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SOIL AGGREGATE STABILITY: CROPPING SYSTEM EFFECTS, SPATIAL VARIABILITY AND CONTRIBUTION TO POTATO YIELD IN MICHIGAN

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Edgar Allan C. Po

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SOIL AGGREGATE STABILITY: CROPPING SYSTEM EFFECTS, SPATIAL VARIABILITY AND CONTRIBUTION TO POTATO YIELD IN MICHIGAN

By

Edgar Allan C. Po

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ABSTRACT

SOIL AGGREGATE STABILITY: CROPPING SYSTEM EFFECTS, SPATIAL VARIABILITY AND CONTRIBUTION TO POTATO YIELD IN MICHIGAN

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Edgar Allan C. Po

Soil structure stability must be maintained to facilitate gaseous and water exchange between the root and its external environment, ensuring optimum potato crop productivity in the process. Seven potato rotation systems (2-year) with varying amounts of carbon (C) inputs were evaluated over 3 years beginning in 2001, for their effects on the dynamics of water stable soil aggregation (WSA) and C sequestration at a field trial located in Central Michigan on an irrigated Alfisol. The systems consisted of four main crops (potato, snapbean, corn, wheat) and three winter cover crops (rye, hairy vetch, and red clover). Regression and correlation analyses were conducted on the relationship of WSA and digital imagery sources (i.e., in-field and archived high-resolution imageries) to potato yield in 2003 and 2004 from two commercial fields. Systems involving sweet corn contributed 2-fold higher biomass than those with wheat or snapbean, and presence of a legume in a cover crop system contributed significantly higher amounts of C inputs (1.2 $Mgha^{-1}$) compared to presence of rye alone (0.7 $Mgha^{-1}$). In 2004, macro-WSAs declined by 13% from 2001 levels for all systems except those with high C inputs, which maintained macroaggregates. Residue C input was a moderate predictor of total soil C (31% of variability explained), whereas macro and micro WSAs were significant predictors of total soil C, accounting for 58 and 72 % of observed variability, respectively. Results from the two commercial fields' stepwise and principal component regression analyses explained an average of 63% and 54% of the yield variance.

The positive contribution of soil structure stability to yield indicates the need for its management. Use of cereals as rotation crop with potato and leguminous cover crop appeared to be an effective means to improve soil structure stability. In-season use of digital imagery can potentially aid in pre-harvest yield mapping and monitoring of important soil physical attributes.

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PREFACE

The three Chapters in this dissertation were written in the style required for publication in the *Soil Science Society of America Journal*. Certain sections of the materials and methods as well as some tables and figures were intentionally repeated, hence will appear redundant.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: EVALUATION OF THE EFFECTS OF SEVEN POTATO SHORT ROTATION COVER CROP SYSTEMS ON SOIL AGGREGATE STABILITY

ABSTRACT

Understanding processes that ameliorate structural degradation in sandy soils is becoming of increasing importance as land values rise and cropping systems intensify. Seven potato rotation systems (2-year) with varying amounts of carbon (C) inputs were evaluated over 3 years for their effects on the dynamics of soil aggregation and C sequestration. The 7 systems evaluated winter management (fallow, rye cover crop, rye-hairy vetch cover crop mixture and red clover cover crop) and alternative crops rotated with potatoes (snap bean, wheat and corn). Both entry points of the 2-year rotations were included each year in the field trial located in Central Michigan on an irrigated Alfisol. The systems were compared individually and grouped into three categories to contrast C inputs from cover crop and crop residues above- and below- ground. Average C input for low (S1 and S4), medium (S2 and S6), and high (S5, S3 and S7) input was 1.2, 2.0, and 2.8 $Mgha^{-1}$ respectively. Response variables included water stable aggregate (WSA) size fraction 4 to ≥2 mm, <2 to ≥1 mm, <1 to ≥0.25 mm, <0.25 to ≥0.106 mm, <0.106 to ≥0.053 mm, macroaggregates (≥0.25 mm), microaggregates (≤0.25 mm), mean weight diameter (MWD), and total soil C. Systems involving sweet corn contributed 2-fold higher biomass than those with wheat or snapbean, and presence of a legume in a cover crop system contributed significantly higher amounts of C inputs (1.2 $Mgha^{-1}$) compared to presence of rye alone (0.7 $Mgha^{-1}$). Only the entry year influenced macro aggregates

in the first year of the trial (2001), whereas both entry year and system influenced aggregate size classes in the fourth year. In 2004, macro-WSAs declined by 13% from 2001 levels for all systems except those with high C inputs, which maintained macroaggregates. Residue C input was a moderate predictor of total soil C (31% of variability explained), whereas macro and micro WSAs were significant predictors of total soil C, accounting for 58 and 72 % of observed variability, respectively.

INTRODUCTION

Soil structure is an important crop production factor affecting numerous processes critical to crop growth and ecological function (Martin, 1953; Pachepsky and Rawls, 2003). Intensification of cropping on Alfisols is becoming common in the Great Lakes region, with high value, low residue crops grown quite frequently, and soil degradation is becoming an urgent problem. Research is required to understand the role of root and above-ground residues in promoting aggregation, C sequestration and soil structure resilience (Rasse, et al., 2000) under continuous wetting and drying (Mikha, et al., 2005; Park, et al., 2007), and freezing and thawing processes, in the face of frequent tillage and harvest operations (Grandy et al., 2002). The ideal cover crop and alternate cash crop rotation with potatoes would be able to maintain or enhance aggregate stability, soil C and structural integrity.

Economic considerations and alternate land use could explain the increasing preference for short crop rotation cycles among potato farmers. From 1950 to 1997 a decline of 20% was observed in the amount of farmland hectarage in the US (Theolbald, 2001). Adoption of alternative crop management strategies becomes contingent on observing improvements in soils over the shortest time period possible. A single application of manure (24.5 Mg ha^{-1}) in a Maine potato rotation trial resulted in significant formation of medium and large stable aggregates, whereas green manure crops of oat and hairy vetch carried out over 5 years had no discernable effects on soil aggregation (Grandy et al., 2002). Comparing a barley-forage rotation with a barley monoculture, Bissonnette et al., (2001) noted a significantly higher aggregation (as measured by mean weight diameter) after 2 years in the rotation. Carter (1992) found relatively rapid management-induced changes in the macro-aggregate size fraction > 1 mm in a tillage experiment.

Aggregates are formed by bridging actions among clay micelles, quartz surfaces, organic colloids (Emerson, 1959), cations and anions (Hillel, 2004). The strength of these bonds decreases as the size of the aggregate increases. Organic carbon (C) protection of aggregates depends upon the degree of C encapsulation and subsequent contributions to bonding strength, as well as the spatial location of C within the aggregate (Jastrow et al., 1996). Carbon derived from recently added organic matter tends to be located on the outer perimeter of aggregates (Kavdir and Smucker, 2005). Intra-aggregate locations of soil C serve as hydrophobic deterrents to water dissolution of aggregates and contribute to the binding of smaller aggregates into larger ones (Chenu et al., 2000). Therefore, the effectiveness of different rotation cropping systems in improving soil structure can be evaluated by looking at enhancements in the proportion of stable macro-aggregates.

The presence of legumes in a crop rotation scheme provides nitrogen (N)-enriched residues, and this may support microbial activity that enhances polysaccharide production and aggregation indirectly, but the mechanisms are not well defined. Mazurak et al. (1954) found a high degree of aggregate stability in potato rotations that involved alfalfa. Under laboratory conditions, alfalfa and clover inputs led to increased mean weight diameter of aggregates in a silty-clay loam soil after only 9 days (Martens, 2000). An equilibrium in the formation of new aggregate binding material may have occurred as no further increases in aggregation were observed. Use of a combination of oat, peas, and hairy vetch as a green manure resulted in a trend ($P < 0.10$) towards improved water stable aggregate stability for a potato rotation system in Maine (Porter et al., 1999). In a cotton production system the use of crimson clover improved aggregate stability by 100%, compared to a non-legume cotton system (Hubbs et al., 1998).

Winter cover crops are used by some producers of high value, irrigated crops such as potatoes; however, farmers generally prefer cold-tolerant and productive cereal cover crops in the Upper Midwest and rarely experiment with legume cover crops (Snapp et al., 2005). A number of researchers have found that soil building and fertility is enhanced by the presence of legumes and legume-cereal mixtures in row crop systems (Griffin and Hesterman, 1991; Honeycutt et al., 1996). In addition to a cover crop, the residues of the main crop rotated with a potato crop are expected to influence soil aggregation and carbon over time. Research has not fully resolved the question of relative benefits of quantity versus quality of residues, in terms of their effect on aggregate formation and long-term soil productivity.

The objectives of this study were to 1) quantify above and below ground C inputs from 7 potato systems with contrasting main crops (snap bean, corn and wheat) and three winter cover crop management systems (fallow, rye, rye-hairy vetch, and red clover), and 2) determine the impact of the potato rotation systems and cropping system phase on the formation of water stable aggregates and soil C dynamics.

MATERIALS AND METHODS

Experimental Design and Treatments

A trial was established April 2, 2001 at the Montcalm Research Farm (MRF; 85°10'32" longitude and 43°21'12" latitude; Montcalm County near Entrican, Michigan). The soil type was a McBride sandy loam (coarse-loamy, mixed Eutric Glossoboralfs; and coarse-loamy, mixed frigid Alfic Fragioorthods) (Ender, 2003). Table 1.1 shows soil properties of the study site from samples collected and analyzed as described below. Seven two year systems were evaluated, namely potato-bare, snapbean-bare (PBSBB, S1); potato-rye, snapbean-rye (PRSBR, S2); potato-rye, sweetcorn-bare (PRSCB, S3); potato-wheat-wheat-rye (PWWR, S4); potato-wheat-wheat/clover-clover (PWWCC,S5); potato-rye/vetch-snapbean-rye/vetch (PRVSBRV, S6); and potato-rye/vetch-sweetcorn-ryevetch (PRVSCRV, S7) (Table 1.2). The treatments were laid out in a randomized complete block design with four replicates. To account for variability in seasonal conditions, two entry-years were included for each system, doubling the total number of systems present each year to 14. Plots were 5.49 m in length by 15.24 m in width. Cultural practices and related field operations for the main crops and cover crops of this study followed Michigan State University recommendations, and were described in Nyiraneza and Snapp (2007).

Monthly precipitation data recorded from the study area in 2001 to 2004 are shown in Figure 1.1. The precipitation values of 991, 827, 478, and 735 mm for 2001, 2002, 2003 and 2004, respectively, indicate that 2003 was a dry growing season and could potentially influence observed soil structure differences between initial measurements taken in 2001, and those taken in 2004. However, precipitation was supplemented with irrigation following standard potato production practice in Michigan, diluting any moisture-related impact.

Carbon and Nitrogen Input

The annual amount of carbon that was incorporated into each of the systems in the cropping cycle was calculated as the total oven-dry weight of above-ground biomass, less any economic product that was removed. Above-ground biomass was collected using two subsamples per plot from 0.25 m^2 quadrats, oven dried at 65°C for 48 hours. Cover crop biomass was measured just before incorporation on 25 April 2002, 23 May 2003 and 20 May 2004. Cash crop biomass was measured just before harvest on 11 July 2002, 24 July 2003 and 12 July 2004 for wheat; 26 August 2002, 20 August 2003, 17 August 2004 for bean and corn and 3 Sept, 2002 for potato (only tubers were measured in 2003 and 2004 for potatoes, and the ratio of tubers to shoot used to estimate aboveground inputs).

To account for the below-ground C contribution, root biomass was measured for cover crops in 2003 and 2004 by collecting a composite of five 2-cm diameter soil cores per quadrat from the 0-25 cm depth (2 quadrats per replicate X 4 replicates). Soil samples were wet sieved using a 4 mm mesh, roots were collected with tweezers and oven dried at 65°C for 48 to 72 hours (until no change in weight). This was expected to be an underestimation of C inputs as root exudates and turnover of roots were not measured due to methodological challenges. For snapbean (Phaseolus sp. L.), corn (Zea mays L.), and wheat (Triticum aestivum L.), the shoot-root ratios used were set to 5:1, 5:1 and 4:1, respectively (Bolinder et al., 1999). For potato, the ratio was 6.7:1, computed from Opena and Porter (1999) and Porter et al. (1999). The average shoot:root ratio found here for cover crops was 1.25:1, similar to the literature values for vegetatively growing cover crops, such as a rye cover crop on a sandy soil in southern Michigan (Snapp et al., 2007). To determine C inputs from total biomass a multiplier of 0.45 was used, based on average C% in residues from this potato rotation trial (Nyiraneza and Snapp, 2007).

Water Stable Aggregates (WSA)

WSA samples were carefully collected using a trowel to preserve aggregates, 5 samples per composite representing a plot, from the 0-10 cm depth on the first (December 21, 2001) and fourth year (November 11, 2004) of the trial. Samples were air dried, sieved through a nest of sieves to acquire a representative sample of soil aggregates sized between 2 and 4 mm. Overall, approximately 80% of the soil material by weight ended up in the less than 2 mm size range.

WSA was determined using a modification of Rasse et al (2000) method by placing approximately a single layer of 4 – 2 mm aggregates (~25g) on top of a nest of 2, 1, 0.25, and 0.106 mm sieves in a water bath container attached to a reciprocating machine with a vertical amplitude of 5 cm running at 35 rpm. Water was then applied to the water bath until it contacted the 2 mm sieve facilitating hydration of individual aggregates by capillary action for 10 minutes and reciprocated for 10 minutes. Sand-free water stable aggregates were determined following the methodology of Grandy et al (2002). For the rest of the text, referral to water stable aggregate size fractions of 2, 1, 0.25, 0.106, and 0.053 mm would refer to aggregate size ranges of < 4 to 2 mm, < 2 to 1 mm, < 1 to 0.25 mm, < 0.25 to 0.106 mm and < 0.106 to 0.053 mm, respectively. Data was also presented as stable macro-aggregates (≥0.25 mm) and micro-aggregates (<0.25 mm). Mean Weight Diameter (MWD) was computed as the summation of the average aggregate size remaining on each sieve, multiplied by the percent of total sample represented by the respective aggregate class as outlined by Kemper and Rosenau (1986).

Soil Properties

A representative soil sample collected above was sieved (< 2 mm) and ground to powdery consistency using a Shatterbox Rotary Grinder (Spex Ind., Edison, NJ) for 2 minutes. Samples were prepared from the ground soil by weighing 60 to 70 micrograms in a crimped tin capsules sent to the Stable Isotope Laboratory at the University of California at Davis, and analyzed for total C and N by Europa Hydra 20/20 isotope ratio mass spectrometer (Europa Scientific, Crewe, UK). Another representative subset of the < 2 mm samples were sent to and analyzed by A&L Great Lakes laboratories (Fort Wayne, IN) for chemical and texture analysis, including determination of available phosphorous, exchangeable potassium, magnesium, calcium, soil pH, buffer pH, cation exchange capacity (CEC), percent base saturation of cation elements and texture components of sand, silt and clay (Ankerman and Large, 2001). Results of phosphorous analyses were expressed as a weak Bray (P1) derived from Mehlich-3 through a regression equation (Calhoun et al., 2002). Soils were sampled again on November 10, 2004 from the 0-20 cm depth using 2 cm diameter augers and 8 samples per composite to represent a plot, to conduct a N mineralization potential aerobic assay. After wet-sieving through a 6 mm sieve, a representative 10 g subsample was incubated at 60% water holding capacity for 30 d at 25°C. NH_4-N and NO_3–N were determined in extracts by colorimetric methods using an autoanalyzer (Lachat Instruments, Milwaukee, WI). Net N mineralization was calculated using the difference between the inorganic N contents at day 0 and at the end of the incubation period (Nyiraneza and Snapp, 2007).

Statistical Analyses

Data analyses were conducted using SAS v9.1 (SAS 2006, Cary, NC) MIXED procedure. Two-factor analyses of variance (ANOVA) were conducted with cropping systems S1 through S7 as factor A, and the two entry years as factor B. The first (2001) and fourth (2004) year data were analyzed separately. The differences between 2001 and 2004 were calculated for each plot and also analyzed. Comparisons among the systems and between the entry years were conducted using Fisher-protected least significant differences. The three groups, namely, low carbon input (LCI consisting of S1 and S4), medium carbon input (MCI consisting of S2 and S6), and high carbon input (HCI consisting of S3, S5 and S7), were compared via linear contrasts. Bonferroni adjustment was used in testing significance of the contrasts when the ANOVA was not significant.

The contribution of water stable aggregates and biomass carbon input to soil C prediction was evaluated through the sum of squares reduction test (Schabenberger et al., 1999; Perez and Kogan, 2003). The test involved comparisons between the sums of squares of single factor reduced model consisting of either water stable aggregates (i.e., macro or micro) or carbon input and the sum of squares of the full model involving all of the afore-mentioned factors.

RESULTS AND DISCUSSION

Entry Year Effects

Incorporation of entry-year as a factor in the experimental design was effective in quantifying the detrimental effects of potato production practices on soil quality. In 2001, soil samples taken after the alternative cash crop of corn, wheat, or snap bean harvest had 58, 46 and 17% higher proportion of water stable aggregates in the larger size classes of 2 mm, 1 mm and the overall MWD, compared to aggregates after the potato main crop (Table 1.3; $P < 0.0001$). A similar decline in aggregate size after potato harvest was documented by Carter and Sanderson (2001).

Additional evidence of soil structure degradation with potato production was documented in 2004 as alternative crops were associated with 11% compared to 9% for the 1 mm size class aggregates after the potato crop (Table 1.4; $P < 0.001$). However, the MWD was not different after the potato crop and the alternative main crops in 2004 (Table 4). After 4 years the alternative crops were not able to maintain the level of aggregation and stability observed in year one of the study (Tables 1.3 and 1.4). Other size fractions showing significant effects of entry year in 2004 were the 0.25 mm and 0.053 mm WSA's, with 10% reduction and 8% increase respectively for the alternative cash crops over the potato entry year.

System Organic Inputs and Soil Response

The limited amount of biomass remaining in the field in potato cropping systems (Mazurak et al., 1954, Rees et al., 2002) necessitates the identification of management systems that enhance residue input and soil C assimilation from the residues. In our study the average amount of C returned to the soil by the seven potato cropping systems was 2.08 Mg ha^{-1} per year (range of 0.93 Mg ha^{-1} [S1] to 3.32 Mg ha^{-1} per year [S7] - Figure 1.2A.). The amount of carbon contributed by S1 in this present study was 44% less than a system consisting of continuous potato in a Canadian study (Angers et al., 1999). Considering that S1 had a bare fallow, a low biomass legume as the alternative cash crop (snap bean), and our site has low soil C (Table 1.1), all of these factors could have contributed to lower growth and thus lower C input at our site than in the Canadian study.

The C input from systems had the following pattern of decreasing magnitude: S7 (potato-rye/vetch, sweetcorn-rye/vetch) > S3 (potato-rye, sweetcorn-bare) > S5 (potato-wheat/clover, wheat/clover-clover) > S2 (potato-rye, snapbean-rye) > S6 (potato-rye/vetch, snapbean-rye/vetch), S4 (potato-wheat, wheat-rye) > S1 (potato-bare, snapbean-bare). Planned contrast between low (S1 and S4), medium (S2 and S6) and high (S5, S3, and S7) carbon input categories indicated the presence of highly significant differences, with low input having an average annual C of 1.164 Mg ha^{-1} while medium and large inputs had 68% and 137% higher carbon returned to the soil, respectively (Figure 1.2B).

Crop growth potential and residue generation has an impact on the amount of C returned to the soil. All systems with corn had higher C contributions (S3 and S7), followed by systems with wheat and rye (S5, S2, S6 and S4; Table 1.4). These results were expected, considering that corn has an efficient C4 photosynthetic pathway, while wheat together with rye are C3 plants, and research has indicated that corn produces 70% more biomass than wheat (Wilhelm et al., 2004).

