C AND N COUPLING THROUGH TIME: SOIL C, N AND GRAIN YIELD IN A LONG-TERM CONTINUOUS CORN TRIAL

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ABSTRACT

Gains and losses of C and N are important in agricultural landscapes. Temporal changes in the pattern of crop yield response to tillage and fertilizer input are commonly observed; often weakly interpreted, in long-term research. A 38-year-long monoculture corn (Zea mays L.) tillage (moldboard plow, no-tillage) by N rate (0, 84, 168, 336 kg N per hectare) trial was sampled to a depth of 100 cm, as was the surrounding grass sod, to determine impacts of tillage and N fertility on soil C and N. Temporal changes in yield due to tillage and N were evaluated, separating the linear/polynomial impact of annual treatments from that due to seasonal weather. Corn yield (and residue C input to the soil), in both tillage systems, rose with increasing fertilizer N rate, as did soil C and N, especially in the upper solum. The yield response to fertilizer N became increasingly positive, especially at higher N rates in tilled systems. The yield response to plowing became increasingly negative with time, though more slowly with adequate N nutrition. Residuals analysis indicated that tillage, in combination with either of the two lower N rates, will not sustain yield. No-tillage, in combination with any of the three higher N rates, will sustain yield. Soil C and N depletion was most associated with land use change (from sod to unfertilized continuous corn, regardless of tillage). Fertilizer N was positively related to soil C and N levels via associated improvements in cropland soil productivity. Tillage negated a large part of the benefit of N fertilization to soil C and N levels. No-till corn yield is greater, and its fertilizer N need is lower. This is a reflection of the superior agroecosystem functions (water and nutrient storage capacity) of this soil, under no-tillage management.

Keywords: Long-Term Research, Carbon, Nitrogen, Fertilizer N, No-Tillage

INTRODUCTION

Textbooks make clear the intimate relationship between carbon (C) and nitrogen (N) in the soil. Brady and Weil (2008) state the following: *"Adequate nitrogen is requisite for adequate organic matter because of the relationship between nitrogen and carbon in humus and because of the positive effect of nitrogen on plant productivity."* As such, gains and losses of both C and N are important in agricultural landscapes. The current emphasis on soil C storage means that understanding soil/crop management practices contributing to soil C gain/loss is important. Again, textbooks generally teach that crop productivity is increased when a needed nutrient (or any other limiting factor) is provided. Plant growth provides much of the C that eventually becomes soil organic carbon (SOC). Because, next to water, fertilizer N is the largest driver of cereal crop growth, it is generally believed that needed plant nutrition contributes positively to SOC. But it is clear that, in the minds of some, there are ambiguities in the relationship(s) between soil C and soil N (Khan et al., 2007; Mulvaney et al., 2009).

Long-term studies are valuable in illuminating these relationships, but especially when the confounding influence(s) of agroecosystem, tillage and time are appreciated/can be accounted for. As the no-tillage (NT) production system permits row-cropping in the absence of soil disturbance (Phillips et al., 1980; Triplett and Van Doren, 1977), long-term NT research trials permit observation of the impact of agroecosystem change in the absence of tillage. In Argentina, rotations involving pasture and row-cropping raise and lower surface soil SOC levels, respectively; a cycle in SOC concentrations that is diminished in amplitude when the row-cropping is done with NT soil management (Diaz-Zorita et al., 2002). Tillage research trials often show greater SOC concentrations in the surface 30 cm of the soil profile, though ten years was required to maximize differences in surface soil SOC levels due to tillage in Kentucky (Diaz-Zorita and Grove, 2002).

The greater C in NT soils, relative to moldboard plowed (MP) soils, is stored in microaggregates within macroaggregates (Chung et al., 2008). Interestingly, SOC may be somewhat less sensitive to tillage than other soil properties. Diaz-Zorita et al. (2004) found that chisel plowing once every two years had no effect on SOC, though this practice diminished the plant available water holding capacity of the soil. Generally the SOC stored in NT soils, indeed, in all soils, has been presumed to be well-coupled with much of the N found in those soils.

Initially, NT soils exhibited reduced N availability to a growing corn crop (Blevins et al., 1983), and N loss mechanisms in NT soils were then investigated. The greater macroporosity of NT soils was found to cause greater NO_3-N leaching, relative to MP soil management (Tyler and Thomas, 1977), but not more than chisel plowing, which is now "conventional" tillage (Stoddard et al., 2005). And even well-drained NT soils exhibited greater denitrification activity (Rice and Smith, 1982). However, most investigators concluded that the lower N availability often observed was usually due to inorganic N immobilization.

Rice and Smith (1984), among the first to conduct short-term immobilization studies on long-term trials with tillage treatments, observed greater fertilizer N retention as organic N in NT soils. It was found that much of the N contained in winter cereal cover crops, grown between each summer cropping season, was not released to the soil (mineralized) in time for recovery during vegetative growth of the summer crop (Huntington et al., 1985). Rice et al. (1986) reported that although N mineralization from unfertilized control plots, as measured by annual corn (*Zea mays L.*) yield, was initially lower in NT soil, 9 years of MP soil management caused the soil to be less consistently superior in N release to the unfertilized crop. This indicated continuing organic matter decline, and the resulting observation that soil N was no less available in NT than MP (Rice et al., 1986).

