ADOPTION OF N-APPLICATION RATES IN DIFFERENT BROCCOLI CULTIVARS BY REFLECTANCE MEASUREMENTS

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ABSTRACT

Horticultural cropping systems are well suited to site-specific sensor techniques and information management systems. However, to date many sensors have been solely developed and tested for arable crops. This project aims to develop the means to rapidly map N-demand in broccoli plants on a site-specific, plant-by-plant basis using reflectance measurements. The aim of this specific study was to monitor nitrogen status in six different broccoli cultivars using reflectance measurements and to derive suitable N-fertilization strategies based on the sensor measurements.

A field study was conducted with 6 different common broccoli cultivars and 4 different N fertilization treatments consisting of 0, 100, 200, and 400 kg N ha^{-1}. The trial focused on different N fertilization treatments in order to determine the range of reflectance changes of the six cultivars under different nitrogen fertilization levels. Timing of N application was set to start of cultivation, i.e. after planting and after a four week growing period. Sensor measurements started two weeks after planting and were carried out once a week until final harvest of broccoli heads. Sensor measurements were carried out on the youngest fully developed leaf of each plant. Leaf scans were taken with a digital, light-sensitive (ISO 200–2400; spectral sensitivity of 250-1300 nm), high-spatial resolution (5140*5140 pixel) imager (S1 PRO, Leica, Germany). The investigation of the whole spectra (380-1300 nm) indicated that wavelength bands around 500-600 nm seem to be well suited for the identification of N status in broccoli. Further, the results showed that N-demand of the different cultivars depends on build up biomass and developmental rate of the plant, leading to a different N demand and a further necessary differentiation in timing of N application. Overall, reflectance measurements enabled to monitor and control N demand in broccoli and to adapt N fertilizer requirements during the growing season. By detailing this data to small areas within a field, through the application of spatial data, the data can be transformed into powerful management tools. This will enable growers to target their production and fertilizer input to market and quality related issues and to deliver broccoli with specific quality attributes.

Keywords: sensors, nitrogen, vegetables, fertilization, decision support

INTRODUCTION

Accurate prediction of nutrient requirements of plants during the cultivation period is necessary for efficient fertilizer use (Wood et al., 1992). Nitrogen (N) is the nutrient most often and most intensively applied to vegetable crops as fertilizer. Nitrogen also is the nutrient most likely to contaminate ground and surface waters. The nitrate form of nitrogen (NO_3) is especially prone to causing contamination when excessive amounts are applied to crops.

Knowledge of crop nitrogen demand is essential in predicting crop needs and, therefore, in developing reliable fertilizer recommendations for growers. Such recommendations are critical, for both economic and environmental reasons (Addiscot et al., 1991). The N demand of a crop is defined as the N uptake over a set period, which allows the maximum dry matter growth rate under a given set of environmental conditions (Grindlay, 1997). The conventional fertilization method of vegetables in the field provides high N amounts to ensure a constant N supply to the plant throughout the crop cycle. The conventional optimal N rate is selected as the one allowing just maximal yield at harvest. Since N demand is variable over time, each plant growth stage and also each cultivar may have a specific N rate at which its growth rate is the fastest. Consequently, the conventional optimal N rates may either underestimate the instantaneous N demand (N uptake rate allowing just maximum growth), at the stages where it is the highest, or overestimate it, at the stages where it is the lowest. This will lead either to yield and quality reduction, or to high N amounts left in the soil after harvest. Especially in this context, the fast and easy determination of vegetable N demand in order to properly estimate needed N fertilizer amounts gains in importance.

One strategy for pursuing profitable yields while avoiding negative environmental impacts is to only apply the amounts of nitrogen that will be used by the growing crop. This can be accomplished by using analytical techniques that monitor nitrogen levels and, thus, avoid insufficient or excessive nitrogen fertilizer applications. The ability to quickly and easily monitor the nutrient demand in crops and more specific in vegetables and to use that information to optimize N fertilizer inputs would directly contribute to improved crop quality and resource use efficiency. The current practice is to submit plant and soil samples to a laboratory for analysis, which can take several weeks or to rely on experience to determine the fertilizer level.

