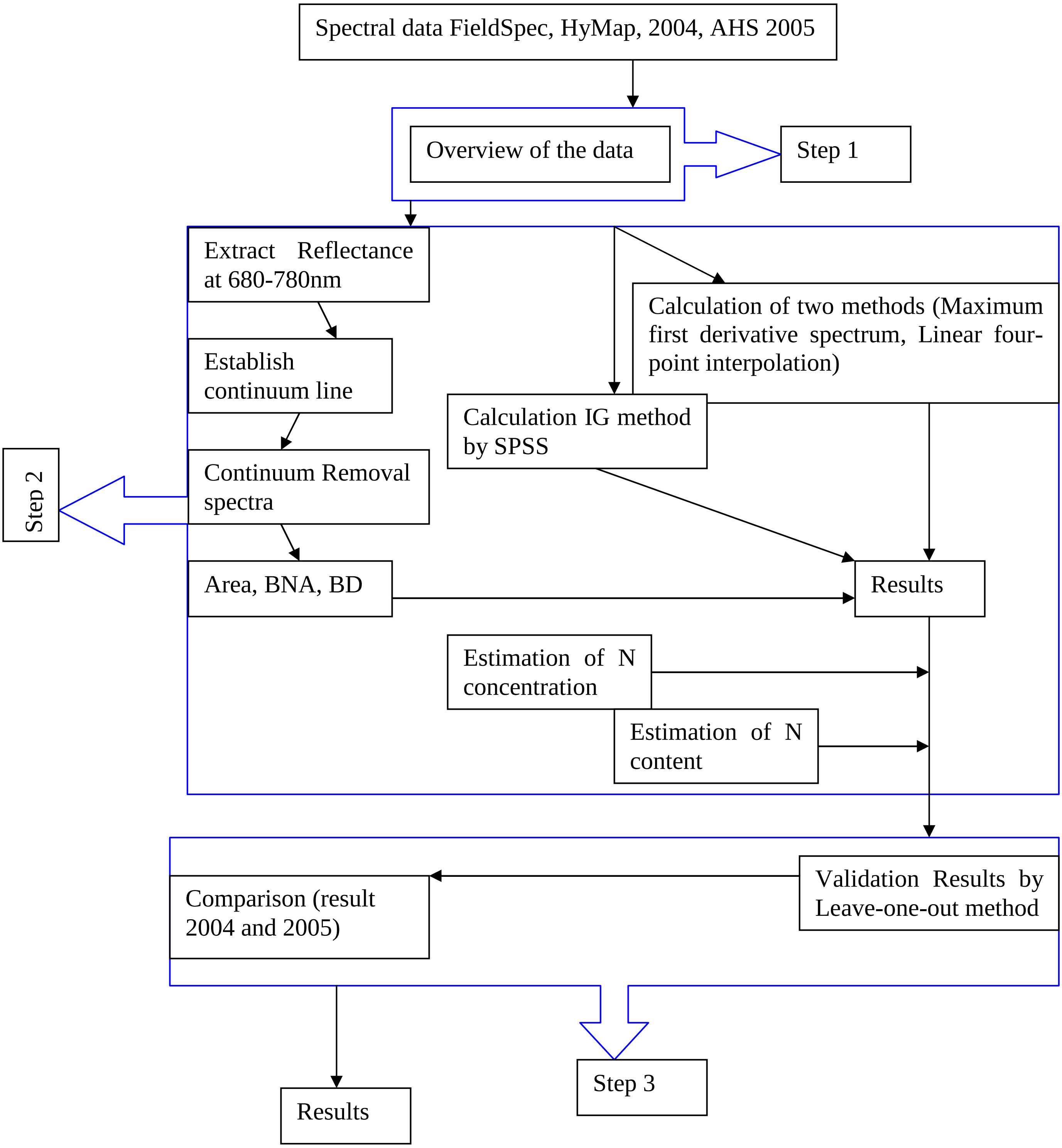


Figure 5. Summarizes the approach used for applying the different techniques for the calculation of the REP to estimate N concentration.

3.5 Validation

Linear regressions will be performed between the spectral indices and the N content. In addition, if results point at non-linear relationships, non-linear regressions will be performed. The result will be validated by use of the leave-one-out-method.

Leave-one-out method

Leave-one-out cross validation is used in the field of machine learning to determine how accurately a learning algorithm will be able to predict data that it was not trained on. When using the leave-one-out method, the learning algorithm is trained multiple times, using all but one of the training set data points. For evaluation, predicted values can be used for calculating the Root Mean Square Error of Prediction ($RMSE_{PRED}$).

The form of the algorithm is as follows:
For k = 1 to R (where R is the number of training set points)
Temporarily remove the kth data point from the training set.
Train the learning algorithm on the remaining R - 1 points.
Test the removed data point and note your error.

Calculate the root mean square error over all R data points. This is called the root mean square error of prediction: $RMSE_{pred}$

Leave-one-out cross validation is useful because it does not waste data. When training, all but one of the points are used, so the resulting regression or classification rules are essentially the same as if they had been trained on all the data points. The main drawback to the leave-one-out method is that it is expensive - the computation must be repeated as many times as there are training set data points.

4 RESULTS

In this chapter the results of the exploration of data of 2004 and 2005 will be presented. The relationship between four methods will be computed and analyzed.

4.1 Comparing the statistics of red edge positions extracted by different techniques

Table 1. Statistics of red edge positions (REP) extracted by various techniques

REP) extraction techniques 2004	Mean (nm)	Minimum(nm)	Maximum(nm)
linear four-point interpolation	719.4707	717.1746	721.1592
Maximum first derivative spectrum	719	705	723
Invert Gaussian fit	713.5379	709.443	716.283
Invert Gaussian fit with Hymap	711.2960	709.98	712.534
REP) extraction techniques 2005	Mean (nm)	Minimum(nm)	Maximum(nm)
linear four-point interpolation technique	721.3413	720.0924	722.8859
Maximum first derivative spectrum	723	721	725
Invert Gaussian fit	716.2623	713.51	718.615

The Table 1 shows the statistics for the REPs extracted by the linear four-point interpolation, maximum first derivative spectrum, and inverted Gaussian fitting techniques. It is evident from Table 1 that the results of REP calculations are dependent upon the choice of method.

4.2 Performance of three techniques for estimating foliar nitrogen concentration

Since linear four-point interpolation, maximum first derivative spectrum and inverted Gaussian fitting techniques are associated, it makes sense to relate those REP indices based on the FieldSpec and Hymap measurements in 2004 and FieldSpec measurements in 2005 with N concentration individually.

The Figure 6 shows the result between N concentration and red edge indices using the three techniques (linear four-point interpolation, maximum first derivative spectrum and inverted Gaussian fitting techniques) of vegetation plots measured with the ASD FieldSpec pro at the Millingerwaard site in 2004.

The Figure 6 (a) (b) (c) (d) show values of the coefficient of determination (R^2) for three techniques. It can easily be seen that the coefficient of determination (R^2) of maximum first derivative spectrum is lower than for the two others. There are only small differences between linear four-point interpolation and IG. Graph (d) shows a very bad R^2 . The reason could be the limited number of spectral bands with HyMap.

