12-2012

Long-Term Effects of Rice Rotation, Tillage, and Fertility on Near-Surface Soil Carbon and Nitrogen Cycling

Jill Marie Motschenbacher
University of Arkansas, Fayetteville

Follow this and additional works at: http://scholarworks.uark.edu/etd

Part of the Agricultural Science Commons, Agronomy and Crop Sciences Commons, and the Soil Science Commons

Recommended Citation
Motschenbacher, Jill Marie, "Long-Term Effects of Rice Rotation, Tillage, and Fertility on Near-Surface Soil Carbon and Nitrogen Cycling" (2012). Theses and Dissertations. 664.
http://scholarworks.uark.edu/etd/664

This Dissertation is brought to you for free and open access by ScholarWorks@UARK. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of ScholarWorks@UARK. For more information, please contact scholar@uark.edu, ccmiddle@uark.edu.
LONG-TERM EFFECTS OF RICE ROTATION, TILLAGE, AND FERTILITY ON NEAR-SURFACE SOIL CARBON AND NITROGEN CYCLING
LONG-TERM EFFECTS OF RICE ROTATION, TILLAGE, AND FERTILITY ON NEAR-SURFACE SOIL CARBON AND NITROGEN CYCLING

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Crop, Soil and Environmental Sciences

By

Jill Marie Motschenbacher
Middle Tennessee State University
Bachelor of Science in Agribusiness, 2006
Middle Tennessee State University
Master of Education in the Administration of Higher Education, 2007

December 2012
University of Arkansas
ABSTRACT

Rice (*Oryza sativa* L.)-based cropping systems are different from other row crops due to the flood-irrigation scheme used from about one month after planting to a few weeks prior to harvest. The frequent cycling between anaerobic (i.e., flooding during the growing season) and aerobic (i.e., generally, the remainder of the year) conditions can influence the rate of soil organic matter (SOM) decomposition, which can greatly influence carbon (C) and nitrogen (N) storage and sequestration in the soil over time. Therefore, a study was conducted on a silt-loam soil (fine, smectitic, thermic, Typic Albaqualf) at the Rice Research and Extension Center near Stuttgart, which is in the Mississippi River Delta region of eastern Arkansas, to evaluate the long-term effects of rice-based crop rotations [with corn (*Zea mays* L.), soybean (*Glycine max* L.), and winter wheat (*Triticum aestivum* L.)], tillage [conventional-tillage and no-tillage (NT)], soil fertility (optimal and sub-optimal), and soil depth (0- to 10- and 10- to 20-cm) after 12 years (1999-2011) of consistent management on SOM, total and water-stable aggregate (WSA) C, total and WSA N, soil physical properties (WSA structure, bulk density, penetration resistance), soil chemical properties (Mehlich-3 extractable nutrients, pH, and electrical conductivity), and soil surface carbon dioxide (CO$_2$) respiration. Results showed that SOM, total C, and total N concentrations increased over time under the NT treatment and in all rotations that did not include corn in the top 10 cm, but were not affected by the fertility treatment applied. The NT/0-to 5-cm treatment combination had 3 to 6 times greater WSA C and N content than all other tillage-depth combinations in the top 10 cm, which did not differ among one another. Despite rotation trends in total C and N, rotations with increased frequencies of corn generally had greater WSA C and N contents compared to rotations with wheat. However, there were no consistently significant differences in soil surface CO$_2$ flux between tillage treatments and/or
among crop rotations after 10- and 11-years of imposed treatment combinations. Results from this long-term experiment suggest that rice rotated with a higher-residue-producing crop, such as corn, may lead to greater C and N sequestration for longer periods of time due to the aggregated form that is predominantly present in the soil. It appears that the management practices of NT and high-residue-producing crop rotations establish a new, greater soil C content equilibrium over time. This long-term research study is important because the results enable a greater understanding of the decadal effects that rice-based crop rotations and conservation management practices have on the physical, chemical, and biological properties of the soil, which in turn, provides insight to the longer-term sustainability of these systems so that they can remain highly productive without detrimental effects to the environment and the soil resource.
This dissertation is approved for recommendation to the Graduate Council.

Dissertation Directors:

____________________________
Dr. Kristofor R. Brye

____________________________
Dr. Merle M. Anders

Dissertation Committee:

____________________________
Dr. Edward E. Gbur

____________________________
Dr. Nathan A. Slaton

____________________________
Dr. Michelle A. Evans-White
DISSEETATION DUPLICATION RELEASE

I hereby authorize the University of Arkansas to duplicate this thesis when needed for research and/or scholarship.

Agreed

_______________________________________________

Jill Marie Motschenbacher

Refused

_______________________________________________

Jill Marie Motschenbacher
ACKNOWLEDGEMENTS

I thank Dr. Kristofor Brye and Dr. Merle Anders for their commitment in guiding me through this doctoral program through academic advising, fieldwork supervision and instruction, and numerous hours of both professional and personal guidance. I would like to thank Dr. Kristofor Brye for his persistence in making me the best all-around person that I am capable in being in our profession by always pushing me to the next level of achievement in writing, speaking, and scholarship through his support and constructive feedback. I would like to thank Dr. Merle Anders for sharing his great insight of scientific research and societal dilemmas associated with food production from an international perspective. Furthermore, I thank Drs. Kristofor Brye and Merle Anders for their support in allowing me to pursue international travel for both instruction and career advancement during my program, in addition to allowing me to obtain many other academic skills through domestic travel for professional meetings, additional academic instruction, and teaching experiences.

I thank my committee members, Drs. Edward Gbur, Nathan Slaton, and Michelle Evans-White for their willingness to serve on my Doctoral Committee, providing personalized instruction in their fields of expertise, and their valuable inputs that made my doctoral education and this Dissertation possible. Field assistance provided by Taylor Adams, Terry Sells, Daniel McCarty, Tara Moss Clayton, Kevin Rorex, Richard McMullen, and Travis Gasnier and other station personnel at the Rice Research and Extension Center is gratefully acknowledged and appreciated.

I thank my family and friends for their love, support, and understanding throughout the years while in pursuit of both my military and academic careers. I give a special thanks to my mother and father, Larry and Barbara Motschenbacher, and my sister, Rachel Motschenbacher.
Anderson who have been there to help me through all of the intellectual and emotional ups and downs associated with both my professional and personal life throughout the years. I thank Suzanne Messer and Jason Auer for being my academic support through most of my Bachelor, Master, and Doctoral Degrees. I also thanks all of the faculty, staff, and my fellow graduate students (2008 to 2012) in the Department of Crop, Soil and Environmental Sciences (CSES) for their constant support in pursuing not only my academic dreams, but also for their support of the charity fundraisers I have been involved in as a part of the CSES Graduate Student Association for three consecutive years. Furthermore, partial funding for this research was provided by the Rice Research Promotion Board and is gratefully acknowledged.
DEDICATION

To my family, who always believed I could do anything that I put my mind to, and to all the other people in the world who believe in the power of trying. I also dedicate this to everyone who has fought to pursue their dreams despite being discouraged by others, whatever those dreams might be. That being said, I should probably dedicate this to the people who try to discourage others from reaching their dreams, for it is those people that give successful people the motivation to prevail just to prove those who doubt them wrong.

“Success is to be measured not so much by the position that one has reached in life as by the obstacles which he [she] has overcome.” ~ Booker T. Washington
# TABLE OF CONTENTS

## CHAPTER 1. Introduction and Literature Review

<table>
<thead>
<tr>
<th>I. Introduction</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>II. Literature Review</td>
<td>4</td>
</tr>
<tr>
<td>A. Rice</td>
<td>4</td>
</tr>
<tr>
<td>i. Global Rice Production and Industry</td>
<td>4</td>
</tr>
<tr>
<td>ii. Rice Characteristics</td>
<td>6</td>
</tr>
<tr>
<td>iii. Rice Soil in the United States</td>
<td>7</td>
</tr>
<tr>
<td>iv. Water Management in Rice Crop Agriculture</td>
<td>8</td>
</tr>
<tr>
<td>v. Nature of Arkansas Rice Industry</td>
<td>11</td>
</tr>
<tr>
<td>B. Importance of Soil Organic Matter</td>
<td>13</td>
</tr>
<tr>
<td>i. Relationship between SOM, Carbon, and Nitrogen</td>
<td>15</td>
</tr>
<tr>
<td>C. Importance of Organic Matter in Relation to Soil Carbon</td>
<td>16</td>
</tr>
<tr>
<td>i. Environmental Influences on SOC Accumulation</td>
<td>17</td>
</tr>
<tr>
<td>ii. Effects of Aerobic vs. Anaerobic Conditions on SOC Decomposition</td>
<td>19</td>
</tr>
<tr>
<td>iii. Soil Aeration and CO₂ flux</td>
<td>20</td>
</tr>
<tr>
<td>iv. Carbon Sequestration</td>
<td>21</td>
</tr>
<tr>
<td>D. Importance of Organic Matter in Relation to Soil Nitrogen</td>
<td>23</td>
</tr>
<tr>
<td>E. Impact of Biogeochemical Cycling on Global Climate</td>
<td>24</td>
</tr>
<tr>
<td>i. Anthropogenic Processes Effecting Natural Biogeochemical Cycling</td>
<td>27</td>
</tr>
<tr>
<td>ii. Global Impacts of Carbon and Nitrogen Gas</td>
<td>28</td>
</tr>
<tr>
<td>iii. Socioeconomic Costs of Climate Change</td>
<td>30</td>
</tr>
<tr>
<td>iv. Carbon Credit Exchange</td>
<td>31</td>
</tr>
<tr>
<td>v. Century Model</td>
<td>31</td>
</tr>
<tr>
<td>F. Long-Term Effects of Rice Management Practices on Soil Carbon and Nitrogen</td>
<td>32</td>
</tr>
<tr>
<td>i. Crop Rotation and SOC Accumulation and N Utilization</td>
<td>33</td>
</tr>
<tr>
<td>ii. Effects of Tillage and Residue Management Practices on SOC and N</td>
<td>34</td>
</tr>
<tr>
<td>iii. Fertility Treatment Effects on SOC Accumulation and N in Soil</td>
<td>36</td>
</tr>
<tr>
<td>G. Long-Term Effects of Rice Management Practices on Soil Physical Properties</td>
<td>38</td>
</tr>
<tr>
<td>i. Bulk Density</td>
<td>38</td>
</tr>
<tr>
<td>ii. Aggregate Stability</td>
<td>40</td>
</tr>
<tr>
<td>III. Justification</td>
<td>42</td>
</tr>
<tr>
<td>IV. Hypotheses</td>
<td>43</td>
</tr>
<tr>
<td>V. Literature Cited</td>
<td>44</td>
</tr>
</tbody>
</table>
CHAPTER 2. Rice rotation and tillage effects on water-stable soil macroaggregates and their associated carbon and nitrogen contents in a silt loam soil

I. Abstract 66
II. Introduction 68
III. Materials and Methods
   A. Site Description 71
   B. Experimental Design and Field Treatments 72
   C. Soil Sampling and Analyses 75
   D. Data Analyses 77
IV. Results and Discussion 78
   A. Water-Stable Aggregation 78
   B. Aggregate C and N Concentrations and C:N Ratios 82
   C. Composite-Soil C and N Concentrations and Ratios 87
   D. Aggregate C and N Contents 88
   E. Composite-Soil C and N Contents 92
   F. Bulk-Soil C and N Content Partitioning 94
V. Summary and Conclusions 96
VI. Literature Cited 99

CHAPTER 3. Long-Term Rice Rotation, Tillage, and Fertility Effects on Chemical Properties in a Silt-Loam Soil 125