Longer duration ^{15}N studies found that immobilization was a greater fate for fertilizer N than either denitrification or leaching, that neither tillage or N rate influenced ^{15}N recovery by the crop, that immobilization occurred to a depth of 90 cm, that one-half of the immobilized N was in the surface 5 cm of NT soil, and was distributed more uniformly in the surface 30 cm of the MP soil (Kitur et al., 1984). The immobilization mechanism likely underlies the many reports from long-term research in Kentucky that have consistently shown that fertilizer N is positively related to SOC in both NT and MP soils (Blevins et al.,1975; Blevins et al., 1983; Frye and Blevins, 1997; Ismail et al., 1994).

Our objective was to examine agronomic and soil data from a long-term tillage by N rate trial for evidence in support of the hypothesis that long use of fertilizer N has resulted in a depletion of soil C and soil N. We determined profile SOC and total N levels resulting from: i) the conversion of an established sod to continuous corn production; ii) the continuous use of NT or MP soil tillage management; and iii) the continuous application of none, agronomically adequate, or agronomically excessive quantities of fertilizer N.

MATERIALS AND METHODS

This field trial was initiated in 1970 on the Kentucky Agricultural Experiment Station farm near Lexington on a site with 1 to 3% slope and exhibiting none to slight erosion. Previously, the site had been a bluegrass (*Poa pratensis* L.) pasture for nearly 50 yr. The climate is temperate, having an average annual rainfall of 110 cm (about 40% falls in summer – May to September), an average annual temperature of 13^{o}C, and a growing season duration of 175 days (Frye and Blevins, 1997). The soil is a moderately weathered Maury silt loam (fine, mixed, semi-active, mesic Typic Paleudalfs), deep, well-drained, and formed in the residuum of loess-capped phosphatic Ordovician limestone. The soil contains no free $CaCO_3$, and the clay fraction, dominated by vermiculite, kaolinite and illite (Frye and Blevins, 1997), also contains significant amounts of amorphous Fe and Al oxides (Chung et al., 2008).

The experimental design is a split-block with four replications, each block split along the long dimension for the tillage treatments, NT and MP, and across the long dimension for four N rates (0, 84, 168 and 336 kg N ha^{-1}). Tillage and N rate treatments have been maintained on the same plots for the duration of the experiment. The site is continuously summer cropped to corn, for grain, which is followed by a winter annual cereal cover crop. Moldboard plowing, to a depth of 20 to 25 cm, is done in the third or fourth week of April each year, about 1 to 2 weeks before planting corn. Secondary tillage of plowed plots is done with two passes of a tandem disk, mixing soil to a depth of 8 cm (Figure 1). Ammonium nitrate is surface broadcast within 1 wk of planting. Corn is harvested in late September or early October each year, and combine-shredded residues are left on the soil surface. After corn harvest, the winter cereal is planted over the entire experimental area, without any tillage, using a NT drill.

Fig. 1. The experimental area: post-tillage and pre-plant.

Three intact soil cores were taken without compression to a depth of 1 m from each plot receiving 0, 168 or 336 kg N ha^{-1}, and in the surrounding sod at each of the four corners of the trial, and divided into 0.1 m increments. This was done in early April, 2008. Same-depth increments were composited and immediately sub-sampled for gravimetric moisture content and subsequent calculation of bulk density. The remainder of the composite was air-dried and crushed to pass a 2 mm sieve. Soil organic carbon (SOC) and total nitrogen (TN) were determined by dry combustion. Clay minerals in the Maury soil contain nonexchangeable ammonium (Kitur and Frye, 1983), which can positively influence TN values, especially deeper in the profile (Black, 1968).

Statistical analysis of the yield and soil data was done via the MIXED model procedure in SAS (SAS, 1997).

RESULTS

Corn growth and color differences due to the fertilizer N treatments are usually dramatic (Figure 2), as are growth and color differences in the winter cereal cover crop (Figure 1), though cover crop dry matter accumulation has rarely been evaluated.

Fig 2. Vigorous mid-vegetative corn growth in the experimental area.

The corn grain yield response to the tillage and fertilizer N rate treatments has generally been significant, though the “pattern’ to the response has changed with time (Table 1). If one ‘lumps’ the entire 40 years together, the crop responded positively to N nutrition and negatively to soil disturbance. The tillage by N interaction is due to a ‘bulge’ in the middle of the production function, with larger no-till corn yields at 84 and 168 kg N/ha. Yield differences due to tillage at the two extreme N rates, 0 and 336 kg N/ha, were smaller.

