# Early Prediction of Soybean Yield from Canopy Reflectance Measurements

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## ABSTRACT

**Correlations between plant canopy reflectance and aboveground biomass can possibly be used for early prediction of crop yield. Field experiments were conducted in 1998 and 1999 on two soil types to assess whether measurements of canopy reflectance at given stages of development could be used to discriminate high from low potential yields among genotypes with known differences in potential grain yield and whether a consistent relationship between yield and canopy reflectance could be used for screening and predicting soybean [*Glycine max* (L.) Merr.] yield in a variety trial. A 3-by-42 factorial experiment, arranged in a randomized complete block design with three replications, was used on each soil type for both years. Three population densities (25, 50, and 75 seeds $m^{-2}$) represented low, optimum, and high levels. Forty-two historical varieties represented nearly six decades (1934–1992) of soybean yield improvement in Canada. Canopy reflectance was measured with a hand-held multispectral radiometer on three sampling dates (approximately R2, R4, and R5 stages) for each site. Grain yield at harvest was measured. Soybean grain yield was highly positively correlated with canopy reflectance, expressed as normalized difference vegetation index (NDVI), at all sampling dates. Regression analyses showed a positive relationship between NDVI and grain yield, with $R^2$ up to 0.80 ($P < 0.01$) and progressive improvement from R2 to R5 stages. Population density did not affect the yield–NDVI relationship at the development stages studied. Our data suggest that canopy reflectance measured nondestructively between R4 and R5 stages adequately discriminates high- from low-yielding genotypes and provides a reliable, fast, repeatable indicator for screening and ranking soybean genotypes based on the relationship between NDVI and grain yield ($R^2$ ranged from 0.44–0.80).**

THE ABILITY to accurately predict yield of field crops such as soybean or maize (*Zea mays* L.) allows producers, economic agencies, and buyers to make decisions with respect to crop management, pricing, and available markets. In breeding programs where a number of new lines are tested against check varieties, an early yet accurate assessment of yield potential can be an important tool for identifying promising genotypes. Clevers (1997) reported that many biotic and abiotic traits are associated with grain yields, including (i) soil characteristics (particle size distribution, bulk density, organic matter, nutrient levels), (ii) agronomic inputs (fertilizers and soil amendments), (iii) field-scale management (tillage, drainage, and irrigation), and (iv) meteorological effects. However, while simulation models can predict yield relatively accurately on a large scale under ideal conditions, they are much less accurate when disease, invertebrate pests, or weeds influence yield or for small research plots (i.e., 5–8 $m^2$).

Remote-sensing techniques, in particular, multispectral visible and infrared (IR) reflectance, can provide an instantaneous, nondestructive, and quantitative assessment of the crop's ability to intercept radiation and photosynthesize (Ma et al., 1996). The input of reflectance into yield production models has been shown to improve yield estimates (Clevers et al., 1994; Clevers, 1997). Colwell (1956) was the first to use aerial IR photographs to monitor plant disease in the field. The amount of reflectance in the near IR (NIR) range ($\lambda$ = 700–1300 nm) is determined by the optical properties of the leaf tissues: their cellular structure and the air–cell wall–protoplasm–chloroplast interfaces (Kumar and Silva, 1973). These anatomical characteristics are affected in turn by environmental factors such as soil water and/or nutrient status (Gausman et al., 1969; Thomas et al., 1971; Blackmer et al., 1994), soil salinity (Gausman and Cardenas, 1968), and leaf age (Gausman et al., 1970). Reflectance in the visible red (R) range ($\lambda$ = 550–675 nm) has been used to estimate leaf chlorophyll and carotenoid (Benedict and Swidler, 1961; Thomas and Oerther, 1972; Filella et al., 1995) levels and, by extension, the photosynthetic capability of the crop.

The use of NIR or R spectral bands singly does not account for seasonal sun-angle differences and can be affected by atmospheric attenuation in the case of satellite-based (vs. ground-based) measurements. To avoid these problems, a number of indices with reflectance near R and NIR wavelengths have been derived and tested for their ability to accurately predict total wet and/or dry crop biomass, leaf water content, and leaf chlorophyll (Tucker, 1979). Among the best was the simple NIR/R ratio, first used by Rouse et al. (1973), and a weighted difference (NIR − R)/(NIR + R), also termed the normalized difference vegetation index (NDVI).

A number of physical and plant anatomical factors can affect reflectance measurements. When the crop does not cover the entire soil surface, reflectance measured from a certain height above ground level will represent the reflectance of both the canopy and the soil surface, rather than just the crop itself. Colwell (1974) showed that for a 37% soil cover, overall reflectance was close to threefold greater on light-colored soils than on darker soils. The area scanned must be consistently representative of the canopy coverage. Daughtry et al. (1982) showed that the coefficient of variation of reflectance measurements over a soybean crop presenting 71% soil coverage decreased exponentially as sensor height increased. They suggested that the sensor's field of view at the soil level should be several times the row spacing.

A number of studies have related the reflectance of various major field crops to ground cover or leaf area

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Published in Agron. J. 93:1227–1234 (2001).

**Abbreviations:** DOY, day of year; G, green; IR, infrared; LAI, leaf area index; MG, maturity group; NDVI, normalized difference vegetation index; NIR, near infrared; R, red.

index (LAI) of barley (*Hordeum vulgare* L.) (Peñuelas et al., 1997), cotton (*Gossypium hirsutum* L.) (Wiegand and Richardson, 1990), maize (Ma et al., 1996), potato (*Solanum tuberosum* L.) (Bouman et al., 1992), soybean (Holben et al., 1980), sugarbeet (*Beta vulgaris* L.) (Clevers, 1997), and wheat (*Triticum aestivum* L.) (Mahey et al., 1991; Stone et al., 1996). Similar relationships have been developed for leaf chlorophyll concentration (Al-Abbas et al., 1974; Peñuelas et al., 1994; Filella et al., 1995).