I. Abstract 126
II. Introduction 128
III. Materials and Methods
   A. Site Description 132
   B. Experimental Design and Field Treatments 133
   C. Soil Sampling and Analyses 135
   D. Data Analyses 136
IV. Results and Discussion 137
   A. Initial Soil Properties 137
   B. Soil Organic Matter 138
   C. Soil pH 142
   D. Soil Electrical Conductivity 143
   E. Extractable Soil Nutrients 145
      i. Phosphorus 145
      ii. Potassium 147
      iii. Sulfur 149
      iv. Calcium 150
      v. Magnesium 151
      vi. Iron 152
      vii. Manganese 153
      viii. Zinc 154
      ix. Copper 156
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Start Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Long-Term Crop Rotation, Tillage, and Fertility Effects on Soil</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>Carbon and Nitrogen in Dry-Seeded, Delayed-Flood Rice Production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Systems</td>
<td></td>
</tr>
<tr>
<td>I.</td>
<td>Abstract</td>
<td>176</td>
</tr>
<tr>
<td>II.</td>
<td>Introduction</td>
<td>178</td>
</tr>
<tr>
<td>III.</td>
<td>Materials and Methods</td>
<td>182</td>
</tr>
<tr>
<td>E.</td>
<td>Site Description</td>
<td>182</td>
</tr>
<tr>
<td>F.</td>
<td>Experimental Design and Field Treatments</td>
<td>183</td>
</tr>
<tr>
<td>G.</td>
<td>Soil Sampling and Analyses</td>
<td>185</td>
</tr>
<tr>
<td>H.</td>
<td>Century Model Simulation</td>
<td>186</td>
</tr>
<tr>
<td>I.</td>
<td>Data Analyses</td>
<td>189</td>
</tr>
<tr>
<td>VII.</td>
<td>Results and Discussion</td>
<td>189</td>
</tr>
<tr>
<td>A.</td>
<td>Initial Soil Properties</td>
<td>189</td>
</tr>
<tr>
<td>B.</td>
<td>Tillage Effects on SOC and TN</td>
<td>190</td>
</tr>
<tr>
<td>C.</td>
<td>Fertility Regime Effects on SOC and TN</td>
<td>194</td>
</tr>
<tr>
<td>D.</td>
<td>Crop Rotation Effects on SOC and TN</td>
<td>196</td>
</tr>
<tr>
<td>E.</td>
<td>Partitioning of SOC and TN within SOM</td>
<td>200</td>
</tr>
<tr>
<td>F.</td>
<td>Soil C:N Ratio</td>
<td>202</td>
</tr>
<tr>
<td>G.</td>
<td>Century Model SOC and TN Contents</td>
<td>202</td>
</tr>
<tr>
<td>VIII.</td>
<td>Summary and Conclusions</td>
<td>205</td>
</tr>
<tr>
<td>IX.</td>
<td>Literature Cited</td>
<td>208</td>
</tr>
<tr>
<td>5</td>
<td>Long-Term Rice Crop Rotation and Tillage Effects on Soil</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>Respiration</td>
<td></td>
</tr>
<tr>
<td>I.</td>
<td>Abstract</td>
<td>226</td>
</tr>
<tr>
<td>II.</td>
<td>Introduction</td>
<td>228</td>
</tr>
<tr>
<td>IV.</td>
<td>Materials and Methods</td>
<td>232</td>
</tr>
<tr>
<td>A.</td>
<td>Site Description</td>
<td>232</td>
</tr>
<tr>
<td>B.</td>
<td>Experimental Design and Field Treatments</td>
<td>232</td>
</tr>
<tr>
<td>C.</td>
<td>Soil CO₂ Sampling</td>
<td>235</td>
</tr>
<tr>
<td>D.</td>
<td>Data Analyses</td>
<td>235</td>
</tr>
<tr>
<td>III.</td>
<td>Results and Discussion</td>
<td>237</td>
</tr>
<tr>
<td>A.</td>
<td>Initial Soil Properties</td>
<td>237</td>
</tr>
<tr>
<td>B.</td>
<td>Tillage and Rotation Effects on Soil Respiration within Sampling</td>
<td>237</td>
</tr>
<tr>
<td></td>
<td>Dates</td>
<td></td>
</tr>
<tr>
<td>C.</td>
<td>Pre-Flood and Post-Flood Release Soil Surface CO₂ Flux in Rice</td>
<td>242</td>
</tr>
<tr>
<td>D.</td>
<td>Soil Surface CO₂ Flux in Rotations with Soybean and Corn Planted</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>during the Growth Period</td>
<td></td>
</tr>
<tr>
<td>E.</td>
<td>Soil Moisture and Temperature Effects on Soil Surface CO₂ Flux</td>
<td>242</td>
</tr>
<tr>
<td>F.</td>
<td>Estimation of Soil Surface CO₂ Flux during the Growth Period</td>
<td>245</td>
</tr>
<tr>
<td>IV.</td>
<td>Summary and Conclusions</td>
<td>245</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>V.</td>
<td>Literature Cited</td>
<td>247</td>
</tr>
</tbody>
</table>

**Overall Dissertation Conclusions**

Appendix 1: Aerial view of Study Site and Plot Plan 262
LIST OF TABLES

CHAPTER 2

Table 1. Summary of the annual nitrogen (N), phosphorous (P), and potassium (K) added to corn, soybean, rice, and wheat to comprise the optimal soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.  

Table 2. Summary of the crop rotations and the number of crops grown in the respective rotations during the 10-yr study period (1999-2009) at the Rice Research and Extension Center Near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.  

Table 3. Analysis of variance summary of the effects of tillage, crop rotation, and soil depth on total water-stable aggregate (TWSA; > 0.25-mm) concentration (g aggregates kg\(^{-1}\) soil), TWSA carbon (C) concentration (C Conc.; 0.25- to 4-mm diameter; g C kg\(^{-1}\) aggregated soil), TWSA nitrogen (N) concentration (N Conc.; 0.25- to 4-mm diameter; g N kg\(^{-1}\) aggregated soil), C:N ratio, and TWSA C and N contents (0.25- to 4-mm diameter; g m\(^{-2}\) soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Interactions that were not significant at the 0.05 level are represented by NS.  

Table 4. Analysis of variance summary of the effects of tillage, crop rotation, soil depth, and aggregate-size class (0.25- to 0.5, 0.5- to 1-, 1- to 2-, 2- to 4-, and > 4-mm diameter) on water-stable aggregate (WSA) concentration (g aggregates kg\(^{-1}\) soil), WSA carbon (C) concentration (C Conc.; g C kg\(^{-1}\) aggregated soil), WSA nitrogen (N) concentration (N Conc.; g N kg\(^{-1}\) aggregated soil), WSA C:N ratio, and WSA C and N contents (g m\(^{-2}\) soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Interactions that are not significant at the 0.05 level are represented by NS.  

Table 5. Analysis of variance summary of the effects of tillage, crop rotation, and soil depth on composite-soil (≤ 0.25-mm diameter) carbon (C) concentration (C Conc.; g C kg\(^{-1}\) soil), nitrogen (N) concentration (N Conc.; g N kg\(^{-1}\) soil), C:N ratio, C content (g C m\(^{-2}\) soil), and N content (g N m\(^{-2}\) soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Interactions that are not significant at the 0.05 level are represented by NS.  

Table 6. Analysis of variance summary of the effects of tillage, crop rotation, and soil depth on bulk-soil carbon (C) and N contents (g C m\(^{-2}\) soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.
CHAPTER 3

Table 1. Summary of crop rotations by year with all rotations tilled prior to planting in 1999 and the no-tillage treatment starting in 2000. Crops used in the rotations include rice (R), soybean (S), corn (C), and winter wheat (W). Crops in parentheses were grown in the winter.

Table 2. Summary of the annual nitrogen (N), phosphorous (P), potassium (K), and zinc (Zn) added to corn, soybean, rice, and winter wheat to comprise the soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

Table 3. Summary of the crop rotations and the number of crops grown in the respective rotations during the 11-yr study period (1999-2010) at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.

Table 4. Analysis of variance summary of the inherent differences of soil properties in plots prior to tillage, fertility, and crop rotation treatments being imposed. Soil particle-size (PS) measurements presented were measured in 2010 and used to calculate bulk density (BD) for 1999. Soil properties and their interactions related to the inherent soil differences in the assigned treatment combinations on soil organic matter (SOM) content, soil pH, electrical conductivity (EC), and extractable phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and sodium (Na) contents prior to any treatment being imposed in 1999. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

Table 5. Analysis of variance summary of the effects of tillage, fertility, crop rotation, time, and their interactions on soil organic matter (SOM) content, soil pH, electrical conductivity (EC), and extractable phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and sodium (Na) contents after 11 years of consistent management. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.050$ are considered non-significant (NS).

Table 5. Summary of irrigation water element concentrations and contents per centimeter of irrigation water at the Rice Research and Extension Center near Stuttgart, AR.
CHAPTER 4

Table 1. Details of spring crop rotations by year with all rotations tilled prior to planting in 1999 and no-tillage treatments starting in 2000. Crops used in the rotations include rice (R), soybean (S), corn (C), and winter wheat [(W)].

Table 2. Summary of the annual nitrogen (N), phosphorous (P), potassium (K), and zinc (Zn) added to corn, soybean, rice, and winter wheat to comprise the optimal soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

Table 3. Summary of the crop rotations and the number of crops grown in the respective rotations during the 11-yr study period (1999 to 2010) at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.

Table 4. Analysis of variance summary of inherent differences among tillage, fertility, and crop rotation treatments on soil particle-size (PS) distributions, estimated soil bulk density (BD), soil organic carbon (SOC) content, total nitrogen (TN) content, SOC fraction of the soil organic matter (SOM), TN fraction of the SOM, and soil carbon to nitrogen ratios (C:N) prior to any treatment being imposed in 1999. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

Table 5. Analysis of variance summary of the effects of tillage, fertility, crop rotation, and time on soil organic carbon (SOC) content, total nitrogen (TN) content, SOC fraction of the soil organic matter (SOM), TN fraction of the SOM, and soil carbon to nitrogen ratios (C:N) after 11 years of consistent management. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

Table 6. Measured and Century-model-estimated values for soil organic carbon (SOC) and total nitrogen (TN) contents under different tillage [tillage (T) and no-tillage (NT)], fertility [optimal (O) and sub-optimal (SO)], and crop rotation [with soybean (S), corn (C), and/or wheat (W)] treatment combinations after an 11-yr study period (1999 to 2010). The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Values presented are from the 2010 sampling period measured and model predictions. Crops in parentheses were grown during the winter.
CHAPTER 5

Table 1. Summary of the crop rotations and planting, rice flooding, rice flood-release, and harvest dates during the 2009 and 2010 study period at the Rice Research and Extension Center near Stuttgart, Arkansas. Crop management dates are summarized for the crops grown during the summer growing period. Crops in parentheses were grown during the winter. Rotations with flooding and flood-release dates represent rotations that had rice planted during the growing season.

Table 2. Summary of the crop rotations and the number of crops that had consistently been produced in the respective rotations during the 10- (2009) and 11-year (2010) study period at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.

Table 3. Summary of the annual nitrogen (N), phosphorous (P), and potassium (K) added to corn, soybean, rice, and wheat to comprise the optimal soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

Table 4. Analysis of variance summary of inherent differences among tillage and crop rotation treatments on soil particle-size (PS) distributions, estimated soil bulk density (BD), soil organic matter (SOM) content, soil organic carbon (SOC) content, total nitrogen (TN) content, SOC fraction of the SOM, TN fraction of the SOM, and soil carbon to nitrogen ratios (C:N) prior to any treatment being imposed in 1999. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

Table 5. Analysis of variance summary of the effects of tillage, crop rotation, and their interaction on soil surface CO$_2$ flux, 2- and 10-cm soil temperature, and 0- to 6-cm volumetric water content (VWC) within sampling dates after 10 (2009) and 11 (2010) years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

Table 6. Summary of estimated soil carbon dioxide (CO$_2$) flux over annual summer growing seasons under different tillage and rice (R) based crop rotations during a 10- (2009) and 11-year (2010) study period at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Tillage treatments included conventional tillage (T) and no-tillage (NT). Rice was rotated with soybean (S) and/or corn (C), with some rotations also including winter wheat [(W)]. Crops in parentheses were grown during the winter.
LIST OF FIGURES

CHAPTER 2

Figure 1. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregates (WSA) in various size classes (> 0.25-mm diameter). The total water-stable aggregate (TWSA) concentration for each tillage-rotation-depth treatment combination is represented by the top of each bar [standard error = 7.9; least significant difference (LSD) = 18.8 to 23.0]. Individual WSA concentrations by size class are represented by the shaded segments within each bar (standard error = 2.4; LSD = 5.5 to 6.9). The LSD values for TWSA and WSA concentrations by size class vary depending on the treatment combinations being compared.

Figure 2. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) effects on the carbon (C) and nitrogen (N) concentration [A] and C:N ratio [B] of the total water-stable aggregates (TWSA; > 0.25-mm diameter). Different letters on bars within each panel for the same variable are significantly different at the 0.05 level.

