Using CTF as the Basis for Novel Farming Systems — Improved Nitrogen Utilization as a Case in Point

Clay Mitchell, The Mitchell Farm, Iowa USA

INTRODUCTION

Intercropping forces controlled-traffic farming, gains its benefits

Strip-intercropping maize and soybeans requires precise co-linear field operations year-after-year to maintain a proper rotation all the way to the crop edges. This forced controlled-traffic farming situation encourages the elimination of tillage and consolidation of wheel traffic that is normally associated with CTF.

In conventional cropping, field operations are often done on intentionally non-parallel swaths; even when some operations are repeatedly done in parallel, yearly passes are not co-linear. Thus, the effects of non-uniformity—whether in residue distribution, tillage depth, fertilizer distribution, planting depth, spray coverage, or other factors—become quickly buried in noise and blurred into a fuzzy picture where yield-limiting factors which follow directly from mismanagement, can never be seen.

In CTF, because all fertilizer, seed, chemical, and machine traffic was linear with the crop rows, misapplication shows up as yield variance between rows and the Recker number can be very closely estimated. Data collected by Bob Recker showed a yield difference of 30 bu/acre in one maize field of The Mitchell Farm last year which had an absolute yield of over 200 bu/acre.

In CTF, remote sensing offers a promising means of nearly direct measurement of the Recker Number.

The Recker Number

The ratio of actual yield to the yield that would have been achieved by all operations completed with uniform target application is known as the Recker Number.

$$\text{Recker} = Y_a/Y_t$$

The defining feature of the Recker Number is the lack of downside yield risk associated with efforts to improve upon it. Unlike precision farming practices that employ intentional variable rate application, solutions for uniformity do not depend upon large geospatial data sets, complex agronomic models, and estimated yield response curves—all of which carry error possibilities that add unique risks. On The Mitchell Farm, efforts to improve the Recker Number carry high expected returns, primarily through more uniform fertilizer application.

Basis for intercropping solution

We can think of strip-intercropping* systems that improve sunlight utilization as expanding our land base in proportion to the Land Equivalent Ratio (LER): The total area of sole crops required to produce the same yields as would be obtained when they are intercropped. The total land-equivalent ratio is the sum of the partial land-equivalent ratios of each component.

Today, in a special circumstance, the set of conditions which define the universe of incremental effects of strip-intercropping are a highly fortuitous convergence of "happy accidents," which has very suddenly made strip-intercropping economically optimal for the two crops that are in both area and value, the most important in the United States: corn and soybeans. Moreover, these special conditions allow gains in LER without an expected increase in yield volatility and without increased operational costs—a pure arbitrage opportunity.

Happy accidents leading to sunlight arbitrage

- Multiple crops as good rotational partners
- Taller crop more valuable than the shorter crop.
- Taller crop C4 photosynthetic process and shorter crop C3 photosynthetic process.
- Both crops optimally planted and harvested on one swath width.
- Intercrop rotation's soil erosion less than soil erosion of mono-crop rotation.
- Both crops available with same set of herbicide resistance.
- Automated guidance available with sufficient accuracy to separate planting and harvest operations for each crop without giving up area.

Table 1. Difference in sunlight utilization between C3 and C4 crops in selected characteristics

Species	**PS pathway**	**gDW/mw/week**
Maize	C4	47
Sorghum	C4	43
Sugarcane	C4	50
Spinach	C3	13
Tobacco	C3	25
Alfalfa	C3	20
		tons/acre
Maize	C4	3.02
Sugarcane	C4	3.67
Rice	C3	2.28
Tobacco	C3	.30
Soybean	C3	.28

Characteristic	**C3**	**C4**
Leaf anatomy	palisade + spongy	bundle sheath
CO_2:ATP:NADPH	1:3:2	1:5:2
gH_20/g dry wgt	450-950	250-350
CO_2 compensation pt.	40-90ppm	2-15ppm
Photorespiration	Yes	No
Temperature optimum	18-25C	30-45C
Dry matter production (tons/hectare/year)	20	40

Importance of herbicide resistant crops

Traditionally, in strip-intercropping each crop strip has to be treated individually. With at least a doubling of required field passes at a per pass cost of $4/acre, strip-intercropping incurs direct incremental production costs of at least $4/acre. Strip-intercropping also narrows available herbicides by non-viability of volatile herbicides, such as Clarity or Banvel, potentially raising herbicide costs and reducing efficacy. Having fewer herbicides to chose from compared to monocropped fields of the same crops means that herbicide options will potentially be more expensive, less effective, and have lower crop tolerance. The inverse and converse will never be true.