Preanthesis NDVI measurements could be used to predict yield or to estimate appropriate midseason fertilizer amendments. While the relationship between reflectance and yield has been extensively studied in wheat and maize, to our knowledge, none of the published studies have included soybean. Therefore, the objectives of this study were to (i) determine whether measured canopy light reflectance can be used to predictively discriminate high from low yield among a large number of historical varieties with known differences in yield potential (Voldeng et al., 1997) and (ii) find the optimum development stage at which yield can be predicted from canopy reflectance measurements. In addition, factors such as soil type and planting density were also examined to determine if they influence canopy reflectance. The overall objective was to determine if canopy reflectance measurements could be used as an accurate, fast, repeatable indicator for screening and ranking soybean genotypes for potential yield.

## MATERIALS AND METHODS

### Experimental Sites and Designs

This study was superimposed on an experiment characterizing physiological traits associated with yield improvements among 42 historical soybean cultivars grown at three population densities at two sites on the Central Experimental Farm at Ottawa, Canada (45°23′ N, 75°43′ W) for 2 yr. In 1998, experiments were conducted on a well-drained sandy loam soil (coarse-loamy, mixed, mesic, Endoaquolls) of the Granby association and an imperfectly drained clay loam (Typic Endoaquolls) of North Gower type, both in the Orthic Humic Gleysol subgroup in Canadian soil classification. In 1999, the experimental sites were a poorly drained North Gower clayey loam Orthic Humic Gleysol (fine-loamy, mixed, mesic, Endoaquolls) and a well-drained Uplands sandy loam Orthic Humo-Ferric Podzol (Haplorthods). In each case, soil samples from four locations within each block (replication) were taken at the depth of 30 cm before planting and tested for available P, K, and S. Sufficient nutrients were applied according to recommendations based on the soil test results.

A 3-by-42 factorial experiment, arranged in a randomized complete block design with three replications, was used at each site-year. Three population densities (25, 50, and 75 seeds $m^{-2}$) represented low, optimum, and high seeding rates relative to current recommendations. The final stands were approximately 20, 40, and 60 plants $m^{-2}$. Of the 42 cultivars representing 58 years (1934–1992) of soybean yield improvement in Canada, 11 were from maturity group (MG) 0, 30 from MG 00, and 1 from MG 000. Detailed genetic background and some agronomic characteristics of these cultivars can be found in Voldeng et al. (1997).

Plot size was 1.6 by 5 m, consisting of four rows spaced 0.4 m apart. Soybean seeds inoculated with *Bradyrhizobium japonicum* at recommended rates were seeded on 21 and 22 May 1998 and 17 and 20 May 1999. Weeds were controlled by chemical spray. In 1998, a tank mix of Lorox [3-(3,4-dichlorophenyl)-1-methoxy-1-methylurea] at 2 kg $ha^{-1}$ and Dual II [2-chloro-6′-ethyl-*N*-(2-methoxy-1-methylethyl)acet-*o*-toluidide] at 2 L $ha^{-1}$ was applied at both sites on 27 May, and a second application of Excel Super {(*R*)-2-[4-(6-chlorobenzoxazol-2-yl-oxy)phenoxy]propionic acid} at 0.67 L $ha^{-1}$, Basagran Forte [3-isopropyl-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide] at 2 L $ha^{-1}$, and Pinnacle [3-(4-methoxy-6-methyl-1,3,5-triazin-2-yl-carbamoylsulfamoyl)thiophene-2-carboxylic acid] at 8 g $ha^{-1}$ was used on the clay loam site on 24 June. In 1999, both fields were sprayed with a tank mix of Excel Super at 0.67 L $ha^{-1}$, Basagran Forte at 2 L $ha^{-1}$, and Pinnacle at 8 g $ha^{-1}$ on 10 June and again with Assure II {(*R*)-2-[4-(6-chloroquinoxalin-2-yl-oxy)phenoxy]propionic acid} at 1.5 L $ha^{-1}$ on 24 June. Plots were combine-harvested, the seed air-dried, and grain yield reported at 130 g $kg^{-1}$ moisture.

### Reflectance Measurements

Canopy reflectance measurements were made with a hand-held multispectral radiometer (MSR16, CropScan, Rochester, MN), which records incoming radiation and light reflectance from the canopy in eight pass bands (460, 507, 559, 613, 661, 706, 760, and 813 nm). Each band has a half peak band of approximately 5 to 15 nm, depending on the specific pass band. The sensing method used is band-limited optical interference filters and photodiodes. The band-limited optical filters only pass wavelengths of irradiance in the pass-band range to the active surface of the detecting photodiode. The photodiode output current is in direct proportion to the number of photons striking the photodiode. This electrical current was converted to a voltage and amplified by the circuitry in the radiometer. The Data Logger Controller measured and logged these sensor millivolt readings. Data of percent reflectance at each pass band were processed subsequently by a computer program using the calibration and correction constants through a minicomputer connected to the sensor. The sensor head was mounted on an adjustable pole. The sensor receptor, facing the center of the plot (between Rows 2 and 3), was parallel to the ground surface, with a view of 0.8- to 1.0-m diam. At each sampling, duplicate measurements were taken within each plot and averaged. Data collection started when the majority of the MG 00 genotypes were at the R2 stage (Fehr and Caviness, 1977) and was repeated two more times [190, 213, and 229 d of year (DOY) for the sand site and 191, 217, and 231 DOY for the loam site in 1998 and 196, 208, and 228 DOY for the loam site and 197, 209, and 230 DOY for the clay site in 1999]. These dates corresponded to R2, R4, and R5 ±10 d of soybean development stages for all genotypes in the experiment. At each sampling date, reflectance measurements for each site were taken on a sunny day for a total of 6 h. Optimum condition is assumed when canopy reflectance is measured within 2 to 3 h of solar noon. Data collection in the current study may have not occurred under ideal conditions but followed the instrument's recommendations (MSR16, CropScan, Rochester, MN). In all cases, variable weather conditions (clouds and wind) were avoided during data collection. For a typical screening or regional variety performance test, it takes only 1 to 2 h for an experiment with 100 plots or less. Sensor readings from pass bands near 613 and 813 nm were used to derive NDVI (Ma et al., 1996) as follows:

$$\mathrm{NDVI} = (\mathrm{IR}_{813} - \mathrm{R}_{613})/(\mathrm{IR}_{813} + \mathrm{R}_{613}) \qquad [1]$$

where IR and R denote percent infrared and red reflectance, respectively, and the subindices denote the wavelength (nm).