When the first 15 years of yield information are ‘lumped’ together, the response to N was more modest and the interaction exhibited a different form (Table 1). Moldboard plow corn was less responsive to N, with greater yield at 0 and 84 kg N/ha. No-till corn responded more positively to N, up to 168 kg N/ha, but the response then leveled. This ‘plateau’ in no-till corn’s N response has continued, though other components to the corn yield response are very different. Looking at the last 15 years (Table 1), the tillage response has become more dramatic, as has moldboard plow corn's N response. The yield interaction was again due to the no-till corn yield 'bulge' at 84 and 168 kg N/ha.

Table 1. Corn grain yields due to tillage and N rate, for several time periods.

Primary Tillage	Fertilizer N Rate	All 40 Years (1970–2009)	First 15 Years (1970–1984)	Last 15 Years (1994–2009)
	kg N/ha	---------------grain yield (kg/ha)----------------		
moldboard plow	0	3760	5400	2660
	84	6690	7550	6460
	168	7420	7710	7660
	336	7780	8060	8020
no-tillage	0	3840	4480	3220
	84	7030	7270	7160
	168	8030	7920	8590
	336	8040	8030	8510
Statistical Summary		--------probability of a greater F value--------		
tillage	T	<0.05	<0.05	<0.01
N Rate	N	<0.001	<0.01	<0.001
till by N	TxN	<0.05	<0.05	<0.05

The profile (1 meter) soil C and N levels found in early 2008 were positively influenced by fertilizer N rate, but that influence was reduced by moldboard plowing, especially at the two higher N rates (Table 2). Relative to no-tillage, plowing lowered soil C and N by 11 and 7%, respectively, at 336 kg N/ha. The fertilizer N benefit to no-till soil C (+ 8 Mg/ha) and N (+ 1 Mg/ha) at 168 kg N/ha was modest. Depletion of soil C (21%) and N (13%), due to corn production (relative to the surrounding grass sod) was most significant, and not different due to tillage, at 0 kg N/ha. Most of that depletion was observed in the upper 40 cm of soil (Figure 3). Moldboard plowing resulted in redistribution of soil C and N, though significant differences (not shown) were confined to the upper 40 cm of soil. Significant differences (not shown) due to the N rate treatments were found as deep as 70 cm

The path by which the corn soils arrived at their current C and N levels is greatly related to the temporal progression in crop productivity. Crop yield generally reflects total crop productivity and the return of biomass C and N to the soil, which acts to maintain soil C and N levels, is assumed proportional to yield. However, the temporal progression in productivity, yield versus year, is made noisy by the strong yield versus seasonal weather relationship. In this trial, the noisy, but significant, yield versus year relationships (Figures 4 and 5) were best described by quadratic models, initially declining and then rising with time.

Examination of Figures 4 and 5 finds that the yield response to the first 168 kg N/ha has increased with time, especially in plowed soils. The yield benefits to plowing, most apparent at 0 kg N/ha, declined with time and greater N nutrition.

Table 2. Soil carbon and nitrogen, to a 1 meter depth, due to tillage and N rate.

Primary Tillage	Fertilizer N Rate	Profile C	Profile N
	kg N/ha	------------Mg/ha-----------	
moldboard plow	0	85	12.8
	168	90	13.6
	336	97	13.9
grass sod	0	108	14.7
no-tillage	0	85	12.8
	168	93	13.8
	336	109	14.9
Statistical	Summary	--probability of a greater F value--	
tillage	T	ns (>0.10)	ns (>0.10)
N Rate	N	<0.01	<0.05
till by N	TxN	<0.05	<0.05

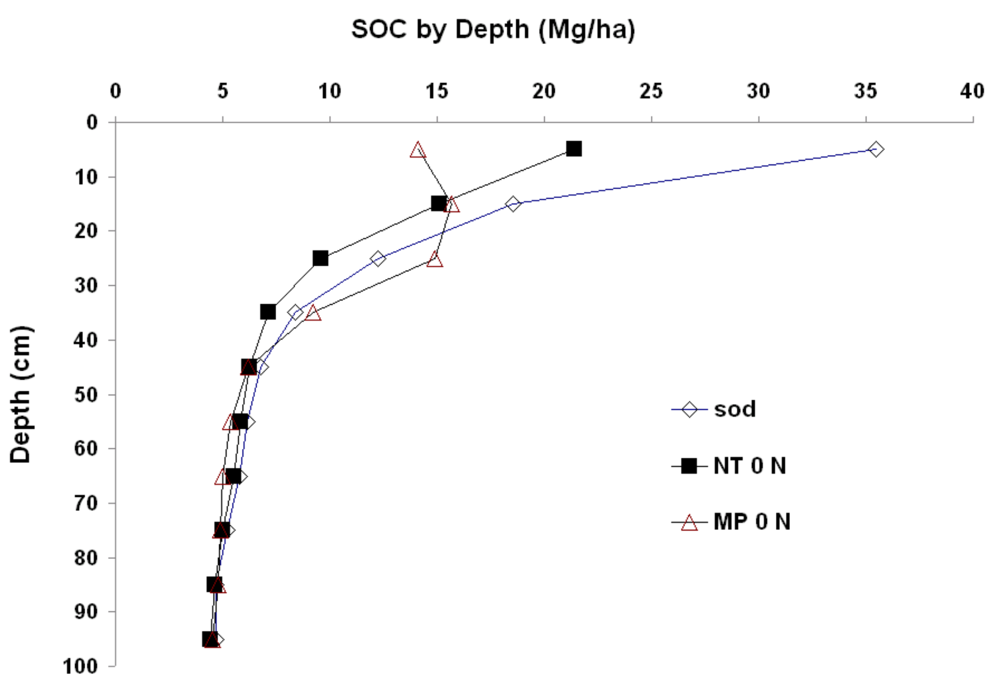

Fig. 3. Soil carbon distribution, to a 1 meter depth, in the un-N-fertilized soils.

