Soil property and soybean yield trends in response to alternative wheat residue management practices in a wheat-soybean, double-crop production system in eastern Arkansas

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ABSTRACT

Growing concerns over the long-term sustainability of agricultural systems require investigation of agricultural management practices that may improve and sustain soil quality and crop productivity over time. Over 20% of the soybean [*Glycine max* (L.) Merr.] area in the highly productive Mississippi River Delta region of the mid-southern United States is in a double-crop rotation with wheat [*Triticum aestivum* (L.)]. Currently, much of the resulting wheat residue is managed by burning followed by conventional tillage, but this combination may not be environmentally sustainable. Therefore, the objective of this study was to determine the long-term effects of tillage [conventional (CT) and no-tillage (NT)], wheat-residue burning (burn and no burn), wheat-residue level (low and high, achieved with differential N fertilization), and irrigation (irrigated and dry-land) on soybean yield, net economic returns, and soil properties in the top 10 cm of a wheat -soybean, double-crop production system. A field experiment was conducted from 2001 through 2007 in the Mississippi River Delta region of eastern Arkansas on a Calloway silt loam (fine silty, mixed, active, thermic Glossaquic Fraglossudalf). Soil bulk density increased in both CT and NT during the first three years, but at a greater rate under NT (0.12 g cm^{-3} yr^{-1}) than CT (0.08 g cm^{-3} yr^{-1}), followed by a decline at a similar rate in both tillage treatments. Soil pH and Mehlich-3 extractable soil Ca and Mg contents increased, while electrical conductivity decreased linearly over time when all treatments were combined. Soil organic matter (SOM) increased over time in all treatment combinations. Total C (TC) increased at a greater rate in the no burn (0.08 kg C m^{-2} yr^{-1}) and high-residue-level (0.07 kg C m^{-2} yr^{-1}) than in the burn (0.05 kg C m^{-2} yr^{-1}) and low-residue-level (0.05 kg C m^{-2} yr^{-1}) treatments. Extractable soil P content declined linearly over time at greater rate under NT (3.3 kg P ha^{-1} yr^{-1}) and high-residue-level (3.4 kg P ha^{-1} yr^{-1}) than under CT (2.6 kg P ha^{-1} yr^{-1}) and low-residue-level (2.4 kg P ha^{-1} yr^{-1}) treatments. Soybean yield declined at a similar rate in the first three years, but increased at a similar rate over the subsequent three years in all tillage-treatment combinations. Increasing SOM and TC over time indicated that the silt-loam soils of the Mississippi River Delta region have the potential to accumulate C in the top 10 cm at increasing rates beyond six years from initial conversion to alternative residue management practices. Implementation of the appropriate residue management practices has the potential to improve soil quality and maintain long-term productivity of silt-loam soils in the Mississippi River Delta region of the mid-southern United States.

Key words: Arkansas, organic matter, residue management, soil carbon, soil properties, soybean, wheat

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INTRODUCTION

Agricultural sustainability is the ability of agricultural systems to remain productive for an extended period of time (Herdt and Steiner, 1995). However, a concern with agriculture today is whether current or conventional agricultural practices sustain production levels without causing irreversible damage, such as soil erosion, soil organic matter (SOM) depletion, and salinity (Denison et al., 2004). Soil organic matter is an important soil-quality indicator because SOM is sensitive to agricultural management practices, particularly tillage, and can be used to relate soil properties and functions across a range of climates, parent materials, land uses, topographies, and management systems to evaluate the sustainability of agricultural systems (Franzluebbers, 2004; Nunes et al., 2007).

The Mississippi River Delta region of eastern Arkansas and Louisiana and western Tennessee and Mississippi is highly agriculturally productive due in part to its relatively warm and wet climate. However, warm and wet climatic conditions are also favorable for rapid decomposition of SOM and C losses. In Arkansas specifically, a long history of cultivated agriculture coupled with the warm and wet climate has resulted in generally low SOM concentrations associated with many cultivated, row-crop agricultural soils (Brye et al., 2004; Brye and Pirani, 2005). Low SOM levels pose a threat to agricultural sustainability in the Mississippi River Delta region due to potential negative effects on soil physical, chemical, and biological properties (Rhoton, 2000). In addition, the general lack of use of organic soil amendments and heavy reliance on inorganic fertilizers in eastern Arkansas has exacerbated the depletion of SOM (Slaton et al., 2004). Agricultural management strategies that increase SOM levels will be necessary in eastern Arkansas for long-term agricultural sustainability to be achieved, such as sustaining crop yields without additional inputs of costly inorganic fertilizers.

Adoption of crop rotation systems with high biomass production is a primary option to increase SOM (Magdof and Weil, 2004). A wheat (*Triticum aestivum* L.)-soybean [*Glycine max* (L.) Merr.], double-crop system is a crop rotation system with the potential to increase biomass production compared to a mono-crop system for improved SOM (Magdof and Weil, 2004). Other benefits of the wheat-soybean, double-crop compared to a mono-crop system include additional income from two crops per year, increased productivity per unit land area, reduced wind and water erosion and reduced nitrate-nitrogen leaching due to the presence of a winter cover crop (Gill, 1997). Currently, the wheat-soybean, double-crop system accounts for approximately 21% of all soybeans produced in Arkansas, which equates to approximately 246,867 ha of the approximately 1.2 million ha of total soybean-planted area (NASS-USDA, 2008a). The wheat-soybean, double-crop system is even more widely adopted throughout the mid-south and southeastern U.S. (Caviness et al., 1986). However, one major challenge facing the wheat-soybean, double-crop production system in eastern Arkansas is deciding on a wheat-residue management strategy that facilitates soybean planting before 15 June each year to avoid a yield loss (Boerma and Ashley, 1982).

Conventional wheat-residue management practices in eastern Arkansas consist of multiple passes with a disk followed by harrowing to obtain a finely aggregated seedbed. In addition, prior to tillage, most producers burn the wheat residue to facilitate tillage and timely soybean planting (Sanford, 1982). Conventional tillage (CT) reduces plow-layer bulk density in the short-term, provides a fine seedbed, and controls weeds for adequate crop growth (Esbenshade et al., 2001). However, it has also been shown that long-term CT can induce soil compaction (Busscher et al., 2000; Brye and Pirani, 2005; Raper et al., 2005), disrupt soil aggregate stability, and increase the accessibility of organic residues to microorganisms, thereby resulting in rapid SOM decomposition and loss of C as carbon dioxide (Reicosky et al., 1995; Needelman et al., 1999; Six et al., 2000a, 2000b).

Some producers in the Mississippi River Delta region have adopted no-tillage (NT) practices in the wheat-soybean, double-crop production system. The use of NT in the double-crop system facilitates timely planting of soybean, limits moisture losses from the germination zone in the seedbed (Padgitt et al., 2000), and reduces farm operating costs relative to CT (Ribera et al., 2004). No-tillage also improves soil aggregate stability due to gradual binding of organic residues with clay particles and microbial by-products as a result of slow crop residue decomposition (Six et al., 2000b). Macro-aggregates protect SOM from rapid decomposition, increase SOM accumulation, and have large inter-aggregate pores for easy root penetration and water and air movement into and through the soil surface (Magdoff and Weil, 2004; Wright and Hons, 2004, 2005a,b). Wright and Hons (2005a) also reported greater soil organic C (SOC) and N (SON) stored in soil under NT than CT when averaged across cropping sequences and soil depths, while others have reported the opposite (Needelman et al., 1999).

The degree of increase in SOM after conversion from CT to NT depends on the duration of tillage, and the magnitude of SOM increase differs by soil depth sampled. In a 2-yr study, Brye et al. (2006a) reported no differences in SOC between NT and CT, but that SOM increased more under NT (0.07%) than under CT (0.02%) in a high-residue treatment in a silt-loam soil in eastern Arkansas. Pikul et al. (2007) also reported no difference in total C (TC) between NT and CT after 4 yr; however, after 10 yr of NT, soil TC was 7% greater than under CT in a clay-loam soil under a corn (*Zea mays* L.)-soybean rotation in South Dakota. In Illinois, NT had 15% greater SOC and total N (TN) in the top 5 cm, but 5.8% lower SOC and TN in the 5 to 15 cm depth than CT (Needelman et al., 1999). However, regardless of tillage, SOC and TN were greater in the top 5 cm than in the 5 to 15-cm depth (Needelman et al., 1999). West and Post (2002) estimated that 85% of SOC sequestered due to a change from CT to NT occurs in the top 7 cm. The magnitude of the SOC increase due to NT has been reported to be larger in low-SOC soils in semi-arid areas than in humid regions (Steinbach and Alvarez, 2006), indicating that the initial SOM level and climate both influence the rate of SOM change due to tillage. Therefore, the characterization of changes in plow-layer SOM over an extended period of time due to alternative tillage practices is essential to evaluate long-term agricultural sustainability.

Producers are also somewhat concerned with potential yield losses with the adoption of NT due in part to increased equipment costs and breaking the cultural norm. Two years of CT resulted in greater soybean yield than in NT, but in the third year, CT had a lower yield than NT in clay and silt-loam soil in eastern Arkansas (Popp et al., 2000). In contrast, Sanford (1982) reported that CT resulted in significantly lower emergence and seedling survival than NT due to substantial moisture loss. Verkler (2007) reported no yield differences between CT and NT after four years of consistent management. However, Verkler et al. (2008) showed that NT had a greater ability to retain water for a longer period of time after irrigation and rainfall events than CT, indicating that NT provides a soil moisture advantage over CT. The apparent inconsistent tillage effects on soybean growth and yield may be related to short-term soil management effects, which further supports the need for long-term field studies.

Since crop residues could interfere with soybean seedling emergence and growth, burning facilitates easy and quick removal of crop residues (Sanford, 1982). However, burning reduces soil C, N, aggregate stability, and water infiltration compared to non-burning (Wuest et al., 2005; Murphy et al., 2006). Murphy et al. (2006) also reported decreased extractable soil P, S, Ca and Mg due to burning. Burning also increases soil pH, but the pH increase is typically temporary, lasting less than one year (Sherman et al., 2005). In addition, burning contributes to the release of greenhouse gases (Boubel et al., 1969; Caldwell et al., 2002; Murphy et al., 2006). Therefore, burning crop residues is a practice that generally degrades agricultural soils and could threaten long-term agricultural productivity and environmental sustainability, which again suggests the need to investigate alternative residue management practices.

Although crop residues are a beneficial source of SOM, there is also concern about potential residue interference and pesticide effectiveness in a wheat-soybean, double-crop production system. The presence of wheat residue has been reported to reduce soybean seedling growth due to allelopathic effects of the wheat residue (Caviness, 1982) and the physical barrier the residue creates, which can reduce sunlight penetration. Improvement or degradation of soil quality due to management practices cannot be easily detected over short periods of time, such as within or after one to two growing seasons (Herdt and Steiner, 1995; Denison et al., 2004). Thus, long-term studies are necessary to evaluate management practices affecting soil quality and crop productivity. However, multi-year studies (i.e., > 5 yr at a minimum) investigating residue management practices effect on soil properties and soybean yield in the wheat-soybean, double-crop production systems in the Mississippi Delta region of the mid-south are limited.