Many strategies have been developed in recent years to meet the challenge of adaption N-fertilizer levels during the growing period to crop demand. Strategies include the development of new sensors or tools to measure crop N status in order to refine in-season fertilizer N management, the development of new soil N tests to improve prediction of soil N supply, the development of new fertilizer N products with release patterns more closely matched to crop N uptake patterns, and the development of site-specific N management strategies. Studies of Graeff et al. (2008) have shown that passive sensor technologies, mounted on agricultural equipment, can not only be used to estimate N status in arable crops, but also in vegetable crops. Spectral information of the crop N status is gained by either passive or active systems tractors or by hand-held devices. Spectral data gathered with reflectometers or spectrophotometers can provide accurate and precise quantification of stress factors in plants (Nilsson and Johnsson, 1996; Riedell and Blackmer, 1999; Lowenberg-DeBoer, 2003). Spectral indices derived from reflectance data or the single use of reflectance data have shown to be indirectly related to the nitrogen status of crops (Dampney and Goodlass, 1997; Hoskinson et al., 1999, Al-Abbas et al, 1974; Adams et al., 2000; Masoni et al. 1996; Graeff et al., 2001].

High nutritional-value broccoli (*Brassica oleracea var. italica*) is an important vegetable containing high vitamin, chlorophyll and protein concentrations (Page et al., 2001). Broccoli heads compose of hundreds of immature florets arranged in whorls on a fleshy stem and each floret consists of an immature flower enclosed within chlorophyll-containing sepals (Page et al., 2001). Therefore broccoli is high in chlorophyll and the plants need large amounts of N for its photosynthetic activities. Adequate inputs of nutrients and especially nitrogen based on growth stage needs can promote plant N assimilation and partitioning within plants (Vagen, 2003; Li et al., 2006, 2008; Yoldas et al., 2008). Negative effects influencing broccoli growth and quality (e.g. stem rot, leaf scorch and bacterial soft rot) may be reduced when adequate N inputs are provided (Gallagher, 1966). Broccoli N concentrations can increase significantly by increasing N input rates (Vagen, 2003; Yoldas et al., 2008) and thus lower the overall quality if too much nitrate is available in marketable heads (Cardenas-Navarro et al., 1999).

Nitrogen uptake by broccoli typically ranges from 150 to 280 kg ha^{-1} (Doerge and Thompson, 1997, Stivers et al., 1993). Rates of N used by broccoli growers may be as high as 400 kg ha^{-1} (Stivers et al., 1993) whereof broccoli florets typically account for 10 to 45 % of the N taken-up. Broccoli is a rapidly-growing crop that takes up little N in its first 40 d of growth, and 90 % or more of its total N accumulation may occur during the final 30 to 50 d preceding harvest (Doerge and Thompson, 1997). Broccoli plants are highly responsive to N fertilizer inputs, and excessive N inputs can result in decreased quality like hollow stem (Stivers et al., 1993). Overall, adequate N amounts are highly important for a successful broccoli production. Nevertheless, broccoli cultivars highly differ in developmental rates, total biomass and thus also in yield potential, potentially necessitating the adoption of N application rates on a cultivar and growth stage specific basis. Plant sensors able to estimate the N demand of broccoli plants during the growing season in specific developmental stages e.g. head formation might enable an optimized way of adapting N fertilizer rates.

Hence, the aim of this specific study was to monitor nitrogen status in six different broccoli cultivars using reflectance measurements and to derive suitable N-fertilization strategies based on the sensor measurements.