Figure 3. Soil depth (0- to 5- and 5- to 10-cm) and aggregate-size class (0.25- to > 4-mm) effects on water-stable aggregate (WSA) carbon (C) concentration. Different letters on each bar are significantly different at the 0.05 level.

Figure 4. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) effects on WSA carbon (C) and nitrogen (N) concentration [A] and rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects on water-stable aggregate (WSA) C concentration [B]. Different letters on bars within each panel for the same variable are significantly different at the 0.05 level.

Figure 5. Rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregate (WSA) nitrogen (N) concentration [standard error = 0.28; least significant difference (LSD) = 0.60].

Figure 6. Tillage [conventional tillage (T) and no-tillage (NT)] and rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects on water-stable aggregate (WSA) nitrogen (N) concentration. Different letters on each bar are significantly different at the 0.05 level.

Figure 7. Soil aggregate-size class effects on the water-stable aggregate (WSA) carbon and nitrogen (C:N) ratio. Different letters on each bar are significantly different at the 0.05 level.
Figure 8. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) treatment combination [A] and rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects [B] on the water-stable aggregate (WSA) carbon and nitrogen ratio (C:N). Different letters on each bar within each panel are significantly different at the 0.05 level.

Figure 9. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) effects on total water-stable aggregate (TWSA) carbon (C) and nitrogen (N) content [A]; rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects on TWSA C content [B]; tillage and rotation effects on TWSA N content [C]; and rotation and soil depth effects on TWSA N content [D] after 10 years of consistent management. Different letters on bars within each panel for the same variable are significantly different at the 0.05 level.

Figure 10. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregate (WSA) carbon (C) content. The total water-stable aggregate (TWSA) C content for each tillage-rotation-depth treatment combination is represented by the top of each bar. The WSA C content by size class is represented by the shaded segments within each bar [standard error = 5.7; least significant difference (LSD) = 11.9 to 16.0]. The LSD values vary depending on the treatment combinations being compared.

Figure 11. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregate (WSA) nitrogen (N) content. The total water-stable aggregate (TWSA) N content for each tillage-rotation-depth treatment combination is represented by the top of each bar. The WSA N content by size class is represented by the shaded segments within each bar [standard error = 0.5; least significant difference (LSD) = 1.0 to 1.4]. The LSD values vary depending on the treatment combinations being compared.

Figure 12. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], and soil depth (0- to 5- and 5- to 10-cm) effects on composite-soil (≤ 0.25-mm in diameter) carbon (C) [A] and nitrogen (N) [B] contents. The composite-soil C and N contents are represented by the shaded segment within each bar [standard error = 11.4 (C) and 1.2 (N); least significant difference (LSD) = 19.4 to 32.5 (C) and 1.9 to 3.3 (N)]. The LSD values vary depending on the treatment combinations being compared.
Figure 13. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], and soil depth (0- to 5- and 5- to 10-cm) effects on bulk-soil carbon (C) content. The bulk-soil C content for each tillage-rotation-depth treatment is represented by the top of each bar [standard error = 13.8; least significant difference (LSD) = 31.3 to 44.6]. The total water-stable aggregated soil (> 0.25 mm in diameter; TWSA) and composite-soil (≤ 0.25 mm in diameter) C contents are represented by the shaded segments within each bar. The LSD values for the bulk-soil vary depending on the treatment combinations being compared.

Figure 14. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], and soil depth (0- to 5- and 5- to 10-cm) effects on bulk-soil nitrogen (N) content. The bulk-soil N content for each tillage-rotation-depth treatment is represented by the top of each bar [standard error = 1.2; least significant difference (LSD) = 2.5 to 3.9]. The total water-stable aggregated soil (> 0.25 mm in diameter; TWSA) and composite-soil (≤ 0.25 mm in diameter) N contents are represented by the shaded segments within each bar. The LSD values for the bulk-soil vary depending on the treatment combinations being compared.

CHAPTER 3

Figure 1. Fertility (optimal and sub-optimal) and time (1999 and 2010) effects on soil pH [A] and extractable soil sodium (Na) content [B] in the top 10 cm. Different letters atop bars are significantly different at the 0.05 level.

Figure 2. Tillage [conventional tillage (T) and no-tillage (NT)], fertility [optimal (O) and sub-optimal (SO)], rotation [rice (R), soybean (S), corn (C) and winter wheat (W)], and time (1999 and 2010) effects on soil electrical conductivity (EC) in the top 10 cm (standard error = 0.015). Least significant difference values vary depending on the treatment combinations being compared (0.023 to 0.042 dS m\(^{-1}\)).

Figure 3. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), corn (C) and winter wheat (W)], and time (1999 and 2010) effects on extractable soil phosphorus (P) [A], manganese (Mn) [B], and zinc (Zn) [C] contents in the top 10 cm. Different letters atop bars within the same panel are significantly different at the 0.05 level.

Figure 4. Fertility [optimal (O) and sub-optimal (SO)], rotation [rice (R), soybean (S), corn (C) and winter wheat (W)], and time (1999 and 2010) effects on extractable soil phosphorus (P) [A] and potassium (K) [B] contents in the top 10 cm. Different letters atop bars within the same panel are significantly different at the 0.05 level.
CHAPTER 4

Figure 1. Tillage [conventional tillage (T) and no-tillage (NT)] and time (1999 and 2010) effects on total nitrogen (TN) in the top 10 cm. Different letters atop bars are significantly different at the 0.05 level.

Figure 2. Rotation [rice (R), soybean (S), corn (C) and winter wheat (W)] and time (1999 and 2010) effects on soil organic carbon (SOC) [A] and total nitrogen (TN) [B] in the top 10 cm. Different letters atop bars within a panel are significantly different at the 0.05 level.

Figure 3. Century-modeled verses measured soil organic carbon (SOC) [A] and total nitrogen (TN) [B] content in the top 10 cm after 11 years of management for 24 different tillage-fertility-rotation treatment combinations.

Figure 4. Century-modeled and measured soil organic carbon (SOC) [A] and total nitrogen (TN) [B] contents in the top 10 cm over time (1999 and 2010) for 24 different tillage-fertility-rotation treatment combinations.

CHAPTER 5

Figure 1. Soil surface carbon dioxide (CO$_2$) flux during the 2009 [A] and 2010 [B] growing seasons under different tillage regimes and rice (R) based crop rotations. Tillage treatments included conventional tillage (T) and no-tillage (NT). Rice was rotated with soybean (S) and/or corn (C) on a biennial or triennial cropping cycle, with some rotations also including a biannual rotation with winter wheat [(W)]. Lines within the graph represent when the all rice plots were flooded early in the growing season and when all floods were released prior to fall harvest.
CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW
INTRODUCTION

A majority of the world’s rice is grown in fields enclosed by earthen levees to retain rain and irrigation water so the soil will be continuously flooded and saturated near the surface during the rice-cropping period. This submergence causes the depletion of oxygen from the soil, which facilitates the proliferation of anaerobic soil microorganisms (Pampolino et al., 2008). The decomposition of SOM is slower in waterlogged soil than in aerated soil. Therefore, saturated soils can accumulate large amounts of OM, which can result in large pools of SOC and N (DeBusk et al., 2001). Irrigated rice fields are unique from other wetland soils in that they are dry between crop rotations. The dry period can lead to aerobic conditions, and, in effect, a rapid breakdown of accumulated SOM. This decline in SOM adversely affects soil productivity, soil quality, and the overall sustainability of rice production (Salinas-Garcia et al., 1997; Sollins et al., 1996; Filcheva and Mitova, 2002). Cycling between anaerobic and aerobic conditions leads to a greater rate of OM decomposition, thus diminishing SOC and N, which essentially leads to increased emissions of C and N gases (Sahrawat, 2004; Debusk et al., 2001; Xu et al., 2007).

The three main gaseous byproducts of rice production that are of special interest are CO$_2$, CH$_4$, and N$_2$O (IPCC, 2007). These three gases are unique due to their ability to insulate the atmosphere, which ultimately leads to global warming (Denman et al., 2007). The increased concentration of GHGs in the atmosphere through anthropogenic processes enhances the natural absorption and emission of infrared radiation. Atmospheric radiation is linked to the temperature of the atmospheric level at which it is emitted, and in the troposphere, the temperature commonly decreases with altitude. Under normal conditions, the infrared radiation emitted into space is in balance with the net incoming solar radiation, which usually happens at around -19 °C. When the concentration of GHGs increases, the infrared opacity of the atmosphere is increased, and the
effective radiation is emitted into space from a higher altitude at a lower temperature. This causes an imbalance called radiative forcing that can only be compensated for by an increase in the global temperature (IPCC, 2001).

With the knowledge that the increase in atmospheric C and N concentration is unnaturally affecting the global climate, the need to find rice production practices that decrease CO₂, CH₄, and N₂O emissions are essential to society’s future. Despite this fundamental responsibility, there has still been relatively little research conducted to evaluate the long-term impacts of rice cropping systems on soil C and N storage and cycling. There have been numerous studies performed investigating the long-term effects of crop rotations on carbon sequestration with crops such as soybean, corn, and wheat in the United States (Salinas-Garcia et al., 1997; Halvorson et al., 2002; West and Post, 2002). However, due to the cyclic anoxic conditions that result from rice production, these studies do not pertain to crop rotations that include flood-irrigated rice. Furthermore, a majority of the rice research that is available has been conducted on paddy-grown rice in Asia, which varies from upland rice by the planting techniques used (transplant water-seeded as opposed to dry-seeded), flooding regimes, harvesting methods, and residue management (De Datta, 1981). These production differences, combined with the information that climatic differences account for a large variation in the amount of C and N loss due to OM decomposition (Carter, 1996), results in findings from paddy rice not being applicable to the geographic area of the Mississippi River Delta region of the southern and mid-southern United States.
LITERATURE REVIEW

Global Rice Production and Industry

Rice (Oryza sativa L.) crops occupy 382 million acres (USDA-FAS, 2009a) of soil around the world, which accounts for 20% of the total grain production worldwide (USDA-FAS, 2009b). The cultivar is considered the world’s most important staple food crop due to its prevalence and societal longevity. Maclean et al. (2002) claimed that rice has fed more people for a longer period of time than any other crop in the history of mankind. Modern-day rice is believed to have evolved from a grass progenitor present on the Gondwana Supercontinent, a southern landmass made up of present-day Asia, Australia, Africa, America, and Antarctica, more than 130 million years ago (Chang, 2003; Greenland, 1997). Overtime, the grass differentiated into distinct forms after migrating to various humid regions throughout the landmass. Deformation of the Gondwana fragments and continental drift led to various isolated cultivars independently evolving on the shifting landmasses (Chang, 2003). Although the topic has been debated, many believe that rice was initially domesticated and cultivated somewhere around 8,000-10,000 years ago (Greenland, 1997). From ancestral varieties in West Africa and South and Southwest Asia, two distinct cultivated species evolved separately: Asia or common rice and African rice (Oryza glaberrina Steud; Chang, 2003). Altogether, there are nearly 120,000 varieties of rice known to exist in the world (IRRI, 2007). As a result of human activities, such as cultivation, domestication, dispersal, and diversification, rice is now grown in more than 100 countries across the latitudinal span of 40°S to 53°N (Chang, 2003). Today, global rice consumption exceeds more than 422,662 Mg per year, 89% of which is consumed in Asia (IRRI, 2009). Furthermore, the cereal grain provides 21% of global human per capita energy and 15% of the per capita protein (Maclean et al., 2002).
Asia produces 91% of the rice grown worldwide, of which the two leading countries of China and India support nearly 52% of the worldwide production. The other 39% of the rice grown is spread out across Africa, North America, South America, Europe, and Australia; thus, rice is essentially grown on every continent besides Antarctica (IRRI, 2009). Climatic conditions vary considerably among these different growing locations. Rice can be grown under extremely moist conditions, like Myanmar’s Arkan Coast which gets 5,100 mm of annual rainfall, to extremely dry conditions, such as the Al Hasa Oasis in Saudi Arabia which gets less than 100 mm (Maclean et al., 2002). Temperatures may vary from a mean annual temperature during the growing season of 17°C (63°F) in Otaru, Japan to 33°C (91°F) in the Upper Sind in Pakistan (Maclean et al., 2002). Rice can also be grown under a large range of solar radiation depending on the cultivar and its adaptation to a latitudinal location (Luh, 1991).