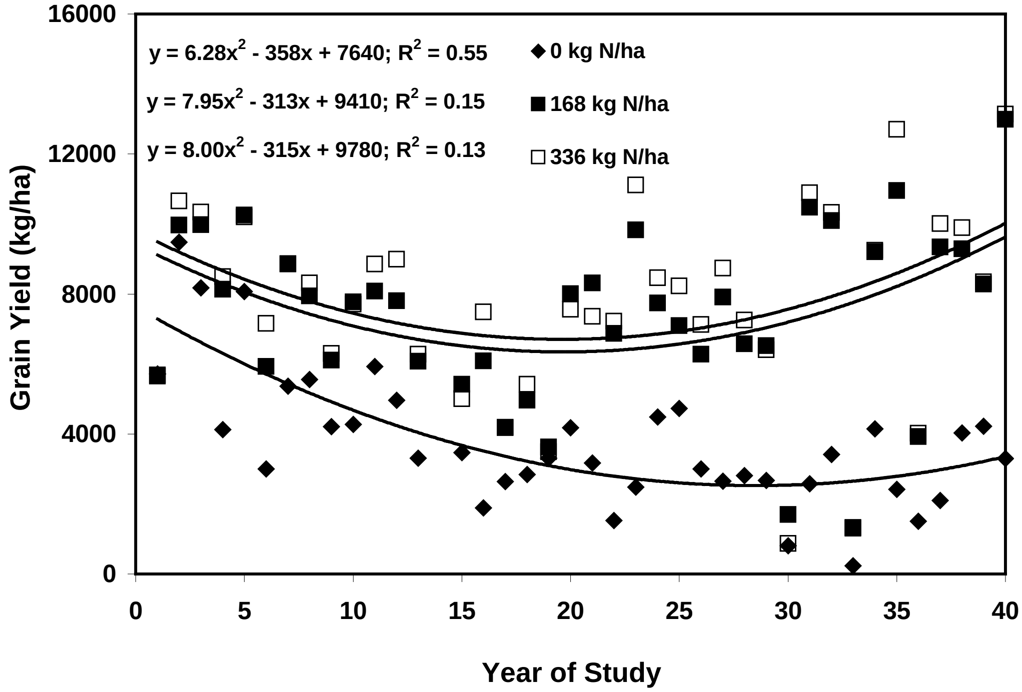

Fig. 4. Annual moldboard plowed corn grain yield response to N.

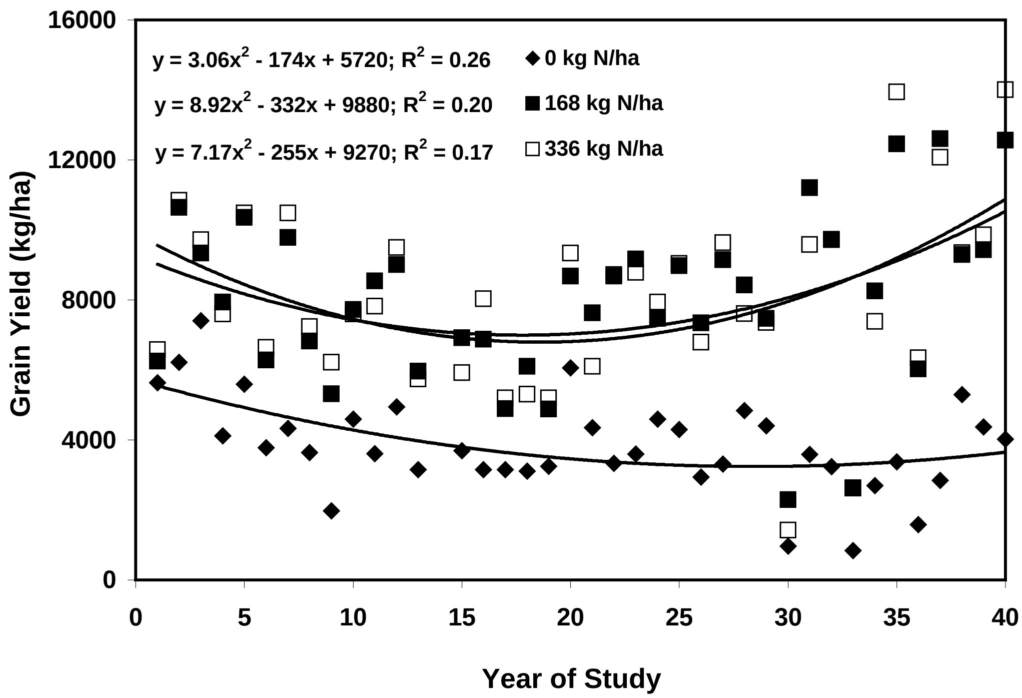

Fig. 5. Annual no-till corn grain yield response to N.