MATERIAL AND METHODS

Field experiments

Field studies were conducted at the experimental station of horticulture (697 mm average annual precipitation; 8.8 °C mean annual temperature), of the

University of Hohenheim, Stuttgart, Germany. The first field trial consisted of six common broccoli cultivars ‘Parthenon’, ‘Marathon’, ‘Olympia’, ‘Ironman’, ‘Monopoly’, and ‘Monterey’ and four N fertilization treatments consisting of 0, 100, 200, and 400 kg N ha^{-1}. The total amount of nitrogen was split in two rates in the 400 kg treatment, broadcast and incorporated in all treatments by hand as KAS (13.5 % NH_4-N, 13.5 % NO_3-N, 12 % CaO). This field trial was used to derive a relationship between spectral properties of broccoli cultivars and their specific nitrogen demand, and to establish the necessary calibrations for the estimation of N fertilizer amounts.

In a second field trial the same cultivars were tested under three different N fertilization treatments consisting of a final amount of 0, 310 (farmers practice) kg N ha^{-1} and a cultivar specific N treatment calculated based on the estimated sensor values resulting in 250 kg N ha^{-1} (Marathon), 250 kg N ha^{-1} (Monterey), 210 kg N ha^{-1} (Parthenon), 210 kg N ha^{-1} (Olympia), 190 kg N ha^{-1} (Ironman), 190 kg N ha^{-1} (Monopoly). The total amount of nitrogen was applied in two rates around floret formation as KAS (13.5 % NH_4-N, 13.5 % NO_3-N, 12 % CaO) in the sensor treatment and as ENTEC 26 applied at setting in the farmers practice treatment.

Broccoli was planted in both trials beginning of July 07 at a rate of 4.5 plants per m². The trial set up was a randomized block design with four replications. Soil N_{min} content was determined in all plots at planting and after final harvest to calculate an N balance for each treatment. Broccoli plants were irrigated to ensure a non-limiting water supply throughout the main growing period. Soil nutrient status analyses were made at the beginning of vegetation period to avoid any other nutrient deficiencies in broccoli other than nitrogen. Plant protection measures were carried out as needed to control weeds and pests. Harvest of broccoli florets started beginning of September as soon as 50 % of the plants of a plot had reached a minimum marketable head size of ∅ 7 cm or tended to show further flower development. Two harvests were accomplished in a weekly interval. Florets were trimmed to market specifications for broccoli and graded for diameter, weight, discoloration, and hollow stem.

Reflectance measurements

Reflectance measurements tarted two weeks after planting and were carried out once a week on the youngest fully developed leaf of each plant until final harvest of broccoli florets. Images were taken with a digital, light-sensitive (ISO 200–2400; spectral sensitivity of 250-1300 nm), high-spatial resolution (5140*5140 pixel) imager (S1 PRO, Leica, Germany). Settings of the imager were chosen according to Graeff (2000). The imager provides an entirely digital and fully automatic process to produce highly accurate digital image data. Three superimposed image tracks are acquired simultaneously by three line sensors mounted in parallel on the instrument focal plane. The imager gives as output the values of trichromatic coordinates L*, a*, b* (CIE, 1986). The imager was used in conjunction with a constant light source (Reporter 21D MicroSun, 21W, Sachtler, Germany). The chosen light source was equipped with a 21W daylight discharge bulb (Sachtler, Germany; color temperature 5500 – 6000 K) which produces more light than normal 50 W tungsten luminaries. It has a luminous flux of 71 lumens per watt, whereas in contrast, the best tungsten bulbs produce only 30 lumens per watt. To ensure a constant light intensity over all measurements and sampling dates the light intensity was calibrated against known references as indicated by Graeff (2000).