More importantly and with much associated risk, uncertainty, and unpredictability, weed competition from incomplete spray coverage or damage from herbicide drift at the strip boundaries reduces boundary yield, precisely where the interactions between the multiple crops are intended to bring yield gains from strip-intercropping. Border rows in a 10 ft swathing system with 30" row spacing can represent over half of total system yield - all of which is at risk when applying crop-specific herbicides.

With herbicide tolerant crops, application passes, timing, cost, and efficacy are the same as in monocropped fields of herbicide tolerant crops. Moreover, such herbicide tolerant crops are generally cheaper and safer to treat than conventional crops. The largest incremental risk associated with strip-intercropping is vanquished.

Table 2. Herbicide resistant crops by registration date

Crop	Bromoxynil	IMI group	Glufosinate	Glyphosate	Sethoxydim	SU group
Alfalfa				2003		
Canola		1999*	1999*	1999*		Canada
Maize		1992	1997	1998	1995/96	
Cotton	1998			1997		
Flax						Canada
Potato				2002		
Rice				2003		
Soybean			1998#	1996		1993
Sunflower		2001				
Sugar beet		2002	2000**	2000**		
Wheat		2001	2005	2003		

Some herbicides are labeled for use across a variety of crops which may be intercropped. For example, the following chemicals may be applied to conventional corn and soybeans: alachlor, sencor, dual, prowl. However, no combination of these chemicals provides affordable, full-spectrum weed control, and crop safety. Therefore, in traditional strip-intercropping, at least one separate pass must be made to treat the corn and soybeans separately. While strip widths may be between 10 and 30 feet, sprayer boom widths are commonly between 60 and 120 feet. Because each strip must be covered individually when spraying crop-specific herbicides, the number of additional passes required increases by 2 to 8 times.

The enabling guidance technology for strip-intercropping

Without automatic guidance, it is usually necessary to plant each crop at the same time with the same planter, generally in a split-planter configuration. Alternatively, visual cues can be used when no-till intercropping into discernable rows. Mean reverting influences upon proper row placement are weak, and crop swaths will eventually result in crossing of the crop borders unless a very narrow fallow strip is added to the border.

On The Mitchell Farm, automatic guidance with RTK precision is used to plant and harvest the maize and soybean strips non-sequentially, and to further gain the benefits of precise placement of fertilizer strips relative to corn, 15" soybeans between old corn stalks, and CTF where only 17% of the ground surface is tracked. All machines on The Farm operate with RTK-level autosteering.

Switching from conventional farming includes the cost necessary to meet the minimum requirements: a tractor with RTK autosteering and an integral planter or planter with centimeter-level implement guidance, whose planting width is an even multiple of the combine header widths. Synergy with no-till/ strip-till and CTF mean that operational costs and machinery capitalization for intercropping farms will be lower than for conventional farms. Notably, each machinery feature necessary and useful for intercropping is also useful in best management practices for monocropping.

***Definitions**

Strip-intercropping is an easily confused term because of confusion with "strip-tillage" and with other methods of intercropping.

- *Intercropping* is growing two or more crops simultaneously on the the same field with the intention of benefitial interactions between the crops. The crops can be interspersed in either time or space.
- *Mixed* or multiple cropping is the growing of two or more crops simultaneously on the same field without a row arrangement
- *Relay* cropping is the growing of two or more crops on the same field with the planting of the second crop after the first one has completed its development
- *Row* intercropping is the growing of two or more crops simultaneously on the same field with a row arrangement
- *Strip* intercropping is the growing of different crops in alternate strips of usually uniform width and on the same field. It has two types; contour strip cropping and field strip cropping. Contour strip cropping follows a layout of a definite rotational sequence and the tillage is held closely to the exact contour of the field. Field strip cropping has strips with uniform width that follows across the general slope of the land.

Intercropping effects on nutrient needs

Preliminary data from strip-intercropping maize and soybeans shows >25% increase in yields of maize border rows with a concurrent decoupling from phosphorus limitations. Recent advances in crop genetics and production technology make row-intercropping (wherein border rows become interspecific on both sides and every row becomes a border row) viable while an increasing maize/soybean value ratio makes the tall-crop favoring system attractive.
Overwhelming evidence suggests that row-intercropping offers a means to increase the percentage N derived from N_2 fixation.