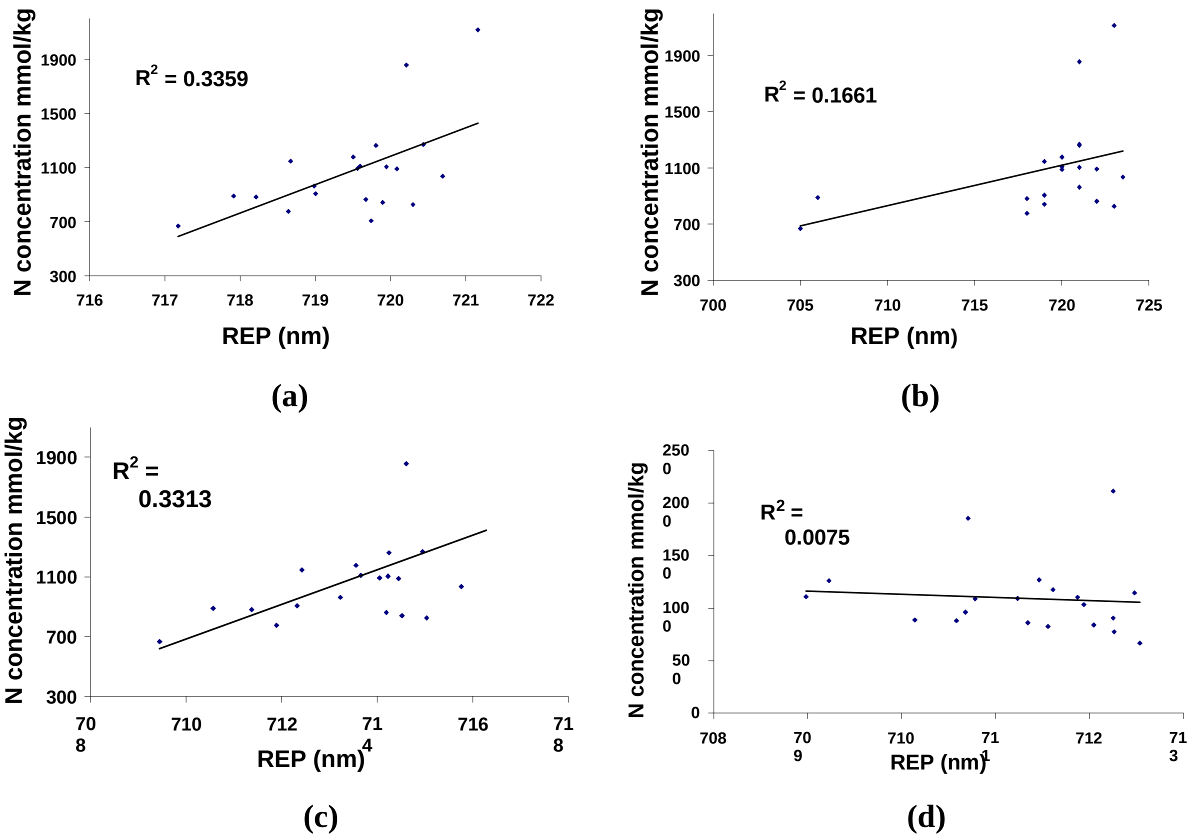


Figure 6. Scatter plots between foliar nitrogen concentration and red edge position (REP) for the FieldSpec measurements in 2004 in Millingerwaard site.
(a) linear four-point interpolation technique
(b) maximum first derivative spectrum
(c) inverted Gaussian modeling (IG)
(d) inverted Gaussian modeling for Hymap data 2004

The Figure 7 shows the result between N concentration and red edge indices based on the three techniques (linear four-point interpolation, maximum first derivative spectrum and inverted Gaussian fitting techniques) of vegetation plots measured at the Millingerwaard site in 2005.

Graphs in figure 7 a, b and c, which are related to linear four-point interpolation, maximum first derivative spectrum and inverted Gaussian fitting technique for FieldSpec data follow the same pattern. These three graphs show that N concentration has highest correlation with IG technique for FieldSpec data and linear four-point interpolation as second.

For these graphs of both 2004 and 2005, we can simply find that maximum first derivative spectrum is less suitable for estimation of nitrogen concentrations from ASD FieldSpec pro measurement data.

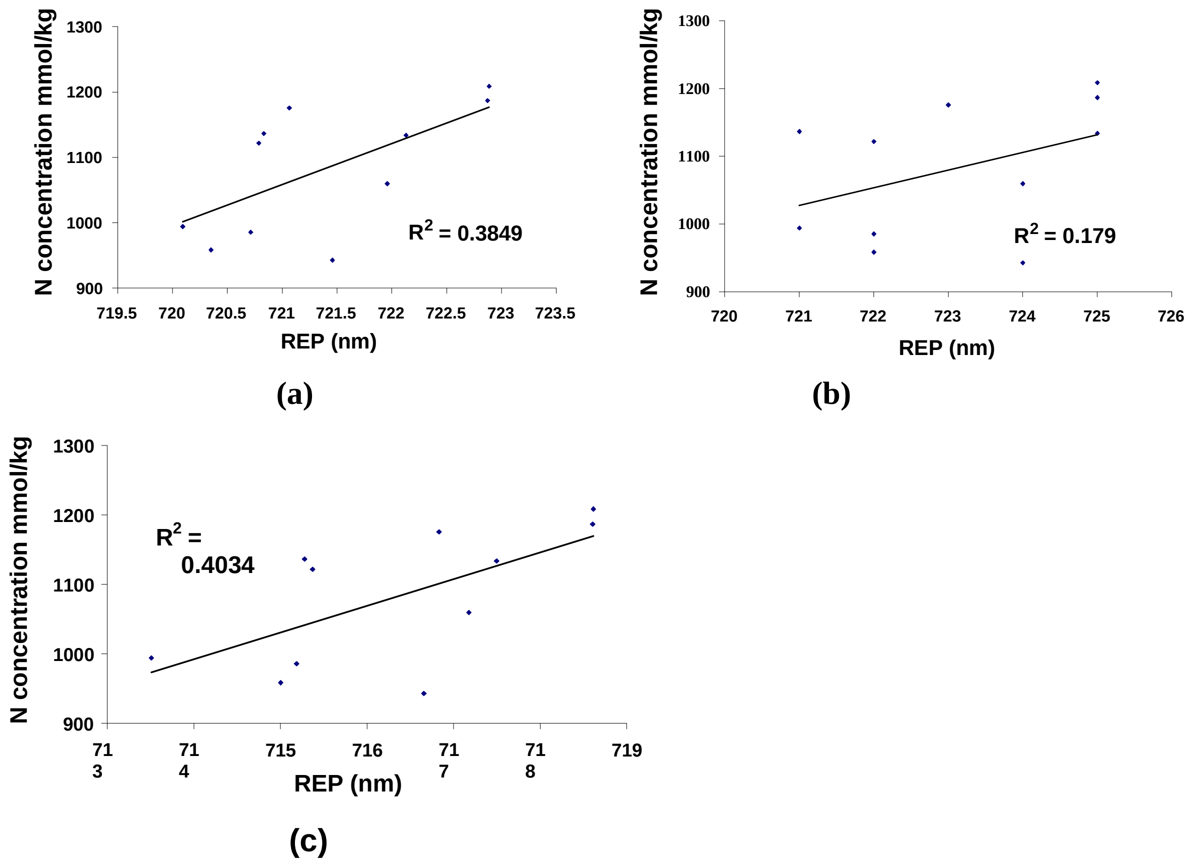


Figure 7. Scatter plots between foliar nitrogen concentration and red edge position (REP) for the FieldSpec measurements in 2005 in Millingerwaard site.