Three plants per plot were used as a sub-sample of the whole plot for the measurements. Images were taken without removing the leaf from the plant. A leaf area of 4.5 cm² was scanned at a point about one-quarter of the way from the base to the tip. The leaf to be measured was laid on a black aluminum plate mounted 15-20 cm away from the optics (1.28/60 mm, LEICA, Germany) of the imager. The imager was oriented vertically and scanned the reflectance through the visible (380–780 nm) and NIR (750–1300 nm) wavelength ranges at given long pass filter intervals at a rate of 1 scan per 24 ms. Selected long-pass filters (Maier Photonics, Manchester, VT, USA), were active at wavelengths longer than 380 nm (400-2000 nm transm. avg. 90 %), 490 nm (500-2000 nm transm. avg. 90 %), 505 nm (500-2000 nm transm. avg. 90 %), 510 nm (520-2000 nm transm. avg. 90 %), 540 nm (550-2000 nm transm. avg. 90 %), and 600 nm (610-2000 nm transm. avg. 90 %), respectively. The long-pass filters had the following general specifications: thickness 3 mm, hard-oxide coating surface, quality 80/50 per MIL-O-13830A, coating quality 60/40 per MIL-O-13830A, and temperature limits - 50 to 100 °C.

For each plant, images were taken performed with the above-mentioned long-pass filters in conjunction with a LEICA Daylight Filter IRa E55 to cut all scans at 780 nm (wavelength ranges indicated with X_{780} nm). A second set of scans was taken without this daylight filter in order to scan in the near-infrared ranges, indicated with X_{1300} nm.

Digital image data were studied to select feature wavelengths, that is, the wavelengths at which contrasts in spectral responses between major object categories became distinct. Images were analyzed with ADOBE® Photoshop 5.0 (file type *.psd, 8-bit) in the L*a*b*-color system (CIE, 1986) by splitting the images into a* and b* parameters in different wavelength ranges. Value L* represents lightness; value a* represents the red/green axis; and value b* represents the yellow/blue axis. Color features were defined using spectral responses at these feature wavelengths in the form of a* and b* parameters. Observations of the spectra of the 11 filter classes revealed that, at certain wavelengths, the contrasts between major object categories were maximized. The reflectance calibrations defined by Graeff et al. (2001) and Graeff & Claupein (2003) were used as starting point to identify possible nitrogen limiting conditions.

Analyses

After taking the images, the measured plants were harvested and the fresh weight was determined at once. Plant samples were dried at 60 °C and total dry matter was determined. The scanned leaf was ground and analyzed for total N concentration according to Dumas (1962) by means of a Heraeus macro-N-analyzer (Hanau, Germany).

Statistical analysis

Analysis of variance (ANOVA) was carried out on all crop and reflectance data using the general procedures of the Tukey minimum significant difference (MSD) test at the 5 % significance level of the Statistical Analysis System (SAS) version 6.12. Regression analyses were performed to determine the association among the plant nitrogen concentration and spectral properties of the plants.

RESULTS AND DISCUSSION

Biomass development

Climatic conditions in 2007 were favorable for growth of broccoli with additional irrigation. Biomass development of the 6 investigated cultivars was slightly different, with some of the cultivars (Marathon, Olympia) developing earlier and faster and thus an overall higher biomass (Fig. 1). The different development rates also had an impact on overall N demand of the cultivar and ideal timing of N application and thus also timing of sensor measurement.

Depending on the different development rates of the tested cultivars, timing of sensor measurement has to be adapted to meet the N demand of cultivars in a more optimized way. Especially cv. Marathon and cv. Olympia seem to develop earlier and faster than the other tested cultivars, necessitating an earlier N fertilizer application to sustain leaf development. Timing of sensor measurements around two weeks before estimated floret formation was ideal for Marathon and Olympia having a huge biomass developed at that stage. Slower developing cultivars like ‘Ironman’ and ‘Monopoly’ might benefit from a later sensor measurement as N demand could be estimated more precisely. Further field trials have to take the different development rates of the cultivars into account to optimize the N fertilization based on sensor measurements.