The objective of this study was to determine the effects of tillage (CT and NT), residue burning (burn and no burn), residue level (low and high), and irrigation (irrigated and dry-land) on soil properties in the top 10 cm, soybean yield, and economic performance over a 6-yr period of management. It was hypothesized that i) soil bulk density, extractable soil nutrient contents, soil pH, and electrical conductivity (EC) changes over time will differ among treatments, ii) SOM, SOC, and TN will be greater, and increase over time at a greater rate under the NT, no-burn, and high-residue than under the CT, burning, and low-residue-level treatments, iii) soybean yield trends over time will be similar among tillage treatments, and iv) alternative residue management practices will be equally or more profitable than current, traditional management practices.

MATERIALS AND METHODS

Site description and experimental design

This study was conducted at the University of Arkansas' Lon Mann Cotton Research Station, near Marianna (N 34^0, 44', 2.26"; W 90^0, 45' 51.56", Cordell, 2004) in the Mississippi River Delta region of eastern Arkansas from fall 2001 through fall 2007. The soil is a Calloway silt loam (fine silty, mixed, active, thermic Glossaquic Fraglossudalf; Web Soil Survey, 2008). The study area was under continuous CT soybean production prior to initiating this field experiment (Cordell et al., 2006).

The original experimental design was a split-strip plot with six replications of each of eight treatment combinations (i.e., tillage-burning-residue level; Cordell et al., 2006). Tillage treatments (CT and NT) represented the main plot and were arranged as a randomized complete block. Burning treatments (burn and no burn) formed the strip plot and were arranged across tillage treatments. Residue level [high (H) and low (L)] represented the strip-split plot within tillage-burn treatment combinations. In 2005, the study area was split in two to add an irrigation treatment (irrigated and dry-land; Verkler et al., 2008). However, to facilitate the addition of the irrigation treatment, irrigation blocks were superimposed on the burn blocks. Of the 48 total plots, there were six replications for every tillage-burning-residue-level combination and three replications for every tillage-irrigation-burning-residue-level combination.

Field management

In fall 2001, the study area was prepared by disking twice followed by broadcast application of 20 kg N ha^{-1}, 22.5 kg P ha^{-1}, 56 kg K ha^{-1}, and 1120 kg ha^{-1} of pelletized limestone prior to wheat planting. Each fall, wheat was drill-seeded with a 19-cm row spacing at a rate of between 90 to 126 kg seeds ha^{-1}. Plots 3-m wide by 6-m long were established in early spring 2002 and were maintained throughout the study period. In early March 2002 through 2004, all plots were broadcast fertilized with 101 kg N ha^{-1} as urea. To obtain different levels of wheat residue, the high-residue plots (n = 24) were broadcast fertilized with an additional 101 kg N ha^{-1} as urea at about the late-jointing stage in approximately late March. In

Spring 2005, no N fertilizer was applied because a wheat stand was not established due to excessive moisture in fall 2004. In 2006 and 2007, only the high-residue plots were broadcast fertilized with 56 kg N ha^{-1} urea in early March, followed by an additional 56 kg N ha^{-1} in late March. Low-residue treatments did not receive any N fertilizer in 2006 and 2007 to ensure that a residue-level difference was achieved.

Wheat grain from the middle 1-m of each plot was harvested in early June each year and aboveground wheat residue was uniformly spread by hand back on each plot. Standing wheat stubble was then mowed to about 3 cm from the soil surface to create a uniform, residue-covered soil surface. After mowing, the burning treatment was imposed followed by tillage, either CT by disking twice to a depth of about 10 cm and seedbed smoothing or NT. In 2005 and 2007, residue burning was not possible due to the absence of a wheat stand in spring 2005 and due to wet conditions at planting in fall 2004 and prolonged wet conditions in spring 2007.

Glyphosate-resistant soybean (maturity group 5.3 for 2002 through 2005 and maturity group 5.4 for 2006 and 2007) was drill-seeded with a 19-cm row spacing in early to mid-June each year. In 2002 through 2004, all plots were furrow irrigated, but in 2005 though 2007 only half of the plots were irrigated four to six times throughout the soybean growing season, while the remaining half of the plots were managed as dry-land soybeans. Weeds and insects were controlled when necessary using University of Arkansas Cooperative Extension Service recommendations (UACES, 2003a, b). Soybeans from the middle 1 m of each plot were harvested with a plot combine in late October to early November each year. Soybean and wheat grain were air dried for approximately 4 wk and weighed to determine plot yields. Soybean grain subsamples were oven dried at 70^{0}C for 48 hr to determine moisture content. Soybean yields were adjusted to and reported at 13% moisture content.

Soil sampling scheme and analyses

Composite soil samples were collected by combining seven to 10 soil cores from the top 10-cm depth from each plot after wheat harvest, but before tillage and soybean planting. Samples were oven dried at 70^{o}C for 48 hr and ground and sieved through a 2-mm mesh screen for chemical analyses. Soil bulk density was determined twice per year by collecting a single 4.8-cm-diameter core sample from the top 10 cm of each plot at the time of composite soil sampling and approximately 8 wks after soybean planting. Soil core samples for bulk density were dried at 70^{o}C for 48 hr and weighed. Soil pH and electrical conductivity (EC) were determined potentiometrically with an electrode in a 1:2 (w/v) soil:water suspension. Total soil N and C were determined by high-temperature combustion using a LECO CN-200 analyzer (LECO, Corp., St. Joseph, MI). Soil organic matter was determined by weight-loss-on-ignition at 360^{o}C for 2 hr (Schulte and Hopkins, 1996). Mehlich-3 extractable soil P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu concentrations were determined based on a 1:10 (w/v) soil-to-extraction solution ratio (Tucker, 1992) using inductively coupled argon-plasma (ICAP) spectrophotometry (CIROS CCD model, Spectro Analytical Instruments, Fitchburg, MA). Concentrations of SOM, TC, TN, and all extractable nutrients were multiplied by the soil bulk density determined at the time of composite soil sampling and the soil sampling depth to express each on a mass-per-area basis. The soil C:N ratio was also calculated by dividing the measured TC concentration by the measured TN concentration.

Precipitation data

Daily precipitation was recorded on station near the study area. Daily precipitation data from 2002 to 2007 were used to calculate mean annual soybean-growing-season (i.e., June through October) precipitation. The 30-yr mean monthly precipitation during the soybean season was obtained from NOAA (2002). Precipitation variability among soybean growing seasons from year-to-year was determined by calculating the coefficient of variation (CV).

Economic analysis

An economic analysis was performed to compare the relative profitability of alternative residue management practices compared to traditional management practices. Residue management practices evaluated consisted of all 16 combinations of tillage, irrigation, burning, and residue level. Costs for each residue management practice were estimated based on production budget estimates published by the University of Arkansas Cooperative Extension Services for double-crop soybean and wheat crops (UACES, 2008). No material or labor costs were assigned for burning. All costs for each of the six years included in this study were estimated using 2007 dollars to allow comparisons of each system over time. Each management systems' costs were generated using the direct expenses of inputs used and field operations performed as per the field management that occurred each year.

Historical five-year soybean and wheat grain prices received by Arkansas producers from 2003 to 2007 (NASS-USDA, 2008b) were adjusted to 2007 prices by multiplying the historical price of each crop in each year with their respective calculated 2007 price index (NASS-USDA, 2008c). The five-year average of real prices for soybean and wheat grain were used to calculate the gross income for both crops in each year to allow comparison of income over the six-year period. Total income from each residue management practice was calculated as a sum of wheat and soybean gross incomes obtained by multiplying the adjusted crop price by the respective mean crop yield for each year. The economic net return of each practice in each year was calculated as the difference between the costs and income. The relative net return of each management practice combination was also calculated as the percentage increase or decrease in net return relative to the traditional management practice (i.e., irrigated-CT-burn-high residue level).

Statistical analyses

The effect of fertilizer-N application on wheat residue level was determined by analysis of variance (ANOVA) for each of the six years of this study. Means were separated using least significant difference (LSD) at $\alpha = 0.05$. The effects of six years of management on soil physical and chemical properties and soybean and wheat grain yields were determined by analysis of covariance (ANCOVA). All soil properties and crop yields were analyzed as dependent variables, the experimental factors investigated (i.e., irrigation, tillage, burning, and residue level) were used as covariates, and year was used as an independent variable. An ANCOVA was performed separately from all other factors to investigate the effect of irrigation because the blocking structure for the irrigation treatment was identical to that for the burn treatment since the irrigation treatment was later superimposed on the original experimental design. In cases where the trend over time did not differ statistically among treatment factors, regression analyses were performed to evaluate changes in soil parameters and crop yields over time. All statistical analyses were performed using SAS (Version 9.1, SAS Institute, Cary, NC). Although the burn treatment was not imposed in 2005 and 2007, burning was included in the statistical models because burning effects on soil quality are likely cumulative and could have manifested themselves in subsequent years.

RESULTS AND DISCUSSION

Wheat residue level differences

The amount of crop residue remaining on the soil surface at the time of soybean planting was greater ($P < 0.05$) in the high- than in the low-residue treatment in all years except for the first and third years of study (Table 1). These results are consistent with Carter (2002) who reported increased C inputs due to increased crop biomass obtained through improved soil fertility and plant nutrition. Since significantly different residue levels were achieved in four of six years of this study, evaluating the effect of residue level as an experimental treatment was assumed to be valid. Despite no residue-level effect in two of six years, residue-level effects are likely cumulative over time, which further justifies the validity of residue level as an experimental treatment.

Table 1. Six-year summary of surface residue levels achieved in the residue treatment (low and high) in a wheat-soybean, double-crop production system on a silt-loam soil in the Mississippi River Delta region of eastern Arkansas.

Year	n[†]	Residue level (kg ha^{-1})	
		Low	High
2002[‡]	12	3916	3254
2003	12	4137	6168*
2004	12	6026	7677
2005	24	2103	3463*
2006	24	6455	11 036*
2007	24	5806	9381*

[†] Number of observations (n)

[‡] Results for 2002 to 2004 were obtained from Cordell et al. (2006). Results for 2005 and 2006 were obtained from Verkler (2007).

* Asterisk indicates a significant difference ($P < 0.05$) between the low- and high residue-level treatments within a given year.

Soil bulk density

Soil bulk density is an important physical characteristic of the soil that affects plant root growth, water infiltration, gas exchange, and hence forms, solubilities, and accessibilities of plant nutrients. Soil bulk density showed a significant ($P = 0.001$) quadratic trend over time, which differed ($P = 0.030$) between tillage treatments (Fig. 1). Soil bulk density initially increased in both tillage treatments; however, the rate of increase was greater ($P = 0.006$) under NT (0.12 g cm^{-3} yr^{-1}) than under CT (0.08 g cm^{-3} yr^{-1}) during the first three years of the study (i.e., 2002 to 2004), but decreased over time at a similar rate thereafter under both tillage treatments (Fig. 1). Soil bulk density trends over the time period of this study were unaffected by the burning, residue-level, and irrigation treatments.