The impact of a cropping system on soil C is dependent on many factors beyond the quantity of C residues added, these include residue quality, the tillage intensity of cropping systems and the soil environment. The proportion of labile to recalcitrant forms of soil C is important, as annual contributions of residues have minimal impact on systems dominated by high proportions of inert carbon (Paul, 2007); whereas in low C soils, the addition of carbonaceous residues can increase total soil C in a relatively short time frame (Shrestha, et al., 2002). Addition of 3.5 times the amount of carbon in S7 relative to S1 did not, however, significantly increase soil C in our experiment (Table 1.4).

As this was a cropping systems experiment, both the quantity and quality of residues varied with treatment. Crop residues were mature with a low N concentration, between 0.9% and 1.6% in 2002 (including snap bean residues). Cover crop residues however were incorporated at vegetative stages and had higher N concentration, particularly the legume-cereal mixtures. Weed biomass from S1 winter fallow was determined using the cover crop protocol and was found to be <100 kg ha each year, so N concentration was not determined for weed tissues. The rye cover crop in S2, S3 and S4 had a mean value of 2.2 N% (standard deviation 0.3), whereas the legume-cereal mixed tissues in S5, S6 and S7 had a mean value of 2.7 N% (standard deviation 0.4). The nitrogenous residues of S5, S6 and S7 could have a priming effect and been associated with accelerated residue decomposition, resulting in limited soil C assimilation (Cope et al., 1958; Rasse, et al., 2000). Presence of leguminous material ensures a relatively faster biomass breakdown compared to biomass of wider C:N ratios. Inclusion of red clover in the S5 potato-wheat system showed 30% higher N mineralization potential (0.26 mg N g^{-}

^{1} d^{-1}) compared to S4 potato-wheat system (0.20 mg N g^{-1} d^{-1}; P = 0.05). No significant effects on N mineralization potential were found for other treatments, which averaged 0.25 mg N g^{-1} d^{-1}.

System Effects and Aggregation

After four years, the cropping systems significantly affected the WSA size fractions of 1 mm, >0.25 mm, >0.106 mm, >0.053 mm, and macroaggregates (≥0.25 mm) (Table 1.4). Mean weight diameter (MWD) demonstrated improvements of 19.5 % in 2004 compared to 2001 levels, averaged across all treatments (Table 1.1). There was a small change in MWD for the low C input systems, based on the planned comparison of S1 and S4 (low C inputs) with all other systems (Figure 3). S1 had a bare winter fallow and demonstrated a trend consistent with no increase in MWD size after 3 years, although this was not significantly different than the other systems. It is interesting that S4 had low tillage intensity, yet was still associated with a limited change in aggregate MWD; this may be explained by the low C inputs associated with this system.

WSA increases above 2001 levels averaged 13%, 4% and 31% for aggregate fractions 1, 0.106 and 0.053 mm, respectively (Table 1.1). In a Maine potato field trial, green manure involving hairy vetch increased the proportion of 1 to 2 mm, and 2 to 6.5 mm aggregate size fractions (Grandy et al., 2002), with no increase observed for small macroaggregates (0.250 – 1 mm). The relatively high increase in the 0.053 mm size fraction in this present study suggests an inherent weakness of aggregates formed by the various systems. Continuous tillage of the soil may also have interfered with aggregate formation. Angers et al. (1999) reported that increases in WSA were observed only after the 6th year and not on the 10th year of a decade-long study. This discrepancy was attributed to different initial moisture contents of the processed samples. The 10th year samples were wetter than those analyzed during the 6th year. Samples in the present Michigan study were air dried prior to wet sieving as opposed to field moist samples used by Angers et al. (1999), therefore initial soil moisture content appeared to have little influence on the proportion of micro-aggregates observed among the seven treatments.

The amount of macroaggregates (diameter ≥ 0.25 mm) decreased for all treatments after four years, except for S5. The 6% decline from an average of 55% in 2001 to 49% in 2004 for this present study was minimal compared to the decline in macroaggregates measured in a potato rotation trial on Prince Edward Island, Canada. Angers, et al. (1999) reported macro-aggregate percentages declined 20%, from 37% in the third year to 17% in the 7th year. In their study, continuous potatoes for 9 consecutive seasons showed the greatest decline in macroaggregates, as was observed in S1 in the present study. The weak natural tendency by sandy soils to form larger aggregates during constant soil tillage may have led to these macroaggregate declines. Under treatment S5 involving potato and wheat/clover species, the minimal tillage disruption compared to the other rotation systems may have contributed to a modest 2% increase in macro-aggregate development above the 2001 data, whereas the other systems experienced as much as a 15% decline. However, no significant difference was observed on the delta macro-aggregates among the seven systems (Figure 1.4).

Soil Aggregation and Carbon Dynamics

Relating the amount of total soil carbon to the amount of macro-, micro-aggregation and residue contributed carbon input (Figure 1.5) showed an inconsistent pattern of high macro-aggregation when total soil carbon was high as in S5 (with high carbon input) while S4 also had high macro-aggregation, but the amount of carbon input was not significantly different from S1 (Figure 1.5). The high amount of aggregation in S5 could be attributed to the reduce amount of tillage received as wheat was grown across seasons and red clover being frost seeded in the spring (Snapp et al., 2004). Both the carbon input and the aggregation contributed significantly to total soil carbon level, as determined based on the sum of square reduction test (Table 1.5). Residue C input was a moderate predictor of total soil C (31% of variability explained), whereas macro and micro WSAs were significant predictors of total soil C, accounting for 58 and 72 % of observed variability, respectively. Inclusion of macro-aggregation components and the amount of carbon input in the full model was able to explain 83% of the observed variability in total soil carbon.

CONCLUSION

The largest input of carbon was associated with the systems involving corn with or without red clover showing three-fold higher C returned than the S1 winter fallow system. Overall, increasing C inputs through inclusion of wheat and red clover (S5) in a rotation appeared to be an effective means to enhance macro-aggregation and improve soil structure relative to S1. The difference between plots sampled for water stability aggregation after potato and those sampled after an alternative cash crop, although still significant, declined from the 2001 level. Residue C input was a moderate predictor of total soil C (31% of variability explained), whereas macro and micro WSAs were significant predictors of total soil C, accounting for 58 and 72 % of observed variability, respectively. The three-parameter full model was able to account for 83% of the observed variation in total soil carbon in 2004.

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Table 1.1 Mean values and standard errors for soil properties in the potato rotation trial at the Montcalm Research Farm, Entrican, Michigan.

Soil Properties	2001	2004
Elevation (m)	288.2±0.17	
Texture (%)		
Sand	75.4±1.15	
Silt	15.6±0.64	
Clay	8.9±0.62	
Water stable aggregates (WSA, %)		
Macroaagregates	55.2±2.28	48.6±1.08
< 4 - 2 mm	3.98±0.28	5.03±0.50
< 2 - 1 mm	9.10±0.43	10.3±0.45
< 1 - 0.25 mm	41.1±1.07	36.1±0.69
< 0.250 - 0.106 mm	23.1±0.91	24.0±0.66
< 0.106 - 0.053 mm	18.3±0.48	24.1±0.59
Mean weight diameter (MWD,mm)	0.77±0.02	0.92±0.04
Chemical profile (0-8 in depth)		
Phosphorus (Bray1) (ppm)	206±6.47	208±5.60
pH (buffer)	6.37±0.17	6.92±0.01
Calcium (ppm)	403±16.2	390±22.3
CEC (meq g^{-1})	3.86±0.12	4.04±0.19
Potassium (ppm)	128±4.68	163±6.46
PH	5.75±0.16	6.13±0.04
Magnesium (ppm)	84.9±2.03	82.5±2.46
Soil organic carbon (%)	0.68±0.04	0.78±0.06
Base saturation, %		
Hydrogen	23.0±1.20	29.8±0.76
Potassium	7.94±0.30	10.8±0.42
Magnesium	17.5±0.63	18.0±0.62
Calcium	48.4±1.84	48.3±1.47

Table 1.2 Rotation system and winter cover crop treatments used in a 2-year potato experiment at Montcalm Research Farm, Entrican, MI.

Cropping System	Main Crop Rotation	Winter management	Field operations (# 2 years $^{-1}$)
S1 PBSBB	Potato/Snap Bean	Fallow (bare) after Potato and Snap Bean	10
S2 PRSBR	Potato/Snap Bean	Rye after Potatoes and Snap Bean	12
S3 PRSCB	Potato/Corn	Rye after Potatoes, Bare after Corn	11
S4 PWWR	Potato/Wheat	Wheat after Potatoes, Rye after Wheat	8
S5 PWWCC	Potato/Wheat	Wheat after Potatoes, Wheat interseeded with Red Clover in March	7
S6 PRVSBRV	Potato/Snap Bean	Rye + Hairy Vetch after Potatoes and Snap Bean	12
S7 PRVSCRV	Potato/Corn	Rye + Hairy Vetch after Potatoes and Corn	12

Table 1.3 Mean water stable aggregate, macroaggregates (Macro-Agg), total soil carbon (TSC), mean weight diameter (MWD) and standard errors across different size classes and potato rotation systems in 2001 at Montcalm Research Farm, Entrican, Michigan.

Cropping System†	Water Stable Aggregate Size Fractions, %						TSC, %	MWD,mm
	>2 mm	>1 mm	>0.25 mm	>0.106 mm	>0.053 mm	Macro-Agg		
S1 PBSBB	3.3±0.6	9.1±1.1	42.5±1.7	24.5±1.7	19.7±0.8	53.1±3.4	0.63±0.06	0.77±0.06
S2 PRSBR	3.4±0.6	10.0±1.1	43.4±1.6	22.2±1.7	17.8±0.8	56.8±3.4	0.51±0.06	0.79±0.06
S3 PRSCB	4.3±0.6	9.4±1.1	45.1±1.9	19.9±1.9	18.6±0.9	54.7±3.6	0.58±0.06	0.76±0.06
S4 PWWR	5.2±0.6	9.0±1.1	44.2±1.7	21.2±1.6	17.8±0.8	58.7±3.6	0.56±0.05	0.83±0.06
S5 PWWCC	3.4±0.7	9.0±1.1	42.2±1.6	23.5±1.7	19.0±0.8	55.3±3.4	0.63±0.06	0.78±0.06
S6 PRVSBRV	3.7±0.6	8.1±1.1	45.1±1.7	22.2±1.6	19.5±0.8	58.1±3.6	0.61±0.06	0.81±0.06
S7 PRVSCRV	3.4±0.7	9.1±1.1	44.1±1.7	20.1±1.7	18.6±0.8	54.5±3.4	0.59±0.05	0.76±0.06
C Input LCI	4.3±0.5	9.0±0.8	43.3±1.4	22.9±1.2	18.7±0.6	55.9±3.0	0.59±0.04	0.80±0.05
MCI	3.5±0.5	9.1±0.8	44.2±1.4	22.2±1.2	18.6±0.6	57.5±3.0	0.56±0.04	0.80±0.05
HCI	3.7±0.4	9.2±0.7	43.8±1.3	21.2±1.1	18.7±0.5	54.9±2.8	0.60±0.04	0.77±0.04
Entry Year AP	3.0±0.4	7.4±0.7	44.6±1.3	22.6±1.05	19.0±0.4	53.0±2.8	0.56±0.03	0.72±0.04
AACC	4.7±0.4	10.8±0.7	43.0±1.2	21.2±1.00	18.4±0.4	58.8±2.7	0.61±0.03	0.84±0.04
Analysis of Variance								
System	ns‡	ns	ns	ns	ns	ns	ns	ns
HCI vs MCI	ns	ns	ns	ns	ns	ns	ns	ns
HCI vs LCI	ns	ns	ns	ns	ns	ns	ns	ns
MCI vs LCI	ns	ns	ns	ns	ns	ns	ns	ns
Entry Year	***	***	ns	ns	ns	**	ns	***
System x Entry Year	ns	ns	ns	ns	ns	ns	ns	ns

†S1 PBSBB = potato-bare, snapbean-bare; S2 PRSBR = potato-rye,snapbean-rye; S3 PRSCB = potato-rye, sweetcorn-bare; S4 PWWR = potato-wheat-wheat-rye; S5 PWWCC = potato-wheat-wheat/clover-clover; S6 PRVSBRV = potato-rye/vetch-snapbean-rye/vetch; S7 PRVSCRV = potato-rye/vetch-sweetcorn-ryevetch; HCI = high carbon input; MCI = medium carbon input; LCI = low carbon input; AP = after potato; AACC = after alternative cash crop. ‡ns not significant; * significant at ≤0.05; ** significant at ≤0.01; *** significant at ≤0.0001

Table 1.4 Mean water stable aggregate, macroaggregates (Macro-Agg), total soil carbon (TSC), mean weight diameter (MWD), carbon (C) input and standard errors for 7 short potato rotation systems in 2004 at Montcalm Research Farm near Entrican, Michigan.

Cropping System†	Water Stable Aggregate Size Fractions, %						TSC, %	MWD, mm	C Input, $Mg ha^{-1}$
	>2 mm	>1 mm	>0.25 mm	>0.106 mm	>0.053 mm	Macro-Agg			
S1 PBSBB	2.8±0.7	7.7±0.9	31.6±1.7	29.9±1.4	27.1±1.6	43.1±2.2	0.64±0.08	0.73±0.06	0.9±0.2
S2 PRSBR	3.7±0.6	8.0±0.9	35.8±1.7	24.1±1.5	27.3±1.6	47.5±2.2	0.61±0.07	0.81±0.05	2.0±0.2
S3 PRSCB	4.0±0.7	11.7±0.9	36.6±1.7	20.1±1.5	22.7±1.6	55.8±2.2	0.68±0.07	0.84±0.06	2.8±0.2
S4 PWWR	4.2±0.7	12.6±0.9	37.0±1.7	20.9±1.4	23.7±1.6	55.4±2.2	0.63±0.07	0.88±0.06	1.4±0.2
S5 PWWCC	5.1±0.6	12.8±0.9	35.1±1.7	22.7±1.4	21.1±1.6	56.2±2.2	0.77±0.08	0.86±0.05	2.2±0.2
S6 PRVSBRV	3.1±0.7	8.6±0.9	36.9±1.7	25.9±1.4	24.4±1.6	49.7±2.2	0.65±0.07	0.93±0.07	1.9±0.2
S7 PRVSCRV	4.2±0.7	11.0±0.9	39.7±1.7	22.2±1.4	22.1±1.6	55.7±2.2	0.66±0.07	0.88±0.06	3.3±0.2
C Input LCI	3.5±0.5	10.1±0.7	34.3±1.3	25.4±1.0	25.4±1.2	49.3±1.6	0.64±0.05	0.80±0.04	1.2±0.1
MCI	3.4±0.5	08.3±0.7	36.4±1.3	25.0±1.0	25.9±1.2	48.6±1.6	0.63±0.05	0.80±0.04	2.0±0.1
HCI	4.4±0.4	11.8±0.6	37.1±1.2	21.7±0.8	22.0±1.1	55.9±1.3	0.70±0.05	0.86±0.03	2.8±0.1
Entry Year AP	3.8±0.4	9.3±0.6	37.8±1.1	23.9±0.8	23.1±1.1	52.7±1.2	0.67±0.04	0.85±0.03	2.0±0.1
AACC	3.9±0.4	11.4±0.6	34.4±1.1	23.5±0.8	25.1±1.1	51.1±1.2	0.66±0.04	0.81±0.03	2.2±0.1
Analysis of Variance									
System	ns‡	***	**	***	**	***	ns	ns	***
HCI vs MCI	ns	***	ns	*	**	**	ns	ns	***
HCI vs LCI	ns	*	ns	**	**	**	ns	ns	***
MCI vs LCI	ns	*	ns	ns	ns	ns	ns	ns	***
Entry Year	ns	***	***	ns	*	ns	ns	ns	ns
System x Entry Year	ns	ns	Ns	ns	ns	ns	ns	ns	ns

†S1 PBSBB = potato-bare, snapbean-bare; S2 PRSBR = potato-rye,snapbean-rye; S3 PRSCB = potato-rye, sweetcorn-bare; S4 PWWR = potato-wheat-wheat-rye; S5 PWWCC = potato-wheat-wheat/clover-clover; S6 PRVSBRV = potato-rye/vetch-snapbean-rye/vetch; S7 PRVSCRV = potato-rye/vetch-sweetcorn-ryevetch; HCI = high carbon input; MCI = medium carbon input; LCI = low carbon input; AP = after potato; AACC = after alternative cash crop. ‡ns not significant; * significant at ≤0.05; ** significant at ≤0.01; *** significant at ≤0.0001.

Table 1.5 Sums of squares reduction test of full and reduced model for total soil carbon as a function of carbon input and proportion of water stable aggregates from a potato short rotation cropping system study at the Montcalm Research Farm near Entrican, Michigan.

Model†	$R^{2‡}$	SS	df	MS	F_{obs}	P
Full	0.83	1.56	37	0.04		
Reduced						
C input	0.31	6.36	42	0.15	22.81	0.01
Stable Macroaggregates	0.58	3.97	42	0.09	11.44	0.01
Stable Microaggregates	0.72	2.65	43	0.06	4.33	0.01

† Regression analyses with full model consisting of macro-, micro- aggregates and C input with reduced model referring to single factor regression analyses involving each of the three independent factors; ‡ R^2 = coefficient of determination; SS = sum of squares; df = degrees of freedom; MS = mean square; F_{obs} = observed F statistics; *P* = probability

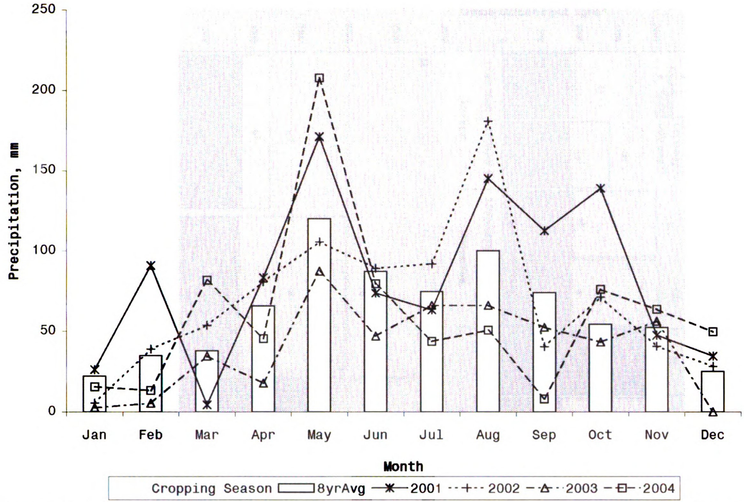

Figure 1.1 Total monthly precipitation at Montcalm Research Farm near Entrican, Michigan for 2001 - 2004, and the 8-year average. Annual precipitation was 991, 827, 478, and 735 mm for 2001, 2002, 2003 and 2004 respectively.