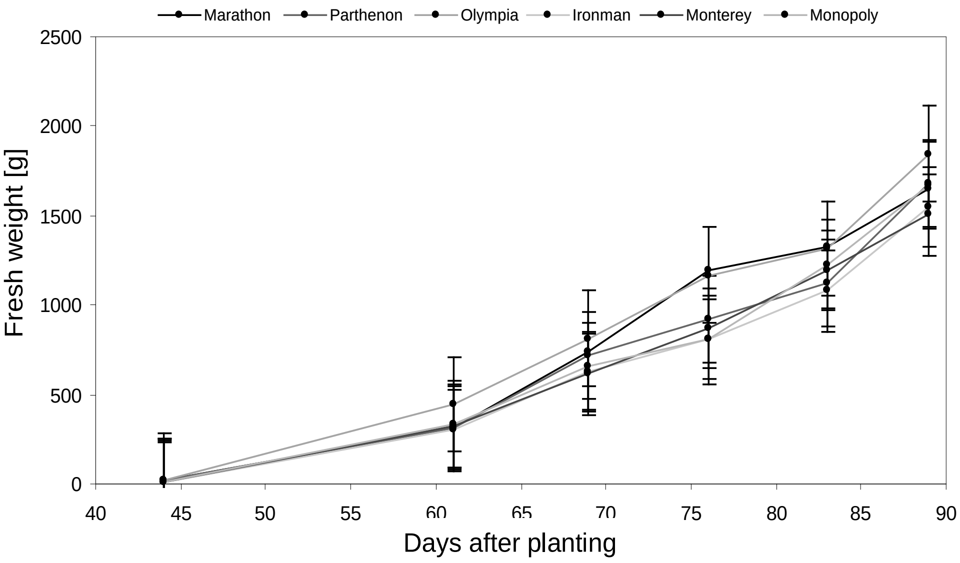

Fig. 1. Development of fresh weight [g] of the tested six broccoli cultivars.

Estimation of N demand based on reflectance measurements

Figure 2 indicates that the reflectance parameter b* increased for all tested cultivars significantly in the visible wavelength range 505_{780} nm with decreasing N concentrations in plant dry matter rates and thus decreasing N fertilization rates. This was true for all tested wavelength ranges in the visible spectra. Reflectance spectra of young unfolded leaves of the treatment 0 N kg ha^{-1} were significantly different from the reflectance spectra of 200 N kg ha^{-1} and 400 kg ha^{-1} leaves. Significant changes in determined reflectance parameters a* and b* revealed that, certain wavelengths especially in the visible spectra maximized the contrasts between a* and b* parameters and thus between N levels. Over all tested wavelength ranges, the visible wavelength ranges 505_{780} nm, 510_{780} nm, and 380_{780} nm seemed to be well suited for the identification of broccoli N status. Further, the results also indicated that due to genetic variation among tested cultivars and thus different development and N-uptake rates, the spectral signatures differed between the cultivars expressed as absolute values and the timing the N concentration decreased below a certain critical level.

The wavelength band in the visible range (380_{780} nm) seemed to be the most important wavelength band for the determination of nitrogen status. Reflectance in the visible region of the spectra is mainly influenced by pigmental changes. Gates et al. (1965) found that the characteristics of plant reflectance are functions of leaf geometry, morphology, physiology and biochemistry. We suppose that N status affected leaf pigments (mainly chlorophyll) of the measured leaves during the growing process and led to the determined reflectance changes.