These results show that NT resulted in a greater increase in soil bulk density relative to CT

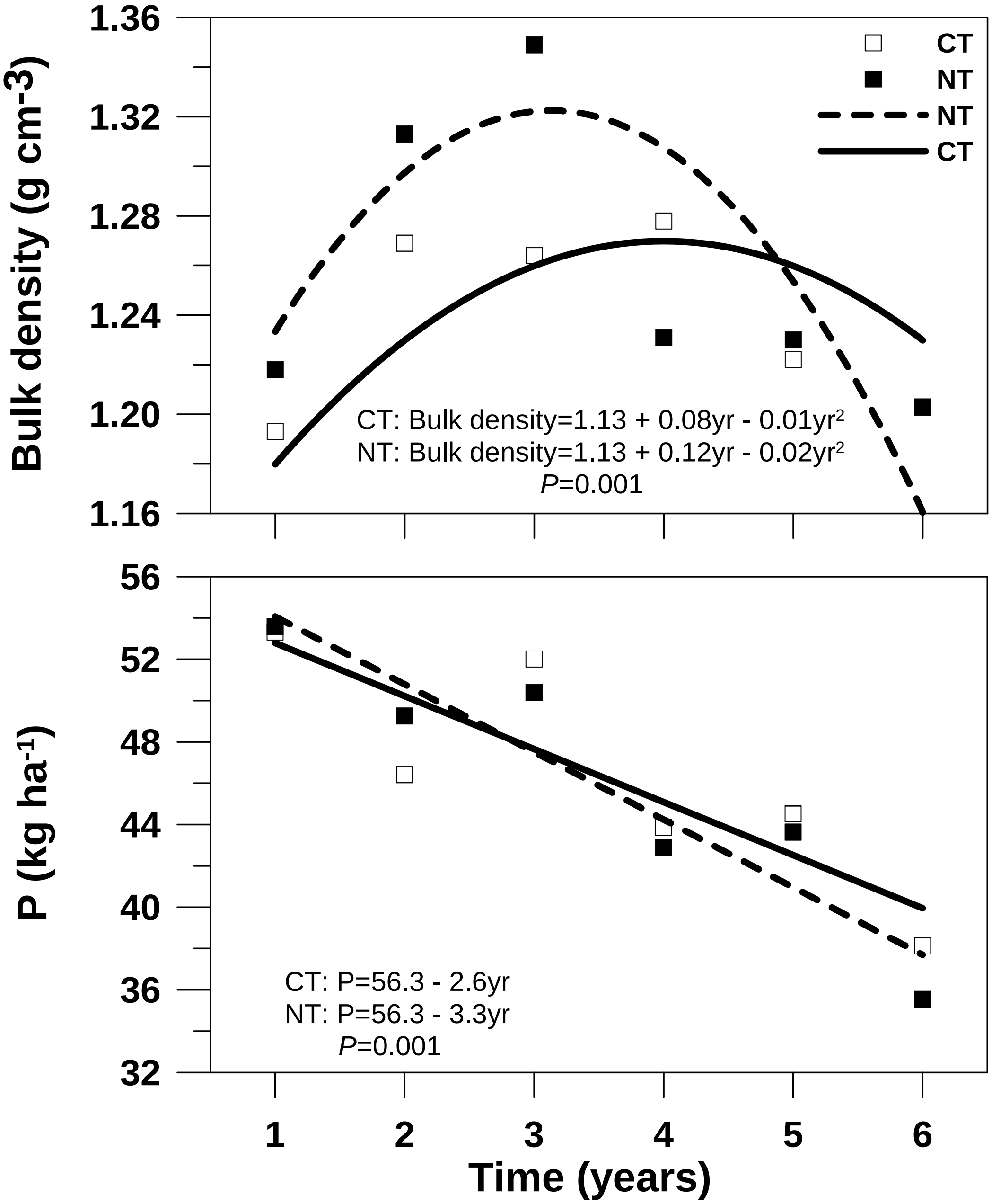

Fig. 1. Influence of tillage [conventional tillage (CT) and no-tillage (NT)] on soil bulk density and extractable P content over time in a wheat-soybean, double-crop system in the Mississippi River Delta region of eastern Arkansas. Time refers to the duration in the wheat-soybean, double-crop rotation.

soon after adoption. Smaller rates of bulk density change after three years of management suggest that the soil is approaching some equilibrium after changes in cropping system and management practices occurred. The increase in soil bulk density shortly after management practice and cropping-system change was likely due to the time period required for soil to build up humus, stabilize structure, and re-establish pore spaces before fully regenerating improved structure as a new equilibrium was approached (Lampurlanes and Cantero-Martines, 2003).

In contrast to this study, Lampurlanes and Cantero-Martines (2003) reported no significant tillage effect on changes in soil bulk density over time in the top 7 cm of loamy soils in Spain after five years of treatment. However, similar to the present study, soil bulk density increased over time and the trend differed between crop management systems, where soil bulk density increased 16% under continuous cropping, 11% under fallow, and 6% in a crop-fallow rotation (Lampurlanes and Cantero-Martines, 2003). In addition, Logsdon and Cambardella (2000) reported no changes in soil bulk density under NT in the top 30 cm, but increased soil bulk density under CT in the top 12 cm after four years in a loamy soil in central Iowa. Comparing between CT and NT, Brye et al. (2006a) and Verkler (2007) reported no significant differences in soil bulk density after two and four years, respectively, of tillage and residue management in the same plots as this study. Past studies generally suggest that soil bulk density does not increase under NT compared to under CT in silt-loam and loamy soils. None of the soil bulk densities measured in the top 10 cm throughout the first six years of this study exceeded 1.6 g cm^{-3}, which is considered the threshold at which root penetration begins to be limited in silt-loam soils (Fulton et al., 1996; Logsdon and Karlen, 2004).

Soil pH and EC

Irrigation and burning (Fig 2; Fig. 3) resulted in differences in soil pH trends (P = 0.001) over time. Although soil pH increased (P = 0.001) under irrigation at the rate of 0.2 standard pH units yr^{-1}, soil pH under dry-land conditions did not change over time (Fig. 2).

Averaged across all treatment combinations, soil pH increased over time at the same rate (P = 0.001) of 0.09 standard pH units yr^{-1} in the two burning treatments. However, the y-intercept was lower (P = 0.003) for the burn (pH = 6.7) than the no-burn treatment (pH = 6.9) (Fig. 3). Although soil pH increased over time, the mean soil pH throughout the whole study area after six years of residue management (i.e., in 2007) was 7.3, which is slightly greater than the optimal pH range for soybean production (pH 5.8 to 7.0) in eastern Arkansas (UACES, 2000). Soil pH trends over time were unaffected by tillage and residue level treatments.

The increase in soil pH may be attributed to progressive dissolution of the lime applied at the initiation of the study in 2001 to adjust soil pH for adequate soybean production. The greater increase in soil pH over time under irrigation than dry-land was likely caused by high concentrations of Ca- and Mg-bicarbonates and a high pH of 9.1 in the irrigation water used in this study. Others have shown increased soil pH due to use of irrigation water high in Ca and Mg bicarbonates (UACES, 2006). In addition, increased soil moisture availability due to irrigation likely contributed to increased dissolution of lime materials applied. Treder (2005) also reported a 0.55-pH-unit increase after seven years of irrigation with alkaline water, but a 0.95-pH-unit decrease in non-irrigated, sandy-loam soils in Poland.

Although soil pH did not differ statistically among all treatments in the first four years of wheat residue management, soil pH was numerically lower under the burn than under the no-burn treatment (Cordell, 2004; Verkler, 2007). The regression analysis with burn and no burn as covariates showed that the initial numerical differences in soil pH between burning treatments were consistently maintained over the 6-yr study period. The consistent lower soil pH under the burn than no-burn treatment may be due to greater mineralization of organic residues under burning and subsequent nitrification. Burning has been reported to cause high N mineralization and nitrification in grasslands of Australia (Romanya et al., 2001).

In contrast to soil pH, soil EC was unaffected by any field management practice in this study and decreased significantly (P = 0.001) over the 6-yr study duration at the rate of 0.012 dS m^{-1} yr^{-1}, (Fig. 4). Decreasing soil EC over the 6-yr study period indicates little potential for the build up of salinity and total soluble salts. In this study, irrigation water had low EC and Na and chloride concentrations (Table 2), which explains why there were no differences in EC between irrigation treatments. In contrast to this study, Nunes et al. (2007) reported increased EC under irrigated relative to rain-fed soils due to the gradual addition of electrolytes from the irrigation water despite overall good water quality. The decrease in soil EC over time in this study may be partly explained by the ability of the winter wheat to scavenge and take up dissolved solutes, especially nitrate-nitrogen (NO_3-N). Mikha et al. (2006) reported a positive correlation between soil EC and NO_3-N (r = 0.74). Therefore, despite the decrease in fertilizer-N input that occurred during this study to achieve contrasting residue levels, a decrease in soil EC over time in non-saline soils, like that of this study, indicates an overall benefit of the wheat-soybean, double-crop system to soil quality.

Soil micronutrients

Trends in extractable soil Fe, Zn, Mn, and Cu contents over time were unaffected by tillage, burning, and residue-level treatments (data not shown). However, extractable soil Fe (P = 0.001), Mn (P = 0.001), and Zn (P = 0.001) (Fig. 5) content trends over time differed by irrigation treatment. Extractable soil Fe and Mn contents increased (P = 0.001) over time at rates of 17.2 kg Fe ha^{-1} yr^{-1} and 10.7 kg Mn ha^{-1} yr^{-1}, respectively, under irrigation,

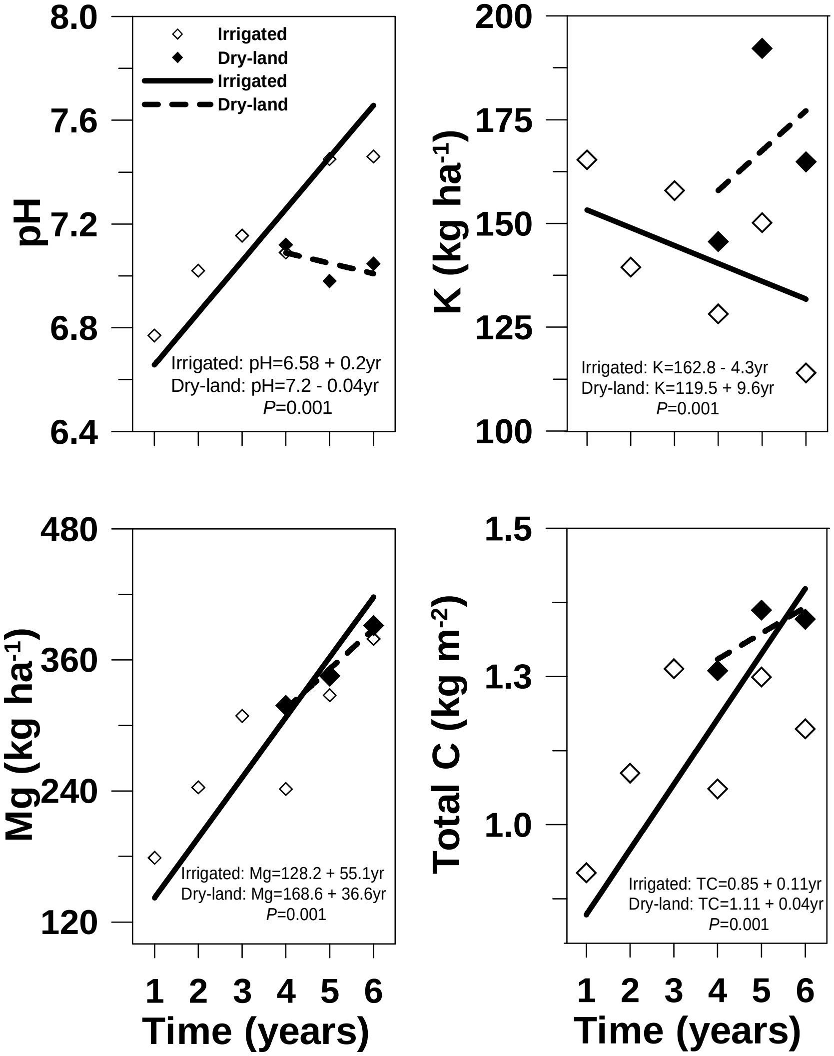

Fig. 2. Influence of irrigation (irrigated and dry-land) on soil pH, extractable soil K and Mg, and total C contents over time in a wheat-soybean, double-crop system in the Mississippi River Delta of eastern Arkansas. Time refers to the duration in the wheat-soybean, double-crop rotation.

but did not change over time under dry-land conditions. In contrast, extractable soil Zn contents differed (*P* = 0.001) between irrigation treatments, and increased at the rate of 0.37 kg Zn ha^{-1} yr^{-1} over the 3-yr period under dry-land conditions, but did not change over time under irrigation (Fig. 5).