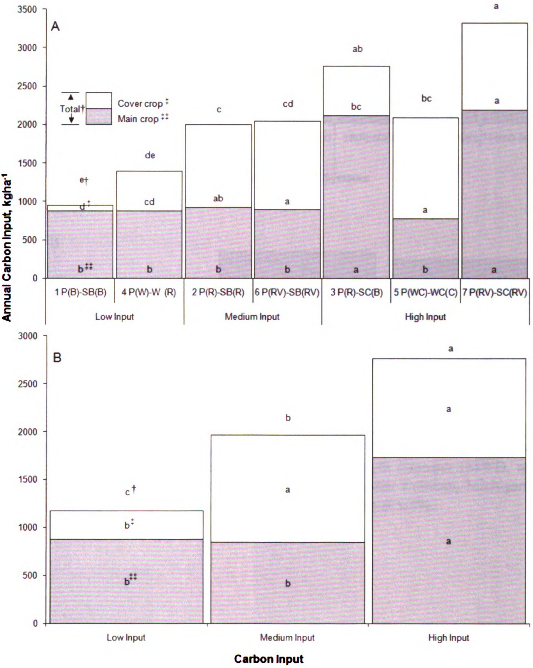

Figure 1.2 Carbon inputs from 7 potato rotation systems (A) and averaged across systems for pre-planned contrasts, S1 and S4 for the low input category, S2 and S6 for the medium category and S3, S5 and S7 for the high C input category (B). The potato rotation systems are described in the text, and C inputs included above- and below-ground organic material averaged over two years (i.e., 2003 and 2004). Bottom, middle and upper letters designate statistical significance for main crop, cover crop, and total C input across but not within systems. Columns with similar letters are not significantly different at 5%.

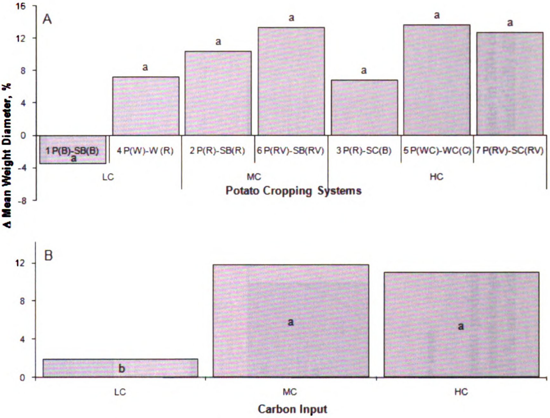

Figure 1.3 Influence of seven short rotation management options for potato production systems (A) and low (LC, 1.2 $Mgha^{-1}$), medium (MC, 2.0 $Mgha^{-1}$), and high (HC, 2.8 $Mgha^{-1}$) C input (B) on the percent change of mean weight diameter (MWD, mm) in 2004 compared to 2001 at the Montcalm Research Farm near Entrican, Michigan. Bars with the same letter designation are not statistically different at ≤ 5%.

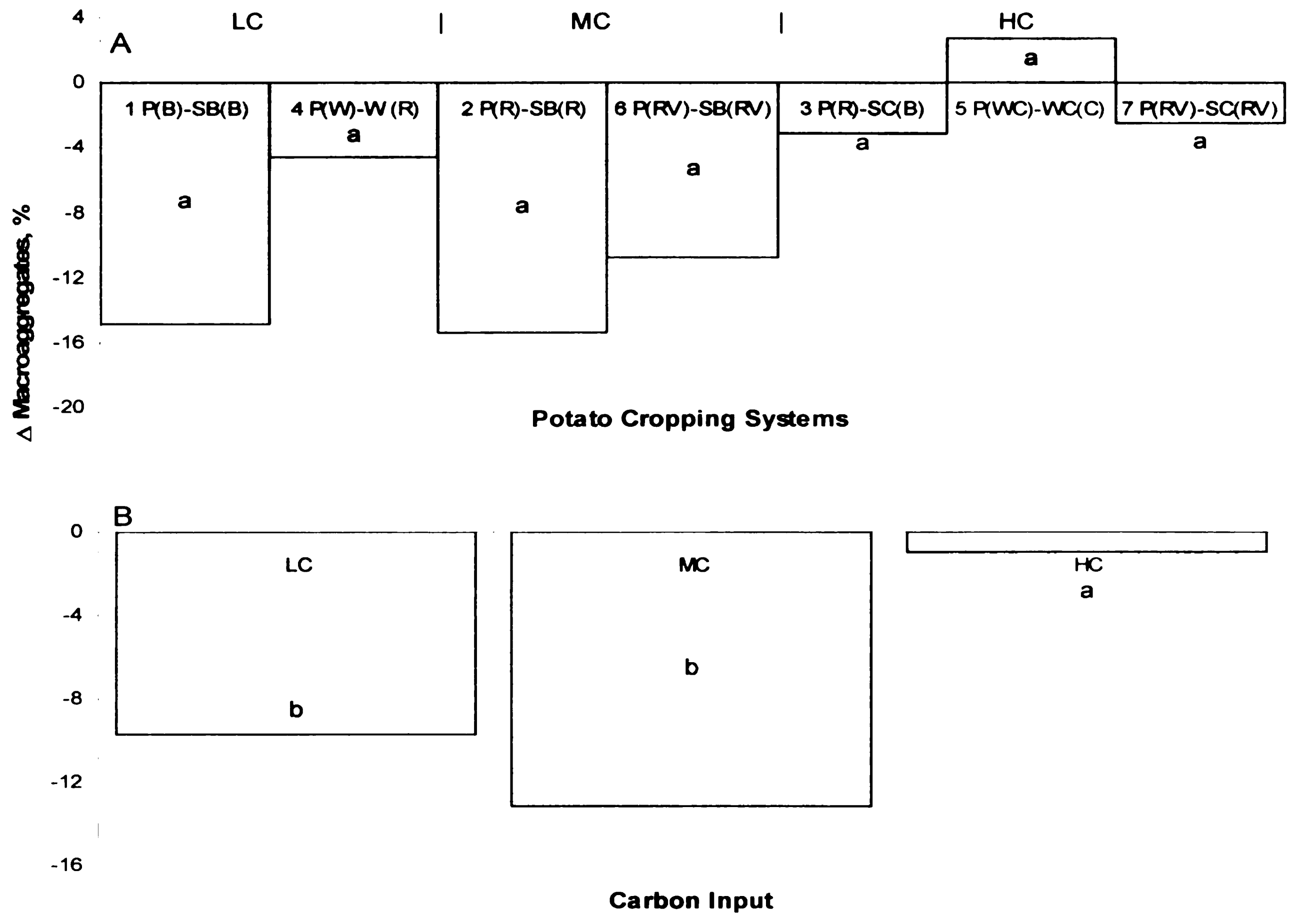

Figure 1.4 Influence of seven short rotation management options for potato production systems (A) and low (LC, 1.2 $Mgha^{-1}$), medium (MC, 2.0 $Mgha^{-1}$), and high (HC, 2.8 $Mgha^{-1}$) C input (B) on the percent change of mean macroaggregates in 2004 compared to 2001 at the Montcalm Research Farm near Entrican, Michigan. Bars with the same letter designation are not statistically different at $\leq 5\%$.

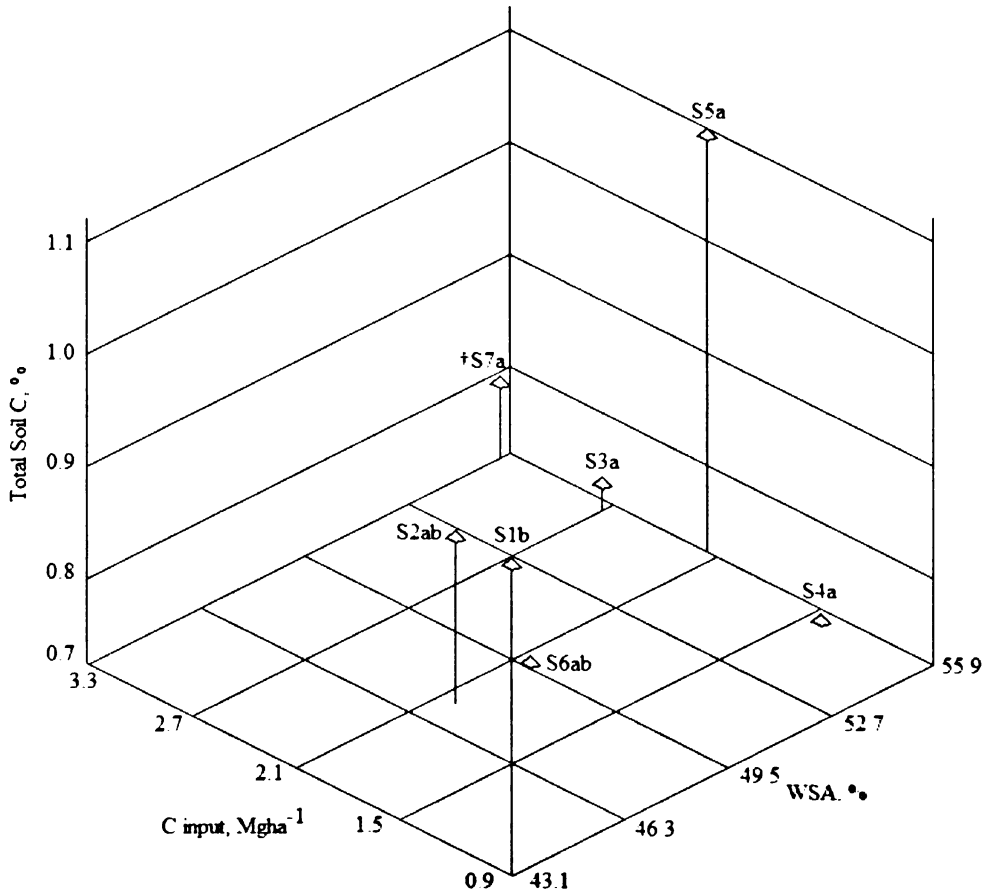

Figure 1.5 Plot of total soil carbon (C, %), carbon input, and water stable macroaggregates (2-0.25 mm diameter) from a potato short rotation cropping system study at the Montcalm Research Farm near Entrican, Michigan. Letters refer to comparisons in water stable aggregates. Systems with similar letters are not statistically different at 5%. †S1 PBSBB = potato-bare, snapbean-bare; S2 PRSBR = potato-rye,snapbean-rye; S3 PRSCB = potato-rye, sweetcorn-bare; S4 PWWR = potato-wheat-wheat-rye; S5 PWWCC = potato-wheat-wheat/clover-clover; S6 PRVSBRV = potato-rye/vetch-snapbean-rye/vetch; S7 PRVSCRV = potato-rye/vetch-sweetcorn-ryevetch;

CHAPTER II: THE RELATIONSHIP OF SOIL PHYSICAL CHARACTERISTICS TO YIELD IN INTENSIVELY MANAGED FIELDS

ABSTRACT

Growers and crop management advisors need information on the major yield determinants across the landscape in order to explain observed yield heterogeneity. A study was conducted in two Michigan commercial fields, designated as fields 1 and 2 in 2003 and 2004, respectively, to evaluate the contribution of water stable aggregates (WSA), soil nutrient status and crop spectral response to potato yield variability. The study area was divided into grids with an effective area equal to 0.05 hectare. In 2003, 108 grid points were sampled from Field 1 to a depth of 10 cm for soil chemical properties and WSA. Prior to potato harvest, plant spectral status was sampled using a customized camera setup. The same was protocol was applied to the second field but this time only 100 grid points were sampled. Stepwise multiple regression was able to account for 66% and 60% of the yield variance Field 1 and 2 respectively. Principal component regression (PCR) analyses had a lower yield variance of 64% and 44% for the same fields. PCR further confirmed the significant contribution of WSAs to potato yield in both fields while spectral plant response was identified as a significant principal component for Field 1. The positive contribution of WSAs to yield indicates the need to manage this aspect of the cropping environment, especially when the chemical requirements of the plants have been comprehensively addressed. The positive role of spectral measurement in predicting potato yield provides a useful monitoring tool.

INTRODUCTION

Farmers use various management tools to address pest, water, soil fertility and related issues, but the underlying variability of soil physical properties are more challenging to manage. Growing potatoes involves a host of variables that one has to understand and properly manage to achieve consistently high yields. Proper fertilization at the onset and during the cropping season; pest and disease management; irrigation timing and schedule, are just a few of the complex factors that result in a bumper potato harvest. Despite the wealth of information and expertise that go into producing a crop of potatoes, variability in yield is still considerable (Verhagen et al., 1995).

Variation in growing conditions and plant response across a field leads to substantial within-field yield differences. In the Netherlands, Verhagen et al. (1995) observed potato tuber yields across a field ranged from 30 to 45 $Mgha^{-1}$. At the Prince Edward Island in Canada, Dehaan et al. (1999) reported an even greater potato yield variability of 11 to 59 $Mgha^{-1}$ based on 7325 observations on an 18 ha field. Cambouris et al. (2006) identified two management zones within a field with 5.9 $Mgha^{-1}$ potato yield differences. Variability caused by erratic water management could mean potato yield difference of 2 $Mgha^{-1}$ (Balchin, 1958). In other crops, within-field variability for corn (*Zea mays* L.) can range from 3.5 to 8.5 $Mgha^{-1}$ or higher an in wheat (*Triticum aestivum* L.), yield can range from 2 to 6 $Mgha^{-1}$ (Mulla and Schepers, 1997).

A number of research strategies are available to deal with yield variability, and usually involve multiple year data analysis. There are many studies dealing with yield variability from the point of view of identifying and preserving observed stable patterns of yield variability and managing identified zones, accordingly (Lark and Stafford, 1998; Taylor et al., 2001; Dobermann et al., 2003; Pringle et al., 2003; Zaman and Schumann, 2006). Cambouris et al. (2006) used an electrical conductivity meter to identify potato management zone within a field that apparently looked uniform, but had considerable yield variability of 5 $Mgha^{-1}$. These studies do not attempt to achieve the same level of productivity across the entire field. On the other hand, studies exist that focus their analyses across the landscape spatial variability without forming management zones (deHaan et al., 1999; Kravchenko et al., 2005; Pettersson et al., 2006).

There are tremendous numbers of potentially important yield determinants. Classifying factors of production into physical and chemical factors could allow the complexity of crop production to appear more manageable from a producer's point of view. The importance of various nutrients to growth and performance of crops is well recognized. Nutrient status is a major production factor, and is usually the first to be addressed in a commercial field setting, as crops respond markedly to nutrient inputs. Despite such efforts to address all nutritional requirements of crops through best management practices, considerable variation still exists in terms of distribution of yield across the landscape.

Irmak et al. (2001) used a decision support system CROPGRO-soybean to improve yield prediction over a field divided into 60 grids. This was a data intensive model requiring information relative to climatic, basic soil information and chemical nutrition, yet correlation between predicted and actual yield was very low at 16%, averaged across the two years covered by the study. Analysis conducted on a per year basis even showed a dismal 1 to 2% correlation coefficient. To improve the regression coefficient, the authors classified the grid locations into the following categories: with and without drainage problems; greater and lower than 2% slope; and a classification scheme based on the moisture retention capacity of soil. Impact of variable physical characteristics of the growing environment was very apparent, with correlation coefficient fluctuating from 90% and above, to 10%. Redulla et al. (2002) pointed out the prominent influence of soil texture on potato yield compared to soil chemical properties. Mackenzie et al. (2000) noted the effect of inadequate moisture on specific gravity decrease and larger-sized of potatoes than when moisture was adequate. Paz et al. (1998) indicated that as high as 69% of soybean yield variability was due to water stress.

Soil structure is an important link in the functioning of the soil-plant-atmosphere continuum, and ultimately impacts yield performance of crops. Cambardella et al. (1996) reported on the relationship between specific soil physical properties and yield variability in a corn-soybean rotation field. Aggregate size distribution contributed significantly as a predictor of yield in five of the seven years of the study. The relationship with yield was not consistent, with 3 out of the 5 years being positive, while negative for the remaining 2 years. An effective way to put these results in perspective is to look at the effect of weather. However, details provided by the study on weather behavior were not available. Arshad and Coen (1992) proposed aggregate stability as one soil physical property that can serve as an indicator of soil quality status. This proposition is not difficult to understand, considering soil structure has an important role to play in such vital crop requirements as moisture availability and aeration, as well as ionic exchange in the soil colloid.

Growers and crop management advisors need improved information on the major yield determinants across the landscape in order to explain observed yield heterogeneity. For example, how much predictive value do soil nutrients have, as opposed to soil physical and biological factors, in terms of the final tuber yield and quality? Redulla et al. (2002) examined the field scale variability of soil physical and chemical factors and its effect on potato yield variability of four fields in Southeastern, Washington. The Pearson correlation coefficient carried out between yield and soil properties resulted in the majority of the pair-wise combinations not being statistically significant. Point yield data was significantly correlated with sand and silt in only one field. Yield in another field was significantly correlated with clay, another component of texture. Stepwise regression conducted on each of the four fields produced unique predictive equations. No uniform set of variables was found to predict point yield, total count, and specific gravity across the fields. In those four fields, soil texture components were the predominant predictor variables compared to nutrient levels, with clay having a positive contribution, and sand, a negative one. The authors surmised that available soil water content was influenced by texture, and this could be the driving factor that accounted for soil texture effects on potato yield, even in these irrigated systems (Redulla et al., 2002).

Topographic features may be closely related to the heterogeneous distribution of factors of production. Potato management zones identified by Cambouris et al. (2006) were based on a collection of soil water regime parameters including water holding capacity, thickness of surface sandy soil and depth of water table. Also in potato, deHaan et al. (1999) found a significant reduction in yield, higher incidence of smaller tubers, as well as loss of soil particles from areas where there was a considerable drop in elevation compared to other areas, in a study conducted at Prince Edward Island in Canada. The authors contend that elevation was not the direct causative factor for the observed reduction in yield, but rather the associated soil degradation brought about by erosion. Phiri et al. (1999) reported a minimal landscape position effect on nitrate content of the soil in a study involving corn in a Southern Africa's steep watershed. Kravchenko et al. (2000) noted the higher accumulation of organic matter in low-lying areas compared to relatively higher positions in the landscape for a field under corn-soybean rotation. Organic matter and phosphorus concentration were negatively correlated with elevation of an area characterized as mixed tall-short grass prairie (Ovalles and Collins, 1986; Aguilar and Heil, 1988).

Traditional soil sampling calls for a limited amount of samples mainly due to cost and time constraints. Availability and utilization of technology that can increase the number of samples if it is feasible and economic to take, will minimize interpolation error between points, and enable a closer examination of the relationship with yield, as generated by geo-position linked yield monitors. Apparent electrical conductivity (EC_a) meter and remote sensing are potentially two such technologies. Rhoades et al. (1989) indicated three ways with which electrical conductivity values measured by an EC instrument was made possible. Electrical current can flow through the hygroscopically held water molecule around the soil particles and a couple of molecular thickness beyond. An electrical charge can be initiated through a continuous aqueous soil solution, as is the case when EC is measured in the laboratory. The third pathway, in the absence of strong hygroscopic properties (as may be the case in sandy soil), electrical conductance may still be possible through movement of electrical charge over soil particles in direct contact with each other. Rhoades et al. (1989) presented EC_a as the summation of the apparent electrical conductivity contributed by exchangeable cations present on, or integrated into the clay mineral structure in addition to metallic minerals, a transmission coefficient, the electrical conductivity of the soil solution and the soil volumetric water content.

Kitchen et al. (2003) employed four analytical methodologies to determine the role of apparent electrical conductivity (EC_a) and topographic features that contributed to yield variability in corn, soybean and wheat. All four approaches demonstrated that EC_a and topographic soil features are important in accounting for yield variability. However, the authors pointed out that in analyzing specific site year data, it is important to take into consideration climate, crop type and specific field characteristics to interpret yield and electrical conductivity relationships. Kravchenko et al. (2003) used a similar electrical conductivity sensor (Veris 3100), and found a strong spatial correlation between electrical conductivity and soybean yield in Michigan. Cambouris et al. (1999) used a geonomic electrical conductivity meter to probe a uniform field for differences in soil moisture regime and successfully identified two distinct management zones with varying potato yield potential.