(a) linear four-point interpolation technique
(b) maximum first derivative
(c) inverted Gaussian modeling

4.3 MBD, Area and BNA estimation using continuum removal indicators

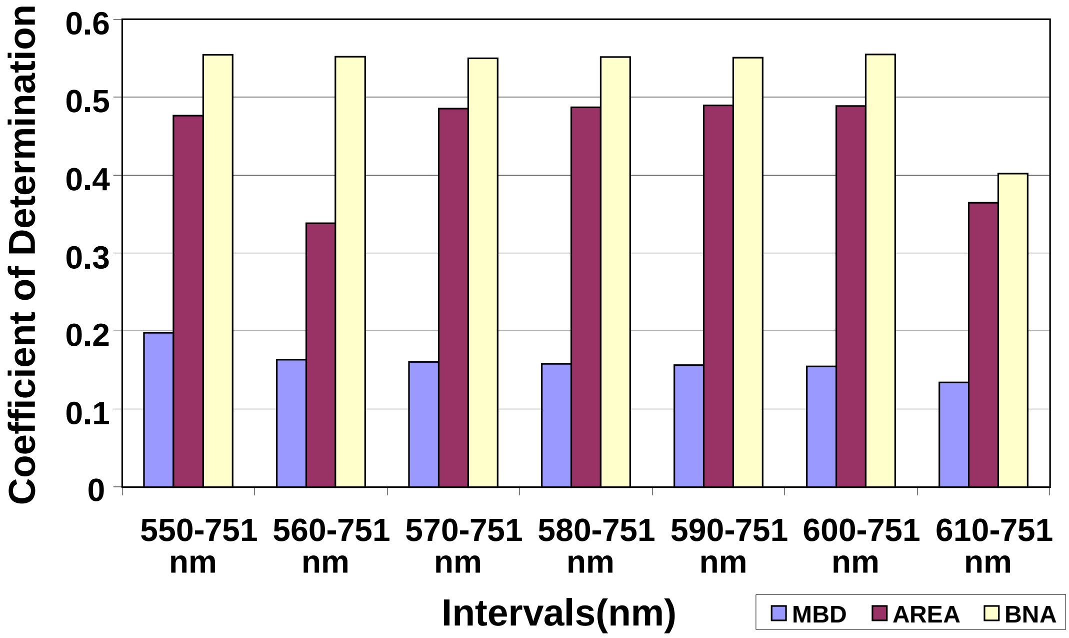
Related to research question 2 to investigate which interval is suitable for applying the continuum removal technique to the chlorophyll absorption region, it is reasonable to start with broad intervals which include the whole red absorption feature around 680 nm (550 nm-751 nm). Once the continuum lines around 680 nm are established, continuum-removed spectra are calculated from the original reflectance spectrum. The end points of the continua of the N absorption features used in this study are defined in Table 2. In the further steps, intervals around those N absorption features were decreased by 10 nm at the left side, and all the procedures were repeated. There are three REP indices based on continuum removal technique. The best interval will be chosen depending on the highest R^2 values for 2004 and 2005.

Table 2. Continuum start and end point definition for the red edge position in the reflectance spectra of vegetation in Millingerwaard 2004 and 2005.

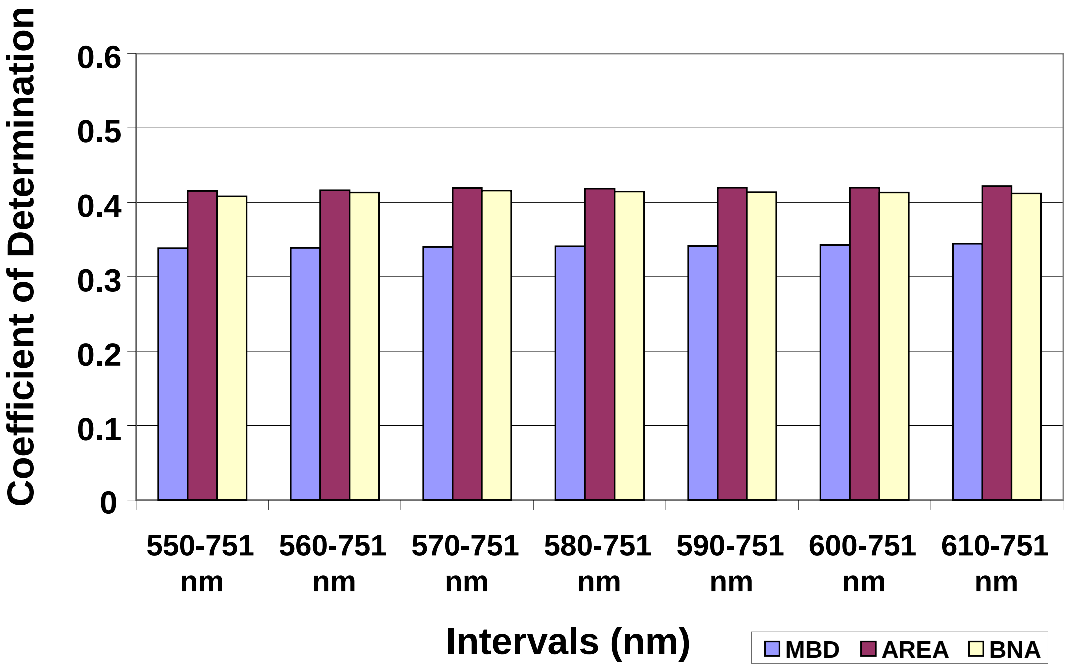
Step	Continuum Line Start (nm)	Continuum Line End (nm)
1	550	751
2	560	751
3	570	751
4	580	751
5	590	751
6	600	751
7	610	751

From the continuum-removed reflectance, the maximum band depth (MBD) in the absorption feature was computed. Then we can find the maximum band depth normalized to the area under the continuum (Area) and also the area under the continuum normalized to the maximum band depth (BNA).

Figure 8 shows the results of the coefficient of determination between nitrogen concentration and indices based on the continuum removal technique (MBD, AREA and BNA) over different intervals at 680 nm of vegetation plots measured with the ASD FieldSpec pro in Millingerwaard site in 2004 and 2005, respectively.
For the 2004 data, (a) show that the maximum value of the coefficient of determination for BNA is 0.5534, for Area it is 0.4895 and for MBD it is 0.1979. Two of them are located in the interval 550 nm to 751 nm and the Area value is located in the interval 590 nm to 751 nm of the spectral signature. The minimum value of the coefficient of determination for BNA is 0.402, for Area it is 0.3645 and for MBD it is 0.1344. There have only fluctuations happened for Area of the spectral signature. MBD and BNA both show a decrease from 550 nm to 610 nm.
Figure 8 (b) shows that the indices are constant over the different intervals. The maximum value of the coefficient of determination for Area is 0.4201, for BNA it is 0.416, for MBD it is 0.3426. There is only 0.041 difference between Area and BNA. The maximum values of Area and MBD are located in the interval 600 nm to 751 nm. The maximum value of BNA is located in the interval 570 nm to 751 nm.
The only reason to explain the fluctuations happened for Area in 2004 data and the constant value over different intervals for Area in 2005, that is a different data source.



(a)



(b)

Figure 8. Coefficient of Determination of continuum removal indices with N concentration for different intervals around 680 nm for FieldSpec data in Millingerwaard site.
a) FieldSpec data 2004 without plots 16 and 18
b) FieldSpec data 2005

Figure 9 shows the best results of the R^2 between nitrogen concentration and indices based on the continuum removal technique (MBD, Area and BNA) of vegetation plots measured with the ASD FieldSpec pro in Millingerwaard site in 2004.

Graphs in figure 9 (a), (b) and (c), which are related to MBD, BNA and AREA respectively, show the coefficient of determination between nitrogen and continuum removal indices. The MBD has lowest R^2.