IMPROVING N UTILIZATION

Applied N

Over 12 million tons of nutrient N are applied to cropland in the United States annually, with half going toward maize production (USDA-ERS, 2006). It is now estimated that applied N to cropland is now great than that from combined natural sources (Vitousek, 1994). The energetic cost of synthesizing N fertilizer through the Haber–Bosch process is 27 GJ t^{-1} NH_3 (Smil, 2001).

N benefit in intercropping

If the intercropped non-legume is taller than the legume, shading will occur and photosynthesis and subsequent N_2-fixation will be reduced (Hardy & Havelka, 1976). Because per plant photosynthate but not canopy level photosynthesis is reduced under higher crop densities, N_2-fixation is similarly reduced under high densities on a per plant but not on a per area (Waters et al., 1998).
Whereas early season N application does not usually increase soybean yields, N fertilization during pod-filling can result in significant yield gains with nearly all applied N translocated to the seed (Afza

et al., 1987, Taylor et al., 2005), or no yield effect whatsoever (Barker & Sawyer, 2005, Schmitt et al., 2001).

While experiments have shown 15% of the N in N_2-fixing soybeans could be transferred to intercropped maize through deposition as ammonium, amino acids, and sloughed-off cells during the growing season, for other legume/non-legume intercrops no field-level transfer is found even though it may be found in the laboratory (Hauggaard-Nielsen & Jensen, 2005). While focus on improving N utilization in intercrops usually focuses on the legume, the choice of non-legume can have pivotal effects. Biomass, grain yield and N acquisition of faba bean were significantly increased when intercropped with maize, and decreased significantly with wheat, irrespective of N-fertilizer application, indicating that the legume could gain or lose productivity in an intercropping situation (Fan et al., 2006).

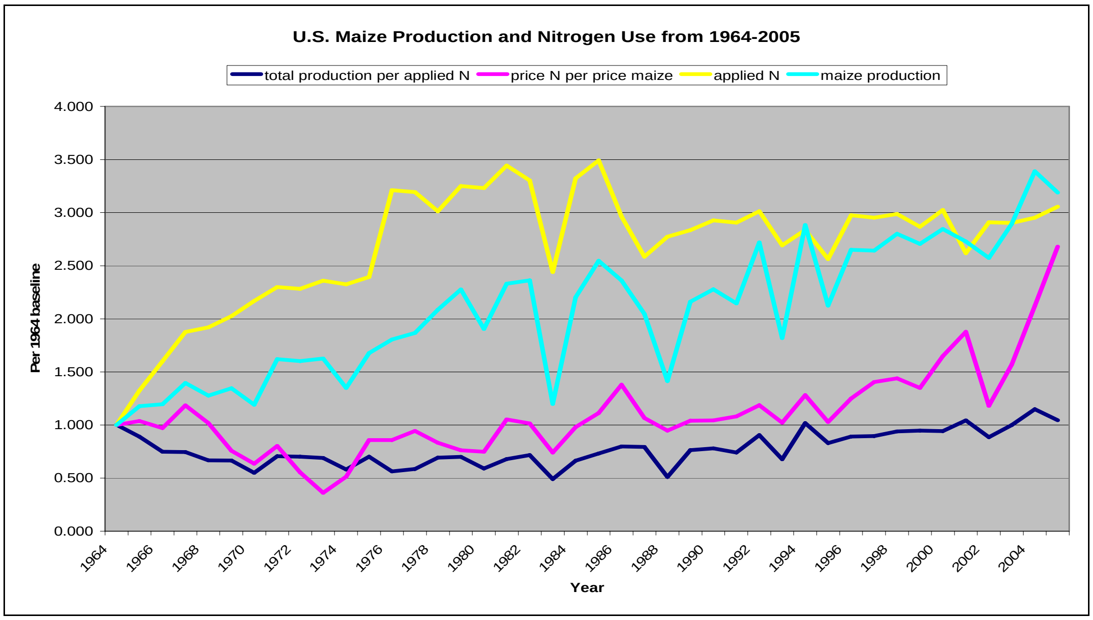

Figure 1 Maize production and price compared with N applied to maize and N price, all compared to 1964 levels. Maize production and total N applied have both tripled. The price of N compared to the price of maize has also nearly tripled. Efficiency of N use (ratio of total maize production to total applied N) has remained relatively unchanged since 1964 (USDA-ERS, 2006).