The use of remote sensing provides another source of fine resolution data to characterize yield potential. Hunt et al. (2005) used a consumer grade digital camera and had variable success in relating biomass of corn, soybean and alfalfa to a normalized green-red difference index with computed regression coefficients of 88%, 39% and 47%, respectively. Adamsen et al. (1999) conducted research in wheat and obtained a correlation coefficient of 96% with green-red ratio computed from digital imagery, with the more traditional measure of vegetation, namely normalized difference vegetation index (NDVI). The green-red ratio was also correlated (91%) with a leaf greenness instrument, Minolta-SPAD meter (Ramsey, NJ).

The objectives of this study were to quantify the relative importance of chemical and physical factors in predicting potato tuber yield. In particular, the contribution of soil structure attributes of water stable aggregate and mean weight diameter, digital spectral characterization and nutrient status were related to potato yield variation.

MATERIALS AND METHODS

Location

The study was conducted on two commercial potato production fields managed by the same farm operator and designated as fields 1 and 2, and sampled 2003 and 2004, respectively. The first field was a 43.5 hectares commercial production field that had been in a potato-based rotation for the past 60 years. Rotation crops included corn (*Zea mays L.*), dry beans (*Phaseolus sp. L.*), and wheat (*Triticum aestivum L.*) Most recently, the rotations of potato (*Solanum tuberosum L.*) cultivars grown in this field included Pike with cereal rye (*Secale cereale L.*) as a cover crop in the winter in 2001, and FL 1833 followed by wheat and rye as cover crops in 2003. It is located at 84°57' longitude and 43°26' latitude, Vestaburg, Montcalm County, Michigan, USA. The second field was a 20.7 hectares commercial field located at 84°52' longitude and 43°26' latitude. For the past 30 years crop rotation practices were similar to those of the first field. When this field was sampled in 2004, it was planted with the FL 1879 potato cultivar and a rye winter cover crop. Two years before, it was planted with Pike and a rye winter cover crop followed by snap beans with wheat as winter cover crop the following year.

Climatic and Soil Conditions

Figure 2.1 shows 6 out of the 9 months of active crop growth period having a higher precipitation in 2004 than in 2003. However, beginning July and up to September, the amount of precipitation in 2004 was lower than in 2003. For both years, precipitation in this time frame was below the 135- and 8- year average. A center pivot irrigation system covered each field, rotating 360° in 24 hour and applying ~1.9 cm of moisture each rotation.

Both fields were composed of Mancelona loamy sand soil series with 0-2% slope (Mb) (Figures 2.2 and 2.3). A small section of field 1 was a variant of the Mancelona loamy sand (Mc, 2-6% slope), as well as Newaygo sandy loam (Nm, 2 to 6% slopes), although this particular soil series was not present in the monitored section of the field. About three quarters of the field 2 field was composed of a complex of Gladwin loamy sand and Palo sandy loam (Ga), with the remainder being Mb. Outside the study area, but still within the field's boundary, was an Epoufette loamy sand and Ronald sandy loam (Ec, 0-2%). Mb and Mc were characterized as well-drained, while Ga was somewhat poorly drained (Schneider, 1960).

Overall soil characteristics showed that field 2 had 50% more organic carbon and 44, 32, and 16% less potassium, magnesium and Bray-1 phosphorous, respectively, than the first field. Field 2 had 8% more sand particles (823gkg^{-1}), 18% lower amount of clay (57.4 gkg^{-1}) and 28% less silt (119.6 gkg^{-1}), as well as higher amounts of macroaggregates (≥0.25 mm aggregate size), 1 and 2 mm water stable aggregate components, compared to field 1 (Table 1). Average volumetric moisture content across the grids was higher in in the first field (15.8%) than in the second field (11.51%).

Sampling Design

Historical soil sample characterization data taken from the study area in previous cropping seasons were used to formulate the sampling design. For field 1, the average ratio of samples per hectare used historically by crop advisors was 1.7:1 for the determination of percent organic matter, phosphorus, potassium, magnesium, calcium, pH, cation exchange capacity (CEC), and zinc. The study area was located at the center of the field where the slope was minimal, to minimize the effect of topography on the potato yield. Prior geographically referenced sampling points for field 2 had a ratio of 2.9 samples for every hectare (Otto, 2004 personal communication).

Field 1(Figure 2.2) was divided into 108 sections, each consisting of 16 rows (spaced at 0.89 m apart) on the northern and southern sides, and approximately 9 m both on the east and west sides from the center of the section, making the effective area equal to 0.05 hectare. Thus, the ratio of sampling points per hectare was 20:1, compared to the earlier ratio of 1.7:1. In a similar manner, a total of a hundred grid points were sampled from field 2 (Figure 2.3).

Sampling for Water Stable Aggregates

Soil samples for water stable aggregate analyses were taken a couple of days before harvest on September 18, 2003 and September 11, 2004 for fiedds 1 and 2, respectively. The composite samples were taken from a 4 meter radius around each grid point to a depth of 10 cm using a trowel. Care was exercised not to unduly compact the soil, and to protect the samples, cardboard boxes were used in transporting and storing them. Extraneous materials such as plant residues and gravel from the soil aggregate samples were removed with the use of an 8 mm sieve, and the samples air-dried for a number of days until they equilibrated with atmospheric water content. The soil sample was sieved using a layer of sieves, with the top having a screen opening of 8, 6.2, 4, 2 mm and a catch pan at the bottom. Rocks, gravel and extraneous materials remaining on the 8 mm were discarded. Soil aggregates that remained on top of the 6.2, the 4 mm, the 2 mm and those contained in the catch pan were placed in separate containers and labeled as the 6.2-4.0 mm, 4.0-2.0 mm and < 2 mm sieve sizes. Results reported here referred to water stable aggregate stability of the 4.0 to 2.0 mm size fraction. Water stable aggregate analysis was previously described in Po (2007).

Chemical and Mechanical Analyses

A representative subset of the samples that passed through the 2 mm sieve during WSA sample preparation were ground to powdery consistency for 2 minutes using a Shatterbox Rotary Grinder (Spex Ind., Edison, NJ). Samples for total carbon and nitrogen analysis were prepared from the ground soil by weighing 60 to 70 micrograms to a tin capsule. Crimped tin capsules were submitted to the Stable Isotope Laboratory at the University of California at Davis for total Carbon and Nitrogen analyses using a Europa Hydra 20/20 isotope ratio mass spectrometer (Europa Scientific, Crewe, UK).

Another representative subset of the < 2 mm samples were sent to and analyzed by A&L Great Lakes laboratories (Fort Wayne, IN) for chemical and texture analysis, including determination of available phosphorous, exchangeable potassium, magnesium, calcium, soil pH, buffer pH, cation exchange capacity (CEC), percent base saturation of cation elements and texture components of sand, silt and clay. Results of phosphorous analyses were expressed as a weak Bray (P1) derived from Mehlich-3 through a regression equation (Calhoun et al., 2002).

In-situ Measurement

The volumetric soil water contents were measured from field 1 and 2 prior to soil sampling on September 17, 2003 and September 10, 2004, respectively using a Trime time domain reflectometer moisture probe (Ettlingen, Germany). Five measurements were taken from each grid points and the average per grid point calculated to represent soil moisture status for each measurement date. Relative soil health was measured using the Veris mobile sensor platform (Veris Technology, Salina, KS) by apparent electrical conductivity (EC_a) and pH during the spring of 2004 (April 20, 2004) in for field 2. Briefly, an electrical pulse is released to the soil through a pair of rotating discs separated by ~57 cm that penetrates the soil to a depth of 6 cm. Voltage drops in the electrical pulse traveling through the soil matrix were measured, and EC_a computed to effective depths of 30 cm (Sudduth et al., 2003).

Bulk density and Infiltration

Laboratory measurements were conducted on soil cores obtained using an aluminum cylinder 7.62 cm in diameter and 7.62 cm inches in height, for bulk density (Blake and Hartge, 1986) and infiltration (Li et al., 2005). The cylinders were randomly installed within 6 transects running from East to West in field 1. A mini-disc infiltrometer from Decagon (Pullman, Washington) with a 6.0 cm suction was used to calculate the unsaturated hydraulic conductivity at each of the grid point where the cylinders were collected. Calculation for unsaturated hydraulic conductivity was adopted from Zhang (1997) where the square root of time was obtained for each set of infiltration readings, and then plotted on the x-axis with volume of water infiltrated on the y-axis. The resulting point distribution was fitted into a second order polynomial and a trend line equation projected using Excel v7 (Microsoft, Redmond, Washington). The coefficient of the squared independent variable (square root of time) was utilized to compute the hydraulic conductivity of the soil. After the hydraulic conductivity measurements were completed, the soil cores were dried in a convection oven for 24 hours, weighed and bulk density calculated using the core method outlined by Blake and Hartge (1986).

Spectral Pictures

An Olympus 340R (Melville, New York) digital camera was utilized to obtain red, green, and infrared images at each of the grid points in field 1 and 2 on August 31, 2003 and August 28, 2004, respectively. Two sets of images were taken per gridpoint, where each consisting of a normal, automatically obtained image and an infrared image using a pass through-filter. Using the camera without a filter in front of it resulted in a picture with pixels composed of a combination of the red, green and blue parts of the spectrum. To extract the green, red and infrared parts of the spectrum, Paint Shop Pro 8 (Ottawa, Ontario, Canada) was used along with a macro program to facilitate the processing of hundreds of pictures in a short time. The extracted green, red and infrared band images were used as input to IDRISI for windows v. 1 (Worcester, Ma) to compute the mean average value of the image pixels (Figure 2.4).

Yield Monitor Data Collection

Potatoes were dug from the field using 1 8-row and 2 4-rows digger. A harvester equipped with an electronic yield monitor (Harvest Master Yield Mapping System for Bulk Crops, HM-500; HarvestMaster, Logan, UT) logging data every two meters (in field 1) and every four meters in field 2 on average, followed the tandem of diggers and loaded tubers into trucks. A total of 1071 datapoints were generated for field 1and roughly half that quantity of 633 for field 2. A tandem of 1 eight row and 2 four row diggers can scoop up 16 rows as it moves from east to west and vice-versa. Therefore, for each grid point, two passes of the harvester were required to cover the total of 32 rows representing each of the 108 grids in field 1 and 100 grids in field 2.

Statistical Analysis

To test the hypothesis that physical factors explain more of the observed variability in potato yield than chemical nutrient level in a commercially run operation, correlations and multiple stepwise regressions were carried out on all soil variable data collected as independent factors, and yield as the dependent factor. To minimize multicollinearity, iterative sequences of computations were conducted through Proc Reg of SAS v.9.1 (SAS 2006, Cary, NC) with the variance inflation factor (VIF) option selected. At each loop, the variance inflation factor (VIF) was monitored and any assumed predictive variable with a VIF of more than 10, an indicator of multicollinearity (Gunst and Mason, 1980; Neter et al., 1989; Hair et al., 1995), was removed from the succeeding computations. The iteration stopped when all assumed predictive variables had VIF's of less than 10. As an alternative approach to handling multi-collinearity, principal component regression was performed using Proc Princomp of SAS.

The significant contribution of physical, chemical and plant response was evaluated through the sum of squares reduction test (Schabenberger et al., 1999; Perez and Kogan, 2003). The ratios of the difference between the sum of squares of the reduced model consisting of single factors of physical, chemical and plant response and the full model involving all of the afore-mentioned factors divided by the difference in the degrees of freedom and the mean square of the reduced model was used as observed F, and compared to tabular F. Presence of a significant observed F indicated the importance of the full over the reduced model.

RESULTS AND DISCUSSION

Spectral Response

The physiological state of the potato crop can impact its interaction with light energy. This interaction provides a feedback mechanism that moderates plant vigor and acts as an independent parameter that influences potato yield. Although digital images were taken at approximately the same time - August 28, 2004 and August 31, 2003 for field 1 and 2 respectively, field 1 had more reflectance in both the unadjusted and adjusted images for the green band (15 and 91%), compared with field 2. On the other hand, the amount of red and infrared reflectance was higher in field 2 than in field 1 for the unadjusted images (92 and 387%, respectively). The higher level of red and infrared in field 2 could be attributed to a high proportion of non-vegetated area, with field 1 having 50% vegetation cover compared with 5% in the second field (Table 2.1). The seeming discrepancy in the vegetation cover between the two fields may be due to differences in timing of planting and potato senescence. Field 2 was planted nearly two weeks earlier (April 29, 2004 vs May 13, 2003) and harvested over a week later than the other field (October 3, 2004 vs September 24, 2003), and had less than ideal soil moisture status towards the latter part of the growing season compared to field 1, which may have accelerated senescence (Figure 2.1). The increased reflectance of the red portion of the visible spectrum was expected. As plant integrity declines, so does the absorptive potential of the biologically active far red phytochrome (PFR), as well as those of the chlorophyll, as senescence exponentially increase over time (Lamb, 2000). The considerable variation in the infrared values between field 1 and 2 could be due to a different cut-off filter used in field 1, with a higher limit of 0.9 nm compared to 0.7 nm in field 2. With vigorous vegetation, infrared light reflection should be high and a corresponding decrease observed as senescence started to set-in (Lamb, 2000). However, no comparative infrared values were taken over the same infrared filter cut-off in both fields and therefore interpretation was only confined to relative differences among the grid points in field 1 and 2 at the end of bulking stage for this particular spectral band. Average infrared values from digital orthophoto were taken at two different dates (April 13, 1999 [field 2]; April 4, 1998 [field 1]), yet showed a minimal difference between the two fields.

Vegetation indices utilizing distinct bands of the electromagnetic radiation spectra have been used to indirectly evaluate plant health and vigor (Seidl et al., 2004). In the absence of a sophisticated spectral measuring device, the green band of a digital image had been utilized as a proxy for infrared (Hunt et al., 2005), since both are strongly reflected by a healthy plant. However, correlation analysis by Yang et al. (2000) indicated a weak and variable correspondence between infrared and green spectral bands, with the highest value obtained at 69DBH (49%) of grain sorghum and declining thereafter to as low as –19% 14DBH.

As vegetation senesces and dries up, the red part of the electro-magnetic spectrum is no longer absorbed, causing an increase in the reflectance of this spectrum to be picked up by digital imagery. Adamsen et al. (1999) showed 10 to 30% more green light than red light being picked up by a digital camera at 41 days before harvest (DBH) in wheat. At the end of the image acquisition period (9DBH), the amount of red was equivalent, if not greater than that of the green light. In both field 1 and 2, green and green by red ratio, respectively, positively explained potato yield.

Field 1, with a significantly higher vegetative cover, had a 124% higher Green by Red ratio compared to field 2 (Table 2.1). At this late stage in the growing period (tuber maturation phase, 24DBH/110DAP [field 1]; 36DBH/121DAP [field 2]), the presence of actively growing vegetative parts could be disadvantageous to yield, since it could divert photosynthates from reallocating to the tuber from the shoot. However, in this case of field 1, the contribution of the unadjusted green band to yield prediction was positive (Figure 2.5). This indicated the presence of high vegetation cover (Table 2.1) but not as a result of new vegetative growth; rather, it was vegetation at its peak of photosynthate production capability.

Yield Predictors

To allow meaningful interpretation of multiple regression equations on the behavior of a dependent variable as a function of independent variables, each explanatory variable must not be collinear or interdependent (Draper and Smith, 1981). Repetitive removal of base predictive variables with unacceptable variance inflation factor (VIF) is a means of addressing this collinearity challenge. VIF is an indicator of severe multicollinearity if more than 10 (Gunst and Mason, 1981; Neter, et al., 1989; Hair et al., 1995). In earlier studies, use of VIF has been used to reduce the total number of assumed predictive variables by 50% (Kok and Veldkamp, 2001; Griffith et al., 2002). There were 15 common variables in both field 1 and field 2 that did not contribute to multicollinearity. A total of 23 predictor variables were selected from the original pool of 42 for field 1, and 21 for field 2 from a pool of 40. After the initial stepwise regression analysis was conducted on the selected pool of predictor variables for each field, 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 to yield prediction, and consisted of bulk density and infiltration rate for field 1, and apparent electrical conductivity for field 2.

The final stepwise regression equation for field 1 explained 67% of potato yield variability. Physical, chemical and spectral variables included in the equation were aggregate stability (mean weight diameter), microelevation, soil texture (the amount of clay), the unadjusted green band, and potassium level (Figure 2.5). 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.

A different situation existed for field 2. Initially, the stepwise regression included mean weight diameter, the red unadjusted band of the digital images, and the base saturation portion of hydrogen all accounting for 44% of the observed potato yield variability. Inclusion of EC_a not only increased the explained variability to 60% (Figure 2.6), but it removed all of the identified yield predictors and replaced it with the green and red unadjusted band ratio, and 0.25 mm water stable aggregate size fraction in the predictive equation (Figure 2.6).

The inclusion of two different proxies of soil structure (i.e., mean weight diameter and 250 mm water stable aggregate) in the yield predictive equation at both fields, show the significant contribution of soil structure to the positive dynamics of soil, plant and environment continuum, resulting in enhanced potato yield. It is interesting that parameter estimates for both soil structure proxies were positive. Field 2 was composed of a soil series that were prone to drainage problems, and 2004 was a relatively wet year (compared to 2003), yet moisture retention may have been a problem, as it was strongly correlated with yield (Table 2.2). On the other hand, field 1 had a higher clay content and soil structure (i.e., mean weight diameter) was able to improve moisture flow, complementing the positive contribution of clay to adsorb water molecules. The year 2004 was associated with reduced precipitation, up to 50% of the long-term average for some months (as low as 75% reduction compared to mean precipitation for September; Figure 2.1). This occurred during the critical phase of tuber enlargement and maturation. Thus, any mechanism that promotes the retention of moisture may contribute positively to potato yield.

To demonstrate that soil structure was part of a complex system of interacting variables that may show synergistic effects, examination of the correlation matrix (Table 2.) was undertaken. In field 1, the amount of clay significantly contributed to the predictive power of the stepwise regression model. Redulla et al., (2002) concluded as well that the amount of clay was associated with well-aggregated soil, and positively contributed to potato yield. On its own, soil structure indices 0.25 mm and MWD showed minimal correlation coefficient with yield, yet these characteristics contributed positively to the final yield prediction equation. In a crop modeling study using CropGro-Soybean, soil structural condition contributed to a significant increase in correlation coefficient between predicted and actual soybean yield. Without consideration of the underlying drainage condition, the correlation coefficient was at a low of 16%, but when the same analysis was done on a subset of data-points from well-drained portions, the resulting correlation coefficient was raised significantly to 98% (Irmak et al., 2001). Even in areas with drainage problems, the correlation coefficient was 59%, showing the significant impact of soil structure on yield.

The relative position of the potato crop in terms of micro-elevation across the field is important, under both excess and deficient moisture conditions (Schneider et al., 1997). Records for 2003 (Figure 2.1) showed a relatively higher precipitation compared to 2004 towards the end of the potato growing season. This may have caused localized flooding conditions leading to detrimental effects to potato root and tuber growth, which is highly sensitive to oxygen deprivation in saturated soil (Curwen, 1993). This could potentially lead to a decline in field 1 yield. However, the positive contribution of micro-elevation to predicting potato yield in field 1 indicated that plants located at relatively higher micro-elevation sites were able to optimize growth and development. Such optimization was manifested in more vigorous growth, indicated by green reflectance, and overall had a positive contribution to yield. Excess moisture appeared to be mitigated by the relative location of the potato plant at higher micro-elevation sites.