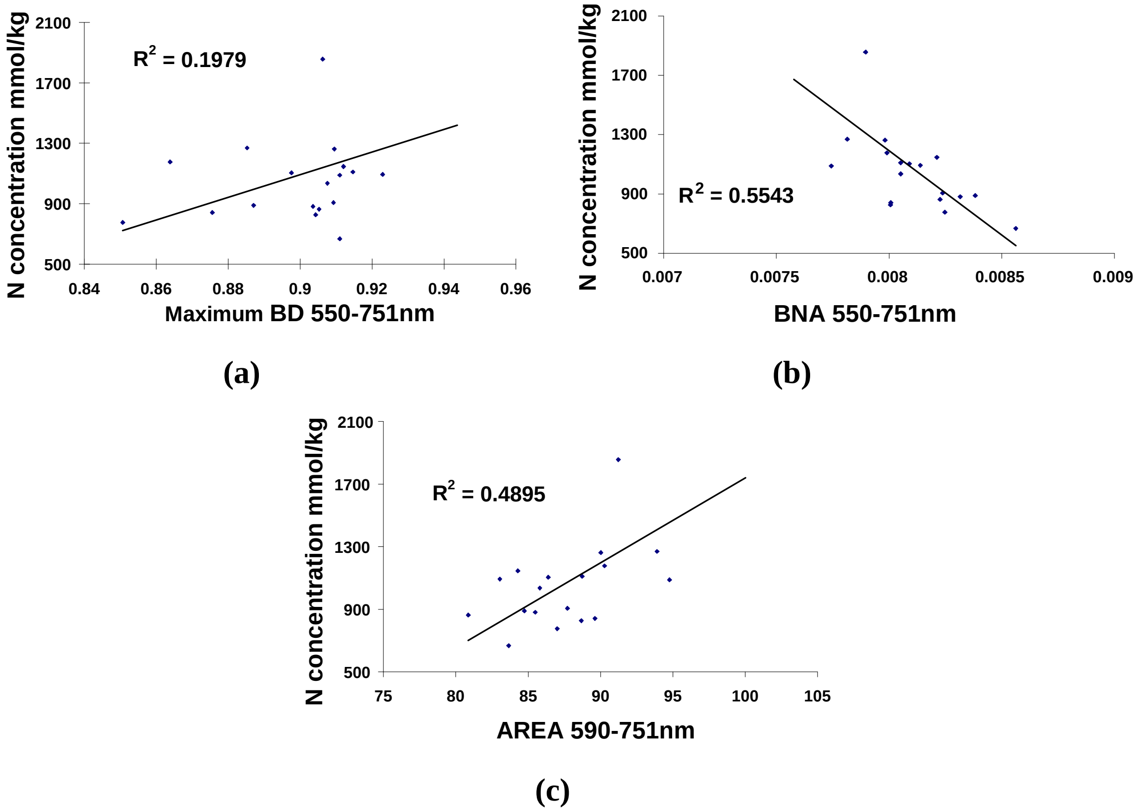
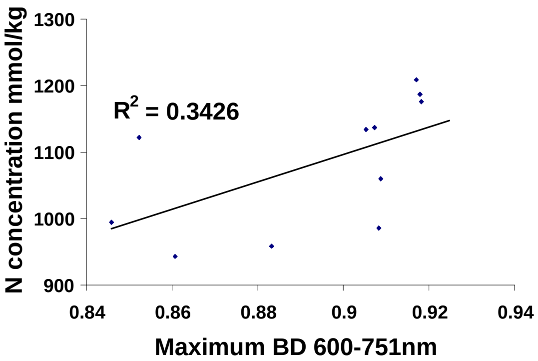
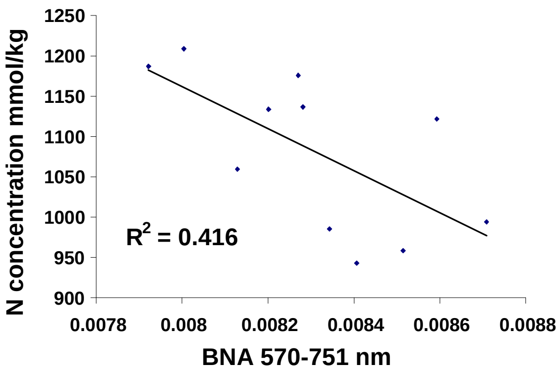


Figure 9. Relationship between various indicators based on the continuum removal technique and the nitrogen concentration for the FieldSpec measurements in 2004 in Millingerwaard site.
(a) Maximum Band Depth
(b) Maximum Band depth normalized to area of absorption feature.
(c) Area

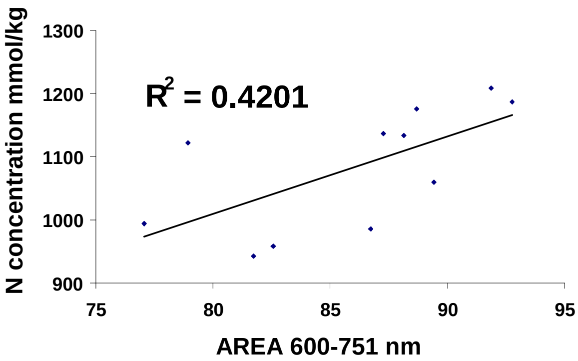
Figure 10 shows the best results of the R^2 between nitrogen concentration and indices based on the continuum removal technique (MBD, Area and BNA) of vegetation plots measured with the ASD FieldSpec pro in Millingerwaard site in 2005.
Graphs in figure 10 a, b and c, which are related to MBD, BNA and AREA respectively, show the coefficient of determination between nitrogen and continuum removal indices. We can find out that BNA and AREA indices have similar result. The MBD has a bit a lower R^2.



(a)



(b)



(c)

Figure. 10. Relationship between various indicators based on the continuum removal technique and the nitrogen concentration for the FieldSpec measurements in 2005 in Millingerwaard site.

(a) Maximum Band Depth

(b) Maximum Band depth normalized to area of absorption feature.

(c) Area

4.4 Performance of REP techniques for estimation of foliar nitrogen content

For checking if there are better results when estimating nitrogen content, we transfer the nitrogen concentration (m mol/kg) to nitrogen content (g/m^2), using the Dry Weight (DW, ton/ha).
The formula be used:

1m mol N =14 mg N

$$N_{content} = N_{concentration} * 14 / 1000 * DW / 10 \qquad (9)$$

The Figure 11 shows the result between N content and red edge indices based on the three techniques (linear four-point interpolation, maximum first derivative spectrum and inverted Gaussian fitting techniques) of vegetation plots measured with the ASD FieldSpec pro data and Hymap data in Millingerwaard site in 2004. Those all have very low R^2 values.