Fungal explanation

While direct transfer of N from soybeans to maize through common mycorrhizal networks (CMN) has been shown (van Kessel & Hartley, 2000), most evidence shows that meaningful quantities of N are only transferred indirectly through the AM hyphae (Hauggaard-Nielsen & Jensen, 2005).
Experimental observations have indicated that arginine in AM fungi is usually the principal nitrogenous product accumulated during periods of ammonium feeding at the uptake site, providing support for the importance of these amino acids in N transfer between fungal and plant cells (Chalot et al., 2006).

For endomycorrhizal networks between maize and soybeans, uptake by the receiver plant of the N excreted by the donor plant root system appears to be the mechanism of N-transfer between plants rather than transfer through the fungi, and the transfer is highly dependent on the degree of contact between the root systems (Hamel et al., 1991). However, the fungi do play important rolls in reducing N loss from soybeans while improved the ability of the maize to recover N lost from soybeans with overall improvement in N use—an effect that would not necessarily be experienced differently under intercropping compared to sole-cropping.

Increased fixation due to soil N depletion

Rather, than transfer through CMN, the explanation for N benefits in intercropping appears to be that the % N due to fixation by the legume is greater in the mixed crop because the non-legume effectively drains the soil of N (Hardarson & Atkins, 2003, Li & Zhang, 2006). Levels of available soil-N influence infection, nodule development, the rate of N_2 fixation, and the senescence of nodules (Hauggaard-Nielsen & Jensen, 2005). With significant uptake by maize of soybean N rhizode-posits, less soil N is available for the soybean to reabsorb and therefore there is reduced N-fixation inhibition within the soybean. When roots have facilitative interactions, soil N depletion forces the legume to fix more N. The increase in N fixation correlates very strongly with total dry matter yield in the intercropping system (Fan et al., 2006).

Glyphosate tolerance

While glyphosate tolerance among both maize and soybeans is the enabling biotechnology for intercropping, it also presents a unique hurdle to optimizing N. Because glyphosate is toxic to the soybean N-fixing symbiont, *Bradyrhizobium japonicum,* N fixation and/or assimilation is slightly affected at label use rate, but consistently reduced at above label use rates of glyphosate and the greatest reductions occurred with soil moisture stress following glyphosate application (Zablotowicz and Reddy, 2007).

Regulation of biological fixation rates

Achieving agronomic benefits from management of the finely regulated and energy intensive processes of biological N fixation through farming practices or breeding, e.g. genetic engineering, can be more reliable in the first effort and achievable in the second through an understanding of the regulation process. The bases for three competing theories are (1) carbon supply at the nodule, (2) oxygen diffusion into the nodules, and (3) feedback inhibition by the product of N fixation (Allaway et al., 2000). Some unification of theories may be found in the critical role that alanine synthesis performs between carbon and N metabolism in bacteroids. While low- and high-density bacteroids secrete similar levels of ammonium, high-density bacteroids secrete alanine and thus have higher total N secretion and carbon metabolism due to synthesis by AldA, indicating an important cross-regulation between carbon and N metabolism (Parsons and Sunley, 2001).

Root distribution interactions

Spatial distribution effects are fundamental root interactions of intercropped species that are easily measured by auger and monolith sampling (Willey, 1979). While the root distribution of maize intercropped with faba bean (*Vicia faba* L.) showed lower increase in root length density than with wheat, the response was consistent with the shallower root distribution of faba bean. The roots of intercropped maize spread under faba bean, and consequently occupied a greater soil volume than sole-cropped maize, providing evidence that agronomic benefits from intercropping can occur from increased lateral root growth and greater root length density due to compatibility of spatial root distribution of intercropped species (Li et al., 2006).

Intercropping N uptake

Because genetic and environmental complexities in a crop setting exceed the categorical decision options perceived by farmers, N transfer is not universally achieved with intercropped legumes and conflicting reports of transfer have been borne out in research. Whereas the N contribution of the intercropped legume to maize has been estimated at 40 kg ha^{-1} (Searle et al., 1981, Wahua & Miller, 1978), others did not find any evidence for such N benefit (Chalka and Nepalia, 2006).