The role of potassium in the growth and development of tubers varies with the intended market. Where the amount of solids is critical for processing potatoes, potassium needs to be monitored closely, more so than when it is intended for the fresh market. Potassium promotes moisture accumulation in the tubers resulting in decreased specific gravity (Lang et al., 1999). The presence of high residual amounts of potassium a couple of weeks before harvest could be an indicator of more than adequate intake by the potato crop, leading to high absorption of moisture into the cellular structure of the tubers, and contributed to higher tonnage. This scenario was very probable considering that just before harvest in 2003, the amount of precipitation was sufficient relative to field 2 towards the end of the cropping season (Figure 2.1). No specific gravity measurements were carried out in field 1. However, for field 2, specific gravity and K showed a correlation coefficient of 23% (P=0.03). In a Washington State study, Redulla et al. (2002) found three out of four monitored fields had significant correlation coefficients ranging from –27 to –41% for the relationship of K and specific gravity. Variability in potassium levels across the field was narrow yet influenced specific gravity values for the harvested potatoes. This was indicated by the standard error of 2.2 ppm for a mean of 92.3 ppm (Table 2.1).

F reduction test and principal components analyses

The importance of physical, chemical and plant response to potato yield based on the sum of square reduction test showed a significant F statistic for the contribution of the three factors to potato yield explaining 70% of variability (Table 2.3). Principal component regression analyses identified six principal components explaining 64% of the observed variability in field 1 potato yield with stepwise F value to retain equal to 5%. Examination of individual components making up the identified principal component yield regressors did not produce a clear set of distinct factors that could explain potato yield. Except for 1st, 3rd and 5th (designated as aggregation, spectral response and vegetation), the remaining principal components both have chemical, spectral and textural parameters making definitive designation difficult (Table 2.4). Field 2 on the other hand, identified two principal components potato yield regressors designated as nutrient status, aggregation and chemical nutrient potential all contributing significant F at 5% level. The principal component regression was able to explain 44% of potato yield variability (Table 2.4). A principal component designated as plant response, was identified but did not significantly contribute to the regression coefficient based on the stepwise procedure.

CONCLUSION

The soil-plant-atmosphere continuum is a complex interaction of physical, chemical and plant factors, but with proper analyses and understanding, can lead to optimization of crop yield. Prudent baseline sampling of commercial potato field enables the farmer to supply critical quantities of nutrients needed for the normal growth and development of the potato crop. However, significant amount of variability in yield persists, despite best management practices, which points out the need to investigate the underlying growth environment, and vigor of the plant, to elucidate the observed variability.

Yield predictive model derived from two potato fields in 2003 and 2004 demonstrated the significant roles played by soil structure, specific spectral bands and derived vegetative index, as well as the amount of potassium. The predictive regression models were able to account for 66% and 60% of the yield variability for field 1 and field 2, respectively. The consistent positive contribution of soil structure characteristics points to the need to manage this aspect of the cropping environment, especially when the chemical requirements of the plants have been comprehensively addressed. The positive role of spectral measurement in predicting potato yield provides a useful monitoring tool as well.

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Table 2.1 Basic statistics for potato yield, specific gravity and regressor variables classified into chemical, physical and spectral factors taken from Fields 1 and 2 in Montcalm County, Michigan in 2003 and 2004 respectively.

Classification	Field	Stat‡	ppm: B_pH	ppm: Ca	ppm: K	ppm: Mg	ppm: P1	EC_a	Base Saturation, %: Ca	Base Saturation, %: H	Base Saturation, %: K	Base Saturation, %: Mg	pH	CEC	C, %
Chemical	1	$\bar{x}$	6.87	502.8	167.7	107.2	14.7	-	46.7	28.3	8.0	16.8	5.7		
		s.e.	0.01	11.1	4.7	1.9	0.2	-	0.6	0.8	0.2	0.3	0.0	0.1	0.01
	2	$\bar{x}$	6.54	575.5	92.3	72.6	14.0	0.18	48.1	37.3	4.2	10.4	5.5	5.9	1.05
		s.e.	0.13	25.2	2.2	3.2	1.2	0.01	1.0	1.3	0.1	0.3	0.0	0.2	0.02

Classification	Field	Stat‡	Elev	MWD	Aggregate size, μm: 53	106	250	1000	2000	≥250	Texture Components, %: Sand	Silt	Clay	MC	k	BD
Physical	1	$\bar{x}$	278.1	1.21	13.3	12.8	45.5	18.8	9.7	73.9	76.4	16.6	7.1	15.8	85.0	1.46
		s.e.	0.3	0.02	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.1	3.9	0.01
	2	$\bar{x}$	251.7	2.18	7.5	6.4	26.2	22.5	37.4	86.1	82.3	12.0	5.7	11.5	-	-
		s.e.	0.1	0.01	0.1	0.2	0.4	0.4	0.5	0.3	0.2	0.2	0.1	0.3	-	-

Classification	Field	Stat‡	Spectral Band, Unadjusted: G	R	IR	Adjusted: G	R	IR	Vegarea
Spectral	1	$\bar{x}$	102.1	99.0	32.4	51.5	49.3	16.2	47.2
		s.e.	0.5	0.5	2.0	1.5	1.4	1.2	1.0
	2	$\bar{x}$	87.3	190.0	160.1	4.8	9.1	8.6	4.6
		s.e.	0.6	1.1	1.2	0.3	0.5	0.5	0.2

Classification	Field	Stat‡	Yield	SG
Dependent	1	$\bar{x}$	22.8	-
		s.e.	0.2	-
	2	$\bar{x}$	17.4	1.0824
		s.e.	0.3	0.0003

† Variables : B_pH = buffer pH ;Ca = calcium ; K = potassium ; Mg = magnesium ; P1 = phosphorus (Bray 1) ; EC_a = aparent electrical conductivity (shallow 0-30 cm); H = hydrogen ; CEC = cationic exchange capacity ($meqg^{-1}$); Elev = elevation; MWD = mean weight diameter, mm; MC = volumetric moisture content; k = hydraulic conductivity, $mmhr^{-1}$; BD = bulk density; Vegarea = vegetated area, %; Yield = $tonsha^{-1}$; SG = specific gravity ; G = green ; R = red ; IR = infrared .

‡ $\bar{x}$ = mean; s.e. = standard error.

Table 2.2a Pearson correlation matrix of selected soil, plant and spectral properties of field 1 in Montcalm, Michigan.

Field 1	C†	MC	Elev	K	Clay	0.250mm	MWD	G_{unadj}	Veg_{cover}	G/R_{unadj}	R/IR_{unadj}
Yield	-0.049ns	0.235 *	0.327**	0.595***	0.474***	0.120ns	0.202*	0.654***	0.056ns	0.224*	0.423***
C		0.035ns	-0.155ns	0.079ns	0.117ns	0.220*	-0.178ns	-0.235*	-0.067ns	-0.166ns	-0.055ns
MC			0.210*	0.327**	0.223*	0.092ns	-0.058ns	0.107ns	0.008ns	0.189ns	0.156ns
Elev				0.289**	-0.075ns	-0.023ns	0.003ns	0.199*	-0.023ns	0.186ns	0.354**
K					0.279**	0.154ns	0.064ns	0.447***	0.129ns	0.167ns	0.333**
Clay						0.320**	-0.051ns	0.210ns	0.128ns	0.054ns	0.077ns
250mm							-0.694***	0.247*	0.037ns	0.146ns	0.271**
MWD								0.054ns	-0.021ns	-0.113ns	-0.148ns
G_{unadj}									0.070ns	0.490***	0.587***
Veg_{cover}										0.109ns	-0.127ns
G/R_{unadj}											-0.004ns

*** - significant at <0.0001; ** - significant at <0.05; * - significant at <0.10; and ns – not significant

† C = % total soil carbon ; MC = volumetric moisture content ; Elev = elevation ; K = potassium ; Clay = % Clay ; 0.250mm = 1 - ≥ 0.250 sized water stable aggregate; MWD = mean weight diameter; G_{unadj} = Green band unadjusted; Veg_{cover} = vegetative cover; G/R_{unadj} = green red unadjusted band ratio; R/IR_{unadj} = red infrared unadjusted band ratio.

Table 2.2b Pearson correlation matrix of selected soil, plant and spectral properties from field 2 in Montcalm, Michigan.

Field 2	C†	MC	Elev	K	Clay	0.250mm	MWD	G_{unadj}	Veg_{cover}	G/R_{unadj}	R/IR_{unadj}	EC_a
Yield	0.171ns	0.488***	-0.150ns	-0.034ns	0.049ns	0.255*	-0.429***	-0.405***	0.349**	0.101ns	0.463***	0.697***
C		0.575***	-0.194ns	0.280**	-0.265**	-0.203*	-0.218*	-0.511***	0.273**	-0.139ns	0.127ns	0.485***
MC			-0.334**	0.232*	0.031ns	-0.115ns	-0.321**	-0.486***	0.396***	0.191ns	0.321**	0.781***
Elev				-0.281**	0.093ns	0.224*	-0.066ns	0.347**	-0.146ns	0.074ns	0.053ns	-0.418***
K					0.122ns	-0.326**	0.139ns	-0.210*	0.122ns	0.045ns	-0.039ns	0.239*
Clay						-0.010ns	0.083ns	0.325**	0.040ns	0.425***	-0.040ns	0.025ns
250mm							-0.629***	0.142ns	0.086ns	0.234*	0.020ns	0.050ns
MWD								0.216*	-0.300**	-0.151ns	-0.175ns	-0.377**
G_{unadj}									-0.427***	0.589***	-0.371**	-0.523***
Veg_{cover}										0.092ns	0.414***	0.510***
G/R_{unadj}											-0.099ns	0.310**
R/IR_{unadj}												0.391**

*** - significant at <0.0001; ** - significant at <0.05; * - significant at <0.10; and ns - not significant

† C = % total soil carbon ; MC = volumetric moisture content ; Elev = elevation ; K = potassium ; Clay = % Clay ; 0.250mm = 1 - ≥ 0.250 sized water stable aggregate; MWD = mean weight diameter; G_{unadj} = Green band unadjusted; Veg_{cover} = vegetative cover; G/R_{unadj} = green red unadjusted band ratio; R/IR_{unadj} = red infrared unadjusted band ratio; EC_a = apparent electrical conductivity.

Table 2.3 Sums of squares reduction test of full and reduced model for potato yield as a function of chemical, physical and plant spectral response variables from a potato yield variability study at two commercial fields in Montcalm County, Michigan.

Model†	R^2‡	SS	df	MS	F_{obs}	P
Full	0.70	8047.65	173	46.52		
Reduced						
chemical	0.62	10761.28	192	56.05	3.07	0.01
physical	0.63	10136.50	187	54.21	3.21	0.01
spectral	0.54	13204.59	197	67.03	4.62	0.01

† Regression analyses with full model consisting of chemical, physical and potato spectral response with reduced model referring to single factor regression analyses involving each of the three independent factors; ‡ R^2 = coefficient of determination; SS = sum of squares; df = degrees of freedom; MS = mean square; F_{obs} = observed F statistics; P = probability

Table 2.4 Stepwise principal component regression analyses of chemical, physical and plant response variables†.

Field	PC axis ‡	Explained Variance	Important Variables‡‡
1	1	0.19	1 mm (-0.31), 0.106 mm (0.30), macroaggregates (-0.29)
	2	0.14	B_pH (0.30), %K (0.30), %Mg (0.30)
	3	0.13	IRRbyIRRa (0.34), %Ca (0.34), RbyIRa (-0.34), GbyIRa (-0.34), IRa (0.32, %H (-0.31)
	5	0.09	Ra (0.44), Ga (0.43), Vegarea (0.43)
	6	0.05	CEC (0.34), Ca (0.31), MWD (0.29)
	7	0.05	K (0.45), K (0.42), BD (-0.30)
	R^2	0.64	
2	1	0.28	Mg (0.27), Ca (0.26), ECa (0.25)
	2	0.17	2 mm (0.33), 0.250 mm (-0.32), B_pH (-0.32)
	R^2	0.44	

† Included 23 and 21 different chemical, physical and spectral response variables in field 1 and 2 respectively (Table 1).

‡ Principal components were derived through stepwise principal component analyses with variable entry and retention selection set at 0.15 and 0.05 contribution to the R^2 respectively.

‡‡ Variables included had the highest three values if correlation with principal components was weak (|eigenvector| < 0.3) or all variables with ≥ 0.3 eigenvetors (as shown in parenthesis).

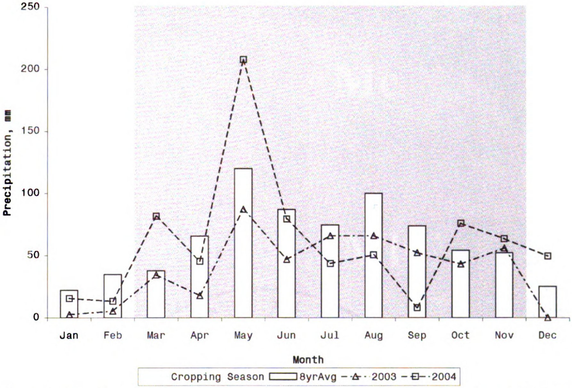


Figure 2.1 Total monthly precipitation at Montcalm Research Farm (Entrican, Michigan) for 2003, 2004, and the 8-year average.

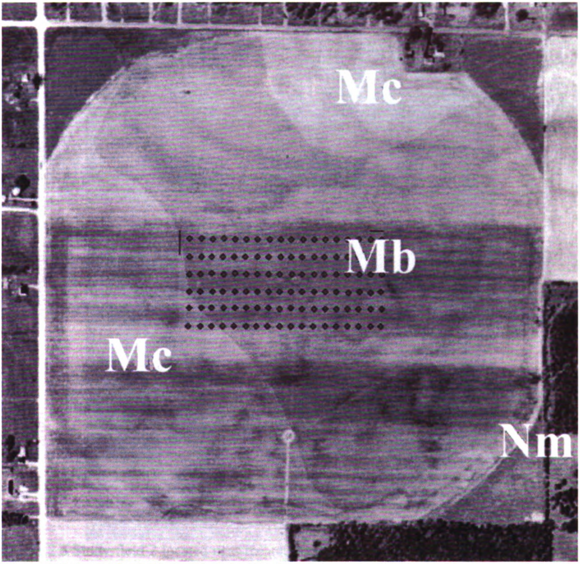


Figure 2.2 Study field 1 located at the Southeast quadrat of Vickeryville-Tamarack Roads in Vestaburg, Montcalm County, Michigan showing the entire field and the location of grid points sampled. Soil types of the area is also shown: Mb (Mancelona loamy sand, 0 – 2% slope), Mc (Mancelona loamy sand, 2 – 6% slope) and Nm (Newaygo sandy loam with 2 to 6% slope).

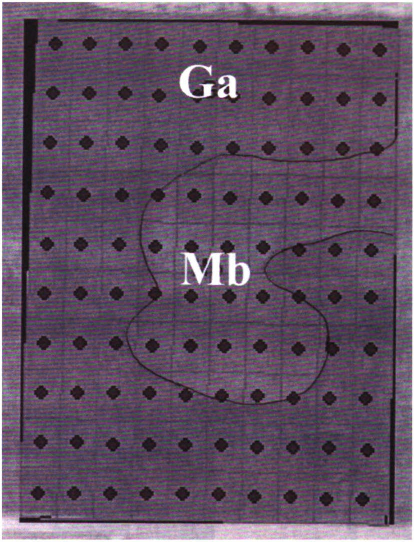
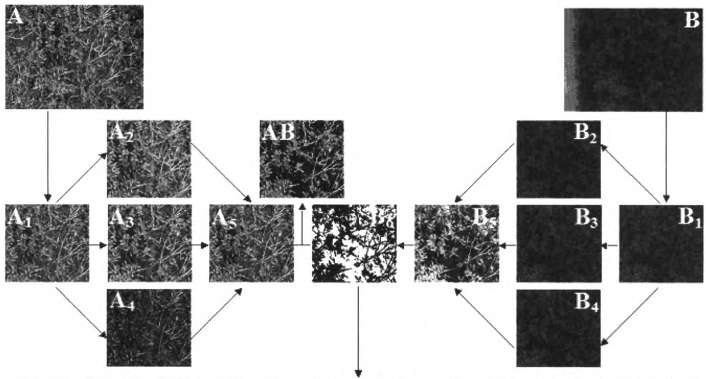


Figure 2.3 Study field 2 located near the southeast quadrat of Tamarack-Bollinger Roads in Vestaburg, Montcalm County, Michigan showing the the location of grid points sampled by this study as well as soil types Ga (Gladwin loamy sand) and Mb (Mancelona loamy sand).



Pixel Count: (Class 1 = Vegetated Areas; 0 - Non-vegetated Areas)

Class	Lower_Limit	Upper_Limit	Frequency	Proportion
0	0	0.99	66124	0.4427
1	1	1.99	83246	0.5573

Figure 2.4 Image acquisition, processing and analyses involving a Red-Green-Blue (RGB, A) image and an Infrared RGB (B) being cropped (A_1 and B_1) to remove edge artifacts, composited into Idrisi for Windows (A_2, A_3, A_4; B_2, B_3, B_4), unsupervised clustering into two groups was then performed on the infrared composite image (B_5) to produce an image with 0 being non-vegetated areas and 1 being vegetated areas (B_6). Pixels having 1 as value in the image were then counted and express as a percentage of the entire image pixels to represent percent vegetated. Original image is in color.

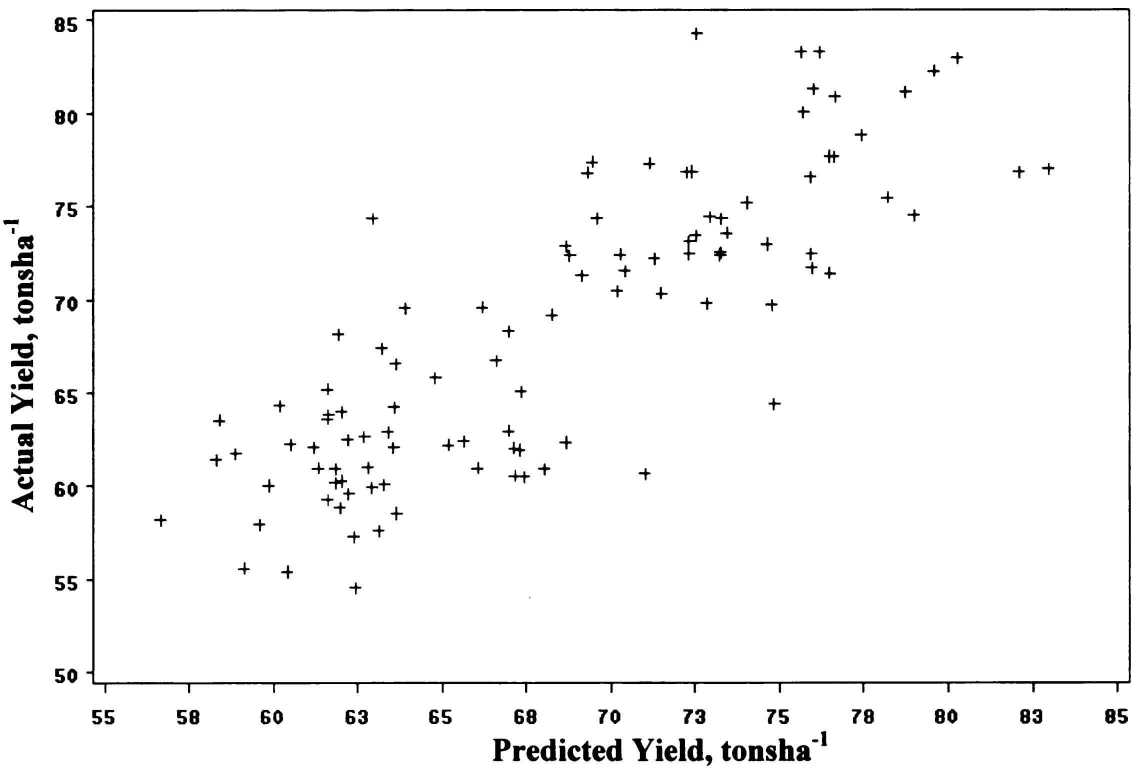


Figure 2.5 Plot of actual and predicted potato yield from field 1 fall of 2003 harvest data using the significant (P<0.0001) stepwise predictive equation of yield = -392.9 + 0.042(K) + 2.3359(Clay) + 8.7985(MWD) + 0.6178(Green Band unadjusted)+1.307(Elevation, m) with adjusted R^2 = 0.67 and an RMSE of 4.38.