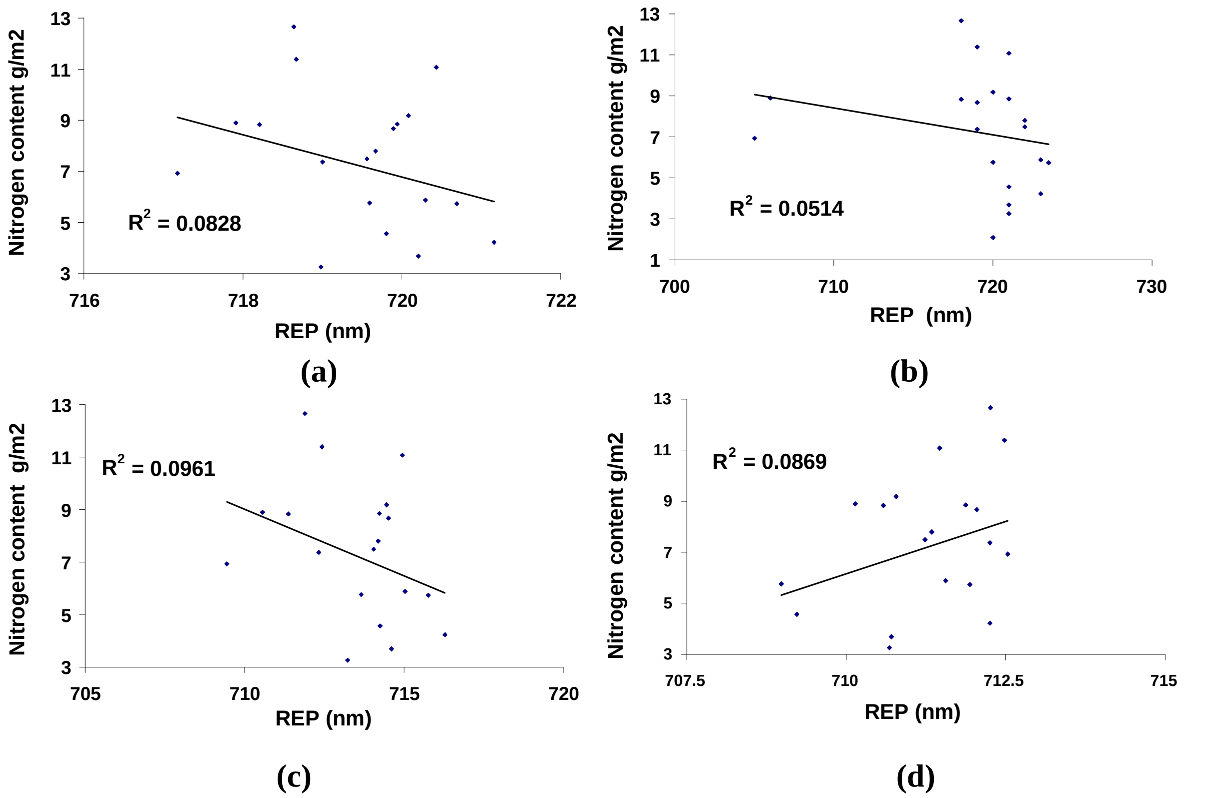
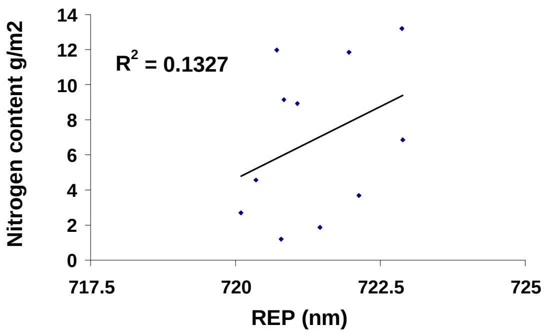
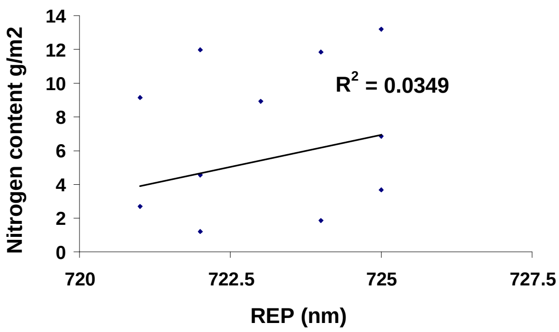


Figure. 11. Scatter plots between foliar nitrogen content and red edge position (REP) for the FieldSpec and Hymap measurements in 2004 in Millingerwaard site.
(a) linear four-point interpolation technique
(b) maximum first derivative spectrum
(c) inverted Gaussian modeling
(d) inverted Gaussian modeling for Hymap data 2004

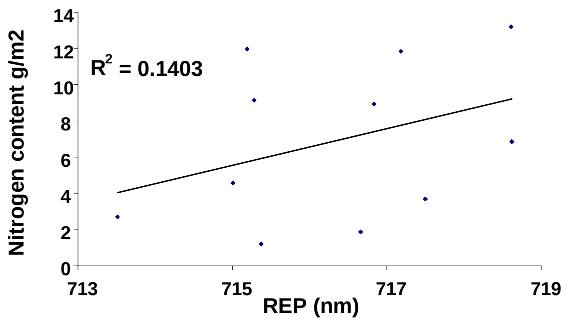
The Figure 12 shows the result between N content and red edge indices based on the three techniques (linear four-point interpolation, maximum first derivative spectrum and inverted Gaussian fitting techniques) of vegetation plots measured with the ASD FieldSpec pro in Millingerwaard site in 2005. There is no result for the AHS sensor because of the limited band setting in the red edge region.
The Figure 12 (a) (b) (c) show value of the coefficient of determination (R^2) for the three techniques. The coefficient of determination (R^2) of maximum first derivative spectrum is lower than the two others, but they all show bad results.



(a)



(b)

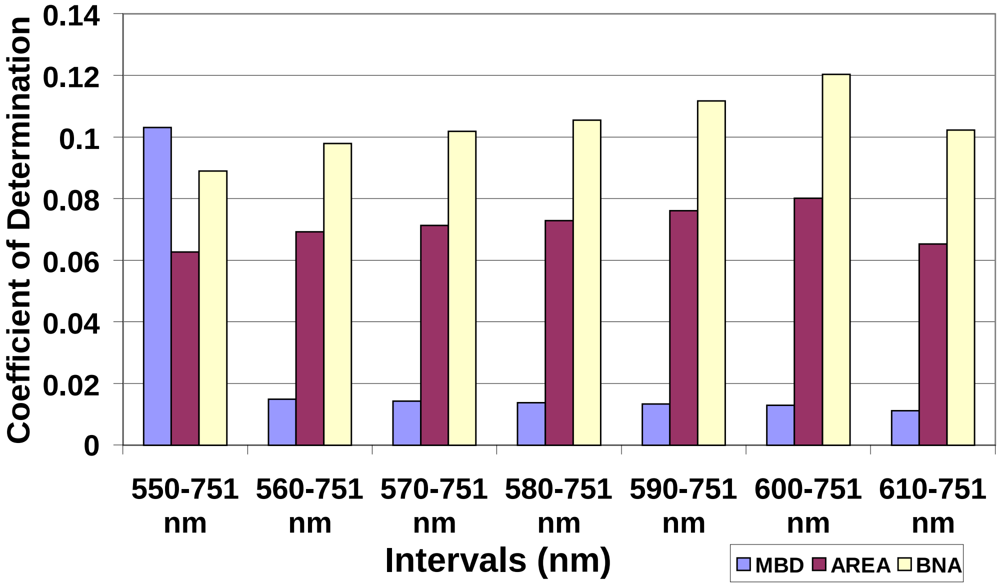


(c)

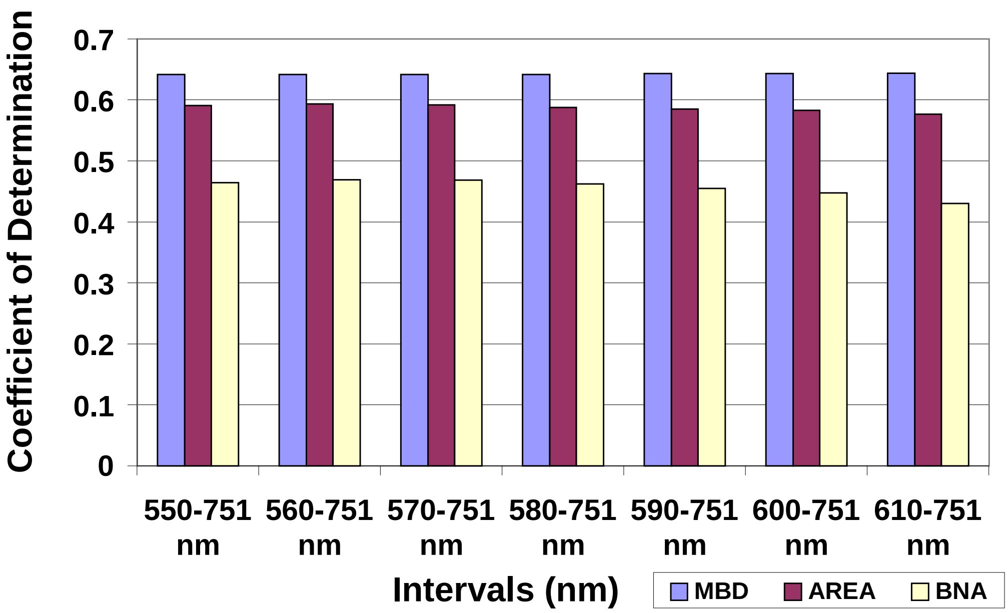
Figure. 12. Scatter plots between foliar nitrogen content and red edge position (REP) for the FieldSpec measurements in 2005 in Millingerwaard site.
(a) linear four-point interpolation technique
(b) maximum first derivative spectrum
(c) inverted Gaussian modeling