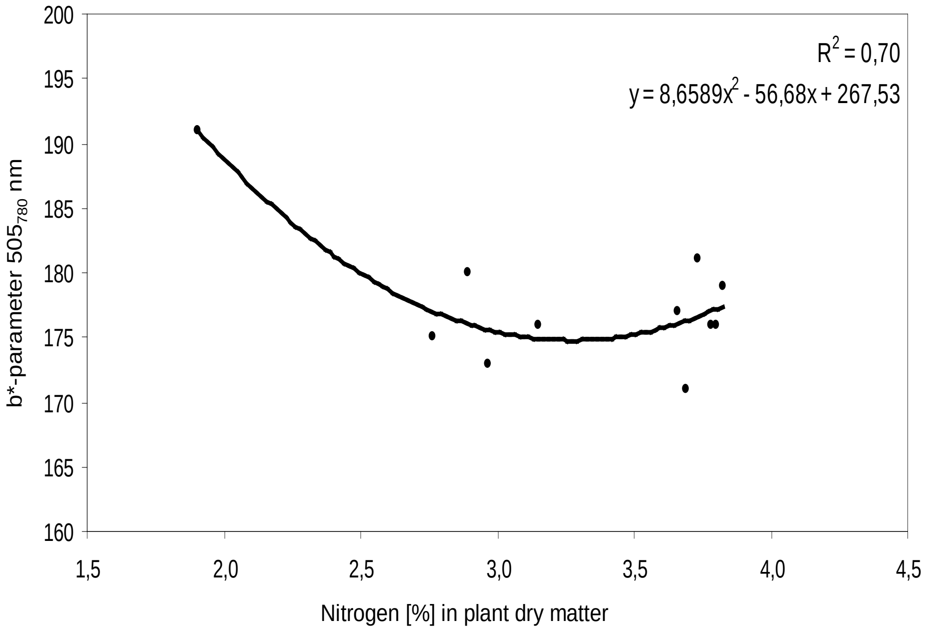

Fig. 2. Correlation of reflectance parameter b* and nitrogen concentration [%] in plant dry matter in the visible wavelength range 505_{780} nm indicated by a quadratic model (R^2= 0.70).

N fertilizer recommendations rates based on sensor measurements

Based on the spectral data, an N-fertilizer recommendation system was developed to optimize N application at the development stage shortly before floret formation. In a first step, the determined reflectance parameter b* was correlated with total N concentration in plant dry matter. Using the derived equations leaf N concentration could be calculated for the corresponding development stage (Zadoks 18). Based on this relationship the reflectance parameter b* was used as a basis for N fertilizer recommendations.

Based on this developed correlation, the relationship between optimum necessary N fertilizer rate and reflectance parameter b* was investigated in the wavelength ranges 505_{780}nm and 510_{780} nm (Fig. 3). This wavelength ranges were selected because identification of N deficiency was clearly possible for all tested cultivars. The correlation between optimum N rate and b* parameter resulted in cultivar specific correlations indicating that the necessary N rate could be determined by reflectance measurements.

However, in order to fully apply the principle of a N recommendation system, different aspects have to be considered. Measurement of reflectance which is inversely related to chlorophyll levels in plant leaves is known to be a predictor of N levels in crops (Benedict and Swindler, 1961). A number of factors such as genetics, growth stage, N form, weather, and data acquisition time all contribute to variations in chlorophyll measurements (Schepers et al., 1992) and have to be taken into account.