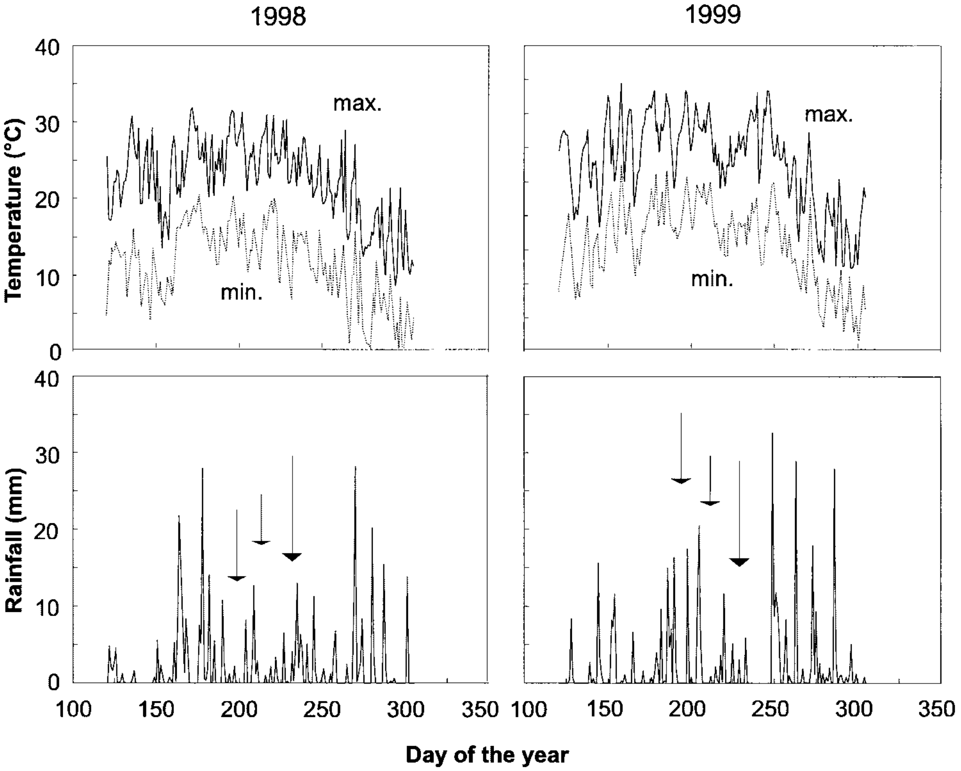

**Fig. 1. Daily minimum and maximum temperatures and total rainfall during 1998 and 1999 growing seasons. Arrows indicate the dates of canopy reflectance measurements.**

### Data Analysis

Pearson's simple linear correlation coefficients between yield and reflectance at individual wavelength bands or indices were calculated for each site-year and sampling date. Partial correlation coefficients were also obtained using the MANOVA options of SAS (SAS Inst., 1990). Regression was then performed to determine the relationship between reflectance and grain yield when both the simple and partial correlation coefficients for a data set were significant. For the regression model, a linear model ($GY = a + bx$) was first fit to each data set, and then several curvilinear models were also tested. Of the models fitted, power regression was chosen because it depicted the shape better with larger $R^2$ values than the linear and other curvilinear models. The power function regression model of three parameters was as follows:

$$GY = a + b(\text{NDVI})^c \quad [2]$$

where GY is grain yield and $a$, $b$, and $c$ are regression coefficients. The analysis was performed with the nonlinear estimation of STATISTICA, version 6 (StatSoft, 1995). The Quasi-Newton estimation method was used with the start value of 0.1 and initial step size of 0.5 for all parameters. In addition, yield as a power function of NDVI was also conducted on data arbitrarily subclassed on the basis of MG, grain yield (low vs. high), days to maturity (early vs. late), plant height (short vs. tall), oil content (low vs. high), and all classes combined in an attempt to assess whether differences existed in NDVI and yield relationships between soybean cultivar groups.

## RESULTS AND DISCUSSION

### Weather Patterns

Mean daily maximum and minimum temperatures over the 1998 growing season (DOY 121–305) were 1.4 and 2.1°C, respectively, above the long-term monthly mean (1961–1999). Mean daily maximum and minimum temperatures over the 1999 growing season (DOY 121–305) were 1.9 and 2.0°C, respectively, above the long-term mean. While temperature followed a roughly similar pattern in both years, the amplitude of temperature variation from day to day was greater in 1999 than in 1998 (Fig. 1). Seasonal total precipitation was 402 mm in 1998 and 415 mm in 1999, representing 69 and 71%, respectively, of the 39-yr mean.

The accumulated rainfall in the week before first planting (DOY 140) was similar (<5 mm) in both years; however, the rainfall between the start and end of seeding consisted of one 5-mm event (DOY 149) in 1998 compared with a >15-mm event in 1999. This and the generally drier conditions before planting in 1999 (data not shown) would have altered both the time and rate of emergence among the different cultivars, resulting in a different pattern of development among cultivars at the first dates (DOY 190 and 191 in 1998 and DOY 196 and 197 in 1999) of reflectance measurement (approximately R2). As one of the goals of this work was to use reflectance measurements to assess the yield potential of cultivars and/or lines during breeding trials, such a variation in growth patterns is useful for assessing if variety differences in yield can be predicted under typical breeding trial conditions.