Figure 13 shows the results of the coefficient of determination between nitrogen content and indices based on the continuum removal technique (MBD, AREA and BNA) over different intervals at 680 nm of vegetation plots measured with the ASD FieldSpec pro in Millingerwaard site in 2004 and 2005, respectively.
Figure 13 (a) shows that the maximum value of the coefficient of determination for MBD is 0.1031, for Area it is 0.0802 and for BNA it is 0.1204. Two of them are located in the interval 600 nm to 751 nm and the best MBD value is located in the interval 550 nm to 751 nm of the spectral signature.
Figure 13 (b) shows for 2005 that there are similar R^2 values for all indices in the different intervals. The maximum value of the coefficient if determination for MBD is 0.6441, for Area it is 0.5908, for BNA it is 0.4962. There is only 0.0946 difference between Area and BNA.

The maximum value of MBD is located in the interval 610 nm to 751 nm. The maximum value of Area is located in the interval 550 nm to 751 nm. The maximum value of BNA is located in the interval 560 nm to 751 nm. It easily can be found out from graph (a) that different intervals have a different R^2 for each index. In case of 2005 data, it's more constant over intervals for each index.



(a)

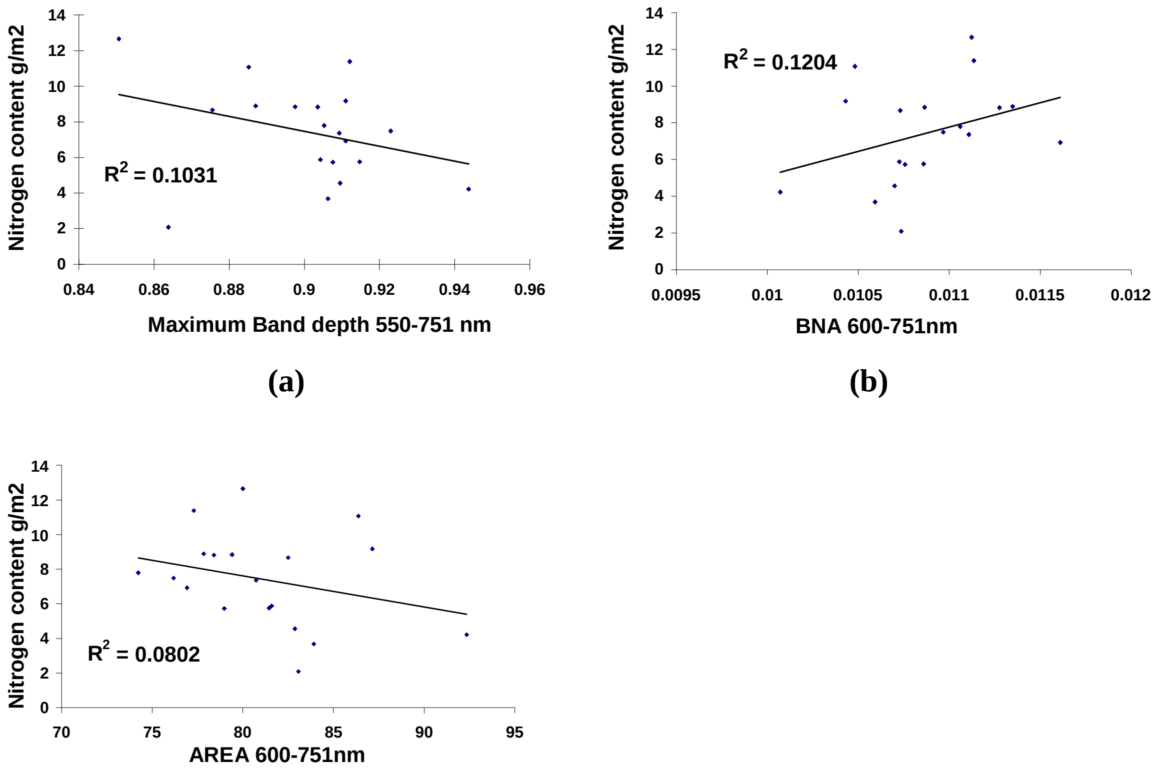


(b)

Figure 13. Coefficient of Determination of continuum removal indices with N content for different intervals around 680 nm for FieldSpec data in Millingerwaard site.
a) FieldSpec data 2004 without plots 16 and 18
b) FieldSpec data 2005

Figure 14 shows the best results of the R^2 between nitrogen content and indices based on the continuum removal technique (MBD, Area and BNA) of vegetation plots measured with the ASD FieldSpec pro in Millingerwaard site in 2004.

The Figure 14 (a) and (b) show a better R^2 based on the MBD and BNA methods than for the Area method (c). For MBD this counts only for the 550nm to 751 nm interval, the rest of intervals have R^2 around 0.015. There are reverse results (MBD better than AREA and BNA estimate by nitrogen content, BNA better than AREA and MBD estimate by nitrogen concentration) if compared with nitrogen concentration based on continuum removal technique with the ASD FieldSpec pro in Millingerwaard site in 2004.



(a) **(b)**

(c)

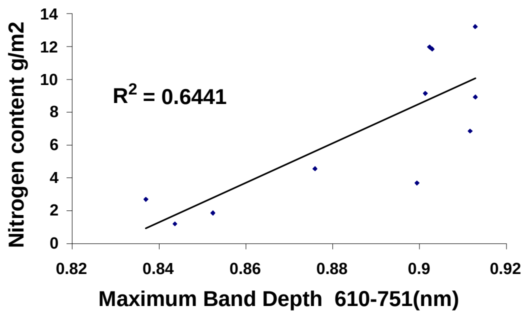
Fig. 14. Relationship between the various indicators based on the continuum removal technique and the nitrogen content for the FieldSpec measurements in 2004 in Millingerwaard site.

(a) Maximum Band Depth

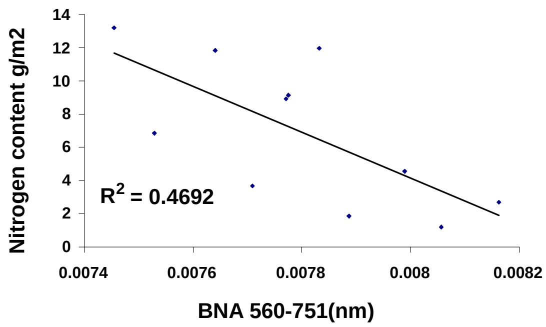
(b) Maximum Band depth normalized to area of absorption feature.