Rice cultivation in the United States dates back to 1685 when the grain was introduced in the colony of South Carolina. In 1728, rice was established in Louisiana, but the crop did not gain popularity until 1887 when it was discovered that rice could be cultivated profitably by machinery on the prairies in the south-western part of the state (Grist, 1959). After this discovery, rice agriculture continued to spread throughout the Mississippi River Delta region, but it was not until around 1912 that rice was commercially produced in California’s Sacramento Valley (Maclean et al, 2002; Flach and Slusher, 1978). Today, nearly 80% of the land area used for domestic rice production occurs in Arkansas (46.7%), California (17.3%), and Louisiana (15.7%), but smaller quantities of rice are also produced in Mississippi (7.7%), Missouri (6.7%), and Texas (5.8%) (USDA-NASS, 2009). Although rice only comprises less than 1% of the total cropland harvested in the US (USDA-ERS, 2009b; USDA-NASS, 2009) and roughly 1.4% of the global production (IRRI, 2009), rice generates almost 3.4 billion dollars in revenues annually in
the United States (USDA-NASS, 2009) and makes up 11.7% of the global rice export market (IRRI, 2009).

**Rice Characteristics**

Cultivated rice is generally considered a semi-aquatic annual grass, but it will survive as a perennial in the tropics by producing new tillers from nodes after harvest (Maclean et al., 2002). The two distinct cultivated species, African rice and common rice, have relatively few morphological differences. Common rice, the primary cultivar grown in the United States, has slightly longer ligules and a nearly smooth fertile lemma and palea (Grist, 1959). Plant height is reliant on the variety and environmental conditions, but can range between 0.4 m to more than 5 m. At maturity, the rice plant has several tillers attached to a central stem, and each productive tiller supports a terminal flowering head or panicle (Maclean et al., 2002).

The life cycle of the rice plant can range from 100 to 210 days, depending on the variety and the environment in which the plant is grown (Vergara, 1991). The morphology of a rice plant can be divided into three main stages: the vegetative phase (from seed germination to panicle initiation), the reproductive phase (from panicle initiation to anthesis), and the ripening phase (from anthesis to full maturity) (Vergara, 1970). The visible growth of the rice plant occurs strictly during the vegetative and reproductive phases. During the ripening phase, the spikelets fill with starch until the caryopsis (the starchy portion of the grain) is hard, clear, and free from a greenish tint. Full maturity for the whole panicle does not occur until 30 days after anthesis, at which time the ultimate yield of the crop can be determined (Vergara, 1991; Maclean et al., 2002).
Rice is considered a high-residue-producing crop and is capable of producing roughly 8.07 Mg ha\(^{-1}\) of above-ground biomass under optimal nitrogen (N) fertilization annually (USDA, 2009; Wilson and Runsick, 2008). The fresh weight content of rice straw consists of 41% carbon (C), 0.5-0.8% N, 0.05-0.1% phosphorous (P), 0.3-2.0% potassium (K), and 0.03-0.17% calcium (Ca) (Bell et al., 2004). If this rice straw is incorporated back into the ground as soil organic matter (SOM), the fibrous tissue can be broken down by microorganisms and utilized for nutrients.

**Rice Soils in the United States**

Soil characteristics that provide optimal growth and development of rice have a slightly acid to slightly alkaline pH range and possess chemical and physical attributes that generally restrict the redistribution and leaching of water from the rhizosphere (Scott et al., 2003). Rice soils are essentially wetland soils because wetlands soils are defined as having free-standing water at or near the surface at a frequency and duration sufficient to support vegetation that is typically adapted for life in saturated soil conditions (EPA, 1977). There are three types of water saturation that occur in soils used for rice production: (1) endosaturation, in which the soil is naturally wet and the water table is at or near the soil surface for at least part of the year, (2) episaturation, where there is saturation of the upper soil layers overlying unsaturated subsoil layers caused from a lack of downward percolation of water due to their high clay and/or sodium content or specific mineralogy, and (3) anthropic saturation, which is similar to episaturation but with anthropogenically controlled flooding and puddled surface soil due to pan characteristics (Maclean et al, 2002; Flach and Slusher, 1978).
A majority of the rice produced in the United States is on alluvial soils in the Mississippi River valley and adjacent areas in the lower coastal plain of Louisiana and Texas, or in the Sacramento River Valley of California (USDA-ERS, 2008). All of these soils used for rice production fall into the thermic or hyperthermic temperature regimes, which indicates that the chemical reactions and physical processes occurring within the soil are faster in comparison to a soil with a lower temperature (Flach and Slusher, 1978), and they are predominately in the fine textural classes, including loam, silt loam, silty clay loam, clay loam, and clay (Scott et al., 2003). Rice soils also have chemically and physically heterogeneous profiles and occur in four orders: Alfisols, Inceptisols, Vertisols, and Mollisols. Nearly 80% of the rice soils in the United States are naturally poorly or somewhat poorly drained (Flach and Slusher, 1978). One reason for this is that the saturated hydraulic conductivity (K_{sat}) in rice soil profiles tends to be low, both form natural and anthropogenically induced conditions, which causes severe restriction in the vertical drainage of water (Scott et al., 2003). Another reason for the poor drainage is due to particle-size distribution, where these soils tend to have a high clay content dominated by montmorillonite. Montmorillonite is a 2:1 molecular structured smectitic mineral with a high specific surface area (630 to 800 m² g⁻¹) that allows the mineral to adsorb a large amount of water molecules and form a nearly impermeable seal at the soil surface or elsewhere in the soil profile, preventing the downward movement of water (Flach and Slusher, 1978; Brady and Weil, 2008).

The presence of aquic soil conditions are indicated by redoximorphic characteristics in the profile, including zones with the accumulation and depletion of manganese (Mn) and iron (Fe) (Mclean et al., 2002). Visually, waterlogged soil conditions are indicated by gray mottles or solid gray coloring immediately below the surface horizon as a result of the reduction of Mn and
Fe compounds from saturated or semi-saturated soil conditions (Brady and Weil, 2008; Schlesinger, 1991). About 78% of the land used to produce rice in the Mississippi River valley and coastal plain are classified in suborders associated with aquic soil conditions, including Aqualfs (51%), Aqueps (21%), and Aquolls (6%). The other 22% of the rice soils are in the suborders related with humid climates and are fine or very-fine soils that are highly impermeable for water, including Uderts (11%), Udalfs (8%), and Udolls (1%). In the California, 35% of the rice soils are classified in the suborder Aquoll and the rest are on dry, fine, montmorillonic soils in the suborders Xerolls (22%), Xererts (31%), and Xeralfs (23%) (Flach and Slusher, 1978).

Although there are a number of ways that rice can be produced in different soils, moisture regimes, and climate conditions, there are two main systems used to manage the soil for production: dry and wet soil management (Mikkelsen and De Datta, 1991). Dry soil management, which is also known as upland rice culture but can be used in irrigated lowland rice production, refers the preparing the land during dry conditions and the rice is treated in the same manner as other cereal crops. Either before seeding (water-seeded) or after seeding (direct-seeded), the land is flooded with water via rain or irrigation. In wet soil management, also referred to as lowland or wetland culture, the land is initially flooded and all soil manipulation is done in wet or submerged soil (Mikkelsen and De Datta, 1991; Flach and Slusher, 1978).

**Water Management in Rice Crop Agriculture**

Rice production is unique in that the crop is usually grown under flood-irrigated conditions after about 1 month post-emergence, where the upper-most part of the soil profile is nearly to completely saturated (Norman et al., 2003). While rice appears to have an elevated water requirement, the actual plant usage is not much different than other cereal crops. The
difference comes from the fact that rice plants can benefit from standing water because the plant is capable of anaerobic respiration and has aerenchyma tissue in the aerial organs through which oxygen diffuses to the roots (Mikkelsen and De Datta, 1991). It is these inherent physiological differences that cause rice to be produced differently from other agricultural crops.

Critical factors that arise in rice crop agriculture concern the supply of water to the soil from rain, reservoir, river, or groundwater, and the ability of that soil to retain water on the surface (Greenland, 1997). In the United States, 40% of the rice irrigation water comes from wells, while the remainder is either diverted or pumped from rivers (Flach and Slusher, 1978). Landscape position essentially determines how water can be supplied to the soil, and soil texture and drainage properties establish the degree to which water can be retained (Greenland, 1997). Due to the gravitational flow of water, a major obstacle that arises with water management is the differentiation of surface topography in a rice field. These elevation differences have a major effect on the uniformity of seed germination, crop yields, weed management, homogeneous fertilization, and water-use efficiency (IRRI-CIMMYT, 2008).

Rice producers combat these topographic differences by precision leveling the field and/or constructing contour levees in order to maintain a uniform shallow flood (5- to 10-cm) across the field during the growing season (IRRI-CIMMYT, 2008; Watkins et al., 2007; Greenland, 1997). Most precision-leveled fields are graded to a 0.05 to 0.2% slope; however, some are leveled to a 0% slope (zero-grade). Although zero-grade leveling is more costly initially, the practice decreases the amount of water needed and eliminates the need to construct levees each year, which decreases irrigation and labor costs when compared to contour-levee rice production. When the field is not zero-graded, contoured levees are constructed annually to maintain the flood throughout the different elevations in the field, which reduces the potential
growing area, decreases field harvest efficiency, and increases the need for tillage to control weeds (Watkins et al., 2007).

During the rice-growing season, water is added to the field through irrigation or precipitation and may be lost during downward percolation through the profile, drainage from the field, seepage through the levees, and evapotranspiration (Scott et al., 2003). Drainage of water from a field is an important factor during the time of rice crop establishment, heavy rainfalls, and during an infestation of crop pests (IRRI-CIMMYT, 2008). To harvest rice, the flood must be released several weeks prior to the targeted harvest window in order to allow the soil to drain and dry out to achieve enough structural stability to support heavy harvesting machinery. If the soil is too wet and not sufficiently dry to provide structural support for a large harvest combine, rice fields can become severely rutted, which can result in elevated soil compaction.

**Nature of the Arkansas Rice Industry**

Of the roughly 1.2 million ha of rice planted and 9.3 million Mg of rice grain produced in the United States annually, over 46.8% of the total rice area (566,800 ha) and over 45.6% of the total grain production (4.2 million Mg) occurs in the Mississippi River Delta region of eastern Arkansas (USDA-NASS, 2009). Arkansas rice producers have averaged a yield of 7729 kg ha\(^{-1}\) over the last five years (2004-2008) (USDA-NASS, 2009), and with a 2008 production value of 1.46 billion dollars, the crop is ranked as the number one cash crop commodity for Arkansas farmers (USDA-NASS, 2009; USDA-ERS, 2009a). The top five cultivars of rice planted in 2007 were short-season long-grain conventional cultivars ‘Wells’ (35.5%) and ‘Francis’ (11%), mid-season long-grain semi-dwarf hybrid ‘CL 161’ (10.2%), short-season long-grain hybrid ‘Rice
Tec XP 723’ (8.5%), and the short-season semi-dwarf medium-grain ‘Bengal’ (7.5%) (Wilson and Runsick, 2008; Beighley et al., 2009).