### Choice of Reflectance Indices

Both simple and partial correlation analyses showed that soybean grain yields were negatively correlated ($P <$

**Table 1. Coefficients of determination ($R^2$) of soybean grain yield as a power function of various reflectance parameters for 2 yr and two soil types each year. Analysis was based on data averaged across densities and blocks for the final sampling dates (approximately R5 stage) in 1998 and 1999.**

| | 1998 | | 1999 | |
|---|---|---|---|---|
| Wavelength (or index)† | Granby sand loam | North Gower clay loam | North Gower clay loam | Uplands sandy loam |
| R | 0.80 | 0.64 | 0.70 | 0.39 |
| IR | 0.60 | 0.50 | 0.59 | 0.09 |
| G | 0.80 | 0.66 | 0.66 | 0.40 |
| IR/R | 0.81 | 0.69 | 0.74 | 0.44 |
| $(IR/R)^{0.5}$ | 0.81 | 0.69 | 0.74 | 0.44 |
| IR − R | 0.69 | 0.59 | 0.66 | 0.23 |
| IR + R | 0.39 | 0.34 | 0.44 | 0.01 |
| NDVI | 0.80 | 0.65 | 0.70 | 0.45 |
| 1/NDVI | 0.80 | 0.65 | 0.71 | 0.45 |
| $(NDVI + 0.5)^{0.5}$ | 0.81 | 0.69 | 0.74 | 0.45 |
| NDVI2 | 0.77 | 0.62 | 0.72 | 0.39 |
| NDVI3 | 0.74 | 0.65 | 0.74 | 0.45 |
| NDVI4 | 0.77 | 0.61 | 0.72 | 0.40 |
| G/R | 0.30 | 0.13 | 0.59 | 0.17 |
| $(G/R)^{0.5}$ | 0.30 | 0.14 | 0.59 | 0.17 |
| G − R | 0.56 | 0.65 | 0.15 | 0.27 |
| G + R | 0.81 | 0.57 | 0.70 | 0.40 |
| NDVIG | 0.33 | 0.13 | 0.55 | 0.18 |
| 1/NDVIG | 0.33 | 0.13 | 0.59 | 0.17 |
| $(NDVIG + 0.5)^{0.5}$ | 0.31 | 0.14 | 0.59 | 0.18 |

† R, red (% reflectance at 613 nm); IR, infrared (% reflectance at 813 nm); G, green (% reflectance at 559 nm); NDVI, normalized difference vegetation index $[(IR_{813} - R_{613})/(IR_{813} + R_{613})]$; NDVI2 = $(IR_{813} - R_{660})/(IR_{813} + R_{660})$; NDVI3 = $(IR_{760} - R_{613})/(IR_{760} + R_{613})$; NDVI4 = $(IR_{760} - R_{660})/(IR_{760} + R_{660})$; NDVIG = $(G_{559} - R_{613})/(G_{559} + R_{613})$.

0.01) with canopy reflectance at the 500- to 650-nm wavelengths ($r = -0.70$ to $-0.90$) but positively associated with reflectance near 700- to 800-nm wavelengths ($r = 0.50$–$0.80$). There was a clear trend for the correlation between yield and reflectance to be greater at the late sampling dates (R4 and R5) than at the early sampling dates (R2). The $r$ values for the correlation between yield and NDVI were among the largest in magnitude and positive. Therefore, it warranted a further quantitative regression analysis.

Our data analyses showed that a power regression of yield as a function of canopy reflectance, expressed as NDVI ($GY = a + b\text{NDVI}^c$), was better than linear ($GY = a + b\text{NDVI}$) or exponential ($GY = a + be^{\text{NDVI}}$) functions (data not shown), particularly for the late sampling date (R5). Similarly, Wanjura and Hatfield (1987) reported a larger $R^2$ value for soybean biomass as a power function of NDVI. Table 1 presents the coefficients of determination for a power regression of various reflectance parameters against soybean grain yield for each soil type in both years. Across soil types, the largest $R^2$ values were obtained for IR/R, $(IR/R)^{0.5}$, and $(NDVI + 0.5)^{0.5}$, ranging from 0.44 to 0.81, with NDVI showing a greater similarity of $R^2$ values (0.45–0.80) for individual site-year. Although individual $R^2$ values for reflectance near 559 nm [green (G)] and 613 nm (R) were high, the other indices involving G and R reflectance showed much lower $R^2$ (0.13–0.55 for NDVIG; see Table 1). The use of different R and IR wavelengths in the NDVI calculation NDVI2 − NDVI4 (parameters defined in Table 1) did not improve the $R^2$ over that obtained for NDVI. Tucker (1979) found similarly high $R^2$ (0.55–0.92) for IR/R, $(IR/R)^{0.5}$, NDVI, and $(NDVI + 0.5)^{0.5}$ for blue grama grass [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths] biomass and chlorophyll content as well as for IR and IR − R. However, these latter parameters were not normalized and were susceptible to illumination changes. Therefore, NDVI was chosen as the parameter with which to investigate the reflectance–yield relationship in soybean given its common use and the only minor improvement in $R^2$ obtained by the $(NDVI + 0.5)^{0.5}$ transformation.

## Effect of Genotype Characteristics

The influence of soybean crop characteristics on the NDVI–yield relationship was investigated for the cultivars studied for which detailed characteristics were available from another study (Voldeng et al., 1997). The $R^2$ values obtained for the yield–NDVI relationship of two soils × three sampling dates (averaged across block and density) are presented in Table 2.

With the exception of the first sampling day (DOY 190) in 1998 for the sandy soil, early mature cultivars (MG 00 and MG 000) showed a larger $R^2$ than the MG 0 cultivars or all maturity groups combined, i.e., early cultivars showed a better yield–NDVI relationship than the later (0 group) genotypes or all cultivars combined (Table 2). This trend was confirmed for all soil × sampling date combinations in terms of splitting the cultivars based on measured days to maturity. For both MG and measured days to maturity, $R^2$ improved with progressive sampling dates, indicating that canopy reflectance measured at a later development stage (approximately R5) was better correlated with yield than at earlier stages.