(c) Area

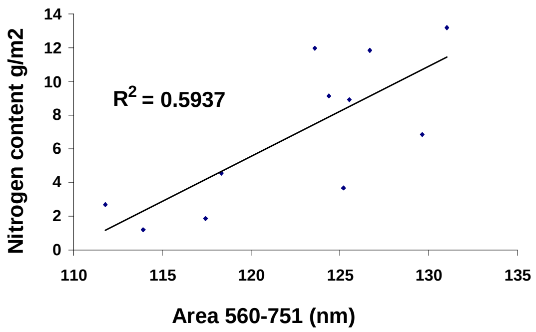
Figure 15 shows the results of the R^2 between nitrogen content and indices based on the continuum removal technique (MBD, Area and BNA) of vegetation plots measured with the ASD FieldSpec pro in Millingerwaard site in 2005.
The Figure 15 (a) (b) (c) show a very good value of the coefficient of determination (R^2) for the three indices. In case of 2005 data, they all have good results whatever estimate for nitrogen by content or concentration, the nitrogen content estimated results are a bit better than nitrogen concentration estimated results.



(a)



(b)



(c)

Fig. 15. Relationship between the various indicators based on the continuum removal technique and the nitrogen content for the FieldSpec measurements in 2005 in Millingerwaard site.
(a) Maximum Band Depth
(b) Maximum Band depth normalized to area of absorption feature.
(c) Area

5 DISCUSSION

In this study, four REP extraction techniques were used which include six REP indices. Both data of 2004 and 2005 have been analyzed for estimating nitrogen concentration and nitrogen content.

Table 3. Correlation (R^2) between foliar nitrogen concentration and red edge position derived form FieldSpec data, Hymap and AHS band setting for the linear four-point interpolation, maximum first derivative spectrum, inverted Gaussian fit and continuum removal techniques.

REP) extraction techniques	FieldSpec2004/2005	Hymap (2004)	AHS (2005)
Linear four-point interpolation technique	0.3359 / 0.3849	Few bands	Few bands
Maximum first derivative spectrum	0.1661 / 0.179	discontinuity	discontinuity
Inverted Gaussian fitting	0.3313 / 0.4034	0.0075	Few bands
Continuum removal 2004/2005			
MBD 550 nm / 550 nm	0.1979 / 0.3426	Few bands	Few bands
Area 560 nm / 600 nm	0.4895 / 0.4201	Few bands	Few bands
BNA 550 nm / 600 nm	0.5543/ 0.416	Few bands	Few bands

The correlations between REP values extracted by the linear four-point interpolation and Inverted Gaussian techniques from FieldSpec data and foliar nitrogen concentration data showed comparable results with those obtained using the techniques BNA and Area, which are based on continuum removal (Table 3). The band setting of the HyMap and AHS instrument appears to be less favorable for the linear four-point interpolation technique. The result of the nitrogen correlation for the maximum first derivative technique is not suitable for the small number of bands in the red edge region of the two coarser resolution spectra. The band setting of AHS shows 4 bands between 680 to 780 nm, which is not enough for using the inverted Gaussian fitting technique. The issue of shortage of bands also applies to the continuum removal techniques.

The accuracy of this estimation is reported both in terms of the R^2 between estimated and measured nitrogen concentration or nitrogen content and the root mean square error of prediction ($RMSE_{pred}$) of these estimations, both absolutely and as a percentage of the mean concentration or content for nitrogen by applying the leave-one-out method. The percentage of $RMSE_{pred}$ is coming from the value of the technique divided by the average of the nitrogen content. Because they have different nitrogen concentration and nitrogen content in 2004 and 2005, it is necessary to show RMSEP as a percentage for easy interpretation, a higher percentage of RMSEP means a higher error. For instance, in case of 2004, the techniques maximum first derivative and IG have R^2 values 0.1661 and 0.3313, and the percentage of RMSEP is 30% and 28%,respectively. In addition, the percentage of nitrogen concentration can not be compare with percentage of nitrogen content, because they have different range of values. The RMSEP can not compared in different years. E.g.: in case of 2004, MBD nitrogen content have R^2 is 0.1013 and RMSEP is 42%. The same RMSEP has occur MBD nitrogen content in 2005, but they have big differences R^2. So that is not comparable.

Table 4. The accuracy with nitrogen concentration and nitrogen content was estimated for both data from 2004 and 2005.

REP) extraction techniques	Data 2004				Data 2005			
	N concentration		N content		N concentration		N content	
	R^2	RMSEP	R^2	RMSEP	R^2	RMSEP	R^2	RMSEP
Linear four-point interpolation	**0.3359**	**28%**	**0.0828**	**30%**	**0.3849**	**7%**	**0.1327**	**67%**
Maximum first derivative spectrum	**0.1661**	**30%**	**0.0514**	**40%**	**0.179**	**9%**	**0.0349**	**72%**
Inverted Gaussian fitting	**0.3313**	**28%**	**0.0961**	**40%**	**0.4034**	**7%**	**0.1403**	**66%**
Inverted Gaussian fitting Hymap	**0.069**	**34%**	**0.0869**	**39%**	**No data**	**No data**	**No data**	**No data**
Continuum removal								
MBD	**0.1979**	**33%**	**0.1013**	**42%**	**0.3426**	**8%**	**0.6441**	**42%**
Area	**0.4895**	**27%**	**0.0802**	**39%**	**0.4201**	**8%**	**0.5909**	**45%**
BNA	**0.5543**	**25%**	**0.1204**	**39%**	**0.416**	**7%**	**0.4692**	**51%**

To compare the strength of the relationship between REPs extracted by different techniques and foliar nitrogen concentration and nitrogen content, the Root Mean Square Error of Prediction was applied to the correlation analyses.

The result has shown a difference in spectral reflectance in response to different nitrogen concentrations or nitrogen contents for the different plots. The shape and position of the red edge is determined by chlorophyll concentration or chlorophyll content within the field of view. REPs extracted by the BNA and Area indices, which are based on continuum removal, show high correlations with foliar nitrogen concentrations and nitrogen content.

In the first part of the thesis, the first three techniques were calculated both with nitrogen concentration and nitrogen content for the data from 2004 and 2005. The maximum first derivative technique has shown lowest result in all cases. Linear four-point interpolation and IG techniques have shown similar results; all have better results for nitrogen concentration. Linear four-point interpolation and maximum first derivative spectrum can not be used on HyMap data and AHS data, because of too limited band setting.

In the other part of the thesis the continuum removal technique was applied to different intervals around the red feature at 680 nm for estimating the spectral interval that could be used to apply the continuum removal technique. Three indices based on the continuum removal technique have shown better results than the first three techniques.

The nitrogen was estimated in two ways, which are nitrogen concentration and nitrogen content, for data 2004 and 2005. There is a difference in the R^2 between estimated nitrogen concentration and estimated nitrogen content for all techniques in both 2004 and 2005. Most results from estimated nitrogen content have shown lower R^2 , but in 2005 there is R^2 of 0.6441, 0.5909 and 0.4692 for MBD, Area and BNA data, respectively. The RMSEP have similar result 42%, 45% and 51% for MBD, Area and BNA data, respectively. The set-up scheme of the field sampling could be one reason for lower R^2 value, in case 2004.

From the different R^2, we can conclude that the continuum removal technique is better than the other three techniques. Maximum first derivative spectrum technique has shown lowest R^2 from all techniques tested. Inverted Gaussian fitting technique has got little better R^2 than linear four-point interpolation technique, but it is more complex.