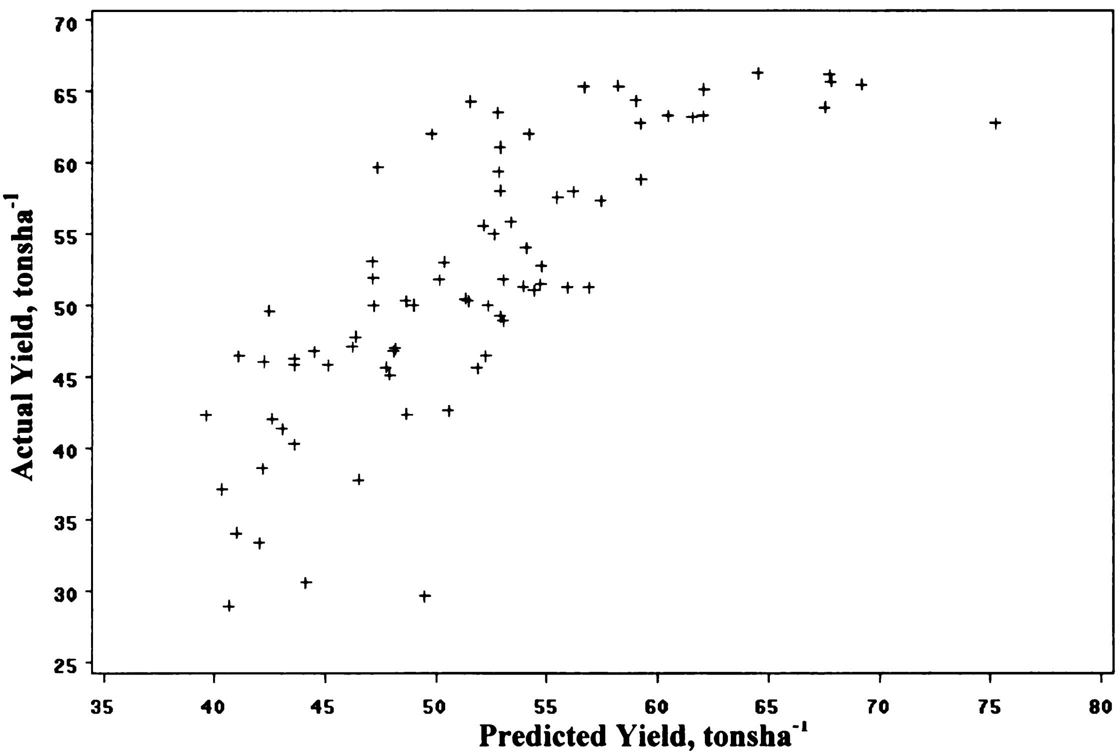


Figure 2.6 Plot of actual and predicted potato yield from field 2 fall of 2004 harvest data using the significant (P<0.0001) stepwise predictive equation of yield = 59.288+0.6997(250mm WSA)-89.259(Green by Red unadjusted ratio)+91.92(ECa) with adjusted $R^2 = 0.60$ and an RMSE of 5.9.

CHAPTER III: SPATIAL BEHAVIOUR OF SOIL PROPERTIES AND THEIR IMPLICATION FOR SAMPLING STRATEGIES IN A POTATO-BASED SYSTEM

ABSTRACT

Current farmer practice of sampling at low spatial resolution of one sample per hectare or less is not sufficient to characterize soil variability and its associated dynamics that affect plant growth and development. A study was conducted in two Michigan commercial potato fields, designated as field 1 and 2, in 2003 and 2004, respectively, to re-assess current recommendations on size of grids used in soil sampling. A high resolution data source - digital orthoquad imagery was evaluated for its potential to indirectly measure select soil properties. In this study, effective sampling grid size was tested in relationship to spatial dependence of yield, which was shown to be 42 m and 50 m for fields 1 and 2, respectively. Semi-variogram analyses of soil quality surrogates of water stable aggregates (WSA) showed moderate to strong spatial dependence, with ranges that coincided to some degree with the observed ideal grid size for both fields based on yield. Use of digital orthophoto (DOQQ) taken at a very high spatial resolution of 1 m ground equivalent is a potential valuable tool for monitoring the levels of important soil physical attributes such as amount of soil carbon, 0.25 and 1 mm WSA size fractions. However, the usefulness of this resource should be put in context by examination of soil survey data. A dramatic improvement in correlation coefficient was

achieved through analysis carried out on the basis of soil type series, rather than across series.

INTRODUCTION

Traditionally, agricultural fields have been managed based on the concept of averages or median soil nutrient requirements (Franzen and Peck, 1993), or what is known as whole field management (Lowenberg-DeBoer and Aghib, 1999). This practice leads to under-application of agricultural inputs in cases where the soil nutrient reserves are low, and over-application where the native supply of nutrients is above the mean value. Such conditions create concerns related to environmental pollution, where over-application occurs (Wollenhaupt et al., 1995), and low crop yield where under-application occurs (Lowenberg-Deboer and Swinton, 1997).

An alternative to whole field management is site-specific management (SSM) or precision agriculture (PA), where the amount of agricultural input is dictated according to the actual soil supply and crop requirement. This takes into account variability in plant growth and development requirements across a landscape, and heterogeneity in field micro-environment. Sensitivity analysis reported in a literature review done by Bongiovanni and Lowenberg-Deboer (2004) have shown that targeted application that reduces the amount of applied nitrogenous fertilizer to approximately half of recommended doses on a whole farm basis resulted in modest profitability above a uniform fertilization strategy. Vetsch et al. (1995) reported a reduction of as much as an average of 60 to 90 kg of nitrogen (ha^{-1}) in optimum nitrogen rate from the conventional single rate applied, in a study in Minnesota for corn. This is consistent with considerable over-fertilization associated with the common practice of non-targeted fertilization.

A review of current fertilizer recommendations by Hergert et al. (1997) concluded that refining knowledge and use of SSM will expose the problems associated with the usual fertilizer management strategy of applying whole field recommendation (plus 20% to account for variability). Varying the amount of lime applied to a moderately acidic field planted with soybeans in Michigan improved overall yield, compared to a single rate application for the entire field (Pierce and Warncke, 2000). Redulla et al. (2002), sampling potato fields in Washington State at a square grid of 0.4 ha interval, concluded that the consistent negative correlation between specific gravity and potassium across three of the four fields they studied, could be a justification for the use of variable rate fertilization based on native potassium availability.

Identification and mapping of stable features of the landscape relative to soil and micro-environmental conditions that can impact crop performance, and managing those stable features as separate units, is an example of SSM. SSM offers a convenient way to harmonize field operations. Through the use of management zones, yield variability for corn and soybean compared to whole field variance was reduced by 40% (Brock et al., 2005). Hornung et al., (2006) compared annual yield performance of grains within management zones identified through bare soil imagery, topographic position and farmer's perception of yield potential (color-based approach) on one hand, and the delineation based on bare soil imagery, cationic exchange capacity, texture and yield from previous year (yield-based approach). They found the color-based approach to be more efficient in identifying stable yielding potential than the yield-based approach. The inclusion of the previous year's yield together with independent variables that were related to yield potential, may have a created a redundancy in the yield-based algorithm.

This may have reduced the effectiveness of the methodology and limited the ability to identify stable zones. Developing empirical relationships between yield, optical and soil properties from previous years, and carrying over the relationship to the current year as input in the identification of management zones, can potentially increase identified zone yielding potential stability. Hornung et al. (2006) agreed that assigning weights to the yield-based data-layer could have improved stable management zone identification. Identification of management zones necessarily increases the amount of soil sampling and related validation activities. Whether the resulting reduction in variability produces a better economic return overall compared to whole farm management requires further study (Brock et al., 2005).

The utilization of SSM raises a number of questions. What are the resources available for its implementation? How much detail is required for the formation of workable empirical yield models? Which variables in agricultural production are likely to maximize the benefits of SSM? Another important question is which statistical approach is most effective to interpolate values between sampled locations?

To dissect the yield variability puzzle, consideration should be given to readily available maps from the United States Department of Agriculture – National Resources Conservation Service (USDA-NRCS) as guides for agricultural production suitability. These maps range from one depicting the entire State of Michigan known as a 5th order soil survey at a scale of 1:5,000,000; a 2nd order 1:190,080 county map; and the high resolution 1st order map at a scale of 1:1000, depicting detailed resources on a parcel of land (Cooper, 2004). Any of these maps can be used as input to a

Geographic Information System software, but no additional detail can be extracted beyond the resolution that was present in the original material.

At first glance, a 1^{st} order survey map is the only one relevant to within field variability analysis. This map, represented on a letter size paper would correspond to roughly 6 hectares on the ground, which may not be sufficient for purposes of mapping within field variability. However, it serves as a starting point for more detailed soil sample characterization. For agricultural production purposes, 1 to 2 soil cores are commonly sampled and analyzed per hectare to obtain information on soil characteristics prior to planting (Hergert, 1998). This sampling density and subsequent soil analysis serves as a basis for fertilizer recommendation for a particular yield target. At this density of sampling, this will provide information resolution that is 600% greater than a 1^{st} order map, but even this is not sufficient for most properties.

The majority of agricultural dealers sampled over the years from 2000 until 2006 (Akridge and Whipker, 2000; Whipker and Akridge, 2001, 2002, 2003, 2004, 2005 and 2006), indicated a higher proportion of surveyed dealers providing sampling services for their customers, who preferred a grid sampling pattern followed by soil type as sampling methodology. Of those that used grid sampling, a majority (ranging from 53 to 60%) followed a 1 hectare sampling grid size. Ultimately, the inherent properties and variability of the soil will dictate the intensity of sampling required to support detailed mapping and understanding of crop response (Kravchenko and Bullock, 2000).

Micromanaging a production field necessitates the presence of a detailed soil property database, which in turn involves intensive sampling. Sampling to detect within field variability can be accomplished primarily in two ways: either by a) a grid of a particular dimension which can be overlain on the field of interest; or b) use of point data collected based on some criteria determined prior to, or during the sampling process. In the first method, data is collected at each intersection of the horizontal and vertical grid positions (Mueller et al., 2001). For the second method, utilization of prior information from the field of interest, such as previously conducted soil surveys or on-the-spot determination of areas of interesting variability, can be used to guide the sampling process (Pocknee et al., 1996). A combination of the two methods was illustrated by Kravchenko and Bullock (2000), where sampling for topographic data involved using semi-regular grids, with the further step of varying the distance between measurements based on the complexity of the topography.

The dimension of the grid used to designate sampling point locations generally varies with the type and number of factors of interest. These factors often include soil texture, desired map quality (Hergert, 1998) and prior spatial structure of a particular variable of interest (Flatman and Yfantis, 1996; Sadler et al., 1998), or limitations imposed by harvest equipment (Hornung, et al., 2006). Single grid cell area values of 0.0625 (Jaynes et al., 2003), 0.4000 (Pocknee et al, 1996; Redulla et al, 2002) and 0.5000 hectare (Morgan et al, 2002) were examples found in the literature.

Once point data is generated, the challenge is to use interpolation across the field to generate surfaces that are representative, and within acceptable constraints. A promising approach involves a system of generating surfaces from a few points in the field, supplemented by the variability shown to occur from a densely sampled variable that has a distribution related to the variable of interest. An example is provided by Heisel et al. (1999), where co-kriging was used to improve estimation of a sparsely sampled weed count variable using an intensively sampled variable of silt content. Results of their study showed that this co-kriging approach reduced the variance by 11 %, compared with a method relying on kriging alone. Colonna (2002) also utilized secondary information to improve predictive ability of both simple kriging with varying means, and a co-kriging interpolation methodology. These methods were used to improve the field map of organic matter distribution.

On the basis of applicability to end-user, simple kriging with varying means, and ordinary kriging or lognormal ordinary kriging, are possibilities which could greatly enhance predictive capability of interpolation methodology. However, these are not available in commercial software packages (Colonna, 2002), or involve complicated computations, including the formulation of a carefully chosen variogram model, as well as appropriate log-transformation methodology (Kravchenko and Bullock, 1999).

Dense information may also be developed from spectral characteristics. An example is provided by a study of a cranberry production site. Color Infrared imagery was taken from an airplane and successfully used to predict cranberry vine density, areas with drainage problems, yield and disease incidence in New Jersey (Pozdnyakova et al., 2002). Visual representation of the area was made possible through kriging algorithms derived from experimental variograms. In a wheat rotational system in Spain, Lopez-Granados (2005) concluded that the use of kriging with varying local means, in combination with spectral data from the blue band of the electro-magnetic spectrum, offered increased precision in the prediction of organic matter, pH and potassium, compared to simple regression and ordinary kriging with regression.

Yield monitor data provides an excellent source for mapping within field variability, as it relates yield data to physical location in the field through global positioning system (GPS) technology. Evaluating the stability of yield data over a period of time could provide unique insights regarding persistent features of the landscape that need to be managed through appropriate interventions. Doberman et al. (2003) reported that there are two components of yield, namely the stable part and the annual random part. If one can remove the random part, then one can maximize the inherent productive capability of the soil. An example of a random effect could be erratic precipitation which can be removed through the application of supplemental irrigation. At the same time, this approach can reduce over- and/or under- application of inputs under irrigated production environment.

The first challenge in the determination of spatial yield stability is the segregation of the production field into grids or areas of interest. To accomplish this in terms of yield potential, multi-year yield data are needed. Blackmore (2000) used three years of yield monitor data to derive annual mean, overall mean and standard deviation for areas of interest. He classified geospatially located data based on the performance of an area as yielding higher or lower than the average, and whether the coefficient of variation was less than or greater than 30. Thus the field was divided into the following categories: a) higher yielding and stable, b) lower yielding and stable, and c) unstable areas. Using this methodology, the resulting map can be used to identify the problematic unstable areas and more directed research can be conducted on these areas. One potential challenge is that the classification scheme may not be sensitive enough to come up with viable management sections to adequately address within field variability

(Doberman et al., 2003). He suggested increasing the number of classes that is developed through Blackmore's (2000) analysis to increase the utility of the map developed as a tool for continuous variable rate management. Ultimately, the number of classes developed is a function of area contiguity, practicality and convenience. Practical considerations include the necessity to take into account farm machinery requirements to negotiate across the field to deliver targeted, specific area tillage and inputs.

Further complicating stability analysis of within field spatial variability pattern is the challenge associated with calibration and accuracy of GPS- yield monitoring equipment. Davenport et al. (2002) monitored two to four fields on a commercial potato farm in southeastern Washington for three years, and found that the yield monitors generally over-estimated potato yield compared to point estimates. This may have been caused by the utilization of different yield monitors at different times, with the corresponding calibration challenge across the study years. Furthermore, the very nature of row crop agriculture presents a unique problem of location stability as the location of rows from year to year varies. As a harvester operates across several rows, even a split-second interval in data generation can translate to substantial differences in yield reported, potentially throwing off comparison between years, since each year data are averaged from different locations in the field.

The objective of the study reported here was to determine the range of spatial dependence of yield and soil structure related properties in Michigan potato production. Specifically, the objective was to evaluate the potential of digital orthoquad imagery high resolution data to correlate quantitatively these datasets with spectral data from a consumer grade digital camera, and select soil properties.

MATERIALS AND METHODS

Location

The study was conducted on two commercial potato production fields managed by the same farm operator and designated as fields 1 and 2, which were studied in 2003 and 2004, respectively. Field 1 is a 43.5 hectare commercial production field that had been in a potato-based rotation for the past 60 years. Rotation crops included corn (*Zea mays* L.), dry beans (*Phaseolus sp.* L.), and wheat (*Triticum aestivum* L.) Most recently, the rotations of potato (*Solanum tuberosum* L.) cultivars grown in this field included Pike with cereal rye (*Secale cereale* L.) as a cover crop in the winter in 2001 and FL 1833 followed by wheat and rye as cover crops in 2003. It is located at 84°57' longitude and 43°26' latitude, at Vestaburg, Montcalm County, Michigan, USA.

The second field was a 20.7 hectare commercial field located near field 1 with the following center geographic coordinates, 84°52' longitude and 43°26' latitude. This field had been in a potato-based rotation for the past 30 years. Crop rotation practices were similar to those of field 1. When this field was sampled in 2004, it was planted with the FL1879 potato cultivars and a rye winter cover crop. Two years before, it was planted with potato (*Solanum tuberosum* L. var Pike) and a rye winter cover crop followed by snap beans with wheat as winter cover crop the following year.

Sampling Design

Historical soil sample characterization data taken from the study area in previous cropping seasons were used to formulate the sampling design. For field 1, the average ratio of samples per hectare used historically by crop advisors was 1.7:1 for the determination of percent organic matter, phosphorus, potassium, magnesium, calcium, pH, cation exchange capacity (CEC), and zinc. The study area was located at the center of the field where the slope was minimal, to minimize the effect of topography on the behavior of soil physical and chemical properties. Prior geographically referenced sampling points for field 2 had a ratio of 2.9 samples for every hectare (Otto, 2004 personal communication).

For field 1, the study area was divided into 108 sections, each consisting of 16 rows (spaced at 0.89 m apart) on the northern and southern sides, and approximately 9 m both on the east and west sides from the center of the section, making the effective area equal to 0.05 hectare. Thus, the ratio of sampling points per hectare was 20:1, compared to the earlier ratio of 1.7:1. The width of the sampling grid was chosen as to accommodate 16 rows of potatoes on the north and south side of the grid center. Tuber diggers normally involve 1 eight row and 2 four row machine diggers for a total of 16 harvested rows in one pass, moving from west to east or vice versa. The east and west length was arbitrary and roughly included a total of six yield monitor data points. In a similar manner, a total of a hundred grid points were sampled for field 2, with the same number of samples taken per hectare.

Sampling for Water Stable Aggregates

Soil aggregates are sensitive to rough handling, and therefore need to be taken prior to major field operations that have a high probability of disrupting the soil structure. A soil sample for soil aggregates was taken September 18, 2003 and September 11, 2004 for field 1 and 2, respectively. This sample was composited from five random locations taken within each of the study area sub-sections, defined by a circle with a radius of 4 m around each grid point to a depth of 0-10 cm using a trowel. Care was exercised not to unduly compact the soil, and to protect the samples, cardboard boxes were used in transporting and storing them. Extraneous materials such as plant residues and gravel from the soil aggregate samples were removed with the use of an 8 mm sieve, and the samples air-dried for a number of days until they equilibrated with atmospheric water content. The soil sample was sieved using a layer of sieves, with the top having a screen opening of 8, 6.2, 4, 2 mm and a catch pan at the bottom. Rocks, gravel and extraneous materials remaining on the 8 mm were discarded. Soil aggregates that remained on top of the 6.2, the 4 mm, the 2 mm and those contained in the catch pan were placed in separate containers and labeled as the 6.2-4.0 mm, 4.0-2.0 mm and < 2 mm sieve sizes. Results reported here referred to water stable aggregate stability of the 4.0 to 2.0 mm size fraction. Water stable aggregate analysis was previously described in Po (2007).