Figures 6 and 7 illustrate the yield versus seasonal weather relationships, using the field trial's annual average yield as a 'proxy' for annual/seasonal weather. That "rain makes grain", in both tillage systems, was evident. The first 168 kg N/ha makes the largest contribution to crop productivity, and thereby to return of residue C to the soil. The slopes and regression coefficients found in these linear models suggest that moldboard corn yield was generally more dependent upon seasonal weather than was no-till corn yield. Individually, they were less 'noisy' than their corresponding year versus year relationships, with one notable exception. That exception is moldboard plow corn yield at 0 kg N/ha, which was better related to the number of years of treatment than to the annual/seasonal weather.

To better understand the contribution of differences in the temporal progression in crop productivity on existing soil C and N levels, 'seasonal residuals' for corn yield were generated for each treatment by removing the 'seasonal trend' according to the linear models given in Figures 6 and 7. An example of the resulting yield residuals, plotted against the field trial's annual average yield, is shown, for no-till and moldboard plow corn at 0 kg N/ha, in Figure 8. The yield residuals, when plotted in this manner, were well distributed about the mean residual (0 kg grain/ha), but their magnitude 'expanded' above and below the mean as the annual average yield rose from 2 to nearly 10 Mg/ha.

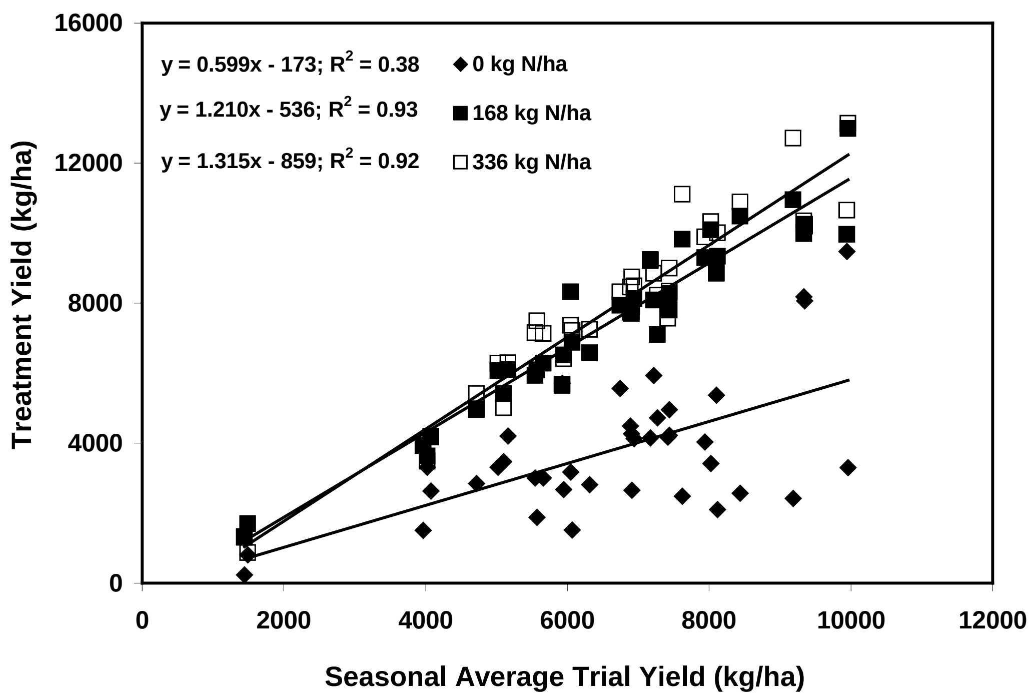

Fig. 6. Seasonal moldboard plow corn yield response to N.