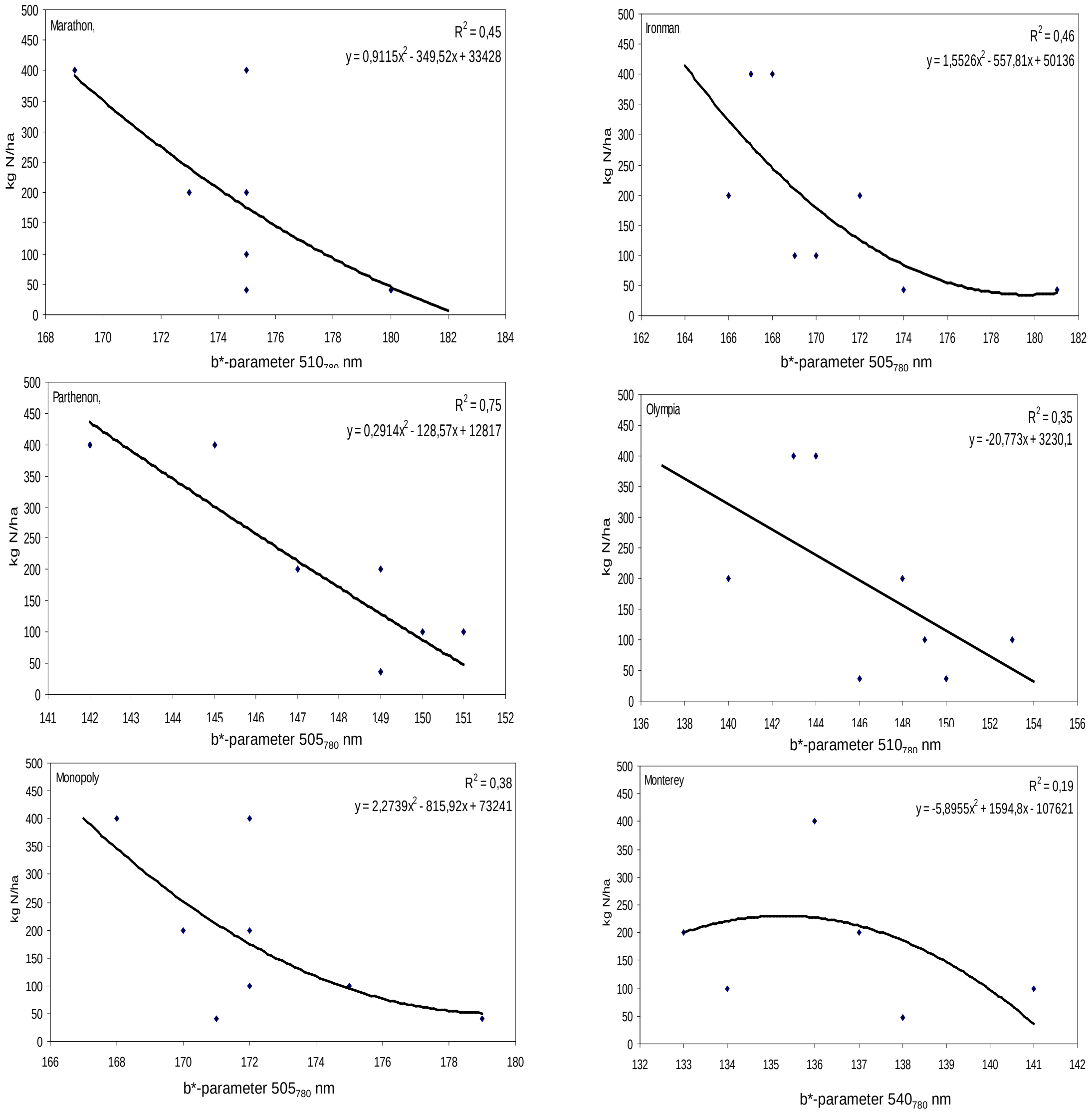

Fig. 3. Cultivar specific correlations between reflectance parameter b* and N demand expressed as N fertilizer rates in kg N ha^{-1}.

Validation of calculated N amounts

Determined regressions between spectral parameters and chemically determined nitrogen amounts were used to calculate the necessary N fertilizer amounts for the second N application rate in field trial 2 around floret formation. Reflectance measurements were taken shortly before floret formation and evaluated for changes in the b* parameter. Determined b* parameters replaced the variables in the equations of the calibration process and let to final calculated N fertilizer amounts. Determined N amounts were applied directly in the field.

The comparison of determined N rates by reflectance measurements with the standard application rate of farmers indicated that determined N rates were roughly 50-120 kg ha^{-1} lower than the standard application rate, while no significant changes were observed between yield and quality levels comparing the different strategies on a cultivar basis (Fig. 4). Hence, N fertilizer rates could be lowered when N demand of cultivars is estimated by fast non-destructive measurements during the growing period.