Rice production initially started in Arkansas on a 0.4 ha plot in Lonoke County in 1902, and now the crop is grown on 566,800 ha of land in 40 of the 75 counties across the state (Slaton, 2001a; USDA-NASS, 2009). Of this area, soil is managed using conventional tillage (CT; 55%), stale-seedbed (35.9%), and some practice conservation tillage through no-tillage (NT; 9.5%) (Wilson and Runsick, 2008). A number of the rice producers manage water using contour levees (54.7%), while other fields are precision leveled (45.3%) or zero-graded (5.5%) (Wilson and Runsick, 2008). Water sources vary with location, but most of the rice area is irrigated with groundwater (80.3%), while 10.2% of the area utilizes water from reservoirs, and 9.5% employ streams, rivers, and other natural water sources (Wilson and Runsick, 2008). Irrigation of the land is accomplished by flooding using contoured levees (68.8%), flooding using a multiple-inlet system (30.6%), and furrow-irrigation (0.6%) (Wilson and Runsick, 2008). A majority of the land in production is rotated every other year with soybean [Glycine max (L.) Merr.] (78.6%), while some is kept in continuous rice production (14.4%) (Wilson and Runsick, 2008). Other rotations that make up the remaining 7% of the planted rice area include corn (Zea mays L.), wheat (Triticum aestivum L.), cotton (Gossypium hirsutum), grain sorghum (Sorghum bicolor L.), oats (Avena sativa L.), and some fields are kept in fallow (Wilson and Runsick, 2008). Following harvest, stubble is managed by rolling (30.4%), tilling (30.0%), burning (23.3%), or winter flooding (20.9%) (Wilson and Runsick, 2008).
Importance of Soil Organic Matter (SOM)

General Properties of SOM

Soil organic matter (SOM) is an essential, but dynamic soil component that controls many of the physical, chemical, and biological properties of the soil (Reeves, 1997; Filcheva and Mitova, 2002). Soil organic matter contributes to the structure of the soil and determines the spatial distribution and heterogeneity of various soil properties (Dexter, 1988). A significant portion of SOM is comprised of litter and the decaying remains of plants, animals, and microorganisms called detritus (Weil and Magdoff, 2004). Rhoton (2000) and Wolf and Snyder (2003) reported that plant residues help maintain soil structure by inhibiting compaction, increasing aggregate stability, preventing water and wind erosion, and facilitating root penetration through increased porosity. McQuaid and Olsen (1998) explained that the aggregation of soil particles into peds and the ability of these peds to withstand slaking is a gauge of soil quality. When the soil is structured with a large fraction of water-stable aggregates, microscopic inter-aggregate pores are formed, which aid in water storage, organic matter (OM) accrual, and microbial activity (Tisdall and Oades, 1982; Juma, 1993). In addition to micropores, relatively large biopores are created by the burrowing motion and the ingestion of SOM by earthworms. This activity promotes root expansion, free-water drainage, and air movement through the soil (Juma, 1993). Therefore, OM contained within agricultural soils inadvertently effects soil tilth, soil fertility, soil aeration, crop productivity, and the retention and infiltration of water (Reeves, 1997; Weil and Magdoff, 2004; Kooistra and van Noordwijk, 1996).

Along with physical properties, SOM also significantly influences the chemical characteristics of the soil. One of the ways SOM influences soil chemistry is by acting as a temporary sink for plant nutrients in agroecosystems (Gregorich et al., 1994). According to
Smith et al. (1993), SOM contains roughly 90-95% of the N, 40% of the P, and 90% of the sulfur (S) in the soil. As organisms in the soil utilize the stored photosynthetic energy and nutrients in the SOM, N, P, and S are mineralized, rendering them accessible to plants (Weil and Magdoff, 2004). The humified OM also adds to the colloidal fraction of the soil, which is recognized as the center of chemical activity in soil. The soil’s ability to store other nutrients such as Ca, K, aluminum (Al), magnesium (Mg) and sodium (Na) makes up the soil’s cation exchange capacity (CEC) (Brady and Weil, 2008). The CEC of the soil is controlled by the amount of SOM, the quantity and mineralogy of the clay, and the pH of the soil (Weil and Magdoff, 2004). Wolf and Snyder (2003) stressed that the CEC helps maintain a more stable supply of available nutrients in the soil by reducing fixation and leaching losses of cations, which can potentially increase crop yields. Since the SOM has a pH-dependent charge, SOM is able to adsorb both negatively and positively charged ionic compounds (Brady and Weil, 2008). Besides cation exchange, the sorption capacity of SOM also influences water holding capacity, anion sorption, heavy metal ion mobility, and soil pH buffering and amelioration (Nichols, 1984; Weil and Magdoff, 2004).

Kimble et al. (2007) reported that SOM has a significant effect on the quantity and diversity of organisms present in the soil. These organisms coexist in the soil and are influenced by one another through nutrient competition or symbiotic relationships (Gilbert et al., 1994; Hodge et al., 2001; Kimble et al., 2007). The size of the living community in the soil, termed the microbial biomass, is consistent with the amount of SOM present (Carter, 2001). Gregorich (1994) explained that SOM serves as the primary source of energy for the soil microbial population, so increases in SOM results in similar increases in microbial biomass. Furthermore, enlargement of decomposable biomass raises the overall microbial respiration rate, which subsequently increases the production of the greenhouse gases (GHGs), such as carbon dioxide
(CO₂) and methane (CH₄) and nitrous oxides (NOₓ) under anaerobic conditions. Soil organic matter not only provides sustenance to the microbial population, but SOM also provides nutrients to the entire soil food web including macrofauna (i.e., earthworms, ants, and termites), mesofauna (i.e., arthropods), and microfauna (nematodes, protozoa, rotifers, and tardigrades) (Weil and Magdoff, 2004). These fauna digest and break down organic materials into simple compounds, which get used by other organisms and distributed back into the soil (Kimble et al., 2007; Ferris et al., 1998).

**Relationship between SOM, Carbon, and Nitrogen**

All OM is predisposed to undergo decomposition in the soil, and the process of decomposition is primarily attributed to bacteria and fungi (Scow, 1997; Wolf and Snyder, 2003). The rate at which the microbes can decompose SOM depends on the location in the soil, type and age of SOM, particle size, and nutrient content, particularly N (Wolf and Snyder, 2003; Seiter and Horwath, 2004). These characteristics are added to the already present environmental factors influencing decomposition such as soil moisture, temperature, aeration, and soil pH (Alvarez and Lavado, 1998; Bayer, 1996; Filcheva and Mitova, 2002).

Decomposition is promoted by an array of soil-inhabiting invertebrates and microorganisms, which fragment and mix plant-derived OM into the soil (Hole, 1981). Some of the softer residues decompose rapidly by microorganisms, but the more resilient fibrous OM breaks down more readily after it is disintegrated by invertebrates. The smaller particles provide a large surface area, which makes the OM more susceptible to microbial and enzymatic breakdown in the intestinal tract of invertebrates. The remaining undigested material is excreted
as a food source for the accompanying microbial population in the soil (Edwards and Arancon, 2004).

The OM in the soil is predominantly composed of C (Wolf and Snyder, 2003). Sundermeiser et al. (2005) estimated the C content of SOM to be around 57% by weight. The C-rich OM is metabolized by most soil organisms in order to obtain C for building essential organic compounds and to retain energy to sustain life. To facilitate reproduction, soil microbes must also acquire N to synthesize N-rich cellular compounds that contain N such as amino acids, enzymes, and deoxyribonucleic acid (DNA; Brady and Weil, 2008). According to the International Rice Research Institute (IRRI, 2002), the ratio of the concentration of C to N in the soil is known as the C:N ratio. Since N is essential to microbial growth and replication, the microorganisms must obtain N either from the material being decomposed or an external source (i.e., inorganic N-fertilizer compounds) in order to continue breaking down organic C (Wolf and Snyder, 2003). If the OM has a high ratio of C to N, the soil microbes will have to either acquire N from the soil solution or decrease the rate of decomposition (Brady and Weil, 2008). A common rule of thumb is that a C:N ratio of 20 to 30 in crop residues maintains an equilibrium mineral-N level in the soil; whereas, any value above 30 results in a net loss of ammonium ($\text{NH}_4^+$) and nitrate ($\text{NO}_3^-$), and a value below 20 results in a net gain of $\text{NH}_4^+$- and $\text{NO}_3^-$-N (Stevenson and Cole, 1999).

**Importance of Organic Matter in Relation to Soil Carbon**

Soil organic matter is a one of the main reservoirs of SOC in the biosphere (Bernsten et al., 2006). Follett (2001) estimated that there are about 1550 petagrams (Pg) of organic C stored
in the world’s soils. This is more than twice the C contained in living vegetation (560 Pg) or in the atmosphere (750 Pg) (Sunquist, 1993). Information on the dynamics of SOC storage in agricultural soils is gaining interest because of its influences on global climate change and crop productivity (Majumder et al., 2007). According to Lal (2004), land management practices have the potential to enhance C accumulation, thereby easing the gaseous C load to the atmosphere and enriching the soil.

Denman et al. (2004) reported that both CO$_2$ and CH$_4$ take part in the natural C cycle, which involves the continuous cycling of C among the oceans, the terrestrial biosphere, and the atmosphere. In the biosphere, plants produce organic compounds by utilizing energy from the sun, water in the soil, and CO$_2$ from the atmosphere. Through the photosynthesis process, C is converted into fibrous plant biomass (Sundermeiser et al., 2002). Some of the C is fixed within the structure of the plant and the remainder is released back into the atmosphere through respiration. When the plant is consumed by animals or decomposed by soil microorganisms, some of the C that was tied up in the plant’s cellular structure is respired in the form of CO$_2$, or as CH$_4$ under anaerobic conditions (Denman et al., 2007). The remainder is returned to the soil as well-decomposed OM (i.e., humus), which serves as a C and energy source for additional soil microbes and plants. As new plants grow, they recapture the CO$_2$ in the air and the C cycle is repeated (Sundermeiser et al., 2002).

**Environmental Influences on SOC Accumulation**

The SOC content present in the soil is a reflection of a long-term balance between additions and losses (Majumder et al., 2008). According to Lal et al. (1998a), there are two categories of pedospheric processes that affect SOC dynamics: SOC-enhancing and SOC
degrading processes. Processes that enhance SOC content are aggregation, humification, plant biomass production, and sediment deposition. Degrading methods include SOM decomposition, soil erosion, and leaching. The rate at which SOM accumulates depends on intrinsic soil and local weather conditions, which include soil texture, pH, mineralogy, water balance, and temperature (Alvarez and Lavado, 1998; Bayer, 1996; Filcheva and Mitova, 2002). Bernsten et al. (2006) stated that the retention of SOC in the pedosphere is governed by a combination of the properties of the soil, usage of the land, management of the soil, and geographic climatic conditions. Bayer (1996) reported SOM accumulation rates as high as 1 Mg C ha$^{-1}$ yr$^{-1}$ in the moist subtropical regions of Brazil using NT management and cover crops.

Soil organic matter accumulation is highest when there is a high annual plant productivity rate and a low decomposition rate (Weil and Magdoff, 2004). Carter (1996) explained that the accrual of SOC is strongly dependent on the decomposition rate of OM, and the decomposition rate relies heavily on the relationship between mean annual temperature and annual precipitation. Tate (1992) and Cole et al. (1993) showed that moist and warm climates promote rapid decomposition, while cooler and wet climates slow down OM turnover. According to Sanchez and Logan (1992), SOM decomposition rates are roughly five times greater in wet tropical regions compared to temperate regions. Under extremely wet conditions, decomposition can become limited by oxygen availability (Wolf and Snyder, 2003). DeBusk et al. (2001) also reported that the decomposition of SOM is slower in waterlogged than in aerated soil. This results in greater accumulations of OM in saturated soils, which essentially increases the amount of stored SOC.

In addition to climatic conditions, another geographic factor that has a substantial impact on SOC accumulation is topography. As indicated by Shaffer and Ma (2001), the landscape
position of upland soils encourages ample drainage and nutrient movement to lower elevations. This transfer can have notable impacts on soil temperature and water retention regimes, thus effecting the accumulation of SOC at various elevations. In extremely low lying areas, runoff water can combine with groundwater to form anaerobic regions, where the surface layers may be meters thick and have 150 to 500g C kg\(^{-1}\) of soil (Weil and Magdoff, 2004). In well-developed soils, Gennadiyev (1997) showed that even slight differences in soil microelevations create microdepressions, which considerably increases (up to 60 cm) the thickness of the humus-enriched horizon in the depressed location. Likewise, slope and aspect are other topographic factors that produce differences in SOC accumulations. Gradients facing away from the equator receive less sunlight, thus reducing the evaporation rate and temperature, which results in soils that are generally wetter, deeper, and richer in SOC (O’Lear and Seastedt, 1994; Neilson et al. 2001; Weil and Magdoff, 2004).