These results may be related to the redox properties of Fe and Mn compared to those of Zn. Iron and Mn undergo biochemical-redox reactions depending on the status of the soil redox potential (Sposito, 1989; Mullen, 2005). Under irrigation, there is likely a greater frequency of at least localized reducing conditions due to a greater potential for the existence of small pockets of saturated pores than under dry-land conditions, which would favor the reduction of Fe and Mn with resulting increased solubilities in soil (Mullen, 2005). Although soluble forms of Fe and Mn are susceptible to leaching losses, it appears that there was less drainage from the plow layer due to the presence of a plow pan (Amuri and Brye, 2008) that likely minimized Fe and Mn leaching. Thus, nutrient concentration from evaporation from the plow layer coupled with an increase in exchangeable forms of Fe and Mn due to weathering of Fe and Mn minerals caused by alternate reduction and oxidation reactions may have increased extractable Fe and Mn in the soil surface under irrigation over time. Alternate bacterial-mediated oxidation and reduction of Fe and Mn has been reported to increase water-soluble and

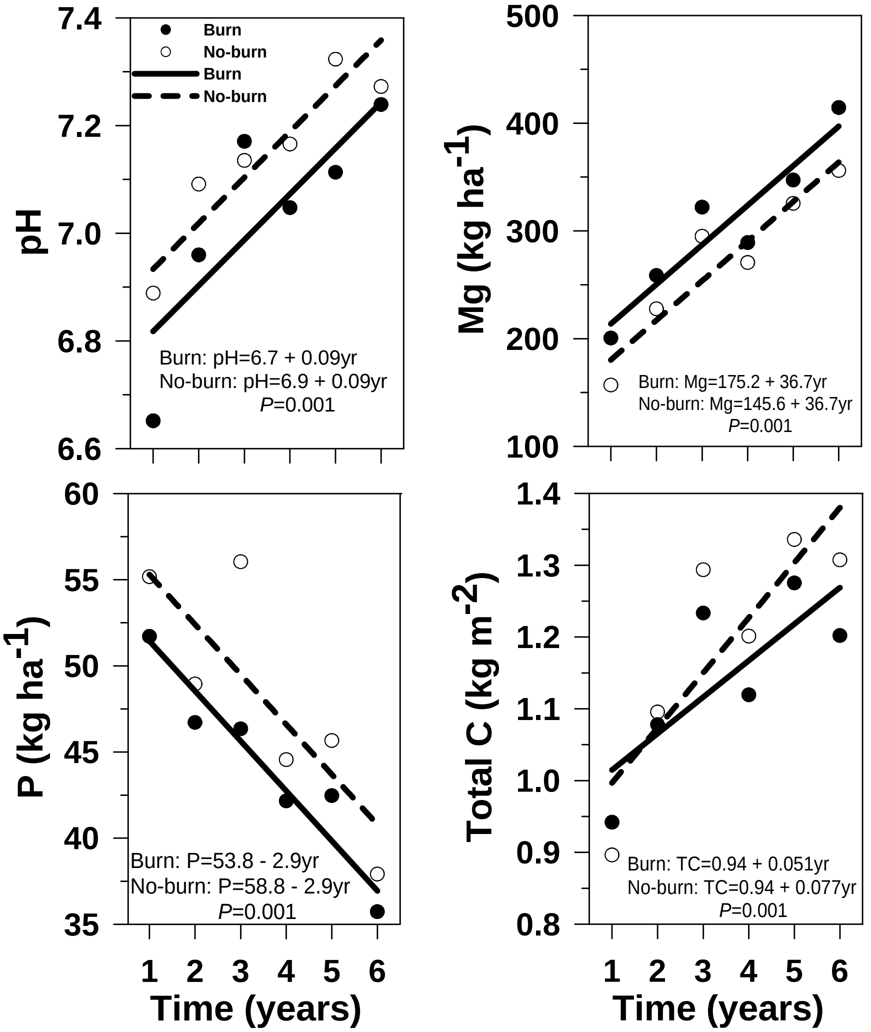

Fig. 3. Influence of wheat-residue burning (burn and no-burn) on soil pH, extractable soil Mg and P, and total C contents over time in a wheat-soybean, double-crop production system in the Mississippi River Delta region of eastern Arkansas. Time refers to the duration in the wheat-soybean, double-crop rotation.

exchangeable Fe and Mn relative to well-crystallized Fe- and Mn-oxide minerals (Berthelin et al., 2006), which results in increased extractable Fe and Mn concentrations. Increasing extractable Zn, a relatively immobile micronutrient, may be associated with reduced Zn uptake by crops under dry-land conditions, hence less export from grain harvest relative to the natural release of Zn in the soil system. Throughout the duration of this study, all measured soil micronutrients (i.e., Fe, Mn, Cu, and Zn) were in the adequate range for soybean production in eastern Arkansas (UACES, 2000).

Soil macronutrients

The effects of alternative residue management practices and irrigation on extractable soil macronutrients over time were variable. Changes in extractable soil Ca contents over time did not differ among tillage, burning, and residue-level treatments, and increased over time at a rate of 26.4 kg Ca ha^{-1} yr^{-1} (P = 0.010; Fig. 4). Extractable soil Mg contents increased at the rate of 36.7 kg Mg ha^{-1} yr^{-1} across tillage, burning, and residue-level treatments (Fig. 3). However, the y-intercept for the regression line characterizing the extractable soil Mg content trend over time was greater (P = 0.001) for the burn than the no-burn treatment (Fig. 3). In contrast to all other field treatments, extractable Mg contents increased at different rates (P = 0.001) between irrigation treatments (Fig. 2). Under irrigation, extractable Mg contents increased at a

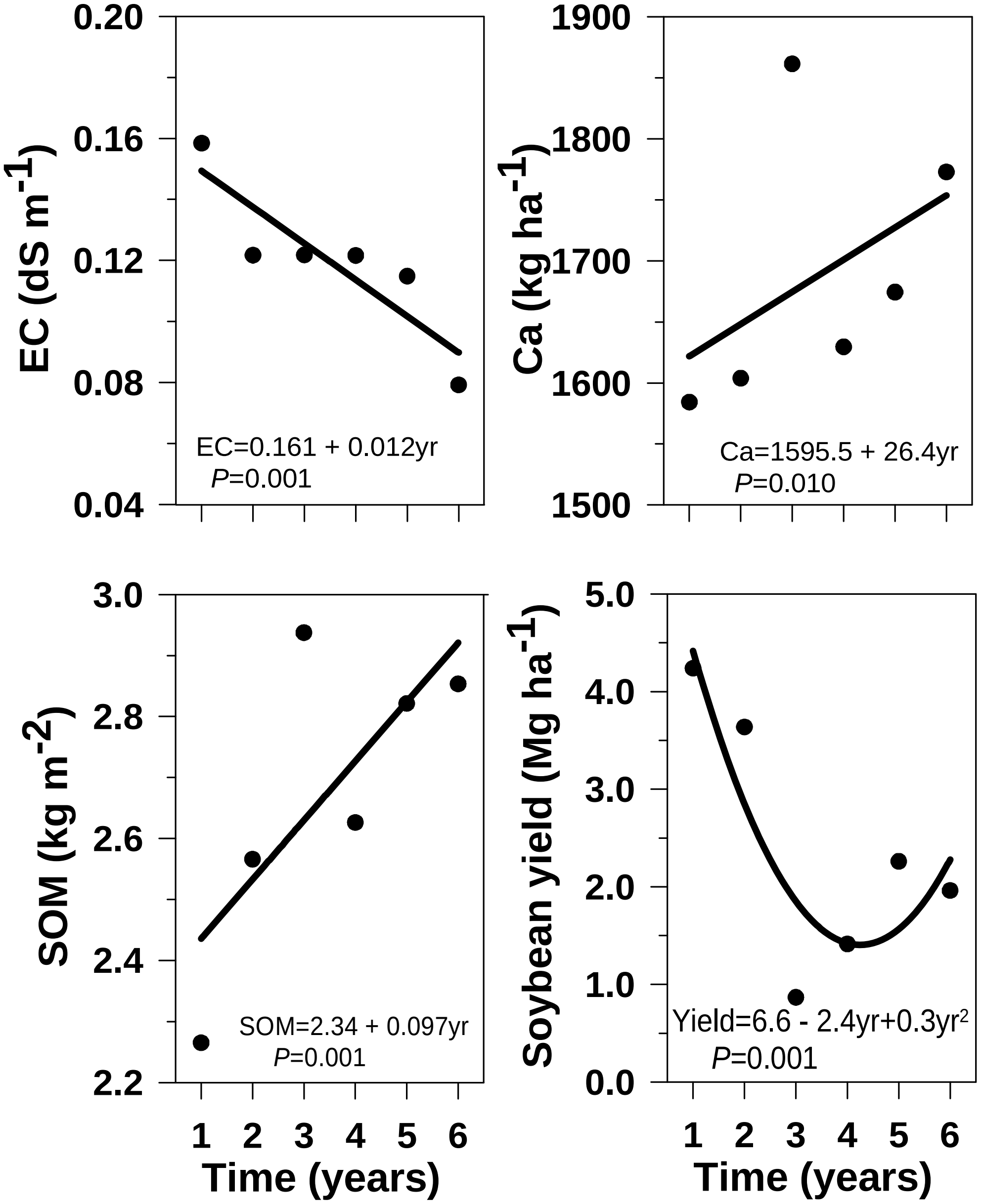

Fig. 4. Soil electrical conductivity (EC), extractable soil Ca and soil organic matter (SOM) contents, and soybean yield over time in a wheat-soybean double-crop system in the Mississippi River Delta region of eastern Arkansas. Time refers to the duration in the wheat-soybean, double-crop rotation.

greater rate (55.1 kg ha^{-1} yr^{-1}) than under dry-land conditions (36.6 kg ha^{-1} yr^{-1}).