Voldeng et al. (1997) reported that the yearly rate of yield improvement for short-season soybean was significantly greater from 1976 onward than before 1976. Splitting the cultivars based on their year of release (before 1976 vs. 1976 or later) showed no consistent effect on $R^2$ values (data not shown). However, lower yielding cultivars (2250–3100 kg ha$^{-1}$) showed larger $R^2$ values

**Table 2. Coefficients of determination ($R^2$) for normalized difference vegetation index (NDVI)–yield relationship among cultivars subclassed on the basis of maturity group (MG), grain yield, days to maturity, plant height, oil content, and all classes combined. Each group is about half of entries (42 varieties). Data are averaged across block and densities for 1998.**

| Soil | Sample date (DOY)† | MG‡ |  | Grain yield§ |  | Days to maturity¶ |  | Plant height# |  | Oil content†† |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | All data |
| Sand | 190 | 0.46 | 0.13 | 0.13 | 0.06 | 0.20 | 0.10 | 0.16 | 0.41 | 0.41 | 0.14 | 0.37 |
|  | 213 | 0.47 | 0.50 | 0.50 | 0.33 | 0.43 | 0.31 | 0.56 | 0.40 | 0.40 | 0.40 | 0.70 |
|  | 229 | 0.43 | 0.85 | 0.84 | 0.61 | 0.88 | 0.48 | 0.90 | 0.50 | 0.50 | 0.67 | 0.80 |
| Loam | 191 | 0.01 | 0.36 | 0.30 | 0.10 | 0.20 | 0.07 | 0.40 | 0.13 | 0.13 | 0.40 | 0.33 |
|  | 217 | 0.31 | 0.63 | 0.59 | 0.20 | 0.64 | 0.28 | 0.80 | 0.09 | 0.09 | 0.60 | 0.53 |
|  | 231 | 0.20 | 0.78 | 0.78 | 0.29 | 0.64 | 0.22 | 0.74 | 0.46 | 0.46 | 0.82 | 0.65 |

† DOY, day of year.
‡ 1 = 0; 2 = 00 and 000.
§ 1 = 2250 − 3100 kg $ha^{-1}$; 2 = 3101 − 3850 kg $ha^{-1}$.
¶ 1 = 101–117 d; 2 = 118–129 d.
# 1 = 0.68–0.81 m; 2 = 0.81–0.98 m.
†† 1 = 180–198 g $kg^{-1}$; 2 = 199–213 g $kg^{-1}$.

than higher yielding cultivars (3101–3850 kg $ha^{-1}$), or all cultivars, for all soil × sampling date comparisons. The better association between yield and canopy reflectance in the low- than high-yielding cultivars was probably related to the fact that older cultivars had greater LAIs than newer ones (Morrison et al., 1999). We hypothesize that the narrow ranges of NDVI for the high-yielding varieties associated with high leaf area densities made it difficult to differentiate among them. Similarly, if $R^2$ values were compared on the basis of the actual measured yield within each year, conditions (i.e., soil type) leading to lower yields showed larger $R^2$ values than conditions leading to higher yields. For example, mean yields for all cultivars for the sandy and loam soils in 1998 were 2060 and 2560 kg $ha^{-1}$, respectively, while $R^2$ values were 0.80 and 0.65. In 1999, yields on the clay and loam soils were 2990 and 3060 kg $ha^{-1}$, respectively, while $R^2$ values were 0.70 and 0.45 (Table 1). This relationship held for all of the reflectance parameters presented in Table 1, except G/R, which showed an opposite trend. This was probably due to the fact that reflectance at G and R is negatively corrected to leaf color (greenness), with no relation to leaf area density (Ma et al., 1996). Table 2 (as well as Tables 3 and 4, discussed below) showed that the $R^2$ values were consistently greater for the lower yielding soil each year. These data indicate that measurements of canopy reflectance discriminated high from low potential yields of soybean varieties and that it is possible to rank genotypes based on their potential yields under specific conditions.

With the exception of the 190 DOY sampling in 1998 on sandy soil, $R^2$ was greater for comparing short (0.68–0.81 m) vs. tall (0.81–0.98 m) cultivars and high-oil (199–213 g $kg^{-1}$) vs. low-oil (180–198 g $kg^{-1}$) content genotypes (Table 2). Whether the difference in these parameters reflect an effect of the parameter itself or its close correlation to yield or MG is not clear, but it has been found that genetic differences in agronomic traits and grain yields are more evident under low fertility (severe stress) than high fertility (Ma and Dwyer, 1998). The different relationships between short and tall and between high- and low-oil groups at the DOY 190 sampling were probably due to the fact that differences in these traits had not developed at the time of sampling. Alternately, it has been noted (Morrison et al., 2000) that cultivars developed before 1976 (low yield and low-oil content groups) had larger decrease in LAI and larger increase in seed oil content with year of cultivar release than

**Table 3. Statistics of power regression functions (GY = $a$ + $b$NDVI$^c$; see Eq. [2]) in 1998 and 1999. Each equation is derived from the 42 varieties tested. Data are averaged across blocks and plant population densities.**

| Year | Sampling date (DOY)† | Parameter | Estimate | SDErr‡ | $R^2$ |
|---|---|---|---|---|---|
|  |  | Sand soil |  |  |  |
| 1998 | 190 | *a* | 1 689.24 | 272.16 | 0.29 |
|  |  | *b* | 71 927.30 | 242 384.00 |  |
|  |  | *c* | 16.17 | 12.67 |  |
|  | 213 | *a* | 292.52 | 2 003.46 | 0.59 |
|  |  | *b* | 7 018.46 | 3 691.22 |  |
|  |  | *c* | 7.29 | 8.89 |  |
|  | 229 | *a* | 1 349.47 | 151.09 | 0.80 |
|  |  | *b* | 3 158.08 | 850.95 |  |
|  |  | *c* | 6.30 | 2.13 |  |
|  |  | Loam soil |  |  |  |
|  | 191 | *a* | 465.33 | 3 073.10 | 0.28 |
|  |  | *b* | 4 578.72 | 1 235.62 |  |
|  |  | *c* | 3.69 | 6.70 |  |
|  | 217 | *a* | −5 135.27 | 54 348.30 | 0.50 |
|  |  | *b* | 11 735.00 | 47 125.40 |  |
|  |  | *c* | 3.40 | 25.38 |  |
|  | 231 | *a* | 1 475.40 | 420.67 | 0.69 |
|  |  | *b* | 5 494.66 | 2 507.53 |  |
|  |  | *c* | 8.78 | 4.68 |  |
|  |  | Clay soil |  |  |  |
| 1999 | 196 | *a* | 1 236.96 | 3 139.94 | 0.32 |
|  |  | *b* | 5 653.71 | 3 248.79 |  |
|  |  | *c* | 7.53 | 15.34 |  |
|  | 208 | *a* | −2 197.78 | 9 572.09 | 0.53 |
|  |  | *b* | 1 337.70 | 1 665.81 |  |
|  |  | *c* | 11.12 | 22.03 |  |
|  | 228 | *a* | 833.01 | 917.46 | 0.74 |
|  |  | *b* | 4 324.91 | 465.03 |  |
|  |  | *c* | 3.64 | 2.02 |  |
|  |  | Loam soil |  |  |  |
|  | 197 | *a* | 699.27 | 3 700.78 | 0.49 |
|  |  | *b* | 5 486.06 | 1 188.69 |  |
|  |  | *c* | 7.09 | 12.38 |  |
|  | 209 | *a* | 2 033.25 | 11 577.70 | 0.40 |
|  |  | *b* | 3 100.27 | 5 485.85 |  |
|  |  | *c* | 14.02 | 166.12 |  |
|  | 230 | *a* | 2 099.63 | 648.93 | 0.44 |
|  |  | *b* | 4 272.48 | 2 374.24 |  |
|  |  | *c* | 10.28 | 8.48 |  |