**Effects of Aerobic vs. Anaerobic Conditions on SOC Decomposition**

The presence or absence of oxygen (O\(_2\)) plays an important role in the process dynamics and management responses of decomposition systems. Generally, an abundant O\(_2\) supply promotes rapid decomposition, whereas a deficiency in O\(_2\) results in a substantially lower decomposition rate (DeBusk et al., 2001; Shaffer and Ma, 2001). Doran et al. (1990) showed that microbial respiration, and thus microbial activity, as greatest when 50 to 75% of the soil pore space is filled with water. When water levels diverge above or below this range, microbial respiration declines. Skopp et al. (1990) described the effect of soil aeration on microbial activity as a delicate balance between having an adequate amount of water for substrate diffusion and microbial movement with enough O\(_2\) for respiration.
In aerobic environments, microorganisms utilize O$_2$ as an electron acceptor for energy-specific adenosine triphosphate (ATP) production during the oxidation of organic C compounds, which act as electron donors (Brady and Weil, 2008; DeBusk et al., 2001). However, under saturated soil conditions, such as those that exist near the surface in a flooded rice field, the supply of O$_2$ is insufficient to meet microbial demands, which forces certain microbial populations to utilize alternate electron acceptors with lower energy such as NO$_3^-$, oxidized forms of iron and manganese [Fe(OH)$_3$ and MnO$_2$], sulfate (SO$_4^{2-}$), and CO$_2$. The byproducts of these reduction reactions include N gases, mineralized forms of Fe$^{3+}$ and Mn$^{4+}$, hydrogen sulfide (H$_2$S), and CH$_4$ (Stumm and Morgan, 1981; Schlesinger, 1997; Debusk et al., 2001). The lower energy yield of reactions that occurs at a reduced redox potential explains the inefficiency of anaerobic metabolism and accounts for the difference in decomposition rates among aerobic and anaerobic microorganisms (Gale and Gilmour, 1988; Albers et al., 1995). This differentiation was illustrated by DeBusk and Reddy (1998), who showed that C mineralization in aerobic conditions can be as much as three times faster than under anaerobic settings.

**Soil Aeration and CO$_2$ Flux**

The flux of CO$_2$ from the soil is a major process in the global C cycle and is a portion of the terrestrial C budget (Bajracharya et al., 2000). Soil aeration pertains to the condition and bioavailability of gases in the soil and the exchange of these gases between the soil and the atmosphere (Scott, 2000). Gases in the soil include the composition and transport coefficients of gases in soil air and the solubility and transport coefficients of gases in soil water (Scott et al., 2003). Soil air composition is different from the atmosphere due to the activities of soil organisms and their interactions with the soil. Generally, soil air is greater in CO$_2$ (1-10%) and
lower in O$_2$ (5-10%) than the atmosphere, which is a result of the decomposition of organic material in the soil and by the respiration of roots and microbes (Montgomery et al., 2000; Castelle and Galloway, 1990; Piñol et al., 1995). Soil CO$_2$ respiration rates have shown to be positively correlated with both soil temperature and soil moisture (Franzluebbers et al., 1995; Raich and Schlesinger, 1992; Raich and Potter, 1995; Wang et al., 2000).

**Carbon Sequestration**

Soil C sequestration is the process of extracting CO$_2$ from the atmosphere through biomass production and storing the C in the soil in a form that is not easily reemitted through rapid decomposition (Sundermeiser et al., 2005). Over time, buried plant debris can become physically or chemically protected from fast disintegration by being retained within or between clusters of microaggregates, or converted into humus (Carter, 1996; De Gryze et al., 2006). Net sequestration can be accomplished with agricultural management practices that return large amounts of plant biomass to the soil, decrease soil disturbance, maintain soil structure, and conserve nutrient and water usage (McCarl et al., 2007; Follett, 2001; Paustian et al., 2000). Agricultural practices that can accomplish this include conservation tillage, decreasing or ceasing fallow periods, discontinuing residue burning, winter cover cropping, switching from monoculture to rotation cropping, and altering fertilizer applications to increase production (Farquhar et al., 2001; Karlen and Cambardella, 1996; West and Post, 2002).

Soil organic carbon accumulation represents the mass balance between primary production and heterotrophic metabolism, which returns C to the atmosphere as CO$_2$ or CH$_4$ (Debusk et al., 2001; Schlesinger, 1977). The formation of organo-mineral aggregates surrounds SOC and physically protects the material from microbial action (Lal, 2007; Kooistra, 1991). The
heterogeneous arrangement of particles and pores is important for microbial accessibility to SOC (Oades, 1993; De Gryze et al., 2006; Blanco-Canqui and Lal, 2004). Juma (1993) showed that inter-aggregate pores < 1 μm in diameter can prevent access by bacteria, and pores sizes between 1-2 μm allowed bacterial access but blocked protozoa and nematodes. Edwards and Bremer (1967) researched the architecture of the aggregate and demonstrated that the relatively stable organic fraction is predominantly present in the inner sections of microaggregates. The ability to retain sequestered SOC within aggregates relies on the architectural stability of the arrangement, which is determined by the quantity and quality of organic residues, the strength of the organic binding agents from microbial polysaccharides and organic mucilages, and the clay content of the soil (Jastrow and Miller, 1998; Blanco-Canqui and Lal, 2004; Tisdall, 1991, 1994; Carter, 1996).

The length of time that C can be stored in the soil relies heavily on the chemical composition of the biomass, which determines the microbial breakdown potential of the substrate (Debusk et al., 2001; Farquhar et al., 2001). The basic framework of vascular plants is primarily made up of carbohydrates, which vary in complexity from simple sugars and starches to cellulose, N-containing proteins, fats and waxes, polyphenols, and lignin (Brady and Weil, 2008). The readily available carbohydrates and amino acids are rapidly broken down by microbes, while the more complex compounds of wax and lignin decompose at a much slower rate (Wolf and Snyder, 2003). Zeikus (1981) showed that of all the structural components, lignin is the most resistant to microbial decomposition. Although partial chemical modification of the phenolic ring structures of lignin has been shown in some species of eukaryotes and prokaryotes, white-rot fungi (Phanerochaete chrysosporium, Coriolus versicolor, Phlebia radiata, and Lentinula edodes) are specifically known to be the most vigorous decomposers of lignin (Heider
and Fuchs, 1997; Zeikus, 1981; Hattori, 1991). After microbial metabolism subsides, the colloidal mixture of modified lignin is combined with newly synthesized compounds to form decay-resistant humus, which may be isolated further by adsorbing to charged clay particles through bridges of polyvalent cations (Brady and Weil, 2008; Edwards and Bremner, 1967).

**Importance of Organic Matter in Relation to Soil Nitrogen**

Nearly all of the N in soil occurs along with C in plant residues and the constituents of SOM, and the ratio of N available in the substrate directly affects the rate of microbial OM decomposition (McGill and Cole, 1981; Weil and Magdoff, 2004). Thus, the C and N cycles are directly linked, so C cycle of the ecosystem cannot be properly examined or modeled without giving reference to N cycling (McGill and Cole, 1981; Weil and Magdoff, 2004). Most of the N in terrestrial systems occurs as organic N (95 to 99%) in the A horizon of the soil, which has a N composition range from 0.02 to 0.5% depending on the usage of the land; however, the lower horizons also contain N, but at a much lower concentration. Soil organic matter is typically composed of 5% N, so the spatial distribution of N closely mimics the distribution of SOM (Brady and Weil, 2008). In addition to organic N, N also occurs in the soil as inorganic NO$_3^-$ and NH$_4^+$, urea, and as dinitrogen (N$_2$), nitrous oxide (N$_2$O), ammonia (NH$_3$), and various nitrogen oxide (NO$_x$) gases (Shaffer and Ma, 2001).

During the decomposition of SOM, organic N is mineralized into NH$_4^+$ by heterotrophic microbes in the process of ammonification. Some of this NH$_4^+$ gets taken up by the plant, immobilized by microbes, volatilized as NH$_3$, or fixed into the interlayers of clay particles, but the rest is subject to oxidation through nitrification to form nitrite (NO$_2^-$) and subsequently NO$_3^-$.
Some of the NO$_3^-$ in the soil can also be taken up by plants and immobilized by microbes, while the rest may be lost through leaching or subject to reduction through denitrification (Brady and Weil, 2008). Periodic cycling between wet and dry soil conditions on a seasonal or more frequent basis produces temporary shifts in O$_2$ availability (Shaffer and Ma, 2001), which impacts fractionation or inorganic forms of N in the soil. Flooded soils are primarily in a reduced state, so NH$_4^+$ is the only inorganic mineral involved in N turnover (Patrick, 1982); whereas both forms of inorganic minerals can be present in an aerobic environment. Through both of the mineral conversion processes of nitrification and denitrification, N gases can be released as nitric oxide (NO), N$_2$O, and N$_2$. The N in these gases can then be returned to the soil through nitrogen fixing bacteria and rainfall (Schlesinger, 1991).

**Impact of Biogeochemical Cycling on Global Climate**

In order to understand the impacts that anthropogenic activities have the global processes, scientists are addressing the idea that the planet is not a stagnate entity, but a continuously evolving systematic formation. Since its initial organization as a planet, Earth has been subject to large-scale cyclic patterns (Degens et al., 1991; Harrington, 1987). This includes the physical yearly rotation of the Earth around the sun and the daily rotation about its axis (Harrington, 1987). There are also cyclic chemical and biological processes that are driven by energy from the sun and radioactive decay from the Earth’s interior. These processes provide a foundation that helps facilitate the dependent cycling of water, rocks, nutrients, and gaseous compounds (Jacobson et al., 2000). The systematic outcome from all of the processes cycling simultaneously
is a climatic environment that is reflective of the cyclic state over a given period of time. Thus, a complex arrangement of biogeochemical cycling determines the Earth’s climate.

The reference to climate refers to the summation of environmental factors, which include the quantity of solar radiation, cloud cover, airborne particulate matter, humidity, precipitation, temperature, atmospheric pressure, and wind present in a geographical area (Schlesinger, 1997). Since solar energy powers the climate system, any change in the amount of solar radiation received on Earth will alter the climate. There are three basic ways that the radiation balance of the Earth can be modified: (1) a change in the incoming solar radiation from a difference in the Earth’s orbit or the sun, often referred to as the Milankovich effect (Charlson, 2000), (2) a change in amount of radiation that is reflected back into space from albedo, and (3) a change in the amount of longwave radiation that is released back into space from the Earth’s surface (Le Treut et al., 2007).

The presence of cloud cover, aerosols, snow, and ice influence global temperature by reflecting, rather than absorbing, the radiation back into space. This energy return, called albedo, causes a cooling effect in the atmosphere. However, clouds and aerosols can also capture the infrared radiation that is being reemitted from the Earth’s surface as latent or sensible heat (greenhouse effect), which can essentially compensate for some of the reflected radiation (Charlson, 2000; Kiehl and Trenberth, 1997). Fine particulate matter from dust storms, forest fires, and volcanic activity, along with seasalt from the ocean, are the primary sources of natural aerosols in the atmosphere (Le Treut et al., 2007; Jonas et al., 1995).

Solar radiation also shapes the storage and cycling of water on the Earth, accurately referred to as the hydrosphere, which influences the thermal conduction of the crust (lithosphere) and the atmosphere (Henshaw et al., 2000; Le Treut et al., 2007). The hydrologic cycle results
from imbalances between precipitation and evapotranspiration at water and land surfaces. Globally, water lost through evapotranspiration is generally greater in oceans than the amount that is received through precipitation, whereas land surfaces generally receive more water from precipitation than is lost through evapotranspiration. However, runoff from the land surface into the ocean balances the deficit caused by vaporization (Henshaw et al., 2000). In total, the hydrologic cycle encompasses all water located in the atmosphere, oceans, rivers, groundwater (hydrosphere), glaciers and ice sheets (cryosphere), soil (pedosphere), and biomass (biosphere). Furthermore, the amount of water in the atmosphere is important to global temperature regulation because like clouds and aerosols, water vapor acts as a boundary that traps longwave radiation in the atmosphere, thus causing surface warming (Bates et al., 2008).

Global nutrient cycling is greatly influenced by the hydrologic cycle and involves rock weathering, vegetative production, biota metabolism, and gas exchanges with the atmosphere (Schlesinger, 1997). Jacobson et al. (2000) claimed that the biosphere is the focal point binding all of the major systems of the Earth together. In order to maintain life, organisms must obtain raw materials and energy from the environment. Through the process of physical and chemical weathering of rocks, essential minerals become available for organisms to utilize (Brady and Weil, 2008). When plants take up these mineral nutrients, they also obtain CO$_2$ from the atmosphere and store the C in the fibrous tissue of the plant. When plant tissue is consumed by biota, nutrients are redistributed onto the soil and a significant portion of the C is released to the atmosphere in the form of CO$_2$ in aerobic conditions or CH$_4$ in anaerobic environments (Schlesinger, 1997). Carbon dioxide can also be emitted into the troposphere and stratosphere through volcanic and tectonic activity in the lithosphere, as well as gas exchange from the ocean (Owen and Rea, 1985; Houghton, 2005). Likewise, N follows a natural cyclic pattern constantly
circulation between N gas in the atmosphere as N₂, NO, N₂O, or NH₃ and organic N assimilated in biomass (Jaffe, 2000).