Table 5. Summary of relative performances of 4 red edge position extraction techniques

REP) extraction techniques	**Complexity**	**Required spectral type**	**Suitability for coarse spectral**	**Correlation with foliar nitrogen**	
				N concentration	**N content**
Linear four-point interpolation	**Easy**	**Reflectance**	**Normal**	**Medium**	**Low**
Maximum first derivative spectrum	**Easy**	**Derivative**	**Poor**	**Low**	**Very Low**
Inverted Gaussian fitting	**Difficult**	**Reflectance**	**Good**	**Medium**	**Low**
Continuum removal					
MBD	**Moderate**	**Reflectance**	**Good**	**Medium**	**High**
Area	**Moderate**	**Reflectance**	**Good**	**High**	**High**
BNA	**Moderate**	**Reflectance**	**Good**	**High**	**High**

Table 5 summarizes the relative performances of the four techniques (with 6 REP indicators) used in this study for extracting the REP. REPs extracted using the continuum removal technique show highest correlation with foliar nitrogen concentration and nitrogen content, being compare with the results obtained using other three techniques (Maximum first derivative spectrum, Linear four-point interpolation and Inverted Gaussian fitting). The results show that the maximum first derivative technique is not an appropriate measure for the red edge position because of the discontinuity created in the REP data. The correlations between the REP and nitrogen for the four different techniques indicate that the accuracy of different techniques depends on the plant material in the measurement area. REPs show the result to be dependent not only on chlorophyll content, but also on additional effects such as in case of vegetation plots 2, 5, 13 and 21 in 2004 which were heavily grazed.

Table 6. Comparing the influence of outlier plots on the R^2 values in 2004

REP) extraction techniques	Data 2004			
		N concentration	N content	
	R^2	R^2 without plots 2,5,13,21	R^2	R^2 without plots 2,5,13,21
Linear four-point interpolation	**0.3359**	**0.3114**	**0.0828**	**0.1406**
Maximum first derivative spectrum	**0.1661**	**0.1618**	**0.0514**	**0.0588**
Inverted Gaussian fitting	**0.3313**	**0.324**	**0.0961**	**0.1575**
Inverted Gaussian fitting Hymap	**0.069**	**0.0045**	**0.0869**	**0.0563**
Continuum removal				
MBD	**0.1979**	**0.083**	**0.1013**	**0.4914**
Area	**0.4895**	**0.3381**	**0.0802**	**0.1167**
BNA	**0.5543**	**0.5719**	**0.1204**	**0.1711**

A difference occurs in the spectral reflectance between HyMap, AHS and FiledSpec. There is not much research done on comparing R^2 of the different techniques for different spectral types. The results show FieldSpec maybe more suitable for estimating biochemical components than HyMap and AHS. The Hymap measures the spectral reflectance from a whole pixel. Another reason for the HyMap sensor could be the height at which measurements were taken. The whole canopy could be measured, while the FiledSpec was held at a distance of +/- 1 m above the ground. HyMap and AHS seems to be less suitable than FiledSpec for prediction of nitrogen concentration and nitrogen content. It also can be caused by the wavelengths interval. Another point to be discussed is the number of sampling points, while dealing with such a complicated heterogeneous dataset. For instance, there are four heavily grazed plots, 2, 5, 13 and 21, they all show higher nitrogen concentration than the other plots. Table 6 shows the statistics for R^2 values determined by the 6 differences REP techniques and also the R^2 values when leaving out plots, 2, 5, 13, 21. We can easily find out when we move out the error plots from estimated of nitrogen concentration in FieldSpec data, that the R^2 values are decrease in difference level for each technique, expect for the REP indicator BNA. It is because BNA is the maximum band depth normalized to the area, which means BNA not only depends on nitrogen concentration but MBD and Area are also important factors. In table 6 all R^2 values increase when we leave out error plots from nitrogen content in FiledSpec data. It is very interesting to find out how this could happen. The nitrogen concentration for plots 2, 5, 13 and 21 is 1270.951 mmol/kg, 1857.3994 mmol/kg, 1177.8269 mmol/kg, 1262.419 mmol/kg, for nitrogen content it is 11.0792 g/m^2, 3.6946 g/m^2, 2.0995 g/m^2, 4.5718 g/m^2, respectively. We can see high nitrogen concentration is not corresponding to high nitrogen content. On the other hand, lot of literature has show that a high nitrogen concentration can generate high R^2. That maybe the reason for R^2 values to decrease when move out error plots. The formula (9) has shown the nitrogen content values come from nitrogen concentration and dry weight of the view plot. The nitrogen content values are the mean value of the viewed point. The nitrogen concentration can work out better if there are homogeneous vegetation plot, it is could be nitrogen content suitable for heterogeneous vegetation plots. The last points is that a larger number of sampling points is needed.

Table 7. The best intervals for nitrogen concentration and nitrogen content in 2004 and 2005

Continuum removal	Data 2004		Data 2005	
	Intervals		Intervals	
	N concentration / N content		N concentration / N content	
MBD	**550 nm- 751 nm**	**550 nm- 751 nm**	**610 nm- 751 nm**	**610 nm- 751 nm**
Area	**560 nm- 751 nm**	**600 nm- 751 nm**	**610 nm- 751 nm**	**560 nm- 751 nm**
BNA	**550 nm- 751 nm**	**600 nm- 751 nm**	**570 nm- 751 nm**	**560 nm- 751 nm**

A difference occurs between data in 2004 and 2005, For 2004, the R^2 values have decreased from nitrogen concentration to nitrogen content, in case of 2005, it shows an increase. That is because of a different data source. Table 7 has shows that best interval for 2004 and 2005. The different rep indices has show different intervals. The dry weight play a role during the nitrogen concentration changing to nitrogen content. Maybe it is the reason for different intervals between nitrogen concentration and nitrogen content in same year.

6 CONCLUSIONS

The most important conclusions from this study are:

(1). The correlation results between REP extracted by maximum first derivative spectrum, linear four-point interpolation, inverted Gaussian fitting and continuum removal techniques and foliar nitrogen concentration and nitrogen content were compared. The results of this study show that the most accurate techniques for the spectral estimation of foliar nitrogen concentration and nitrogen content were BNA and Area indices, which are based on the continuum removal technique. The best interval will be chosen depending on the highest R^2 values for 2004 and 2005. The best interval for 2004 and 2005, it is 550 nm to 751 nm for Area rep index in nitrogen concentration, it is 610 nm to 751 nm for MBD rep index in nitrogen content. Related to research question 3, the technique continuum removal is the best technique for estimating nitrogen content and nitrogen concentration.

(2). The maximum first derivative technique is not a suitable measure for the red edge position because of the discontinuity it creates in the REP data for both narrow and wider bandwidth spectra.

(3). The linear interpolation technique is simple to implement when compared with other techniques. For instance, technique IG need help from software Statistical Package for the Social Sciences (SPSS), the continuum removal technique needs to make continuum line and decide on the suitable interval.

(4). The inverted Gaussian fitting technique did not work well with FieldSpec Pro FR spectroradiometer data and Hymap data, but it is the only technique that can extract the REP from Hymap data. Limited data from the two coarser resolution spectra (Hymap and AHS) and FieldSpec measurements could be the reason that IG are given bad result.

(5). The REP can not be extracted from AHS spectral bands due to their spectral position.

(6). To decide which one is better to estimate nitrogen concentration and nitrogen content, a sufficient number of data points is required.

7 RECOMMENDATIONS

- Further analysis is required to be taken on a sufficient number of data plots while dealing with such homogeneous vegetation to reduce bad influence.
- There is other important REP extraction technique to be considered which is linear extrapolation. The linear extrapolation technique could mitigate the destabilizing effect of the double-peak on the correlation between nitrogen and REP.
- During my thesis research a double-peak was located between 690 nm and 740 nm. For instance, Clevers et al. (2004) used the Analytical Spectral Devices (ASD) FieldSpec FR spectroradiometer with a 1 nm spectral resolution and observed two peaks in canopy spectra of grass near 700 and 720 nm. This is the first and second peak in the derivative spectral curve of the red edge. It is also should be considered in further research.
- The BNA and Area have a high correlation with rep estimation nitrogen content. The nitrogen concentration can work out better if there are homogeneous vegetation plots. Maybe nitrogen content is more suitable for the heterogeneous vegetation plots, which we wish to test on further to be sure about this result.

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