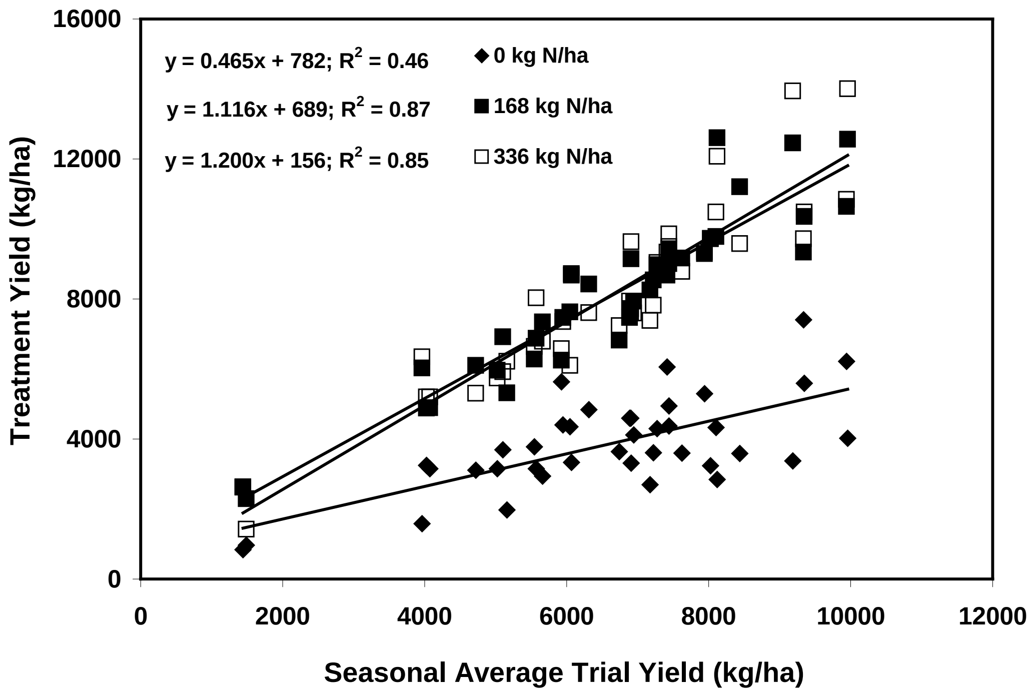

Fig. 7. Seasonal no-till corn yield response to N.

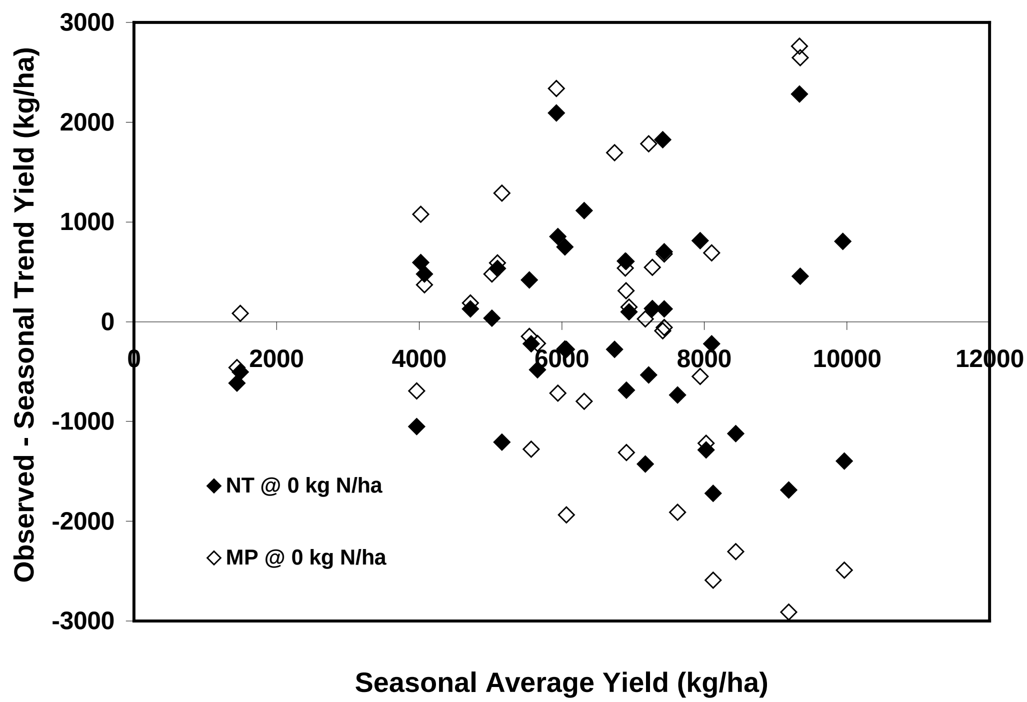

Fig. 8. Seasonal yield residuals, at 0 kg N/ha, after removal of linear seasonal yield trend.

When the seasonal yield residuals were plotted against time (year), the temporal sustainability of each of the treatments becomes more evident. Seasonal yield residual versus year plots, for both no-till and plowed corn yields, are shown in Figures 9, 10 and 11 for 0, 168 and 336 kg N/ha, respectively. At 0 kg N/ha (Figure 9), there is a steep decline in the seasonal yield residuals with time, in both tillage systems. The rate of decline is twice as great on the moldboard plow soil as on the no-till soil, indicative of the greater early yield potential in the first years of plowing the old pasture. The lower rate of decline in un-N-fertilized no-till corn yield residuals reflects both the lower yield potential observed in the first years of study and the greater yield potential found in the last years.

At 168 kg N/ha, the agronomically optimal N rate (Figure 10), there is an increase in the seasonal yield residuals with time, in both tillage systems. These yield residual versus year relationships exhibited somewhat greater regression coefficients than the comparable yield versus year relationships shown in Figures 4 and 5. The rate of increase is twice as large on the no-till corn soil as on the moldboard plow soil, again reflecting both the lower yield potential of no-till corn in early years of the study, as compared to the lower yield potential of moldboard plow corn in the later years of the trial.