Chemical and Mechanical Analysis

Samples that passed through the 2 mm sieve during WSA sample preparation were ground to powdery consistency for 2 minutes using a Shatterbox Rotary Grinder (Spex Ind., Edison, NJ). Samples for total carbon and nitrogen analysis were prepared from the ground soil by weighing 60 to 70 micrograms to a tin capsule. Crimped tin capsules were submitted to the Stable Isotope Laboratory at the University of California at Davis for total Carbon and Nitrogen analyses using a Europa Hydra 20/20 isotope ratio mass spectrometer (Europa Scientific, Crewe, UK).

Samples were analyzed by A&L Great Lakes laboratories (Fort Wayne, IN) for chemical and texture analysis, including determination of available phosphorous, exchangeable potassium, magnesium, calcium, soil pH, buffer pH, cation exchange capacity (CEC), percent base saturation of cation elements and texture components of sand, silt and clay . Result of phosphorous analysis was expressed as a weak Bray (P1) derived from Mehlich-3 through a regression equation (Calhoun et al., 2002).

Moisture Content and Hydraulic Conductivity Calibration

A Trime moisture probe (Ettlingen, Germany) was used to measure volumetric moisture content across the field. Prior to using the unit, a calibration procedure was undertaken by filling up a 19-liter container with soil from AB 12 field to a bulk density of approximately 1.60 g $(cm^3)^{-1}$, adding a known volume of water to bring moisture content to 24%. A 100-watt incandescent bulb was placed a couple of centimeters from the soil surface to induce evaporation from the soil surface. The entire setup was placed on top of a Sartorius weighing scale (Model No. 3862 MP8-1; Bradford, Mass.). The Trime sensor prong was centrally inserted to 15 cm and attached to a Compaq Ipaq pocket PC (Palo Alto, California) interfaced with a customized program to communicate with the Trime unit. The communication software was set to obtain volumetric moisture readings every 30 minutes for a total of approximately 260 hours. At the end of the calibration period, two soil cores were taken from the top 10 cm of the soil, oven dried at 105°C for 24 hours, and the bulk density computed. A one-is-to-one correspondence between gravimetric and volumetric moisture content was plotted with a R^2 of 0.99.

***In-situ* Measurement**

The volumetric soil water contents were measured across 108 grid points at the field 1 and 100 grid points at the field 2 site, prior to soil sampling on September 17, 2003 and September 10, 2004, respectively. The effects of time on changing soil water contents were compensated for by taking single volumetric soil water content readings at each grid point during a single pass across the field. . This procedure was repeated 5 times, and the average per grid point calculated to represent soil moisture status across time for each measurement date.

Bulk density and Infiltration

In addition to the volumetric moisture content data, laboratory measurements were conducted on soil cores obtained using an aluminum cylinder 7.62 cm in diameter and 7.62 cm in height, for bulk density and infiltration. The cylinders were randomly installed within 6 transects running from East to West in field 1 for a total of 18 cylinders for each transect and each cylinder represent an area of 0.05 ha. The area chosen for coring was cleared of vegetation, and with the use of a special ramming device, the cylindrical core was rammed vertically through the soil. Extreme care was exercised to minimize as much as possible compacting or disrupting the natural soil structure. Once the top rim of the cylindrical core was flush to the external soil level and the internal soil level was also flush with it, a spade was used to extract the soil core. A flat knife was used to scrape off any excess soil beyond the top and bottom of the cylindrical core and then a special box was used to transport the cores to the laboratory.

A mini-infiltrometer from Decagon (Pullman, Washington) with a 6.0 cm suction was used to calculate the unsaturated hydraulic conductivity at each of the grid point using the collected soil cores. The process involved filling up the device under water and then plugging the top end with a rubber stopper. An absorbent tissue was used to adjust the water level within the cylinder by making contact to the plastic porous membrane at the bottom of the infiltrometer cylinder. The center of the soil core was leveled carefully, making sure that the least possible disruption to the soil structure was done. The infiltrometer was placed vertically at the center of the core and readings on the side scale were obtained every ten seconds. After approximately 30 ml of water was dispensed by the setup, the infiltration was terminated. In most instances, the infiltration rate of these sandy soils was very rapid, making it impossible to determine the water level at specific moments in time with accuracy. To remedy the situation, a camera setup was used whereby pictures were snapped every ten seconds and readings were later taken off the pictures. A software, exifextracter (BR software; Eiksmarka, Norway), was used to extract information imprinted by the camera on the digital picture, reflecting the time when the picture was taken, as well as other camera parameters. Extracted information were then tabulated in an excel spreadsheet to act as values for the X-axis of time. To increase the accuracy of the readings taken of the pictures, GrabIt software (Datatrend Software; Raleigh, North Carolina) was used for length measurements plotted on the Y-axis. This is a novel approach that can provide precision for rapidly infiltrating soils such as those used in the study.

Calculation for unsaturated hydraulic conductivity was adopted from Zhang (1997) where the square root of time was obtained for each set of infiltration readings, and then plotted on the x-axis with volume of water infiltrated on the y-axis. The resulting point distribution was fitted into a second order polynomial and a trend line equation projected using Excel v7 (Microsoft, Redmond, Washington). The coefficient of the squared independent variable (square root of time) was utilized to compute the hydraulic conductivity of the soil. After the hydraulic conductivity measurements were completed, the soil cores were dried in a convection oven for 24 hours, weighed and bulk density computed using the core method (Blake and Hartge, 1986).

Spectral Pictures

Availability of a detailed 1st order map is not widespread. In 1998 the National Cooperative Soil Survey Services of the US federal government has completed mapping Michigan with a 1m resolution per pixel Digital Orthophotography Quarter Quads. These images were computer altered and generated in a way that distortion normally associated with digital images taken at a resolution of 1:12000 or lower tend to distort areas away from the center of the image. Furthermore, the spectral band present in a DOQQ are not the usual red, green and blue, but in its place, spectral data obtained from infrared, red and green were used respectively. The possibility of analyzing the spectral distribution of infrared, red and green for its correlation with yield monitor data was undertaken.

An Olympus 340R (Melville, New York) digital camera was utilized to obtain red, green, and infrared images at each of the grid points in fields 1 and 2 on August 31, 2003 and August 28, 2004, respectively. The camera was attached to a palm pilot handheld (M100, Milpitas, California) with an installed freeware program that controlled the camera settings, ensuring uniformity in procedure, as well as firing up the camera (Palmshot v. 1). Two image monitoring events were captured where each consisted of a normal, automatically obtained image and an infrared image using a pass through-filter. Using the camera without a filter in front of it resulted in a picture with pixels composed of a combination of the red, green and blue parts of the spectrum. To extract the green, red and infrared parts of the spectrum, Paint Shop Pro 8 (Ottawa, Ontario, Canada) was used along with a macro program to facilitate the processing of hundreds of pictures in a short time. The extracted green, red and infrared band images were used as input to IDRISI for windows v. 1 (Worcester, Ma) to compute the mean average value of the image pixels. The average green, red and infrared values were tabulated in Microsoft Excel for windows, imported to Statistical Analysis Software where relevant correlation analyses were calculated (SAS 2006, Cary, NC).

Yield Monitor Data Collection

Potatoes were harvested with two types of tuber harvestors, one with a 4 row and the other an 8 row capacity. The harvesters were equipped with an electronic yield monitor (Harvest Master Yield Mapping System for Bulk Crops, HM-500; HarvestMaster, Logan, UT) logging data every two meters (in field 1) and every four meters in field 2 on average. A total of 1071 datapoints were generated for field 1 and roughly half that quantity of 633 for field 2. A tandem of 1 eight row and 2 four row harvesters can scoop up 16 rows as it moves from east to west and vice-versa. For each grid point therefore two passes of the harvester was required to cover the total of 32 rows representing each of the 108 grids in field 1 and 100 grids in field 2.

Statistical Analysis

Prior to variogram analyses, soil and plant factors were examined for normality. Variogram analyses were conducted using ArcGIS v. 9 (Redlands, Ca). Vector distance and direction for each grid point and the rest of the grid points were computed for both field 1 and 2. For each field, the resulting vector distances were classified into lag width equivalent to the modal, mean, or the shortest distance between points. The maximum lag distance was approximately equal to one-half the longest distance from any point, and the number of lag interval was the quotient between the maximum lag distance and the lag width. For points belonging to a specific lag width, the mean of the variance divided by two was computed and designated as the semivariogram (Isaaks and Srivastava, 1989).

An experimental variogram was computed by plotting a two-dimensional graph of lag distance on the x-axis and semivariogram values on the y-axis, which was then fitted with a single or a combination of mathematical curve function. For each variogram point a minimum of 30 to 50 pairs were required as a rule of thumb (Journel and Huijbregts, 1978) and this requirement was satisfied by the computed variogram for each of the two fields. Visual examination of the resulting semi-variogram dictates the use of any of the popular mathematical curve function of exponential, gaussian, and spherical, to mention a few.

Spatial dependence was evaluated using Chang et al. (1999) where the nugget to sill ratio of less than 0.25 serves as an indicator of strong spatial dependence, with ratios equivalent to between 0.25 to 0.75, and those with greater than 0.75 as having moderate to weak spatial dependence.

RESULTS AND DISCUSSION

Climatic and Soil Conditions

Overall soil characteristics showed that field 2 had 50% more organic carbon and 44, 32, and 16% less potassium, magnesium and Bray-1 phosphorous, respectively, than the field 1 (Table 3.1). Field 2 had 8% more sand particles (823gkg^{-1}), 18% lower amount of clay (57.4gkg^{-1}) and 28% less silt (119.6gkg^{-1}), as well as higher amounts of macroaggregates (≥250 μm aggregate size), 1 mm, and 2 mm water stable aggregate components, compared to field 1. Average volumetric moisture content across the grids was higher in field 1 (15.8%) than in field 2 (11.51%). Fields 1 and 2 were both composed of Mancelona loamy sand with 0-2% slope (Mb). A small section of field 1 was composed of a variant of the Mancelona loamy sand (Mc, 2-6% slope) as well as Newaygo sandy loam (Nm, 2 to 6% slopes), although this particular soil series was not present in the monitored section of the field. Field 2 was one-quarter composed by Mancelona, and three-quarter Gladwin loamy sand complex, with Palo sandy loam at a slope of 0-2% (Ga). Outside the study area but still within the field 2 boundary, was Epoufette loamy sand and Ronald sandy loam (Ec, 0-2%). Mc and Mb were well-drained, Ga was somewhat poorly drained, while Ec was poorly drained to very poorly drained, dark colored soil (Schneider, 1960).

Spatial Distribution of Yield

Global spatial trend analyses conducted on yield monitor data derived from the fields 1 and 2 indicated the presence of a spatial pattern roughly following the location of the two soil series present in field 2 (Mancelona (Mb) and Gladwin (Ga), Figure 3.1.) and a slight tilt towards a northeast-southwest trend in field 1, reflecting the location of the Mancelona 0-2% slope (Mb) soil series sandwiched by Mancelona 2-6% (Mc) slope on both sides (Figure 3.2.) These spatial trends justified a second order trend removal conducted on the yield data prior to geostatistical analyses (Johnston et al. 2001). The removal of the physical trend allowed modeling of yield as a function of distance, un-confounded by other factors.

The magnitude of spatial correlation observed among the yield monitor data points was different for the two fields studied. For field 2 (Figure 3.3.), the nugget to sill ratio of 0.05 indicated a very strong spatial dependence, while for the field 1, the ratio was moderate at 0.41 (Figure 3.4.). Chang et al. (1999) indicated that a nugget to sill ratio of less than 0.25 serves as an indicator of strong spatial dependence, with ratios equivalent to 0.25 to 0.75, and those with greater than 0.75, as having moderate to weak spatial dependence. The range of spatial dependence among the yield monitor data points was approximately 50 and 42 meters for fields 2 and 1, respectively. At this level of spatial dependence, current sampling grid size of 1 ha (Akridge and Whipker, 2000; Whipker and Akridge, 2001; Whipker and Akridge, 2002; Whipker and Akridge, 2003; Whipker and Akridge, 2004; Whipker and Akridge, 2005; Whipker and Akridge, 2006) do not cause redundancy in information but if sampling intensification need to be increased to improve accuracy of agricultural input recommendation maps, grid size have to be increased from 4 to 5 times the current level.

Use of a 1:12000 map resolution Digital Orthophotography Quarter Quads (DOQQ) images with a 1m per pixel resolution supplemented by satellite imagery, has been successfully used to improve the accuracy of coarse resolution satellite data when compared to previously published soil surveys when classifying soils based on drainage characteristics (Peng et al. 2003). Correlation analysis of pixel values for the green, red and near infrared from DOQQ's with yield in the field 2 resulted in non-significant probability values. However, subdividing the datapoints based on the underlying soil series remarkably improved the correlation coefficient, with the infrared part of the DOQQ spectral reflectance for yield data recorded from a Mancelona soil environment improving from –16.74% (P=0.0959) to 58.39% (P=0.0027). A slight improvement was observed for yield data recorded on the Gladwin soil series from a non-significant –16.74% to –25.18% (P=0.0282) (Table 3.3). On the other hand, in field 1, significant correlations with yield were obtained with correlation coefficient equal to –21.22% (P=0.0306) for the infrared band; -42.10% for red (P<0.0001); and –38.08% for green (P<0.0001) parts of the electromagnetic spectrum captured by the DOQQ (Table 3.2) for the entire field. No significant departure from the above trend was observed when the two soil series in field 1 were split and analyzed separately. This result was not suprising as the two soil series in field 1 were closely related, being modest slope variations of Mancelona. Spatial analysis of DOQQ pixels in the field 1 resulted in an ill-defined semi-variogram, indicating the inability to pick up subtle short range soil characteristic changes that could otherwise shed light on observed variability in yield.

Coleman and Tadesse (1995) used the three spectral bands found in a DOQQ to relate observed soil properties in a study involving 99,877 hectares of land encompassing 26 different soil series. Significant correlations were observed between clay and the infrared, red and green bands of the DOQQ (34, 38 and 39% for red, green and blue, respectively, all significant at 1%) and drainage classes. The authors concluded that due to time difference and season when the imagery were taken, it was an inadequate resource to use in differentiating surface soils for purposes of predicting soil properties such as organic matter. In the present study, use of in-season, near ground digital imagery also resulted in low correlation values for the amount of clay and the green spectrum (21% at $P \leq 0.05$ and 32.5% at $P \leq 0.01$, for fields 1 and 2, respectively). The amount of carbon, though, was significantly correlated with the green spectrum (-23.5 at $P<0.05$ and –51.1% at $P<0.0001$ for fields 1 and 2, respectively; Table 3.5). These findings illustrated the potential to document variability of critical soil properties indirectly through digital camera imagery.

DOQQ and Selected Soil Attributes

Further analysis of data taken from field 2 indicated a very significant improvement in the correlation coefficient of several soil physical characteristics, when background soil series information was integrated into the analysis. By splitting the dataset into two groups corresponding to the location of the background soil series, improvement in the correlation coefficient was observed. Looking at the infrared band, an improvement in correlation coefficient from 4% ($P=0.63$) to 53% ($P=0.06$) was observed in the amount of clay, and from 11% ($P=0.25$) to 63% ($P=0.02$) for the 0.25 mm water sable aggregate size fraction for the Mancelona soil group series (Table 3.3). Also demonstrating a significant improvement in correlation coefficient were the following: the 1 mm water stable aggregate size fraction, the ratio between micro and macro-aggregates, apparent electrical conductivity and the percent amount of soil carbon. However, no improvement was observed for the Gladwin soil series, with the amount of clay actually dropping several folds in terms of correlation relationship compared with whole field values. A similar trend was observed in other soil quality parameters mentioned previously. Examination of the other two bands in the DOQQ did show improvement in the correlation coefficient, but not as dramatic as observed in the infrared part of the spectrum.

Spatial Behavior of Selected Soil Attributes

The spatial distribution documented here is consistent with the primary driver of soil processes appearing to be dependent on soil series variability, in the sampled areas. Results of geostatistical analyses of mean weight diameter (MWD) and the 2 mm water stable aggregate size fraction showed strong autocorrelation in field 1, with a nugget to sill ratio of 0.009 and 0.22, respectively. In field 2, the spatial structure was weak for the MWD and the 2 mm aggregate size fraction, with a 0.82 and 0.74 nugget to sill ratio, respectively (Table 3.4; Chang et al., 1999). The larger field 1 was composed of three different soil series, but the sampled area for this study was composed of one type and would therefore be expected to exhibit uniformity in attributes, particularly in soil structure, as opposed to field 2 which was composed of two markedly different soil series across the study area. Spatial uniformity in field 1was previously observed in the variogram parameters derived for yield (Figure 3.4). The Mancelona 2 – 6% slope soil series surrounded the sampled Mancelona 0 – 2% in field 1, and played a role in the observed spatial structure MWD, and the largest component of water stable aggregate, the 2 mm aggregate size fraction (Figure 3.2).

The other soil structure related properties of 1, 0.25, 0.106 and 0.053 mm size fractions had moderate spatial dependence (Table 3.4), as the nugget to sill ratio was within the range of 0.25 to 0.74 for all of these characteristics (Chang et al., 1999). The observed range of spatial dependence ranging from 27 m to 54 m (Table 3.4) were roughly within the identified range of spatial dependence for yield of 50 m and 42 m for fields 2 and 1, respectively (Figure 3.3 and 3.4).

The strength of spatial dependence have implications on the accuracy of interpolated maps as well the size of grids one follows when sampling for a host of soil physical, chemical and plant properties. In the presence of strong, well-define spatial dependence, accuracy of interpolated map is high compared to instances when spatial structure is weak (Kravchenko, 2003). Sample size is critical in classical hypothesis testing as it influence the degrees of freedom needed for pattern detection. Presence of autocorrelation over-estimate effective sample size leading to increased probability of having false positive results (type I error; Segurado et al. 2006). Sampling grid size have to be adjusted to prevent autocorrelation and the range of spatial dependence obtained from a fitted theoretical variogram is a good guide. Between the prevailing grid size of 1 ha (Whipker and Akridge, 2006) and the grid size used in this study of 0.05 ha, variogram analyses of yield data from fields 1 and 2 indicated middle value of 0.18 and 0.25 ha as effective grid size to prevent autocorrelation respectively.

CONCLUSION

The current farmer practice of sampling and representing a grid size of 1 hectare is not sufficient to reflect the true status of soil structure and its associated dynamics that affect plant growth and development. The extent to which intensification of the sampling regime will be required is expected to vary with field heterogeneity. In this study, a recommended guide for ascertaining the extent of new sampling regime was found to be the spatial dependence of yield. This was shown to be 42 m and 50 m for fields 1 and 2, respectively. Semi-variogram analyses of soil quality characteristics, notably water stable aggregates, were shown to have moderate to strong spatial dependence, with ranges roughly coinciding with the observed ideal grid size for yield at both fields. Analyses of data using traditional statistical methodology of simple or multiple regressions can satisfy the assumption of independence among samples.

Use of digital orthophoto (DOQQ) undertaken at a very high spatial resolution of 1 m ground equivalent was shown to have potential as a valuable tool for improving the documentation of variability in soil physical attributes such as amount of soil carbon, 0.25 and 1 mm water stable aggregate size fraction. However, the usefulness of this tool has to be put in context by examination of soil survey data. A dramatic improvement in correlation coefficient seemed to be possible only when analysis was done on a per soil type series, and not across series. Furthermore, the degree of difference among the various soil series present may also play a role in the great improvements observed, as was the case in the field 2 where the Gladwin soil series was markedly different from the

Mancelona. In field 1, the difference between Mancelona on a 0 to 2% slope was not much when compared to the Mancelona soil series on a 2 to 6%.

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Table 3.1 Basic statistics for potato yield, specific gravity and regressor variables classified into chemical, physical and spectral factors taken from field 1 and 2 in Montcalm County, Michigan in 2003 and 2004 respectively.