**Anthropogenic Processes Effecting Natural Biogeochemical Cycling**

Global warming due to anthropogenic activities is a major topic among today’s scientist and policy makers. According to International Panel on Climate Change (IPCC; 2007), climate change refers to any change in the climate over time, whether from natural variability or human influence, that can be statistically identified by changes in the mean and/or variability of its properties. This climatic shift is being felt around the globe through elevated daily temperatures, dissolving polar icecaps, rising ocean levels, and increasing occurrences of natural disasters (Denman et al., 2007). Over the last 100 years, global temperatures have increased 0.74 ± 0.18 ºC, most of which has occurred in two distinct periods, 1910 to 1945 and since 1976. During the past 50 years, the average temperature increase has been 0.13 ± 0.03 ºC per decade (IPCC, 2001, 2007). Although the variation might seem minute, it has shown that having just a slight increase in global warmth creates a vast transformation in the biophysical and biogeochemical processes on Earth (Trenberth and Shea, 2005; Zhou et al. 2003; Denman et al., 2007).

Human activities alter the biogeochemical cycling on the planet by changing the amount of solar radiation that is reflected back into space and the amount longwave radiation that is returned back to the Earth’s surface (IPCC, 2007). The entrapment of infrared energy in the lower atmosphere, known as the greenhouse effect, is a naturally occurring phenomenon that makes biological life possible. Without the warming of the Earth, the planet would be inhabitable (Schneider, 1989). However, this warming effect can be enhanced with increased concentrations

---

1. 1906-2005 – 90% confidence interval
2. 1956-2005 – 90% confidence interval
of insulating gases and particulate matter, due to the increased inability for radiation to escape back up to space. Technically, greenhouse gases (GHGs) and aerosols are released into the atmosphere from both natural processes and human induced activities (Charlson, 2000). However, as evident in the time progression of global temperature following the industrial revolution, the primary contributors to the upsurge in both airborne particulate matter and atmospheric GHG concentrations appear to be human-induced processes (Falkowski et al., 2000). Humans enhance the greenhouse effect through the oxidation of sulfates, discharge of industrial particles, biomass burning, fossil fuels combustion, deforestation, and soil disruption (Jonas et al., 1995; Charlson, 2000). Duxbury (1994, 1995) estimated that agricultural practices contribute to 25, 65, and 90% of total anthropogenic emissions of CO₂, CH₄, and N₂O, respectively.

**Global Impacts of Carbon and Nitrogen Gas**

The concept of global warming is attributed to an array of different factors, but is primarily attributed to three main GHGs that are present both naturally and from anthropogenic influences: CO₂, CH₄, and N₂O (IPCC, 2007). The most influential of these components contributing to this worldwide phenomenon is CO₂ (IPCC, 2007; Le Treut et al., 2007; Weil and Magdoff, 2004). Global concentrations of CO₂ have been noticeably increasing since the 1850s. Since that time, the concentration in the atmosphere has steadily increased from 280 parts per million (ppm) to over 380 ppm in 2008 (Kimble and Follett, 2002; Tans, 2008). Annual emissions of CO₂ have risen by 80% between 1970 to 2004 (21 to 38 Pg yr⁻¹), and in relation, CO₂ emissions represented 76.7% of the total anthropogenic GHG emissions in 2004 (ICPP, 2007). The anthropogenic enrichment of CO₂ in the atmosphere is partly due to fossil fuel
combustion and in part due to land-use changes. Agricultural operations contribute substantially to the CO$_2$ concentration through soil cultivation, expansion into natural ecosystems, and the mineralization of SOC (Kimble et al., 2002).

The other key C gas that contributes to global warming is CH$_4$. Methane is produced from anaerobic decomposition and made up 14.3% of the GHG emissions in 2004 (ICPP, 2007). The global atmospheric concentration of CH$_4$ has increased from a pre-industrial value of 715 ppb (parts per billion) to 1774 ppb in 2005 (ICPP, 2007). Although CH$_4$ is present in much smaller quantities than CO$_2$, CH$_4$ absorbs between 20-25 times as much radiation as a molecule of CO$_2$, which is analogous to the global warming potential of the gas (Farquhar et al., 2001; Ramaswamy et al., 2001; Lashof and Ahuja, 1990). While CO$_2$ can be removed from the atmosphere by exchanges with the biosphere, lithosphere, and the ocean, CH$_4$ is primarily removed by chemical oxidation in the lower parts of the atmosphere following a 8.4 year mean resistance time (MRT) (Sundquist and Visser, 2005; Denman et al, 2007). Thus, the concentration of CH$_4$ in the atmosphere reflects the balance between the supply and its rate of oxidation in the atmosphere (Sundquist and Visser, 2005). Since CH$_4$ is released under anaerobic conditions, the leading sources of CH$_4$ emissions are wetlands, landfills, ruminants, rice agriculture, and industrial processes (Wuebbles and Hayhoe, 2002). According to Reicosky et al. (2000), approximately one-third of the annual global CH$_4$ emissions in the U.S. are produced from agriculture operations. In rice agriculture, it has been shown that climate factors which are linked to plant growth influence the quantity of CH$_4$ emissions by determining how much substrate will be available for methanogenesis or methanotrophy (Matthews and Wassmann, 2003; Sass et al., 2002). Lu et al. (2000) showed that methane emission rates from rice plants can reach
1.53 mmol plant\(^{-1}\) day\(^{-1}\) throughout the growing season, with 24 to 46% coming from root exudation.

The primary N gas that contributes to global warming is N\(_2\)O. Concentrations of N\(_2\)O in the atmosphere have risen from a pre-industrial value of 270 ppb to 319 ppb in 2005 and made up 7.9% of the annual GHG emissions in 2004 (ICPP, 2007). Similar to CH\(_4\), a molecule of N\(_2\)O has the potential to absorb 300 times more radiation than a CO\(_2\) molecule (Lashof and Ahuja, 1990; Albritton et al., 1995). The MRT of N\(_2\)O in the atmosphere is approximately 114 years before the gas is destroyed through chemical reactions primarily in the stratosphere (Denman et al., 2007). The largest global source of N\(_2\)O emissions is believed to be from nitrification and denitrification in soils, which is particularly prominent in the tropics (Matson and Vitousek, 1990; Bouwman et al., 1993; Schlesinger, 1997). N\(_2\)O emissions are increased when land is disturbed through cultivation and deforestation (Matson and Vitousek, 1990; Keller and Reiners, 1994) and/or fertilized with products such as manure (Bouwman et al., 1995; Mosier et al., 1991). Other sources that contribute to atmospheric N\(_2\)O concentrations include nitrification in the ocean (Oudot et al., 1990; Nevison et al., 1995), biomass burning, industrial emissions (Prather et al., 1995), and rice agriculture (Norman et al., 2003).

**Socioeconomic Costs of Climate Change**

Understanding the consequences of human influences on global climate change is critical for formulating innovative agricultural practices, economic policies, and energy conservation strategies that will affect civilization for generations to come. Rosenzweig et al. (2007) stated that a shift in global climate can restructure the geographic production of agronomic resources such as timber, food and fiber crops, livestock, and fisheries. Furthermore, the climate change
will also impact energy consumption, water usage, transportation, tourism, and human health vulnerabilities across the globe (CEC, 2009).

**Carbon Credit Exchange**

Falkowski et al. (2000) asserted that although there is not any one process that will assimilate all of the anthropogenically produced CO$_2$ from the last 200 years, scientists can use a systematic approach to help decrease the overall quantity of CO$_2$ in the atmosphere. The problem with managing the production of GHGs from agricultural practices is primarily attributed to the conflicting interest between grower profitability and environmental quality. It is important to find improved management practices that will decrease overall emissions and are less detrimental to the soil, while still maintaining similar yields and profitability. If these practices are going to be readily accepted by farmers, there needs to be an incentive in doing so.

In addition to societal and ecological benefits, producers may also gain an economic advantage from utilizing modified rice management practices. An increased accumulation of C in rice fields may allow farmers to acquire C credits, a theoretical source of monetary stocks that could be sold in an exchange market. This market, known as the Chicago Climate Exchange (CCX), is a trading system much like today’s leading stock markets. These C credits could be purchased by large industries in order to counterbalance their CO$_2$ emissions, thus providing a supplemental income for rice producers (Brye, 2009).

**Century Model**

One of the ways that scientists have been able to obtain a better understanding of global C and N cycling is through various computer-based modeling programs such as the CENTURY
Model. The CENTURY Model is a well-known, extensive agroecosystem computer simulation model that demonstrates the relationship between plant production, management practices, and SOM dynamics. The Model uses measured C and N concentrations in the soil and computes future concentrations by simulating the pools and monthly fluctuations of the minerals (Throop et al., 2004). These mineral simulations are derived from previously recorded concentrations, crop rotations, tillage practices, fertilization regimes, irrigation routines, and harvest methods utilized in the system. The input information is used to conduct a comprehensive system assay pertaining to the long-term effects of management practices on the productivity and sustainability of agroecosystems and on global change (Parton et al., 1987; NREL, 2006).

**Long-Term Effects of Rice Management Practices on Soil Carbon and Nitrogen**

An important aspect of soil management practices is to maintain physical properties in a way that supports crop growth and ensures an adequate amount of the biomass gets redistributed back into the soil (Lal, 2007). A number of studies have been conducted on the changes in SOC due to different production practices. In a large scale intensive cropping system, the long-term balance of SOC is altered from natural conditions due to the increased oxidative losses from continuous cultivation and larger accumulations from crop residues, which can lead to either a net build up or reduction of SOC stock (Kong et al., 2005). Reicosky et al. (1995) showed that there is a strong relationship between crop residue and SOM accumulation in the top 15 mm of soil, and that SOM accumulation is controlled by crop variety, tillage, fertilization, and climate.
Increasing the amount of SOC in the soil requires the addition of enough crop residue biomass to exceed the losses from oxidation and reduction, erosion, and leaching (Follett, 2001). This can be accomplished by using crop rotation systems and winter cover cropping, which can influence the volume, distribution, and turnover of the active and passive pools of SOC (Franzluebbers et al., 1994). Dick et al. (1998) reported that crop rotation and cover crops are an effective way to facilitate C sequestration, especially when combined with NT and optimal fertilization. Granatstein et al. (1987) performed a 10-year study on winter wheat-legume rotations using different tillage regimes and observed the greatest increases in total C and total N in rotations with a high frequency of N-fixing legume crops. West and Post (2002) determined that enhancing the rotation complexity, including changing from monoculture to continuous rotation cropping, crop-fallow to continuous monoculture or rotation cropping, or increasing the number of crops in a rotation system, can sequester an average of 20 ± 12 g C m$^{-2}$ yr$^{-1}$, with the exclusion of a change from continuous corn to corn-soybean which may not lead to a significant change in SOC.

Rice is one of several high-residue-producing crops, along with corn and winter wheat, that is capable of producing 8.1 Mg ha$^{-1}$ (rice), 9.6 Mg ha$^{-1}$ (corn), and 3.0 Mg ha$^{-1}$ (winter wheat) of above-ground biomass under optimal N fertilization (USDA, 2009; Wilson and Runsick, 2008). Rice is a unique crop to add to a crop rotation because it is unlike all other row crops in that rice is grown under nearly to completely saturated soil conditions (Norman et al., 2003), which slows the rate of SOM decomposition and affects N cycling dynamics. Aulakh et al. (2001) reported that C sequestration in a sandy-loam soil in India was 69 to 107% greater when wheat residues were added to flooded rice, and that incorporating crop residue in a rice-
wheat rotation has the ability to increase SOM while maintaining high yields. Furthermore, Aulakh et al. (2001) showed that wheat residue incorporation immobilized mineral N during the fallow period, but the amount of mineral N increased rapidly at the start of the flooded rice season when green manure or urea N was applied. Although crop rotations involving high-residue-producing crops like corn typically show a substantial increase in SOC, the anaerobic conditions under which rice is grown also affect the breakdown of crop residues in the soil. Witt et al. (2000) demonstrated that soils continuously cropped with flooded rice had 11 to 12% more C sequestration and 5 to 12% more N accumulation than soils that supported a dry-season, maize-flooded rice rotation. This was attributed to a 33 to 41% increase in the estimated amount of mineralized C and decreased input of N from biological N fixation during the dry-season maize-cropping period (Whitt et al., 2000).

Effects of Tillage and Residue Management Practices on SOC and N

One of the most influential outcomes that came from the industrial revolution was the modernization of agriculture. The development of the cultivating machinery allowed farmers to increase production while decreasing labor costs. Although these inventions transformed the agricultural industry, they also induced a downward spiral of environmental quality. These innovative machines led to an enormous emission of GHGs from the combustion of fossil fuels and severe soil disruption through tillage (IPCC, 2001).