Total N uptake for maize soybean, maize cowpea, maize greengram, and maize blackgram averaged 37.5, 22.1, 18.5, and 17.1% over sole maize in a multiyear study while maize cowpea and maize soybean were superior in reducing N uptake by weeds (Elmore and Jackobs, 1986). An increase in total N of sorghum intercropped with nodulating soybeans was reported, but not when intercropped with non-nodulating soybeans (Fried and Broeshart, 1975). This beneficial effect of the nodulating soybean on sorghum was attributed to transfer of N from the legume to the non-legume

^{15}N techniques

Using ^{15}N-enriched ammonium sulfate, (Kessel and Roskoski, 1988) maize intercropped with cowpea showed lower atom % ^{15}N excess values than the monocropped maize. This was caused by excretion of fixed N by the legume and subsequent uptake of N by the maize. ^{15}N techniques were used to test row spacing effects on N_2-fixation, yield, and N uptake in maize and cowpea at row spacings of 40, 50, 60, 80, and 120 cm and intercropped at row spacing of 40, 50, and 60 cm (Claasen and Wilcox, 1974, Feng and Barker, 1992, Magalhäes and Huber, 1989). Using the^{15}N-dilution method, the percentage of N derived from N_2-fixation by cowpea and the recovery of N fertilizer and soil N uptake was measured for both crops at 50 and 80 days after planting. Maize grown at the closer row spacing accumulated most of its N during the first 50 days after planting, whereas maize grown at the widest row spacing accumulated a significant portion of its N during the last 30 days before the final harvest, 80 days after planting.

Areas for research

While intercropping is typically viewed as a system for low synthetic N inputs, field-level studies range from no fertilizer N to high fertilizer N, but consistently use uniform application methods that do not attempt to localize the fertilizer relative to the non-legume/legume arrangement (Altier, 1992, 1990, Chalka and Nepalia, 2006, Chu et al., 2004, Dahlan, 1981, Dalal, 1974, Eaglesham et al., 1981, Elmore and Jackobs, 1986, Fan et al., 2006, Gondwe, 1992, Hamel et al., 1991, Hauggaard-Nielsen and Jensen, 2005, Kessel & Roskoski, 1988, Li et al., 2006, Li and Zhang, 2006, Mangoendidjojo, 1983, Martins and Cruz, 1998, Mason et al., 1986, Peters, 1986, Searle et al., 1981, Shen and Chu, 2004, Waterer et al., 1994, YanBo et al., 2005). Agronomic practices such as root-zone banding, and use of nitrification inhibitors and encapsulated fertilizers would present a novel means of matching fertilizer location, source, and timing to the maize/soybean system that is consistent with modern production practices. Managing fertilizer release by encapsulation with polymer-coated urea is just beginning to make inroads in grain production and has been used successfully to delay fertilizer availability for soybeans until pod-fill (Schmitt et al., 2001).

Phosphorus is analogous to N in that both nutrients are known to move through CMN, which is of particular interest in intercropping. Also, both nutrients exist in the soil largely in organic, solution, fixed, and exchangeable form unlike potassium which is largely in mineral form. While nitrate moves primarily through mass flow and phosphorus through diffusion, ammonium moves primarily through diffusion and preferential uptake may be advantageous. The most significant difference is that nitrate leaches readily whereas phosphorus is not very mobile, with most loss occurring in runoff. N is therefore managed with applications intended exclusively for the current crop, whereas phosphorus is applied with regard to its residual effects.

Previous analyses comparing tradeoffs of synthetic N fertilizer to N from legumes attempt to construct absolute value models that include nuances of leaching, a range of rotational options that may include pastures or non-harvested crops, and environmental hazards as far reaching as, eutrophication, global warming, groundwater contamination, and stratospheric ozone destruction (T.E. Crews). However, farm-level decision-making depends not on absolute yield models, but incremental effects on input cost and yield which fully encompass both the economics and scope of management options particular to the farm.

PRELIMINARY DATA

Methods

In order to test the effects of interspecific root interactions between maize and soybeans on phosphorus response, a replicated trial was conducted in 2006 in a field intercropped in 9 m swaths. No-till seeding was done on May 9 with maize planted in 12 rows on 30” centers and soybeans seeded in 24 rows on 15” centers in a North-South orientation. Maize and soybean rows were separated by 22.5”. Four swaths of maize were divided into 800 ft subplots and planted at 3 different populations. N was applied at 4 different rates on sets of 4 rows with all blocks and treatments described in the following figure. Phosphorus was uniformly applied at 150 lbs of nutrient P per acre.