Similar to soil pH, the increasing extractable soil Ca and Mg contents over time were also expected due to the progressive dissolution of lime applied at the beginning of the study. In addition, the increase in extractable soil Mg at a greater rate under irrigation than dry-land condition can be explained as being due to continuous addition of Mg from irrigation water, as shown by the high Mg concentration in the irrigation water used in this study (Table 2).

Results also suggest that there was greater release of Mg due to burning than non-burning. A high release of Mg due to burning was also reported by Sherman et al. (2005). However, a similar rate of change in extractable Mg contents between burning and non-burning was reported in two 2-yr studies from 2002 to 2003 by Brye et al. (2006a) and from 2005 to 2006 by Verkler (2007). Similarly, Murphy

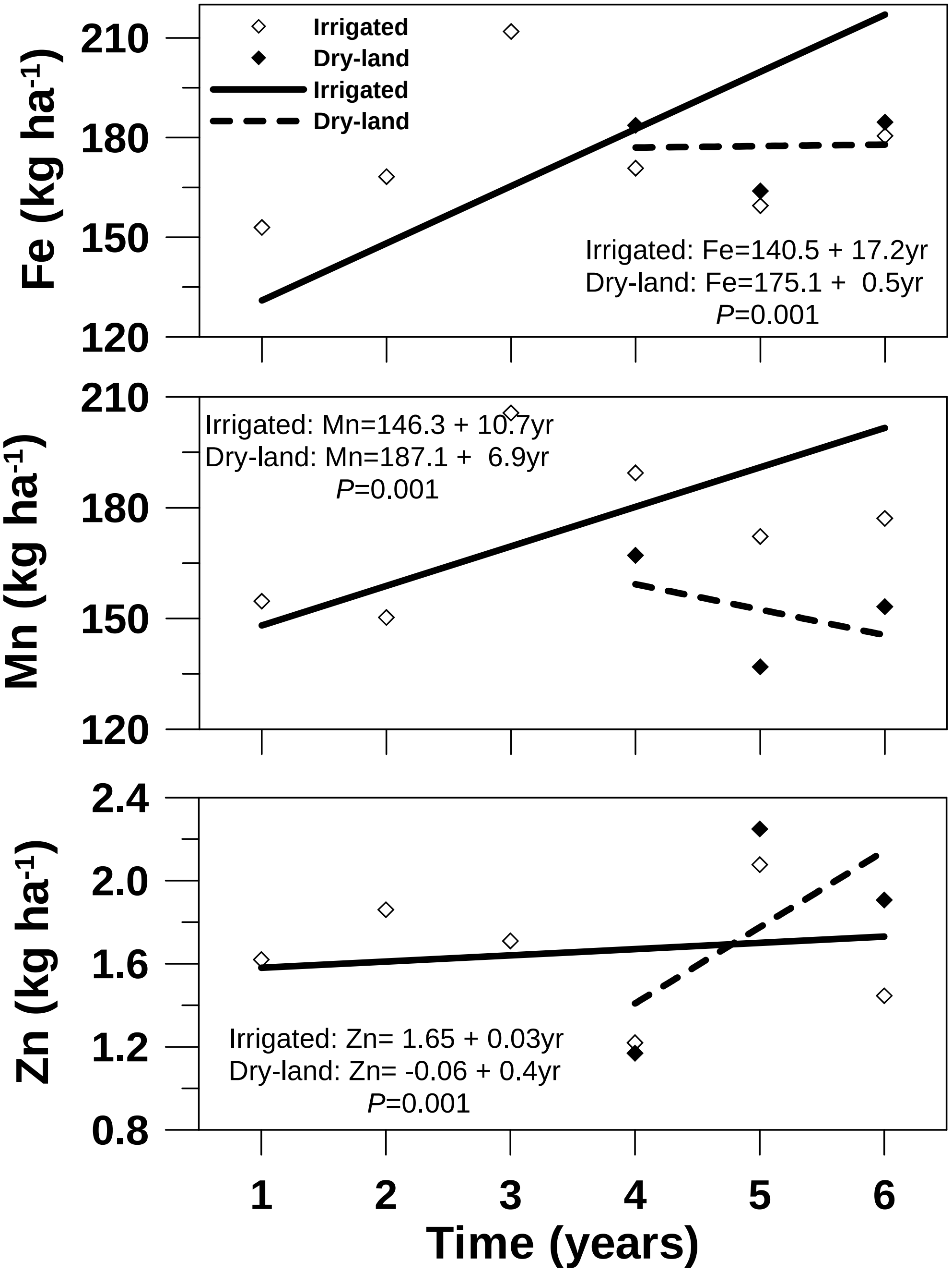

Fig. 5. Influence of irrigation (irrigated and dry-land) on extractable soil Fe, Mn, and Zn contents over time in a wheat-soybean, double-crop system in the Mississippi River Delta region of eastern Arkansas. Time refers to the duration in the wheat-soybean double-crop rotation.

et al. (2006) reported no differences in exchangeable Mg concentrations between burn and no burn after one year of treatment.

There were no significant trends in extractable soil Na and K contents over time after six years of management in any tillage, burning, or residue-level treatment combination. The lack of any trend in extractable soil Na content over time indicates little potential for sodium build up. However, regression analysis with irrigation as a covariate showed a significant linear trend over time for extractable soil K content (*P* = 0.004; Fig.2), which differed ($P = 0.001$) between irrigation treatments. Extractable soil K contents decreased linearly at the rate of 4.3 kg K ha^{-1} yr^{-1} under irrigation, but increased under dry-land conditions at the rate of 9.6 kg K ha^{-1} yr^{-1} (Fig. 2). These results suggest that irrigation depletes K from the top 10 cm of soil due to increased K uptake by crops and potential leaching below 10 cm.

Table 2. Well water quality parameters determined in 2004 for irrigation water used at the Lon Mann Cotton Research Station, Marianna, eastern Arkansas.

Water quality parameter†	Level
pH	9.1
EC (dSm^{-1})	0.5
P (mg L^{-1})	0.2
K (mg L^{-1})	1.9
Ca (mg L^{-1})	110
Mg (mg L^{-1})	48.1
Na (mg L^{-1})	17.1
$SO4^{2-}$ (mg L^{-1})	26.6
Fe (mg L^{-1})	< 0.01
Cu (mg L^{-1})	< 0.01
Cl^- (mg L^{-1})	24.0
Sodium adsorption ratio	0.3
Bicarbonates (mg L^{-1})	691

† Obtained from Brye et al. (2006a)

Potassium was applied in 2005 to all plots to replenish an average low soil-test-K level, which was less than adequate for optimal soybean production in 2004. The applied K fertilizer increased soil K content in year five and six of the study (i.e., 2006 and 2007, respectively) to levels similar to those in the first two years of the study (i.e., 2002 and 2003; Fig 2). Decreased soil-test-K under irrigation and increased soil-test K under dry-land conditions demonstrates that irrigation increased plant demand for available K followed by removal through grain harvesting and/or increased K leaching losses. In contrast to results from this study, Russell et al. (2006) reported low exchangeable soil K under N-fertilization than under a non-fertilized control in fine-loamy soils in Iowa. In contrast, Black (1973) reported no significant effect of N and P fertilizer application rate to wheat on exchangeable soil K in a sandy-loam soil in Montana. However, exchangeable soil K was greater when wheat residue was returned to the soil than when residue was removed, suggesting that crop residue removal through burning or baling results in reduced soil fertility (Black, 1973). Rhoton (2000) compared tillage treatments and reported greater soil K content under NT than CT in the top 2.5 cm in a wheat-soybean, double-crop system on a silt-loam soil in Mississippi. In addition, DuPreez et al. (2001) reported increased soil K content in the top 25 cm due to wheat residue burning in a continuous wheat-fallow system in South Africa. In contrast to previous studies where K fertilizer was not applied (Black, 1973; DuPreez et al., 2001; Russell et al., 2006), K fertilizer was applied to maintain adequate soil-test K for crop production in the current study and that of Rhoton et al. (2000).

Extractable soil P contents decreased ($P = 0.001$) over time. Extractable soil P content trends over time differed ($P < 0.05$) between tillage (Fig. 1), burning (Fig. 3), and residue-level (Fig. 6) treatments. Averaged across all other treatments, extractable soil P decreased ($P = 0.001$) at a similar rate of 2.92 kg P ha^{-1} yr^{-1} in both burn treatments (Fig. 3). However, the magnitude of soil P loss over time was greater under burning than under non-burning as illustrated by a lower ($P = 0.002$) y-intercept for extractable soil P over time in the burn compared to in the no-burn treatment (Fig. 3). Extractable soil P also decreased at a greater rate ($P = 0.039$) under NT (-3.3 kg P ha^{-1} yr^{-1}) than CT (-2.6 kg P ha^{-1} yr^{-1}) (Fig.1) and at a greater rate ($P = 0.005$) under the high- (3.4 kg P ha^{-1} yr^{-1}) than under the low-residue treatment (2.4 kg P ha^{-1} yr^{-1}) (Fig. 6). As indicated by the y-intercept of the regressions, all tillage and residue level treatments had similar initial P contents of 56.3 kg P ha^{-1}.

Increased P availability may be associated with greater SOC under NT and the high-residue-level treatment. Rhoton (2000) reported a positive correlation between extractable soil P concentration and SOM. In this study, extractable soil P contents decreased over time in all treatments despite an increase in SOM over time in the same residue treatments (to be discussed below). The lack of differences in extractable soil P content trends between irrigated and dry-land soybean could be due to the relative immobility of P in soils that minimizes the direct impact of added irrigation water on soil P under non-flooded conditions. Therefore, the greater decrease in extractable soil P over time due to NT and a high-residue level could be explained by a combination of greater P uptake by soybean and subsequent export in harvested grain under NT and greater P uptake by wheat facilitated by the added N fertilizer. Phosphorus loss after burning may be due to removal of ash with mineralized forms of P through wind and water erosion early in the season before soybean canopy development.