Classification	Field	Stat‡	Variables† ppm: B_pH	Ca	K	Mg	P1	EC_a	Base Saturation, %: Ca	H	K	Mg	pH	CEC	C, %
Chemical	1	$\bar{x}$	6.87	502.8	167.7	107.2	14.7	-	46.7	28.3	8.0	16.8	5.7		
		s.e.	0.01	11.1	4.7	1.9	0.2	-	0.6	0.8	0.2	0.3	0.0	0.1	0.01
	2	$\bar{x}$	6.54	575.5	92.3	72.6	14.0	0.18	48.1	37.3	4.2	10.4	5.5	5.9	1.05
		s.e.	0.13	25.2	2.2	3.2	1.2	0.01	1.0	1.3	0.1	0.3	0.0	0.2	0.02

Classification	Field	Stat	Elev	MWD	Aggregate size, µm: 53	106	250	1000	2000	≥250	Texture Components, %: Sand	Silt	Clay	MC	k	BD
Physical	1	$\bar{x}$	278.1	1.21	13.3	12.8	45.5	18.8	9.7	73.9	76.4	16.6	7.1	15.8	85.0	1.46
		s.e.	0.3	0.02	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.1	3.9	0.01
	2	$\bar{x}$	251.7	2.18	7.5	6.4	26.2	22.5	37.4	86.1	82.3	12.0	5.7	11.5	-	-
		s.e.	0.1	0.01	0.1	0.2	0.4	0.4	0.5	0.3	0.2	0.2	0.1	0.3	-	-

Classification	Field	Stat	Spectral Band, Unadjusted: G	R	IR	Adjusted: G	R	IR	Vegarea
Spectral	1	$\bar{x}$	102.1	99.0	32.4	51.5	49.3	16.2	47.2
		s.e.	0.5	0.5	2.0	1.5	1.4	1.2	1.0
	2	$\bar{x}$	87.3	190.0	160.1	4.8	9.1	8.6	4.6
		s.e.	0.6	1.1	1.2	0.3	0.5	0.5	0.2

Classification	Field	Stat	Yield	SG
Dependent	1	$\bar{x}$	22.8	-
		s.e.	0.2	-
	2	$\bar{x}$	17.4	1.0824
		s.e.	0.3	0.0003

† Variables : B_pH = buffer pH ;Ca = calcium ; K = potassium ; Mg = magnesium ; P1 = phosphorus (Bray 1) ; EC_a = aparent electrical conductivity (shallow 0-30 cm); H = hydrogen ; CEC = cationic exchange capacity ($meqg^{-1}$); Elev = elevation; MWD = mean weight diameter, mm; MC = volumetric moisture content; k = hydraulic conductivity, $mmhr^{-1}$; BD = bulk density; Vegarea = vegetated area, %; Yield = $tonsha^{-1}$; SG = specific gravity ; G = green ; R = red ; IR = infrared .

‡ $\bar{x}$ = mean; s.e. = standard error.

Table 3.2 Selected soil properties of field 1 showing significant correlations with digital orthophoto quarter quad.

Soil Property	Infrared	Red	Green
Microaggregates (%)	0.2004 *	0.1787 *	0.1761 ns
Volumetric Moisture Content	0.0398ns	0.0102 ns	0.0600 ns
0.053 mm	0.1972 *	0.2154 **	0.2125 **
0.250 mm	0.0161ns	-0.1426 ns	-0.1256 ns
macro:micro aggregate ratio	-0.2110 *	-0.1983 *	-0.1965 *
Infiltration, $mmhr^{-1}$	-0.1297ns	-0.1761 ns	-0.1532 ns
Sand (%)	-0.2427**	-0.3433 **	-0.3339 **
Silt (%)	0.2054 *	0.3580 **	0.3312 **
Clay (%)	0.0801ns	-0.0320 ns	0.0056 ns
OM (%)	0.2534**	0.4365***	0.3984 **
yield ($Mgha^{-1}$)	-0.2122**	-0.4210***	-0.3808***
Gu	-0.1483ns	-0.4419***	-0.4071 **
Ru	0.0403ns	-0.1272 ns	-0.1177 ns
Iru	0.0123ns	0.2443 **	0.2096 *
Ira	0.0173ns	0.2614 **	0.2104 *

*** - significant at <0.0001; ** - significant at <0.05; * - significant at <0.10; and ns – not significant.

Table 3.3 Selected soil properties for field 2 as a whole (whole), datapoints found on Mancelona (Mb) and Gladwin (Ga) soil series sampled in fall 2004 showing correlations with digital orthophoto quarter quad image taken in 1997.

VARIABLE	INFRARED			RED			GREEN		
	WHOLE	Ga ONLY	Mb ONLY	WHOLE	Ga ONLY	Mb ONLY	WHOLE	Ga ONLY	Mb ONLY
Yield (tonsha^{-1})	-0.167ns	-0.252**	0.584**	-0.023ns	-0.025ns	-0.122ns	-0.061ns	-0.053ns	-0.065ns
SG	-0.189*	-0.257**	0.597*	0.059ns	0.053ns	0.013ns	0.117ns	0.108ns	0.116ns
Cover (%)	-0.336**	-0.351**	-0.166ns	0.114ns	0.165ns	-0.262ns	0.104ns	0.148ns	-0.283ns
Volumetric MC	-0.217**	-0.230**	0.133ns	-0.046ns	-0.077ns	0.14ns	-0.049ns	-0.086ns	0.157ns
0.250 mm	0.115ns	0.015ns	0.634**	0.048ns	0.124ns	-0.265ns	0.143ns	0.216**	-0.165ns
1 mm	-0.131ns	-0.063ns	-0.470ns	0.014ns	-0.063ns	0.303ns	-0.117ns	-0.208*	0.237ns
Ratio	-0.006ns	0.052ns	-0.362ns	0.028ns	-0.052ns	0.430ns	-0.100ns	-0.182*	0.316ns
EC_a	-0.263**	-0.300**	0.531*	-0.088ns	-0.140ns	-0.006ns	-0.080ns	-0.143ns	0.073ns
Elevation, m	0.220**	0.252**	0.124ns	-0.031ns	-0.004ns	-0.327ns	0.091ns	0.140ns	-0.384ns
PctCarbon	-0.227**	-0.184*	-0.492*	-0.151ns	-0.185*	-0.015ns	-0.260**	-0.285**	-0.162ns
Sand (%)	0.137ns	0.175ns	-0.361ns	0.078ns	0.035ns	0.486*	0.102ns	0.070ns	0.502*
Silt (%)	-0.157ns	-0.168ns	-0.022ns	-0.156ns	-0.115ns	-0.417ns	-0.210**	-0.169ns	-0.505*
Clay (%)	0.048ns	-0.010ns	0.531*	0.166*	0.174ns	0.102ns	0.231**	0.218**	0.242ns
Gu	0.436***	0.465***	0.174ns	0.056ns	0.010ns	0.471ns	0.189*	0.164ns	0.583**
Ru	0.386***	0.436***	-0.314ns	0.098ns	0.083ns	0.623**	0.088ns	0.078ns	0.643**
Iru	0.361**	0.402**	-0.366ns	0.079ns	0.084ns	0.493*	0.062ns	0.078ns	0.431ns
Ga	-0.185*	-0.213**	0.165ns	0.067ns	0.140ns	-0.443ns	0.040ns	0.098ns	-0.442ns
Ra	-0.248**	-0.268**	-0.001ns	0.111ns	0.179*	-0.359ns	0.081ns	0.135ns	-0.369ns
Ira	-0.182*	-0.204*	0.102ns	0.105ns	0.178*	-0.376ns	0.081ns	0.138ns	-0.371ns

*** - significant at <0.0001; ** - significant at <0.05; * - significant at <0.10; and ns – not significant

Table 3.4 Variogram profile for soil structure related properties of field 1 and 2.

Field	Properties	Range (m)	Nugget	Sill	N:S
1	2 mm	49.34	1.92	8.38	0.23
	1 mm	27.86	4.34	8.00	0.54
	0.250 mm	36.10	3.31	10.50	0.31
	0.106 mm	53.00	2.33	3.58	0.65
	0.053 mm	27.72	1.46	2.12	0.69
	MWD	41.27	0.00	0.02	0.01
2	2 mm	30.23	17.11	23.05	0.74
	1 mm	54.26	6.81	9.34	0.73
	0.250 mm	40.77	8.65	14.47	0.60
	0.106 mm	35.66	0.40	1.12	0.36
	0.053 mm	30.28	0.46	0.90	0.50
	MWD	30.13	0.01	0.01	0.82

Table 3.5a Pearson correlation matrix of selected soil, plant and spectral properties of field 1 in Montcalm, Michigan.

Field 1	C†	MC	Elev	K	Clay	0.250mm	MWD	G_{unadj}	Veg_{cover}	G/R_{unadj}	R/IR_{unadj}
Yield	-0.049ns	0.235 *	0.327**	0.595***	0.474***	0.120ns	0.202*	0.654***	0.056ns	0.224*	0.423***
C		0.035ns	-0.155ns	0.079ns	0.117ns	0.220*	-0.178ns	-0.235*	-0.067ns	-0.166ns	-0.055ns
MC			0.210*	0.327**	0.223*	0.092ns	-0.058ns	0.107ns	0.008ns	0.189ns	0.156ns
Elev				0.289**	-0.075ns	-0.023ns	0.003ns	0.199*	-0.023ns	0.186ns	0.354**
K					0.279**	0.154ns	0.064ns	0.447***	0.129ns	0.167ns	0.333**
Clay						0.320**	-0.051ns	0.210ns	0.128ns	0.054ns	0.077ns
250mm							-0.694***	0.247*	0.037ns	0.146ns	0.271**
MWD								0.054ns	-0.021ns	-0.113ns	-0.148ns
G_{unadj}									0.070ns	0.490***	0.587***
Veg_{cover}										0.109ns	-0.127ns
G/R_{unadj}											-0.004ns

*** - significant at <0.0001; ** - significant at <0.05; * - significant at <0.10; and ns - not significant

† C = % total soil carbon ; MC = volumetric moisture content ; Elev = elevation ; K = potassium ; Clay = % Clay ; 0.250mm = 1 - ≥ 0.250 sized water stable aggregate; MWD = mean weight diameter; G_{unadj} = Green band unadjusted; Veg_{cover} = vegetative cover; G/R_{unadj} = green red unadjusted band ratio; R/IR_{unadj} = red infrared unadjusted band ratio

Table 3.5b Pearson correlation matrix of selected soil, plant and spectral properties from field 2 in Montcalm, Michigan.

Field 2	C[†]	MC	Elev	K	Clay	0.250mm	MWD	G_{unadj}	Veg_{cover}	G/R_{unadj}	R/IR_{unadj}	EC_a
Yield	0.171ns	0.488***	-0.150ns	-0.034ns	0.049ns	0.255*	-0.429***	-0.405***	0.349**	0.101ns	0.463***	0.697***
C		0.575***	-0.194ns	0.280**	-0.265**	-0.203*	-0.218*	-0.511***	0.273**	-0.139ns	0.127ns	0.485***
MC			-0.334**	0.232*	0.031ns	-0.115ns	-0.321**	-0.486***	0.396***	0.191ns	0.321**	0.781***
Elev				-0.281**	0.093ns	0.224*	-0.066ns	0.347**	-0.146ns	0.074ns	0.053ns	-0.418***
K					0.122ns	-0.326**	0.139ns	-0.210*	0.122ns	0.045ns	-0.039ns	0.239*
Clay						-0.010ns	0.083ns	0.325**	0.040ns	0.425***	-0.040ns	0.025ns
250mm							-0.629***	0.142ns	0.086ns	0.234*	0.020ns	0.050ns
MWD								0.216*	-0.300**	-0.151ns	-0.175ns	-0.377**
G_{unadj}									-0.427***	0.589***	-0.371**	-0.523***
Veg_{cover}										0.092ns	0.414***	0.510***
G/R_{unadj}											-0.099ns	0.310**
R/IR_{unadj}												0.391**

*** - significant at <0.0001; ** - significant at <0.05; * - significant at <0.10; and ns - not significant

† C = % total soil carbon ; MC = volumetric moisture content ; Elev = elevation ; K = potassium ; Clay = % Clay ; 0.250mm = 1 - ≥ 0.250 sized water stable aggregate; MWD = mean weight diameter; G_{unadj} = Green band unadjusted; Veg_{cover} = vegetative cover; G/R_{unadj} = green red unadjusted band ratio; R/IR_{unadj} = red infrared unadjusted band ratio; EC_a = apparent electrical conductivity.

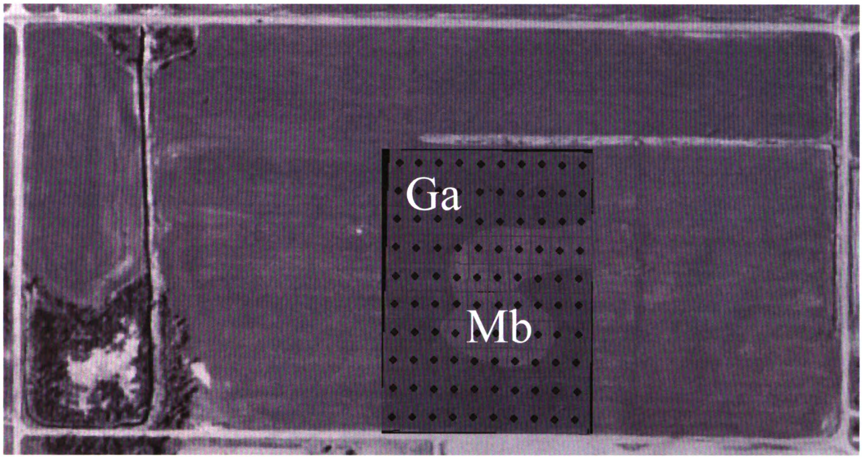

Figure 3.1 Digital Orthophotography Quarter Quad image detailing location of field 2 superimposed by soil series map showing presence of Mancelona loamy sand (Mb) and Gladwin loamy sand and Palo sandy loam (Ga) soil series. Original is in color.

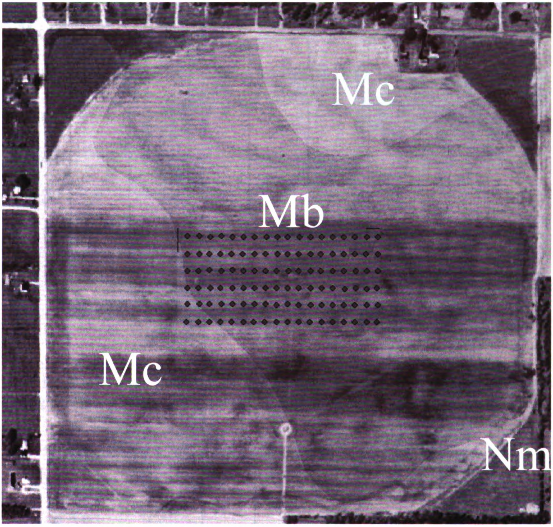

Figure 3.2. A section of a digital orthophotography quarter quad (DOQQ) image detailing location of field 1 superimposed by soil series map showing presence of Mancelona loamy sand with 0 to 2 percent slope (Mb), Mancelona loamy sand with 2 to 6 percent slope (Mc), and Newaygo sandy loam (Nm).

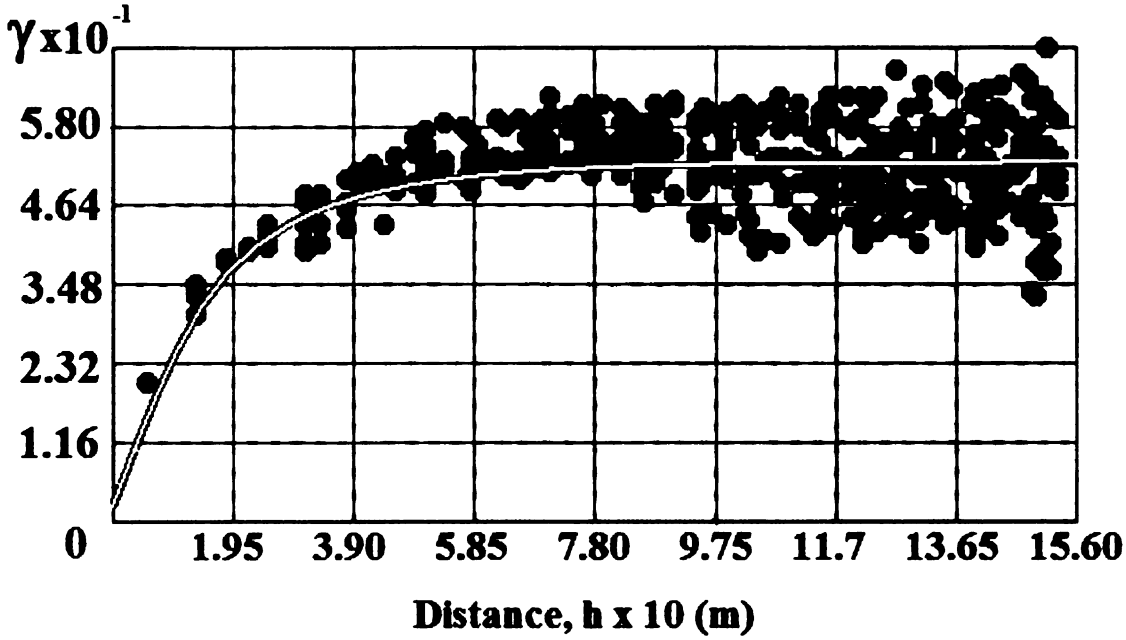

Figure 3.3 Semi-variogram (γ) plot for yield data taken from field 2 during the fall of 2004 fitted with exponential model (white line) showing a strong spatial dependence among data taken within a range of approximately 50 m.

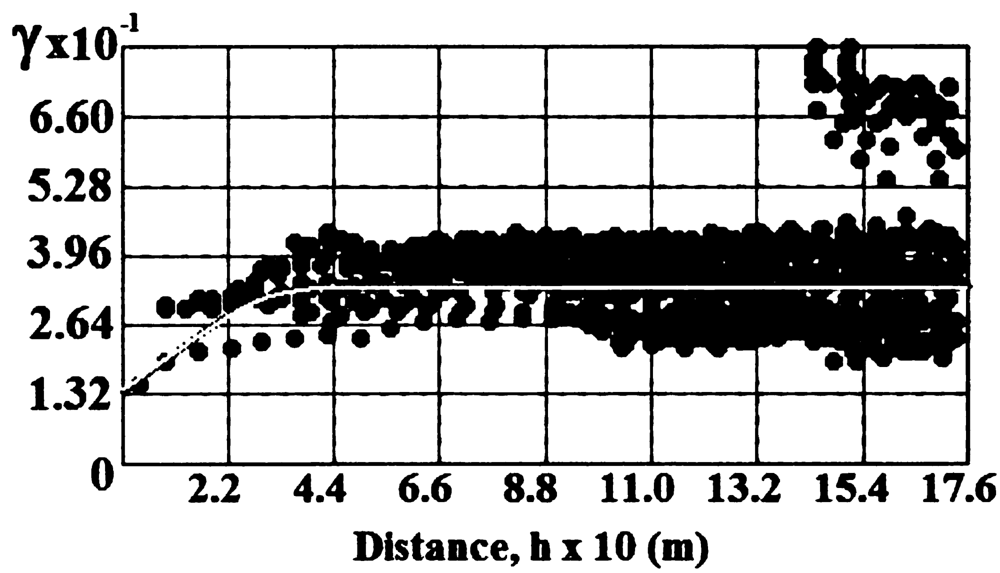

Figure 3.4 Semi-variogram (γ) plot for yield data taken from field 1 during the fall of 2003 fitted with exponential model (white line) showing a moderate spatial dependence among data taken within a range of approximately 42 m.