† DOY, day of year.
‡ SDErr, standard error of estimates.

**Table 4. Statistics of power regression functions ($GY = a + b\text{NDVI}^c$; see Eq. [2]) in 1998 and 1999. Each equation is derived from the 42 varieties tested. Data are averaged across blocks and sampling dates.**

| Year | Population (seeds m$^{-2}$) | Parameter | Estimate | SDErr† | $R^2$ |
|---|---|---|---|---|---|
| 1998 | | Granby sand loam | | | |
| | 25 | a | 1 204.69 | 525.33 | 0.45 |
| | | b | 5 148.79 | 5 847.32 | |
| | | c | 6.76 | 6.50 | |
| | 50 | a | 1 955.88 | 151.03 | 0.38 |
| | | b | 27 519.80 | 48 123.10 | |
| | | c | 23.07 | 11.59 | |
| | 75 | a | 1 219.65 | 1 240.40 | 0.43 |
| | | b | 2 681.45 | 909.73 | |
| | | c | 4.45 | 6.95 | |
| | | North Gower clay loam | | | |
| | 25 | a | 476.49 | 10 459.60 | 0.33 |
| | | b | 3 814.55 | 7 520.82 | |
| | | c | 3.31 | 17.23 | |
| | 50 | a | 1 998.82 | 133.46 | 0.32 |
| | | b | 30 067.4 | 82 494.4 | |
| | | c | 23.74 | 16.69 | |
| | 75 | a | 2 424.58 | 164.95 | 0.37 |
| | | b | 79 673.40 | 242 620.0 | |
| | | c | 35.18 | 22.80 | |
| 1999 | | North Gower clay loam | | | |
| | 25 | a | −814.78 | 1 734.06 | 0.80 |
| | | b | 6 985.68 | 876.41 | |
| | | c | 4.54 | 2.67 | |
| | 50 | a | 1 381.84 | 1 149.35 | 0.59 |
| | | b | 4 519.69 | 1 809.39 | |
| | | c | 10.10 | 10.43 | |
| | 75 | a | 1 196.49 | 1 433.01 | 0.62 |
| | | b | 6 421.81 | 2 233.54 | |
| | | c | 8.80 | 8.07 | |
| | | Uplands sandy loam | | | |
| | 25 | a | 2 400.11 | 242.32 | 0.56 |
| | | b | 29 347.00 | 34 890.90 | |
| | | c | 33.94 | 13.93 | |
| | 50 | a | −4 242.41 | 24 260.90 | 0.59 |
| | | b | 9 647.69 | 22 915.50 | |
| | | c | 1.84 | 6.39 | |
| | 75 | a | 2 236.92 | 1 361.98 | 0.37 |
| | | b | 6 418.65 | 8 202.29 | |
| | | c | 16.45 | 23.67 | |

† SDErr, standard error of estimates.

those developed afterwards. These inherent cultivar morphological and physiological differences may have influenced the yield–NDVI relationship differently.

## Influence of Sampling Dates

The regression equation parameters and $R^2$ values were generated for all soil × sampling date combinations for both 1998 and 1999 (Table 3). Soybean varieties in this short growing-season region are indeterminate, and yield potential is set at the later stages. As a result, $R^2$ values for the yield–NDVI relationship were increased with later sampling dates on almost all occasions. Mahey et al. (1991) demonstrated that sampling dates had a significant impact on the yield–NDVI relationship in wheat, with the correlation coefficients between NDVI and yield becoming larger after flowering than at booting. However, the relationship broke down during senescence. Stone et al. (1996), also working with wheat, found no such differences in the $R^2$ for 1/NDVI vs. yield among Feekes Development Stages 4 through 6. The improvement in $R^2$ values between yield and NDVI in this study was similar to that observed for maize by Ma et al. (1996) where measurements were taken only within a relatively short period before, during, and after flowering but not extending to near maturity like those of Mahey et al. (1991).

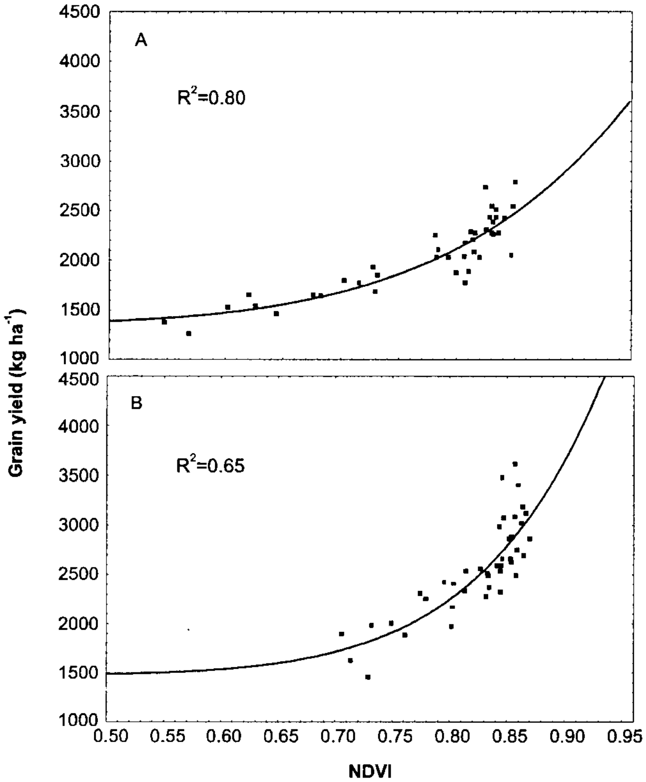

**Fig. 2. Grain yield of soybean cultivars as a power function of canopy reflectance expressed as normalized difference vegetation index (NDVI), measured at R5 stage in 1998 on (A) Granby sand loam and (B) North Gower clay loam. Data points are the means of 18 measurements (3 blocks × 3 densities × 2 subsamples).**