Extractable soil S did not vary over time (data not shown) and was unaffected by tillage, burning, residue-level or irrigation treatments. Extractable soil S averaged 17.4 kg S ha^{-1} in the top

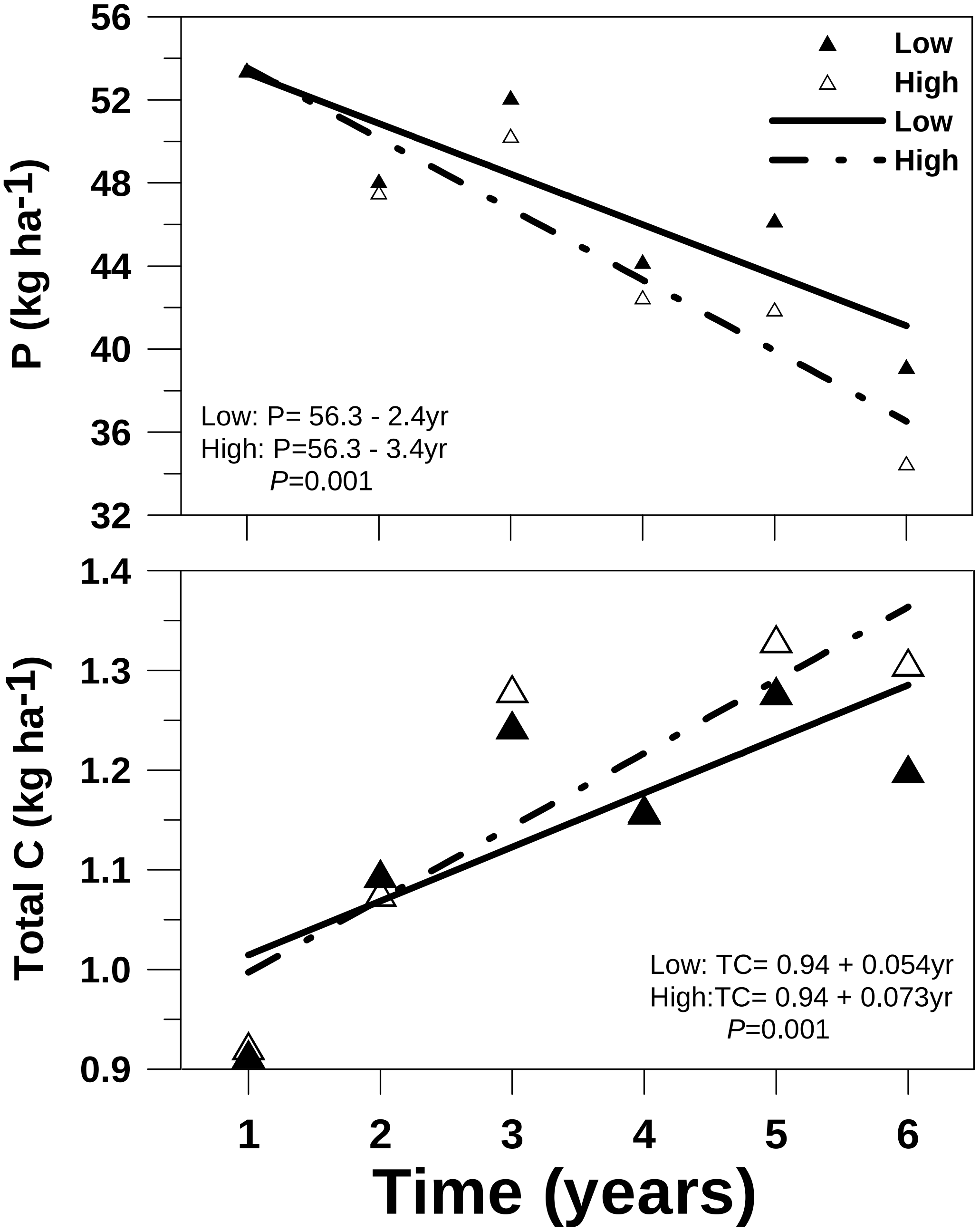

Fig. 6. Influence of wheat-residue level (low and high) on extractable soil P and total C contents over time in a wheat-soybean, double-crop system in the Mississippi River Delta region of eastern Arkansas. Time refers to the duration in the wheat-soybean, double-crop rotation.

10 cm across all treatments over the 6-yr study period.

Soil organic matter and total soil C and N

The rate of change of SOM content in the top 10 cm was unaffected by tillage, burning, or residue level over the first six years following management-practice conversion from continuous, cultivated soybean to the wheat-soybean, double-crop production system. However, averaged across all treatments, SOM increased over time at a rate of 0.097 kg m^{-2} yr^{-1} (P = 0.001; Fig. 4). Adding wheat as a second, relatively large biomass-producing crop to the annual rotation likely resulted in increased

SOM in the top 10 cm over the first six years of this study. The increase in SOM over time indicates an overall benefit of the double-crop production system at improving SOM in cultivated agricultural soils. Liebig et al. (2004) also reported greater SOM in an intensive cropping-system rotation than in a continuous monoculture production system with a fallow period. Similarly, Carter (2002) reported increases in SOM with increases in C input level through an increase in primary production, plant nutrition, organic amendments, and an increase in the proportion of residue returned to the soil in soils with low SOM levels. A review of SOC sequestration studies in the southeastern US reported a SOC sequestration rate of 0.022 kg m^{-2} yr^{-1} with an increase in cropping system complexity relative to a mono-cropped system regardless of tillage (Franzluebbers, 2005). Dallal et al. (2003) showed an exponential decrease in SOC concentration with increasing time of cultivation in continuous cereal cropping systems in northern Australia. Therefore, double-cropped systems with NT or minimum soil disturbance have the potential to increase SOM in agricultural soils.

As with SOM, changes in soil TN over time were unaffected by imposed treatments (data not shown), but unlike SOM, soil TN showed no significant trend over time. Soil TN in this study fluctuated from year to year over the six years of the field study. The lack of significant changes in soil TN over time may be associated with winter wheat's ability to absorb residual N and the wide C:N ratio of the wheat residue returned to the soil (C:N ≈ 55). Similar to the present study, Salinas-Garcia et al. (1997) reported no effect of N fertilizer rate on soil TN after 16 years of N fertilization and tillage treatments in a sandy-clay-loam soil in Texas under a corn-cotton (*Gossypium* sp.) rotation. However, soil TN was greater in NT than in an intensively tilled treatment, suggesting that the placement of crop residues makes a greater contribution to changes in the soil N pool of SOM than N fertilization (Salinas-Garcia et al., 1997). In contrast to the results of this study, a comprehensive analysis of the effects of fire on N cycling revealed that burning increased the amount of soil ammonium- and nitrate-N because of rapid organic residue mineralization due to the elevated temperature during combustion (Wan et al., 2001).

Soil TC content changes over time were affected ($P < 0.05$) by irrigation (Fig. 2), burning (Fig. 3), and residue-level treatment (Fig. 6). Six years of irrigation resulted in a greater ($P = 0.001$) increase in soil TC (0.11 kg C m^{-2} yr^{-1}) than three years of dry-land soybean production (0.044 kg C ha^{-1} yr^{-1}) (Fig. 2). The rate of increase in soil TC was also greater ($P = 0.008$) under the no-burn (0.077 kg C m^{-2} yr^{-1}) than under the burn treatment (0.051 kg C m^{-2} yr^{-1}; Fig. 3). The high-residue-level also had a greater ($P = 0.047$) rate of soil TC increase (0.073 kg C m^{-2} yr^{-1}) than the low-residue-level treatment (0.054 kg C m^{-2} yr^{-1}; Fig.6). The mean rate of soil C storage observed in both tillage treatments in the first six years of this study was 0.064 kg C m^{-2} yr^{-1}.

These results show there is potential for soil C accumulation in the Mississippi River Delta region with the adoption of the wheat-soybean, double-crop system. Irrigation resulted in a greater soil TC accumulation rate than dry-land soybean, possibly because of a slower rate of organic residue decomposition due to reduced oxygen diffusion in moist soil caused by a greater proportion of pores filled with water and greater soybean biomass production under irrigated compared to dry-land conditions. The greater rates of soil TC accumulation under the no-burn and high-residue-level than under the burn and low-residue-level treatments shows that there is also a greater potential for soil C accumulation when residue is left unburned and when greater residue mass is produced. The low rate of soil TC storage under burning may be due to the substantial loss of biomass-C during combustion. The greater TC increase of in the high- than in the low-residue-level treatment is also supported by a lower surface CO_2 flux under the high- than under the low-residue-level treatment measured in the same plots as this study in 2002 and 2003 (Brye et al., 2006b). In contrast to these results, Grandy et al. (2006) reported greater accumulation of SOC under NT by 0.026 kg C m^{-2} yr^{-1} compared to intensive tillage in the top 5 cm of sandy-loam soils of southwestern Michigan. In this study, CT consisted of disking as opposed to moldboard tillage followed by disking as the CT method in the study by Grandy et al. (2006). Therefore, depth of residue burial and the extent of soil disturbance may explain much of the difference in near-surface SOC storage rates between NT and tilled soils in the Grandy et al. (2006) study and the lack of difference in this study.

It has been established that greater SOC sequestration is associated with a lower rate of soil surface CO_2 efflux due to reduced soil disturbance, despite a similarly sized labile organic C pool in soils that are both tilled and untilled (Franzluebbers et al., 1998). Considering that the rate of soil C storage over time was similar under both tillage treatments (0.064 kg C m^{-2} yr^{-1}), the greater soil C storage rate under the no-burn and high- than under the burn and the low-residue-level treatments also suggests that refraining from burning crop residues and increased biomass production through improved soil fertility may result in greater soil C sequestration in arable soils than the simple conversion from CT to NT. Godsey et al. (2006) reported 18 to 23% greater SOC concentration under NT than under CT in the top 15 cm of a silt-loam soil in Kansas. Diaz-Ravina et al. (2005) also reported 9.9 Mg C ha^{-1} more under NT relative to CT, and greater TN under NT than CT in the top 5 cm of a sandy-loam soil in temperate humid zone of Spain after 8 yr of NT. No-tillage also resulted in greater C accumulation in the top 5 cm than under CT in a sandy-loam soil in southwestern Michigan (Grandy et al., 2006).

The wide variation in C accumulation results could be associated with soil textural differences. The rate of C loss is generally greater in coarse-textured soils under CT than in fine-textured soils under a similar tillage treatment. Hao and Kravchenko (2007) reported increasing TC with increasing clay and silt contents, decreasing TC with increasing sand content, and that sand and silt contents had been reported to explain more than 40% of the variability in TC under NT compared to that under CT.

The soil C:N ratio did not vary over time and was unaffected by any of the residue management or irrigation treatments. However, despite the soil C:N ratio being unaffected by burning, the quality of SOM, as defined by the amount of labile C present, has likely changed somewhat over time since annual burning has added a more recalcitrant C fraction back to the soil in the form of incompletely combusted organic residue (i.e., black C) compared to the relatively labile C fraction being added in the only slightly decomposed residue (Kaal et al., 2008). This is because burning has been reported to cause rearrangements of C and N forms in organic residues, and hence synthesis of new structures that are resistant to decomposition (Gonzalez-Perez et al., 2004; Almendros et al., 2003).

Table 3. Monthly soybean growing-season precipitation for six years in a wheat-soybean, double-crop production system in the Mississippi River Delta region of eastern Arkansas. The coefficient of variation (CV) for the 5-month growing season for each year is also provided.

	Growing season precipitation (cm)							
	Month							
Year	June	July	Aug.	Sept.	Oct.	Total	Monthly mean	CV (%)
2002	0.3	13.4	8.1	8.7	10.7	41.2	8.2	59.5
2003	5.3	10.2	5.3	8.7	2.5	32.0	6.4	47.7
2004	15.7	8.1	1.3	0.4	9.9	35.4	7.0	90.1
2005	0.4	9.6	10.8	14.7	1.1	36.7	7.3	86.0
2006	5.1	3.2	5.2	11.1	4.3	28.9	5.8	52.8
2007	9.2	15.3	2.3	7.6	4.9	39.3	7.9	62.9
30-yr mean†	11.2	9.7	6.9	8.0	9.6	45.5	9.1	18.0

† Obtained from NOAA (2002)

The mean rate of C storage observed across all treatment combinations in the first six years of this study was 0.064 kg C m^{-2} yr^{-1}, which is only slightly greater than the global mean soil C storage rate of 0.057 kg C m^{-2} yr^{-1} reported by West and Post (2002) for the conversion from CT to NT. Franzluebbers et al. (1998) expressed C sequestration as a proportion of SOC per unit C input and reported greater SOC storage under NT compared to that under CT regardless of cropping intensity after 9 years. However, under CT, SOC storage increased with increasing cropping intensity in the warm climate of south-central Texas (Franzluebbers et al., 1998). These studies and the current study show that reducing soil disturbances, high-intensity cropping systems, such as double-cropping, and retaining crop residues have great potential to sequester C in soils of the warm southern regions of the US in both irrigated and dry-land systems.