Yield results were harvested by a single row-harvester which collected GPS-based grain flow at 1 second intervals to create a yield map. The harvester recorded cumulative results for each of the 144 rows. For each row, total yield was also recorded by a grain cart with weigh scales. After harvest, soil cores were taken from within each row and combined into 144 representative samples from which phosphorus levels were tested with a Melich-3 extraction method.

RESULTS

The mean yield for outside rows was 242 bu/acre and the mean yield for inside rows was 192 bu/acre. Soil phosphorus varied by row from 9 to 47 ppm. Yield response by row position is shown in Figure 3.

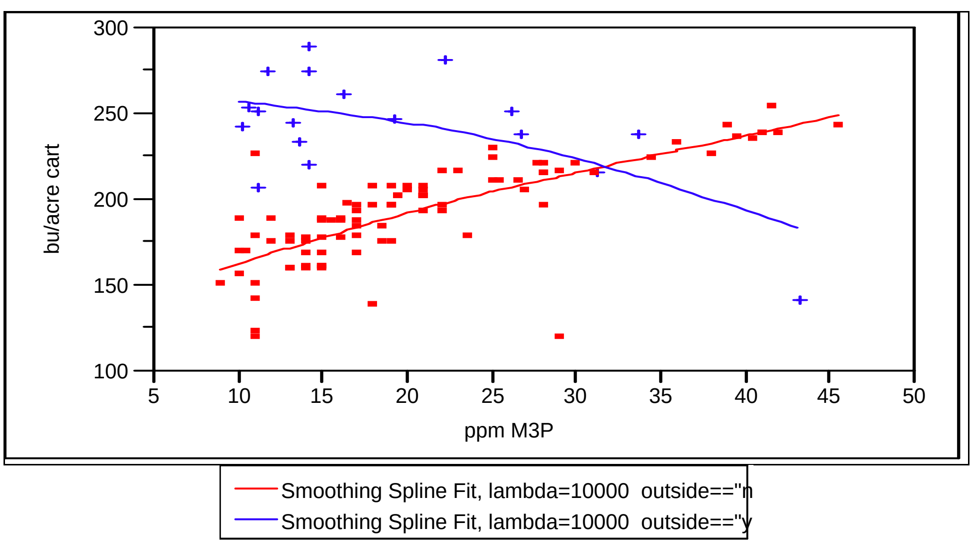

Figure 2. Bu/acre cart by ppm M3P

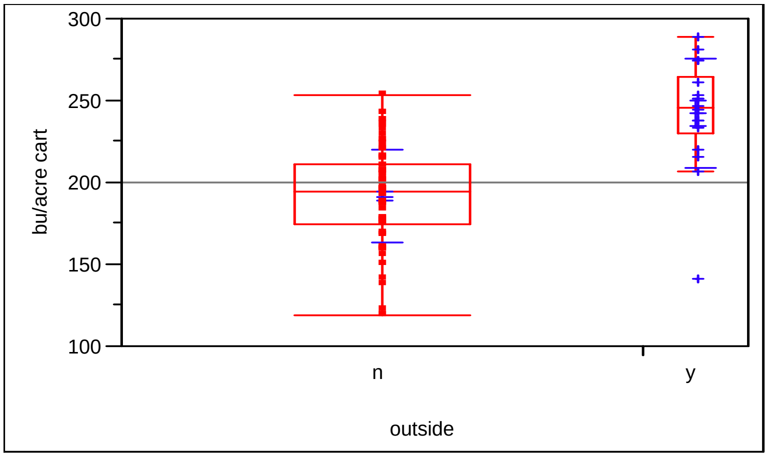

Figure 3. Bu/acre cart by outside

Table 3.Means and Standard Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
n	120	191.7	28.5	3.0	185.7	197.6
y	24	242.3	33.8	8.0	225.5	259.1

DISCUSSION

Phosphorus concentration varied by more than a factor of 5 even though application was intended to be equal. Reasons for variation include field-level geospatial variations as well as multi-year cumulative systematic variations due to imperfect fertilizer application equipment. Phosphorus was strictly yield-limiting for interior rows and showed strong correlation across all yield levels. Yield on outside rows was not only higher than the yield of interior rows, but was independent of phosphorus concentration.

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