In general, the yield–NDVI relationship was linear (data not shown) at the first two sampling dates (R2 to R4), but fairly clearly a power relationship was required to describe the relationship at the third sampling date (R5) (Fig. 2 and 3). Changes in equation parameters across year and site indicate that caution must be taken when estimating grain yield under specific conditions. The degree of scattering, especially in the loam site of 1999 (Fig. 3B), was probably due to several factors, namely (i) larger variability in radiation during the day of reflectance measurement associated with large number of plots involved, (ii) weeds in some of the plots, and (iii) different potential yields among genotypes with similar canopy structure. It is relatively easy to alleviate and/or avoid problems no. i and ii because yield–NDVI relationships are applicable for a variety performance test, which usually contains 100 plots or less. Measurement of canopy reflectance would take only 1 to 2 h, with minimum variability in radiation during the measurement, and it is also easier to keep the field weed free. For concern no. iii, as Morrison et al. (1999) noticed, LAI has significantly decreased with year of cultivar release for the last 58 yr and that some of the current

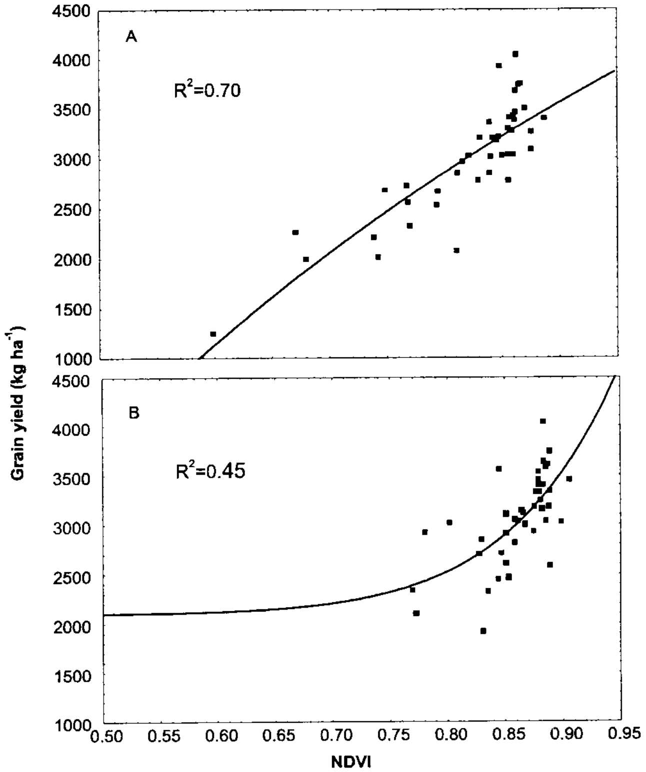

**Fig. 3. Grain yield of soybean cultivars as a power function of canopy reflectance expressed as normalized difference vegetation index (NDVI), measured at R5 stage in 1999 on (A) North Gower clay loam and (B) Uplands sandy loam. Data points are the means of 18 measurements (3 blocks × 3 densities × 2 subsamples).**

soybean cultivars had similar grain yields but with distinct canopy structure (ranges of LAI). The NDVI is strongly related to leaf greenness and LAI or aboveground biomass (Ma et al., 1996). Thus, predicting soybean yield based on the yield–NDVI relationship should take the genotypic canopy structure into account. Fortunately, however, there are generally much smaller ranges in a performance test than our historical variety test.

## Influence of Planting Density

Table 4 shows the regression equations and $R^2$ values generated for all soil type × planting density combinations for both 1998 and 1999. Except for the larger $R^2$ each year for low-yielding soils (previously discussed), no apparent pattern in $R^2$ variation emerges either across soil types or plant population densities. The minor variations (particularly in 1998) and the lack of any pattern in $R^2$ across planting densities suggest that seeding density was not an important factor in determining the yield–NDVI relationship. This may in part be due to the fact that a full canopy coverage already existed at the first sampling date for the lowest density (25 seed m$^{-2}$), so the relative canopy and/or soil reflectance was not the issue it might have been at an earlier developmental stage. For this reason, use of the correcting factors for soil reflectance in the R and IR was not necessary (Clevers, 1988).

## CONCLUSIONS

From the data presented, it is evident that a number of factors influence the yield–NDVI relationship. Growth conditions or cultivar differences that result in lower yields enhance the association (larger $R^2$) while later maturing cultivars show lower $R^2$ values than early cultivars. Differences in the strength of the yield–NDVI relationship were also observed with maturity, plant height, and seed oil content. The soil type, while it did not affect reflectance in terms of background vs. canopy because all measurements were taken when canopy was closed, influenced $R^2$ within each year based on its effect on yield; lower yielding soils showed a larger $R^2$. While planting density did not affect the yield–NDVI relationship at the development stages studied, across densities, the $R^2$ increased as development proceeded. This pattern was similar to one observed previously in maize (Ma et al., 1996). Considering the number of samples involved in this study (378 plots for a single site-year), a minimum of 6 h was required for canopy reflectance measurement. It was assumed to be ideal when reflectance measurements were taken under constant sun angle, solar radiation, and wind-free conditions. In reality, such an ideal situation does not occur in field experiments with a large number of observations as was the case in this study. However, as a screening performance trial usually consists of 100 plots or less, data collection can be taken under optimum weather conditions; thus, a better relationship is expected between NDVI and grain yield. Therefore, our study suggests that measurement of soybean canopy reflectance at the R5 stage differentiated high- from low-yielding genotypes; thus, there are potential uses of canopy reflectance as a reliable, quick, repeatable indicator for ranking genotypes in screening and estimating grain yield. Further research is being undertaken to refine the conditions for using canopy reflectance as a yield indicator in a breeding program.