Soybean and wheat yield

The trend of soybean yield over time did not differ among treatments and showed a significant ($P = 0.001$) quadratic relationship with time with a common initial declining rate of -2.43 Mg ha^{-1} yr^{-1} during the first three years followed by an increasing rate of 0.29 Mg ha^{-1} yr^{-2} during the subsequent three years (Fig. 4). In contrast, wheat yields had no significant trend over time (data not shown) and averaged 2.44 Mg ha^{-1} across all treatments and years. The soybean yield increase after the third year may be due to the soil approaching or attaining some equilibrium after the change in cropping system from continuous soybean to the wheat-soybean, double-crop production system. Similar to this study, Grandy et al. (2006) reported no soybean, corn, or wheat yield loss from 14 years of NT when compared to CT in a sandy-loam soil of southwestern Michigan. These results show that the yield variability among years is comparable between tillage treatments.

Year-to-year soybean yield differences are often due to growing-season weather variability. Andresen et al. (2001) used crop simulation models to show that water availability and air temperature are important causes of year-to-year crop yield variability in the Great Lakes region of the US. Smith et al. (2007) also reported less annual soybean yield variability under NT than CT when growing-season precipitation was above the 30-yr mean precipitation. Changes in soybean yield over time in this study were similar between NT and CT despite the mean growing-season precipitation being below the 30-yr mean in all six years (Table 3). However, the two years with the lowest soybean yields (i.e., 2004 and 2005) had the greatest monthly precipitation variability (> 80%) with the lowest monthly precipitation in August and September 2004 corresponding to about the R3 to R6 soybean growth stages and in June 2005 corresponding to about the VE to V3 growth stages.

The 6-yr yield and precipitation trends show that the distribution of rainfall throughout the growing season plays a greater role in determining yield than total and mean growing-season rainfall. It appears that the confounding interactions of climatic conditions, pest pressure, and soil physical properties (Kravchenko et al., 2005) may have caused year-to-year yield variations in this study regardless of the imposed soil and residue management practices. This likely occurred because the whole study area received similar soybean pest control and fertility management, and there was no visually observable disease, insect, or weed pressure in any treatment combination throughout the study. Therefore, it appears that NT has a similar potential to increase soybean yield in the wheat-soybean, double-crop system as CT.

Economic returns for alternative management practices

Net returns varied among treatment combinations as well as from year-to-year due to year-to-year variations in crop growing conditions. Soybean and wheat growing conditions were poor during three of the six years of this study and resulted in reduced crop yields. Both wheat and soybean growing conditions were adequate in 2002, 2003, and 2006. Over the initial six years of the wheat-soybean, double-crop rotation, net returns were greatest in the first year of the study (2002) in all treatment combinations ranging from \$565 ha^{-1} obtained under the irrigated-CT-no-burn-high-residue combination to \$864 ha^{-1} obtained under the irrigated CT-burn-high-residue level combination (i.e., the traditional practice). In 2003, all treatment combinations had positive net returns and treatment combinations with NT had greater net returns than treatment combinations with CT (Fig. 7). All treatment combinations produced a net loss in 2004 due to the lowest soybean yields in the six years of study that were possibly the result of poor soil physical properties due to high soil bulk density (Fig. 1) and delayed planting (Cordell et al., 2006).

After the introduction of the irrigation treatment in 2005, net returns continued to fluctuate and differed among treatment combinations under both irrigated and dry-land conditions. In 2005, net returns in all treatment combinations were negative for both irrigated and dry-land conditions (Fig. 8). In 2005, there was no income from wheat. Soybean was planted twice due to poor stand establishment, thereby increasing the soybean cost of production resulting in a net loss in all treatment combinations in 2005. In 2006, all treatment combinations with irrigation had positive net returns. The treatment combinations with dry-land conditions had negative net returns except for those combinations with a high-residue level (Fig. 8). In 2007, all treatment combinations with NT produced positive net returns, except for the NT-burn-low-residue combination under dry-land conditions, which had a negative net return of \$-10 ha^{-1}. In contrast, all CT treatments produced negative net returns ranging from \$-68 ha^{-1} to \$-164 ha^{-1} regardless of residue level and irrigation in 2007. In 2007, wheat yields were low because of poor wheat growth conditions caused by a late frost at approximately the jointing stage of wheat growth that resulted in reduced gross income from wheat.

Fluctuation in net returns from year-to-year can be attributed to the different management practices and their resulting yields. In good years, the NT-burn combination with irrigation maintained the greatest net returns of all treatment combinations regardless of residue level. During two of the three years with poor crop growth conditions, all alternative management practices with NT-burn treatment combinations maintained the smallest net losses compared to treatment combinations with CT. In addition, in years when all treatment combinations had negative net returns (i.e., 2004 and 2005), NT produced 72% less negative net returns compared to CT.

The generally greater net return or less net loss under NT in this study was due to reduced costs under NT compared to CT. In this study, six-year

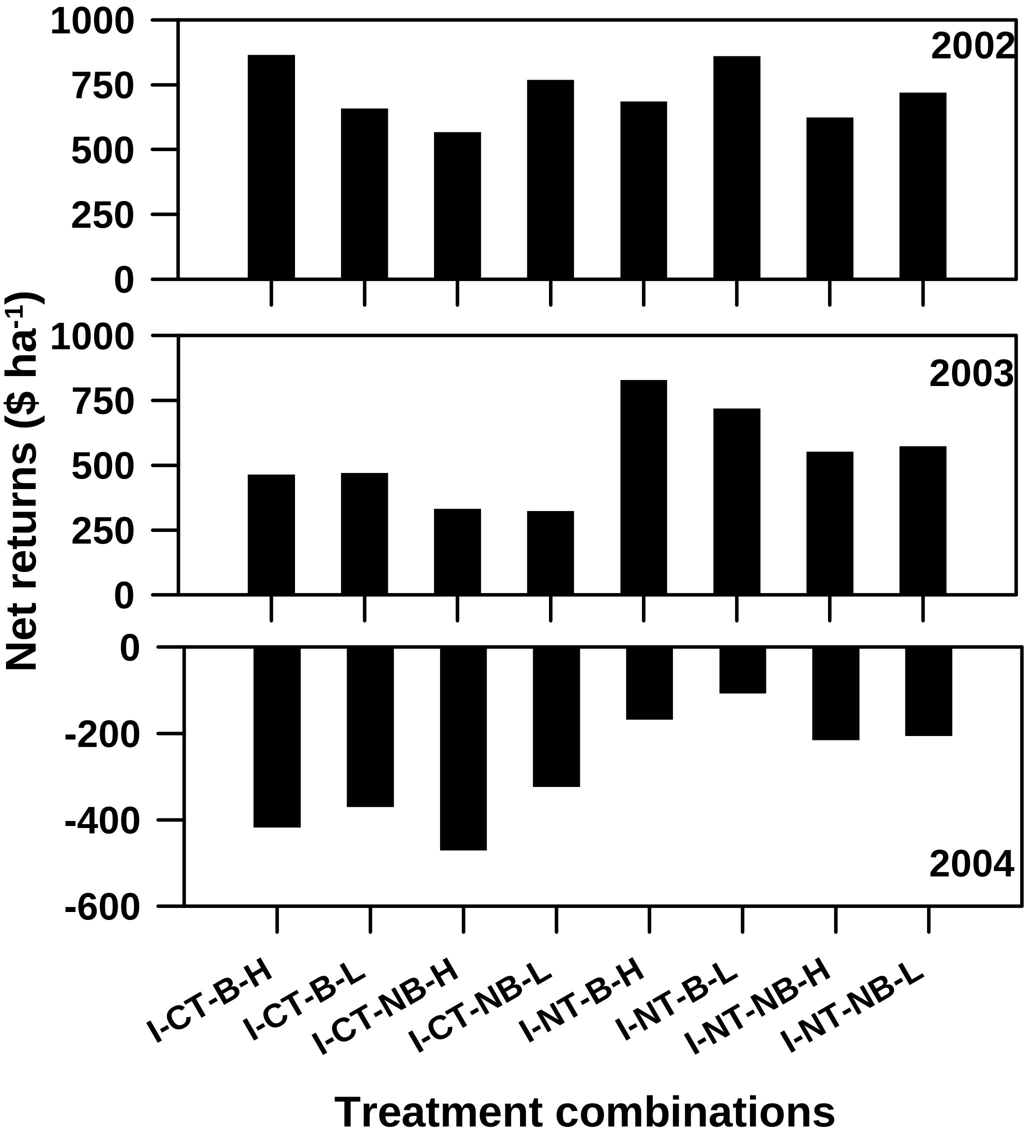

Fig. 7. Net economic returns for eight treatment combinations of irrigation (I), tillage [conventional tillage (CT) and no-tillage (NT)], burning [burn (B) and no burn (NB)], and residue level [low (L) and high (H)] from 2002 to 2004 in a wheat-soybean, double-crop production system in the Mississippi River Delta region of eastern Arkansas.

average CT costs were 18% greater than NT due to extra machinery operations and fuel costs under CT compared to under NT. Similar to the current results, Ribera et al. (2004) reported 33% less net negative returns in wheat-soybean, double-crop system with NT management compared to CT in a silty-clay-loam soil in Texas and concluded that NT was the preferred management option. Meyer-Aurich et al. (2006) also reported increased profitability under reduced tillage compared to intensive tillage due to a combination of increased yields and reduced costs of soybean production. Over the six years of this study, soybean (Fig. 4) and wheat (data not shown) yields did not differ significantly between treatment combinations. These results suggest that alternative management practices with low production costs are more profitable than high-cost practices (i.e., multiple tillage operations) that cannot be justified by the income produced with yields similar to those obtained under the low-cost management practices.