At 336 kg N/ha, the agronomically excessive N rate (Figure 11), there is also an increase in the seasonal yield residuals with time, and again in both tillage systems. Again, the regression coefficients for the yield residual versus year relationships are somewhat better than those for the comparable yield versus year relationships in Figures 4 and 5. And although the rate of increase is again twice as large for no-tillage as for moldboard plowing, there was no further increase over those observed at 168 kg N/ha (Figure 10).

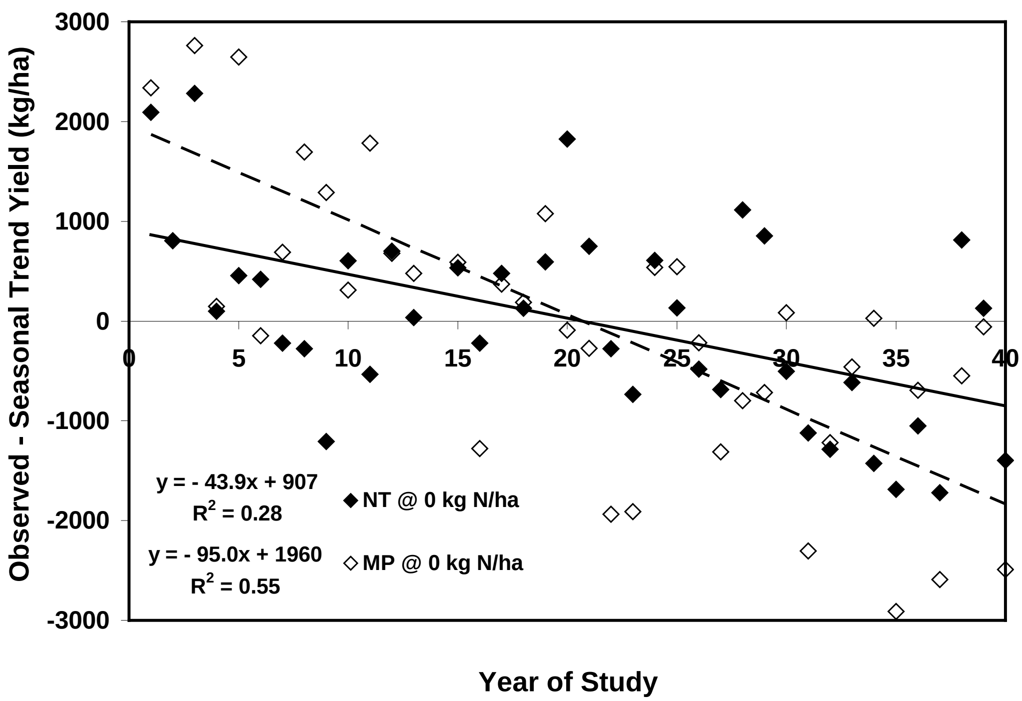

Fig. 9. Seasonal yield residuals, at 0 kg N/ha, plotted on an annual basis.

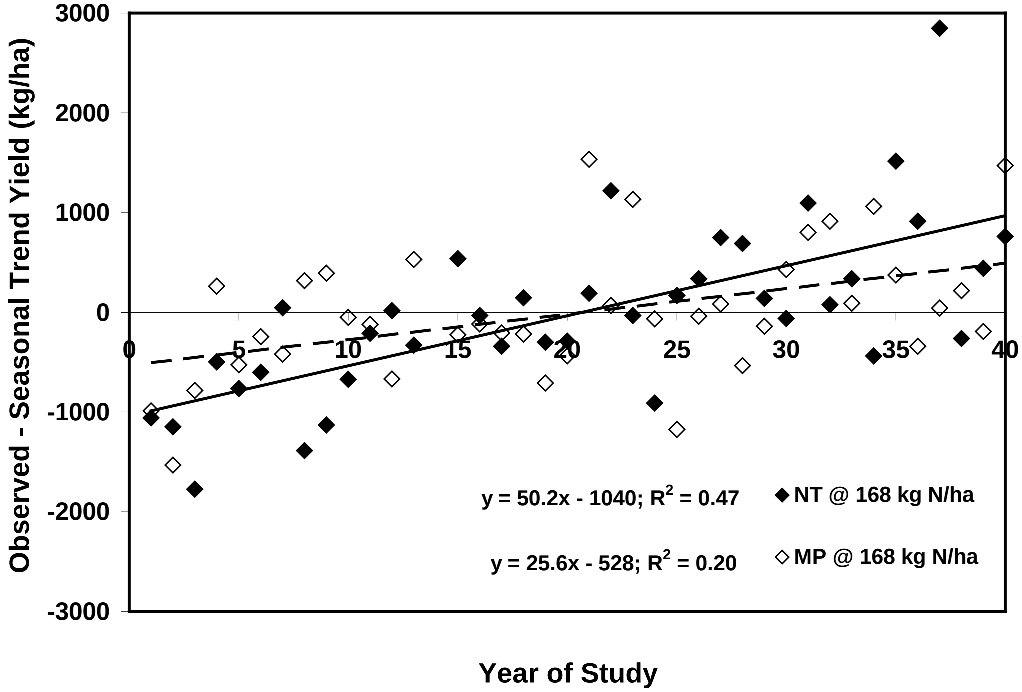

Fig. 10. Seasonal yield residuals, at 168 kg N/ha, plotted on an annual basis.

