Potato yield is a product of the interaction between genetic yield potential and the external production environment. The soil production environment can further be subdivided into chemical (macro- and micronutrients) and biophysical components. Soil matrix properties determine retention of moisture, facilitation of gas exchange between the soil and the aerial environment, and the ability to sequester carbon through different bonding mechanisms. Soil nutrients are intensively managed by commercial growers during the entire potato production cycle. As such, biophysical characteristics of the soil are expected to have a greater role than chemical properties in accounting for potato yield heterogeneity. This is particularly relevant to the poorly structured coarse soils where the majority of potatoes are grown in North America. If a dominant role for soil biophysical properties is ascertained, soil structure remediation recommendations are available for potato production on sandy soils.

Soil structure is an important link in the functioning of the soil–plant–atmosphere continuum and is expected to impact crop yield performance. It influences soil moisture status and aeration as well as ionic exchange in the soil colloids. Aggregate stability is directly related to soil structure in terms of physical function to support crop growth, and thus is an excellent indicator of soil quality status. The ability of the potato plant to utilize available nutrients and moisture can be hampered by a non-optimum internal plant condition (e.g., presence of disease or insect infestation) leading to reduced photosynthesis and ultimately reduced yield. There is a considerable body of literature that positively correlates near-infrared reflectance with disease prevalence as well as environmental stress in plants.

A recent study reported in Agronomy Journal was conducted to quantify potato yield heterogeneity in a commercial production environment and determine predictive soil and plant spectral properties for tuber yield spatial analyses. The study was conducted at two commercial potato production fields managed by the same farm operator and designated as Fields A1 and A2, sampled in 2003 and 2004, respectively. The fields were located in Vestaburg, Montcalm County, Michigan. All field operations were left to best management practices developed by the cooperating commercial grower over the years.

Precipitation in the study area was documented using records from the nearby Montcalm Research Farm weather station. Annual precipitation for both years was below the 135-year average. Supplemental irrigation water application is the industry standard and was performed in these fields based on soil water content determination through the hand-feel method conducted by an experienced irrigator. A center-pivot irrigation system covered each field, rotating 360° in 24 hours and applying about 1.9 cm of moisture each rotation. Fields A1 and A2 are both composed of a Mancelona loamy sand with a slight
slope, and about three quarters of Field A2 is composed of a complex of Gladwin loamy sand and Palo sandy loam. The soil complex in Field A2 is somewhat poorly drained.

Historical soil sample data taken from the fields were used to formulate the sampling design. Soil was tested for percent organic matter, phosphorus, potassium, magnesium, calcium, pH, cation exchange capacity (CEC), and zinc. Soil samples for water-stable aggregate analyses were taken before harvest on Sept. 18, 2003 and Sept. 11, 2004 for Fields A1 and A2, respectively.

**Spectral reflectance images**

An Olympus 340R (Melville, NY) digital camera was utilized to obtain red, green, and near-infrared spectral images at each of the grid points in Fields A1 and A2, on Aug. 31, 2003 and Aug. 28, 2004, respectively. The red, green, and near-infrared band images of the electromagnetic spectrum were extracted using a photo-editing software (Photoshop, San Jose, CA) with a macro program to facilitate the processing of hundreds of pictures within a short time. The extracted green, red, and near-infrared band images were used as input to a geographic information software (IDRISI for Windows v1, Worcester, MA) to compute the mean average value of the image pixels (Fig. 1), as well as to generate different spectral ratios between the green, red, and near-infrared part of the electromagnetic spectrum through the overlay function. Unsupervised clustering into two groups using the cluster module of IDRISI was performed on the near-infrared composite image to produce a Boolean image, with 0 being non-vegetated areas and 1 being vegetated areas. Pixels with a 1 value in the image were counted and expressed as a percentage of the entire image pixels to represent percent vegetated. A copy of the RGB (red-green-blue) and near-infrared images was multiplied with its corresponding Boolean image to segregate vegetation from non-vegetated areas, and the resulting image was classified as an adjusted spectral image. Spectral bands and ratios reported here can be distinguished based on the subscript, for example, G_adj, G/R_adj, and R/IR_adj were computed based on the adjusted images of the G (green), R (red), and IR (near infrared) bands. Use of an “unadj” subscript such as G_unadj, G/R_unadj, and R/IR_unadj were computed using non-adjusted digital images.

**Potato yield response**

The mean total tuber yields for both fields were moderately higher than those reported in 2005 from a variety trial conducted at the Michigan State University Montcalm Research Farm, indicating that the commercial management practices followed were effective.

In general, the climatic conditions in 2003 were conducive to potato production, and Michigan potato yield levels were higher by 1.5% compared with 2004. Precipitation in 2003 was well synchronized with potato growth stages and provided consistent moisture supply during the critical tuber bulking period of late summer, whereas 2004 had higher precipitation overall, but 50% below average late in the growing season. More than 80% of Michigan commercial potato fields, including the two monitored in this study, are provided supplemental irrigation through pivot systems. However, potato tuber is a high-moisture (75–80% moisture content), fresh commodity product, and rainfall remains an important source of moisture with a significant influence on potato tuber yield.