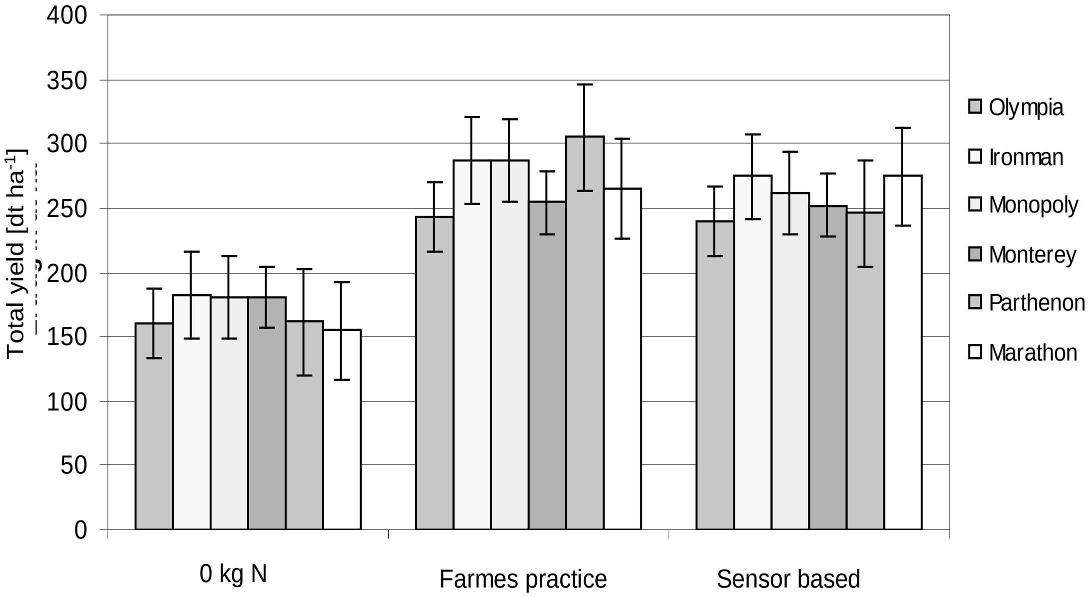

Fig. 4. Total yield [dt ha^{-1}] of all six tested broccoli cultivars in the validation trial.

Other researchers have also reported broccoli aboveground N uptake well in excess of 300 kg ha^{-1} (Zebarth et al., 1995). However, the pattern of N uptake, with low N uptake early in the season followed by a period of rapidly increasing uptake, illustrates the management challenge posed by broccoli production. An adequate supply of N is required all season. Pre-plant or early-season applications of N may be inefficiently used because of low plant N demand. N application around floret formation was fully used by the broccoli plants in our experiment, wherefore a split of nitrogen fertilizer amounts is highly recommended in broccoli production. Estimating the N demand of broccoli plants around floret formation by fast and easy spectral measurements, will help to improve yield and quality and contribute to the reduction of N left in the soil after harvest in intensive horticultural cropping systems.

CONCLUSION

The results of this study represent a simple approach using reflectance measurements to evaluate the nitrogen status of broccoli plants and to derive N fertilizer recommendations out of determined spectral values. The approach indicated to be an effective technique for estimating N fertilizer amounts for six different broccoli cultivars around floret formation in specific wavelength ranges. The spectral properties showed high correlations with chemically determined N concentrations and required less time and labor than current standard methods. Furthermore the study revealed that differences in seasonal development of tested cultivars necessitate multiple time frames for an in-season sensor measurement to precisely adapt fertilization treatments to N demand and biomass development of the cultivar. Future research opportunities to improve the efficiency of fertilizer N utilization will also have to include the development of practical methods to predict the magnitude of soil N mineralization and the development of affordable controlled-release fertilizer N products with improved N release characteristics. Evaluation will continue.

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