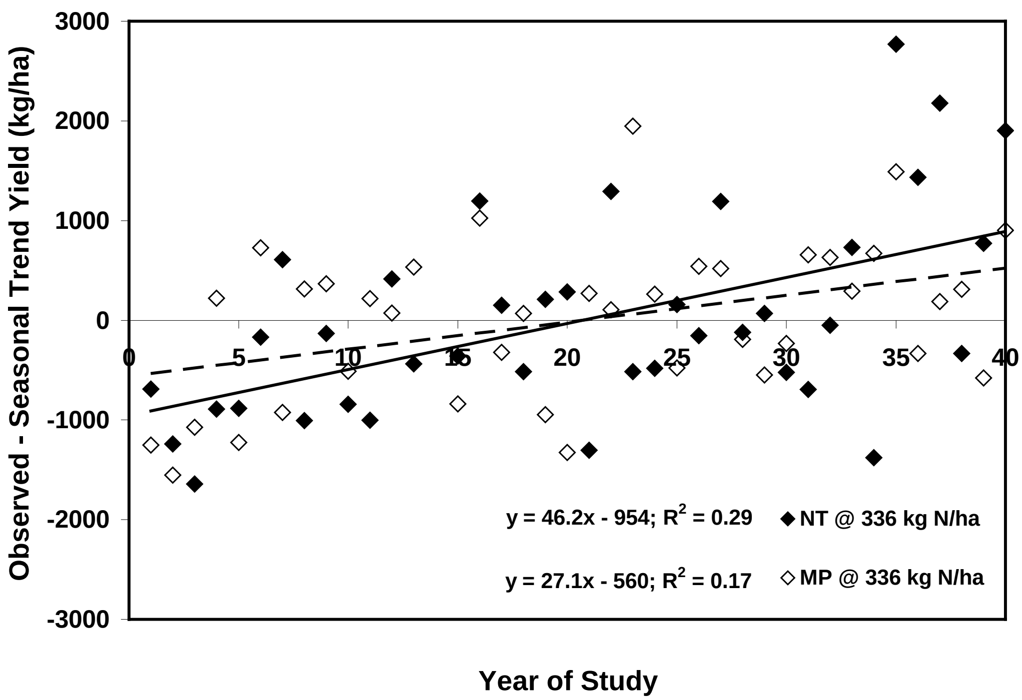

Fig. 11. Seasonal yield residuals, at 336 kg N/ha, plotted on an annual basis.

SUMMARY/CONCLUSIONS

Corn yield (as well as residue C and N return to the soil), in both tillage systems, rose with increasing fertilizer N rate, as did soil C and N, especially in the upper solum. The yield response to fertilizer N became increasingly positive with time, especially at higher N rates, in plowed soils. The yield response to plowing became increasingly negative with time, though more slowly with adequate N nutrition. The greatest yield response (residue C return) was observed with the first 168 kg N/ha. Without fertilizer N, continued annual moldboard plowing induced yield limitations that were more significant than those due to annual/seasonal climate. Temporal analysis of yield residuals resulting from the removal of seasonal trend indicated that the absence of N fertilization, regardless of tillage, caused declines in yield residuals with time, while N addition caused increases in residuals (productivity) with time. Excessive N fertilization did not improve the rate of increase in yield residuals with time. No-tillage, in the absence of fertilizer N, resulted in a slower decline in yield residuals with time than did moldboard plowing. When fertilizer N was used, no-tillage resulted in a steeper rate of increase in yield residuals with time, reflecting the greater ability of corn hybrids to express genetic potential on well-managed no-till soils.

Soil C and N depletion was most associated with land use change (from sod to unfertilized continuous corn, regardless of tillage). The agronomically adequate fertilizer N rate was positively related to soil C and N levels via associated improvements in cropland soil productivity, but soil C and N gains, relative to un-N-fertilized soils, were modest. Moldboard plowing negated a large part of the benefit of N fertilization to soil C and N levels. Soil C and N increases were much greater with the agronomically excessive N rate, though crop productivity was not greatly increased. This suggests that mechanisms other than improved crop productivity that also lead to greater soil C and N sequestration are involved. The C to N ratio of both crop and cover crop residues are likely lower at the greater N rates. Relative to the grass sod, all corn soils exhibited less N, than C, loss. This indicates that there is greater N conservation by the corn soils' heterotrophic communities. Therefore, the likely lower C to N ratios found in crop and cover crop residues resulted in greater soil C and N sequestration at the agronomically excessive N rate, and especially in no-tillage soil. On-average, the no-till corn production system is now more efficient in its use of N and seasonal weather. This is a reflection of the superior agroecosystem functions (water and nutrient storage capacity) of this soil, under no-tillage management.

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