**Fig. 1.** Image acquisition, processing, and analyses involving an RGB (A) image and a near-infrared RGB image (B) being cropped (A1 and B1) to remove edge artifacts, composited into IDRISI for Windows (A2, A3, A4; B2, B3, B4). Unsupervised clustering into two groups was performed on the near-infrared composite image (B5) to produce an image with 0 being non-vegetated areas and 1 being vegetated areas (B6). Pixels with a 1 value in the image were counted and expressed as a percentage of the entire image pixels to represent percent vegetated.
Spectral reflectance

Potato spectral reflectance was taken as a proxy for plant health in this study, since it is difficult to account for all factors affecting potato yield. Digital images were taken at approximately the same time, Aug. 31, 2003 and Aug. 28, 2004 for Field A1 and A2, respectively, yet Field A1 had more reflectance in both the unadjusted and adjusted images for the green band (15 and 91%, respectively) compared with Field A2. The amount of red and near-infrared reflectance was higher in Field A2 than in Field A1 for the unadjusted images (48 and 80%, respectively). The higher level of red and near-infrared in Field A2 is presumably related to senescent plant tissues and vegetation cover at less than 5% in A2 compared with 47% in A1. The significant difference in vegetation cover between the two fields may be due in part to growth and maturity patterns in the dry fall of 2004, as Field A2 was planted nearly two weeks earlier than A1 (Apr. 29, 2004 vs. May 13, 2003), yet vegetation health by late August was poor. Field A2 had 33, 23, and 84% less rainfall in July, August, and September of 2004 compared with Field A1 rainfall in 2003. The combined effects of early planting and significant moisture stress could have accelerated senescence in Field A2. Figure 2 shows the typical vegetation cover in Fields A1 and A2 during sampling.

Fig. 2. Typical vegetation cover in Fields A1 (A) and A2 (B), when spectral images were taken in 2003 and 2004, respectively.
With vigorous, healthy vegetation, near-infrared light reflection should be high and a corresponding decrease will be observed as senescence begins. The interpretation of observed near-infrared values was confined to within study Fields A1 and A2 at a late stage in the growing season (tuber maturation phase, 110 days after planting in A1; 121 days after planting in A2) and not between fields. The red part of the electromagnetic spectrum is no longer absorbed by senescent plant tissues, causing an increase in the reflectance of this spectrum to be picked up by digital imagery. In the current study, different spectral indices were positively correlated to potato yield: the unadjusted green, the green/red ratio, and the red/near-infrared spectral band or ratios in Field A1, and the red/near-infrared unadjusted ratio in Field A2.

**Correlation analyses**

As observed previously in the literature, soil texture helped determine yield potential in the A1 field. Clay content was positively correlated to tuber yield in this field; however, no similar relationship was found in Field A2. In a potato field study, researchers concluded that soil clay content was a driving factor in the formation of a well-aggregated soil and positively contributed to potato yield. In the current study, the influence of soil moisture on yield was consistent. It was positively correlated in both fields.

The experimental areas in both fields were purposively located so as to minimize the impact of micro-elevation, a factor that has been shown to markedly influence potato tuber yield. Micro-elevated areas in Field A1 with localized soil saturation late in the 2003 season may have led to detrimental effects on tuber growth, due to the known sensitivity of potatoes to oxygen deprivation. Indeed, the correlation values for Field A1 showed a positive relationship between elevation and yield. A year later, in Field A2, elevation did not have a significant relationship with yield. However, plants located at low topographical positions may have benefited in this field—although this did not translate into detectable yield benefits—as soil moisture was negatively correlated to elevation in 2004.

The role of potassium in the growth and development of tubers varies with the intended market. Where the amount of solids is critical, as in processing potatoes, potassium needs to be monitored closely. Potassium promotes moisture accumulation in the tubers, resulting in decreased specific gravity, which influences market acceptability.

**Yield predictors**

Based on a SAS Proc Reg routine and variation inflation factor behavior of the dataset, a total of 23 predictor variables were selected from the original pool of 42 for Field A1 while 21 predictor variables were selected from the original pool of 40 for Field A2. There were 15 common variables in both Fields A1 and A2 that did not contribute to multicollinearity. After the initial stepwise regression analysis was conducted on the selected pool of predictor variables, the analysis was repeated for a second time to determine if additional variables would contribute significantly to yield prediction. These additional predictor variables were hypothesized to be important for yield prediction and consisted of bulk density and infiltration rate for Field A1 and apparent electrical conductivity for Field A2. The final stepwise regression equation for Field A1 accounted for 67% of the potato yield variability. Physical, chemical, and spectral variables included in the equation were aggregate stability (mean weight diameter), topography, soil texture (the amount of clay), the unadjusted green band, and potassium level. Inclusion of infiltration rate and bulk density in the pool of predictive variables did not affect the variability explained, and neither one of these variables was included in the final regression equation.

In Field A2, the stepwise regression initially included mean weight diameter, the red unadjusted band of the digital images, and the base saturation portion of hydrogen, which together accounted for 44% of the observed potato yield variability. Inclusion of apparent electrical conductivity not only increased the explained variability to 60%, but it removed all of the identified yield predictors and replaced them with the green and red unadjusted band ratio and 250-μm water stable aggregate size fraction in the predictive equation.

The yield predictive models derived from commercial potato fields demonstrated the significant roles played by soil structure, specific spectral bands, and derived vegetative index, as well as soil potassium status. These attributes proved critical for developing predictive regression models that could account for more than 60% of the yield variability observed. The inclusion of two proxies for soil structure (i.e., mean weight diameter and 250-μm water-stable aggregate) showed the significant contribution of soil structure to the positive dynamics of the soil, plant, and environment continuum, enhancing our understanding of how to reduce potato yield variability in a commercial context, where coarse-textured sites predominate. This study has relevance to environmentally friendly potato production as well; the findings are consistent with a need for soil structural geo-referenced information, given its indirect and direct effects on plant yield response.