## REFERENCES

Al-Abbas, A.H., R. Bar, J.D. Hal, F.L. Crane, and M.F. Baumgardner. 1974. Spectra of normal and nutrient deficient maize leaves. Agron. J. 66:16–20.

Benedict, H.M., and R. Swidler. 1961. Nondestructive method for estimating chlorophyll content of leaves. Science 133:2015–2016.

Blackmer, T.M., J.S. Schepers, and G.E. Varvel. 1994. Light reflectance compared with other nitrogen stress measurements in corn leaves. Agron. J. 86:934–938.

Bouman, B.A.M., D. Uenk, and A.J. Haverkort. 1992. The estimation of ground cover of potato by reflectance measurements. Potato Res. 35:111–125.

Clevers, J. 1988. The derivation of a simplified reflectance model for the estimation of leaf area index. Remote Sens. Environ. 25:53–69.

Clevers, J.G.P.W. 1997. A simplified approach for yield prediction of sugar beet based on optical remote sensing data. Remote Sens. Environ. 61:221–228.

Clevers, J., C. Büker, H.J.C. van Leeuwen, and B.A.M. Bouman. 1994. A framework for monitoring crop growth by combining directional and spectral remote sensing information. Remote Sens. Environ. 50:161–170.

Colwell, J.E. 1974. Vegetation canopy reflectance. Remote Sens. Environ. 3:175–183.

Colwell, R.N. 1956. Determining the prevalence of certain cereal crop diseases by means of aerial photography. Hilgardia 26:223–286.

Daughtry, C.S.T., V.C. Vanderbilt, and V.J. Pollara. 1982. Variability of reflectance measurements with sensor altitude and canopy type. Agron. J. 74:744–750.

Fehr, W.R., and C.E. Caviness. 1977. Stages of soybean development. Iowa Coop. Ext. Serv. Spec. Rep. 80. Iowa State Univ., Ames.

Filella, I., L. Serrano, J. Serra, and J. Peñuelas. 1995. Evaluating wheat nitrogen status with canopy reflectance indices and discriminant analysis. Crop Sci. 35:1400–1405.

Gausman, H.W., W.A. Allen, V.I. Myers, and R. Cardenas. 1969. Reflectance and internal structure of cotton leaves, *Gossypium hirsutum* (L.). Agron. J. 61:374–376.

Gausman, H.W., W.A. Allen, R. Cardenas, and A.J. Richardson. 1970. Relation of light reflectance to histological and physical evaluations of cotton leaf maturity. Appl. Opt. 9:545–552.

Gausman, H.W., and R. Cardenas. 1968. Effect of soil salinity on external morphology of cotton leaves. Agron. J. 60:566–576.

Holben, B.N., C.J. Tucker, and C.J. Fan. 1980. Spectral assessment of soybean leaf area and leaf biomass. Photogramm. Eng. Remote Sens. 46:651–656.

Kumar, R., and L. Silva. 1973. Light ray tracing through a leaf cross-section. Appl. Optics 12:2950–2954.

Ma, B.L., and L.M. Dwyer. 1998. Nitrogen uptake and use of two contrasting maize hybrids differing in leaf senescence. Plant Soil 199:283–291.

Ma, B.L., M.J. Morrison, and L.M. Dwyer. 1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agron. J. 88:915–920.

Mahey, R.K., R. Singh, S.S. Sidhu, and R.S. Narang. 1991. The use of remote sensing to assess the effects of water stress on wheat. Exp. Agric. 27:423–430.

Morrison, M.J., H.D. Voldeng, and E.R. Cober. 1999. Physiological changes from 58 years of genetic improvement of short-season soybean cultivars in Canada. Agron. J. 91:685–689.

Morrison, M.J., H.D. Voldeng, and E.R. Cober. 2000. Agronomic changes from 58 years of genetic improvement of short-season soybean cultivars in Canada. Agron. J. 92:780–784.

Peñuelas, J., J.A. Gamon, A.L. Fredeen, J. Merino, and C.B. Field. 1994. Reflectance indices associated with physiological changes in nitrogen- and water-limited sunflower leaves. Remote Sens. Environ. 48:135–146.

Peñuelas, J., R. Isla, I. Filella, and J.L. Araus. 1997. Visible and near infrared reflectance assessment of salinity effects on barley. Crop Sci. 37:198–202.

Rouse, J.W., Jr., R.H. Haas, J.A. Schell, and D.W. Deering. 1973. Monitoring vegetation systems in the Great Plains with ERTS. p. 309–317. *In* Proc. Earth Res. Tech. Satellite-1 Symp., Goddard Space Flight Cent., Washington, DC. 10–14 Dec. 1973.

SAS Institute. 1990. SAS/STAT user's guide. Version 6. SAS Inst., Cary, NC.

Statsoft. 1995. STATISTICA. Release 5. StatSoft, Tulsa, OK.

Stone, M.L., J.B. Solie, W.R. Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE 39: 1623–1631.

Thomas, J.R., L.N. Namken, G.F. Oerther, and R.G. Brown. 1971. Estimating leaf water content by reflectance measurements. Agron. J. 63:845–847.

Thomas, J.R., and G.F. Oerther. 1972. Estimating nitrogen content of sweet pepper leaves by reflectance measurements. Agron. J. 64:11–13.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127–150.

Voldeng, H.D., E.R. Cober, D.J. Hume, C. Gillard, and M.J. Morrison. 1997. Fifty-eight years of genetic improvement of short-season soybean cultivars in Canada. Crop Sci. 37:428–431.

Wanjura, D.F., and J.L. Hatfield. 1987. Sensitivity of spectral vegetative indices to crop biomass. Trans. ASAE 30:810–816.

Wiegand, C.L., and A.J. Richardson. 1990. Use of spectral vegetation indices to infer leaf area, evapotranspiration and yield: I. Rationale. Agron. J. 82:623–629.

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