In this study, irrigation did not maintain positive net returns for all treatment combinations in all years. Irrigation resulted in negative net returns during years with poor crop growth conditions

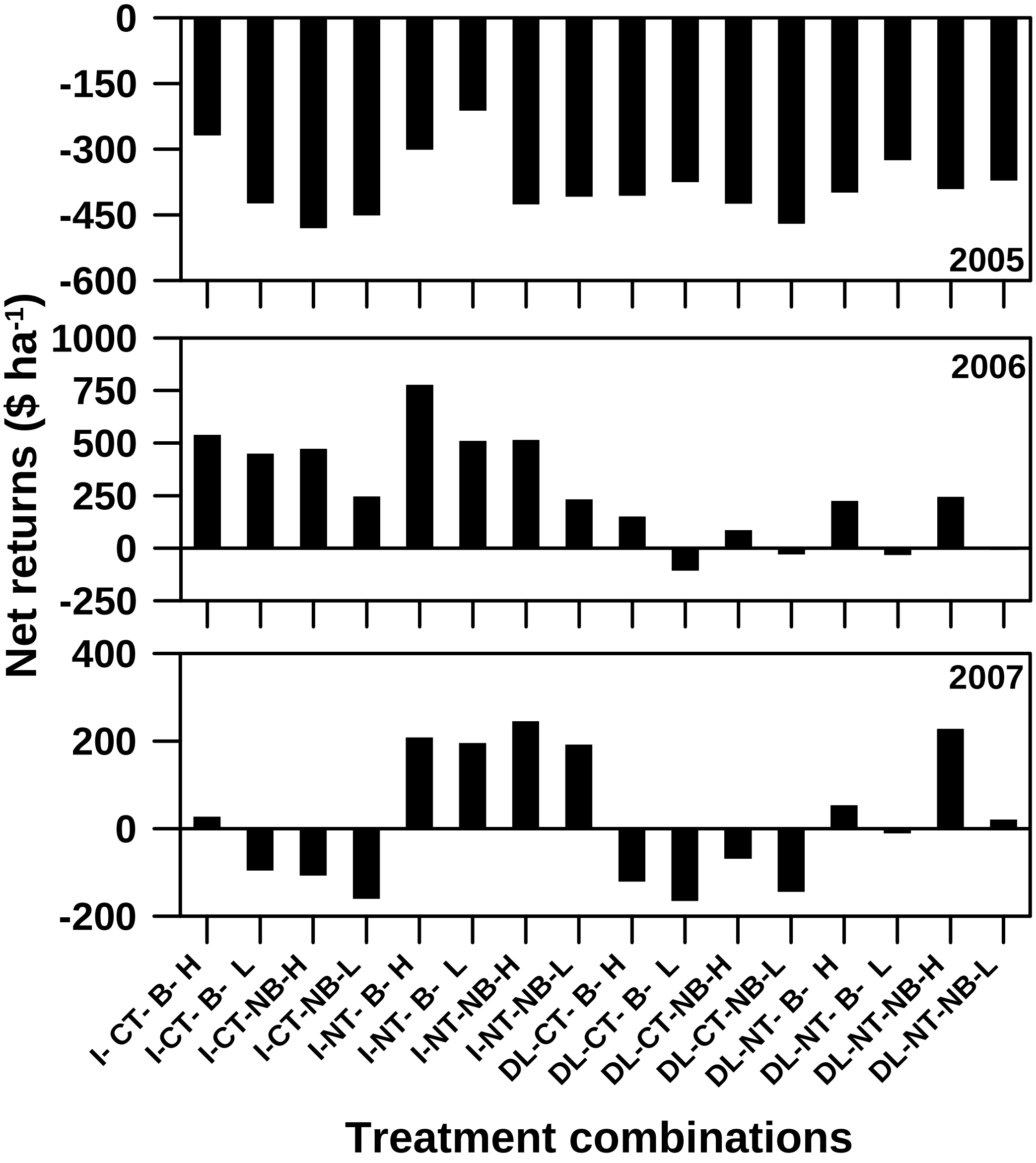

Fig. 8. Net economic returns for 16 treatment combinations of irrigation [irrigated (I) and dry-land (DL)], tillage [conventional tillage (CT) and no-tillage (NT)], burning [burn (B) and no burn (NB)], and residue level [low (L) and high (H)] from 2005 to 2007 in a wheat-soybean, double-crop production system in the Mississippi River Delta region of eastern Arkansas.

because of reduced soybean yield that was not sufficient to offset high irrigation costs. Even though production costs for dry-land treatments were 30 to 38% below those for irrigated treatments in 2005 through 2007, net returns were still lower for dry-land treatment due to lower soybean yields and thus lower revenues than under irrigated treatments. In contrast, Parsch et al. (2001) reported relatively stable net positive returns over six years for irrigation compared to dry-land soybean production in clay soils in eastern Arkansas. However, under adequate and well-distributed rainfall, dry-land soybean production had greater net returns than under irrigated soybean systems (Parsch et al., 2001).

These results also show that NT and a high residue level have great potential to maintain and improve profitability across years under both irrigated and dry-land conditions. In contrast to this study, Parsch et al. (2001) reported greater net returns under CT than NT due to high variable costs as a result of greater demand of herbicides under NT. In this study, herbicide was applied for weed control uniformly under all treatment combinations. Similar to this study, Ribera et al. (2004) reported a lower overall cost per hectare under NT than CT, despite greater costs of herbicides under NT, and concluded that management systems with the greatest net return or least negative net return would be preferred. Thus, in this study, the irrigated-NT-burn combination at either residue level would be the preferred combination among the alternative management systems evaluated.

Comparison of economic performance

Comparison of economic returns among alternative residue management practices relative to the traditional practice over time enables evaluation of the most economically sustainable management options. In the first year of this study, the traditional practice (irrigated-CT-burn-high-residue) was equally as profitable as the irrigated-NT-burn-low-residue level treatment combination (Table 4). In the second year (2003), all alternative management practices were 1 to 79% more profitable than the traditional practice, except for the irrigated-CT-no-burn-high-residue (-28%) and CT-no-burn-low-residue (-30%) combinations. In the third year (2004), all management practices were 11 to 60% more profitable than the traditional practice despite all having net losses. The NT-burn combination, regardless of residue level, had the greatest percent profitability relative to the traditional practice in 2003 and 2004. Therefore, under all irrigated treatment combinations, the NT-burn combination at any residue level had the best economic performance of all treatment combinations relative to the traditional practice.

From the fourth to the sixth year of this study, there were 16 treatment combinations after the introduction of the irrigated and dry-land treatments. In the fourth year (2005), all treatment combinations were less profitable than the traditional practice, except for the irrigated-NT-burn-low-residue combination, which was 21% more profitable than the traditional practice (Table 4). In 2006, all alternative management practices were 5 to 119% less profitable compared to the traditional practice, except for the irrigated-NT-burn-high-residue combination, which was 44% more profitable relative to the traditional practice (Table 4). In addition, the most unprofitable practice relative to the traditional practice was the dry-land-CT-burn-low-residue combination. In 2007, all irrigated treatment combinations with NT were more profitable than the traditional practice regardless of burning and residue level (Table 4). However, only the combination of NT and a high residue level, either burned or non-burned, under dry-land conditions were more

Table 4. Percent net returns for each alternative management practice combination relative to the traditional management practice combination (i.e., irrigated-CT-burn-high-residue-level) for six years in a wheat-soybean, double-crop production system in the Mississippi River Delta region of eastern Arkansas.

Treatment combinations[†]	2002	2003	2004	2005	2006	2007
	%					
Irrigated:						
CT-burn-low	-24	1	11	-58	-17	-455
CT-no burn-high	-35	-28	-13	-79	-12	-500
CT-no burn-low	-11	-30	23	-68	-55	-698
NT-burn-high	-21	79	60	-12	44	682
NT-burn-low	0	55	74	21	-6	633
NT-no burn-high	-28	19	48	-59	-5	819
NT-no burn-low	-17	24	51	-52	-57	620
Dry-land:						
CT-burn-high	-[††]	-	-	-51	-72	-552
CT-burn-low	-	-	-	-40	-119	-716
CT-no burn-high	-	-	-	-58	-84	-355
CT-no burn-low	-	-	-	-76	-105	-638
NT-burn-high	-	-	-	-49	-59	99
NT-burn-low	-	-	-	-21	-106	-136
NT-no burn-high	-	-	-	-46	-55	757
NT-no burn-low	-	-	-	-38	-101	-23
Irrigated-CT-burn-high	0	0	0	0	0	0

[†] Conventional tillage (CT), no-tillage (NT), low residue level (low), and high residue level (high).

[††] All treatment combinations were irrigated in 2002, 2003, and 2004.

profitable than the traditional practice (Table 4). Reduced wheat income under the low N rate and reduced soybean income under dry-land conditions resulted in less net returns under the dry-land-NT-low-residue combination than under the traditional practice despite the low costs in the alternative treatment combinations.

In contrast, all alternative management practices with CT were 355 to 716% less profitable than the traditional practice in 2007 (Table 4). The large profitability differences among treatment combinations with CT relative to the traditional practice in 2007 compared to the other five years was due to greater fuel and machinery operation costs. In 2007, the field was disked four times due to excessive drought caused by a ryegrass (*Lolium* spp.) infestation in spring 2007. Increased tillage operation costs in combination with low wheat income and lower soybean yields than the traditional practice resulted in lower percent profitability for all treatment combinations with CT relative to the traditional practice in 2007 compared to that in all other years. Thus, increasing the frequency of tillage passes across a field for seedbed preparation did not improve soybean yields, but reduced the profitability of CT.

These results show that the irrigated-NT treatment combinations, regardless of burning and residue level, had greater percent profitability relative to the traditional practice in three out of six years of this study. In addition, the irrigated-NT-burn treatment combination maintained a consistently equal or greater profitability relative to the traditional practice in all six years. Thus, it appears that NT with or without residue burning would ensure greater profitability or less loss than the traditional practice during both good and poor crop growing conditions. However, since burning crop residues does not generally return much organic material to the soil, residue burning likely does not directly contribute to increased SOM, and hence may not sustain long-term productivity of Mississippi River Delta region soils. If the environmental and social costs of burning are considered, burning could reduce profitability in the long-term. The irrigated treatment combinations with NT-no-burn at any residue level ranked third in all years in maintaining consistent greater percent profitability or the least loss relative to the traditional practice. The management practices with the lowest profitability relative to the traditional practice were the treatment combinations with CT regardless of burning, residue level, or irrigation and CT in combination with dry-land conditions in years where irrigation treatments were included (2005 to 2007).

Similar to this study, Sanchez-Giron et al. (2007) also reported 12% greater gross and net margins with dry-land NT than with moldboard plowing in a wheat-forage legume [vetch (*Vicia sativa* L.) or peas (*Pisum sativum* L.)] rotation in a loamy soil in Spain, and that NT maintained the greatest profit per unit area compared to intensive tillage. In the silt-loam soils of the Mississippi River Delta region of eastern Arkansas, the moisture conservation (Verkler et al., 2008) and reduced costs associated with NT contributes to the NT practice being more profitable than CT under dry-land soybean production. These results show that alternative residue management practices with NT can provide the best economic performance.

CONCLUSIONS

Refraining from burning wheat residue provides a greater rate of soil C accumulation in the top 10 cm of a silt-loam soil in eastern Arkansas regardless of tillage and residue level compared to residue burning. The high-residue-level treatment increased SOC storage at a greater rate than the low-residue-level treatment likely due to increased above- and belowground biomass production. Tillage, burning, and residue level had no effect on soil TN and C:N ratio. All treatments resulted in similar soybean yield trends, and the soybean yield trend appears to be influenced most by growing-season rainfall distribution. No-tillage, burning wheat residue, and a high N fertilizer rate for wheat grain in the wheat-soybean, double-crop system resulted in greater soil P depletion than with CT, unburned residue, and a low N fertilization rate. Therefore, NT and non-burning appear to be viable alternatives to CT and residue burning that have potential to improve soil quality with any residue level in the wheat-soybean, double-crop production system.

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