Soils that have been degraded through excessive tillage tend to be low in OM due to an increased amount of exposed surface area, which facilitates aerobic decomposition (DeBusk et al., 2001). Carbon makes up nearly half of the mass of OM (Montgomery et al., 2000), and it has been shown that cultivating the land influences the dynamics of SOC and the amount of CO₂ that
is emitted from the soil due to the aeration of the SOM (Paustian et al., 1995; Reicosky et al., 1995). The reduction of tillage intensity by switching from CT to NT has been widely recognized as an application that increases the amount of C storage in soils (Lal and Kimble, 1997; Doa, 1998; Kern and Johnson, 1993; Dick et al., 1998) and influences N cycling (Shaffer and Ma, 2001). McCarty et al. (1998) reported that remarkable increases in organic C (38%), biomass C (33%), total N (30%), and biomass N (87%) present in the surface layer of the soil three years after the transition from CT to NT. In an 18-year study on a rice-wheat rotation, SOC, N, and microbial biomass C and N were greater in the top 5-cm in NT compared with CT; whereas, C and N concentrations were greater in the 5- to 10-cm and 10- to 20-cm depths in CT compared with NT (Xu et al., 2007).

Although flooded conditions in rice-based crop rotations alter the environmental conditions contributing to C sequestration and N cycling, studies on differentiated tillage regimes implemented on non-flooded soils can also provide insight on the impacts of soil disturbance. West and Post (2002) showed that among 67 non-flooded long-term studies, the average sequestration rate was $57 \pm 14$ g C m$^{-2}$ yr$^{-1}$ for land that was converted from CT to NT systems, with the exclusion of wheat-fallow systems. They also estimated that the C sequestration rates max out between 5 and 10 years after conversion from CT to NT, and after 15 to 20 years, the soil will reach a greater equilibrium C concentration. Salinas-Garcia et al. (1997) confirmed that reduced tillage (RT) increased SOM, soil microbial biomass C, inorganic N, and labile C and N pools when compared to plowed systems in a long-term corn-cotton rotation experiment in Texas. Byre et al. (2006b) reported that the amount of SOC increased in a 2-year period under NT than CT in a wheat-soybean double-cropping system in east-central eastern Arkansas. In the same cropping system, Byre et al. (2006a) reported that soil surface CO$_2$ flux rates were 38%
greater from CT than from NT plots. Curtin et al. (2000) also showed that soil surface CO$_2$ flux was greater under CT than NT in continuous wheat and fallow-wheat rotations, which was attributed to both the decomposition rate of plant residues and the amount of aeration in the soil. Reicosky and Lindstrom (1993) attributed the large initial rate of soil surface CO$_2$ flux after tillage in CT to the release of CO$_2$ in newly exposed soil pores and from dissolution or direct oxidation of C substrates. With an estimated 3.4 billion ha of land in cultivation worldwide today, cultivated agricultural is a sizeable contributor to the overall accumulation of CO$_2$ in the atmosphere (Goklany, 1998).

In addition to soil disturbance, the removal of plant residues during harvest depletes the soil of OM and prevents the reuse of C and N compounds by the soil. Furthermore, Dabney et al. (2004) showed that tillage following residue removal increased soil loss between 26 and 47% compared to NT. Karlen et al. (1997) reported a reduction of SOM from residue removal diminishes soil quality due to decreased tilth, water-holding capacity, nutrient availability, CEC, aggregate stability, and microbial biomass. Yadvinder-Singh et al. (2004) projected that rice-wheat production systems generate 10 to 14 Mg ha$^{-1}$ of crop residues annually. Both Yadvinder-Singh et al. (2004) and Aulakh et al (2001) reported that wheat residues left on the soil surface increased SOC and provided large amounts of N to the following rice crop.

**Fertility Treatment Effects on SOC Accumulation and N in Soil**

The status of the fertility of the soil affects the amount of biomass produced, which is directly correlated with the amount of crop residues that are returned to the soil as SOC (Follett, 2001). Results from Halvorson et al. (2002) support this relationship that N fertilizer increased crop residue quantity that has returned to the soil in two dryland cropping systems in North
Dakota. Lal et al. (1998b) determined that soil fertility management practices add an average of 50 to 150 kg ha\(^{-1}\) of SOC to the soil every year. Clapp et al. (2000) had similar findings with a 13-year study on corn, which showed that adding N fertilizer increased SOC storage in NT systems. In contrast to adding fertilizer, Power and Doran (1988) showed that omitting N fertilization in NT corn increased soil microbial N immobilization during residue decomposition, which decreased plant-available N.

Most rice cultivars grown in the United States require 135 to 200 kg N ha\(^{-1}\) of N fertilizer to produce profitable grain yields (Norman et al., 2003). Shen et al. (2007) indicated that when compared to untreated plots, chemical fertilizer-treated plots produced a net gain of 16 to 18 g SOC kg soil\(^{-1}\) in a rice-wheat agroecosystem in China. The 18-year study on a rice-wheat rotation performed by Xu et al. (2007) showed the greatest increase in SOC, total available N, and microbial biomass C and N using a combination of organic and inorganic N-P-K fertilization treatments. Pampolino et al. (2008) showed that after 17 to 21 years of continuous rice cultivation in the Philippines with two to three crops grown per year, the concentration of total SOC and total soil N was greater in the topsoil (0- to 20-cm depth) with N-K, N-P, and N-P-K fertilization than with no fertilization. Studies by Manna et al. (2005) and Yadav et al. (1998) have also shown that inorganic fertilizer application can maintain or increase SOM when one or two rice crops are grown per year.
Long-Term Effects of Rice Management Practices on Soil Physical Properties

Bulk Density

The enhancement of soil quality is vital to sustaining, and perhaps improving, long-term agricultural productivity, namely crop yields (Pulleman et al., 2000; Karlen et al., 2008). Soil bulk density (BD), the ratio of the dry soil mass to the volume it occupies, is often one of a suite of measured soil properties that is an indicator of soil quality (Wolf and Snyder, 2003; Karlen et al., 1997, 2008). Soil BD is related to soil compaction in that the BD is relatively greater in compacted than in non-compacted soil.

Compacted soil with a relatively large BD can negatively affect numerous soil and plant properties and processes. Soil BD has been shown to be directly related to soil strength (Diana et al., 2008; Carter et al., 2006; Page-Dumroese et al., 2006; Elliot et al., 1998; Souch et al., 2004) and soil penetration resistance (Amuri and Brye, 2008; Ehlers et al., 1983; Whalley et al., 2005; Unger, 1996; Vaz and Hopmans, 2001; Hirth et al., 2005; Lampurlanes and Cantero-Martinez, 2003; Krizek et al., 2003), which is another soil property that is often used to quantify the degree of soil compaction. In contrast, soil BD has been shown to be inversely related to SOM (Diana et al., 2008; Son et al., 2003), water-holding capacity (Diana et al., 2008; Lampurlanes and Cantero-Martinez, 2003; Karamanos et al., 2004), soil particle size (Brady and Weil, 2008), total porosity (Mahboubi et al., 1993; Chan, 2002; Afyuni and Wagger, 2006), infiltration capacity (Vervoort et al., 2001; Radcliffe et al., 1988; Diana et al., 2008), hydraulic conductivity (Mahboubi et al., 1993; Afyuni and Wagger, 2006; Lampurlanes and Cantero-Martinez, 2003), gas exchange (Khan et al., 2000), seedling emergence (Chan, 2002; Soyelü et al., 2001), root penetration (Hirth et al., 2005; Diana et al., 2008; Lampurlanes and Cantero-Martinez, 2003;
Karamanos et al., 2004), nutrient mobility (Girma et al., 2006; Diana et al., 2008), and invertebrate movement (Hirth et al., 2005; Townshend and Webber, 1971).

Soil BD has been shown to be affected by several crop management practices, particularly tillage and crop rotation (Cassel et al., 1995; Grevers and Bomke, 1986; Lal et al., 1994; NeSmith et al., 1987; Lampurlanés and Cantero-Martínez, 2003), and compactness is generally greater under RT, specifically NT, due to machinery traffic and the lack of surface soil disruption and mixing accomplished by annual plowing (Mahboubi et al; 1993; Lal et al., 1989; Afyuni and Wagger, 2006; Wagger and Denton, 1989; Myers and Wagger, 1996; Karamanos et al., 2004). Soil BD has also been shown to be higher when a high residue-producing crop, such as sorghum, is grown in rotation with a low residue-producing crop, such as soybean, when compared to a low residue-producing monoculture cropping (McVay et al., 2006). Shaver et al. (2003) reported that each ton ha\(^{-1}\) of crop residue added to the soil reduced BD by 0.01 g cm\(^{-3}\) and increased effective porosity by 0.3% over a 12-year period. Since soil BD has been shown to be inversely related SOM (Diana et al., 2008; Son et al., 2003), in that increasing SOM generally decreases soil BD by adding additional pore space without adding much additional mass, crop rotations with a large frequency of high-residue-producing crops that are managed using cultural practices that return crop residues to the soil could at least maintain a near-surface soil BD that is favorable for gas exchange, water infiltration, and plant growth.

To harvest rice, the flood must be released several weeks prior to the targeted harvest window in order to allow the soil to drain and dry out to achieve enough structural stability to support heavy harvesting machinery. If the soil is too wet and not sufficiently dry to provide structural support for a large harvest combine, rice fields are often severely rutted, which can result in elevated soil BD and compaction (Lima et al., 2009).
Aggregate Stability

Understanding the mechanisms in which a soil aggregate stores and interacts with SOC is crucial to developing management strategies that will increase C sequestration at a regional and global scale (Blanco-Canqui and Lal, 2004). Soil aggregates play an important role in maintaining soil aeration, water infiltration, soil structural stability, and physical protection for SOM storage (Bird et al., 2002; Yoo and Wander, 2008; Hassink and Whitmore, 1997; Oades and Waters, 1991). The water-stable aggregation, which is the ability of an aggregate to maintain its structure in the presence of wet conditions, of agriculturally managed soil is directly affected by tillage practices, crop rotation, fertilization treatments (Angers and Carter, 1996), and irrigation regimes (Tisdall, 1996).

Reduced-tillage and NT practices have been shown to increase the number and stability of soil aggregates, which are positively correlated with optimal soil structure (Chaney and Swift, 1986; Flanzluebbers, 2004; Haynes and Knight, 1989; Douglas et al., 1986; Horne et al. 1992). Wolf and Snyder (2003) theorized that aggregate formation increases because of the overall increase in the SOM content in response to decreased soil disturbance. According to Haynes and Beare (1996), SOM sequentially supplies energy for the microbial production of mucus and cementing agents, which have the ability to bind soil particles into aggregates. This assumption is backed up by findings from Caesar-TonThat and Cochran (2002), who showed that ligninolytic basidomycete fungi produce polysaccharides, glycolipids, or glycoproteins that bond soil particles together into water-stable aggregates. However, Chaney and Swift (1986) showed that cementing agents produced from microbial degradation do not contribute to long-term stability of the aggregate.
The magnitude of soil aggregation due to crop rotation is highly dependent on the crop species being grown and the amount of residue that a particular crop returns to the soil from above- and below-ground biomass (Angers and Carter, 1996), which can be increased with optimal fertilization. Kay (1990) reported that crop rotations which include legumes and/or grasses promote the formation of stable aggregates and favorable soil structure. Zotarelli et al. (2005) showed the mean weight diameter of aggregates to be greater under more diverse rotations, which included a leguminous green-manure crop, than in a continuous wheat-soybean rotation. However, Arrigo et al. (1993) showed that soil aggregates were more stable in rotations that included maize and wheat (wheat/soybean-maize, soybean-maize) than in soybean monoculture and soybean-sunflower (*Helianthus annus* L.) combinations. Six et al. (2000) explained that the extent and stability of aggregation is dependent on the decomposition rate of a particular crop residue. Slower decomposition of the substrate enables a greater number of stable micro-aggregates to form within macro-aggregates, which increases the overall stability of the macro-aggregate.

In rotations that include rice, the maintenance of irrigation water on the soil surface during the cropping period affects aggregate formation and stability. Saturated soil conditions not only affect the decomposition rate of OM, but Tisdall (1996) stated that the soil water content affects the bonds between OM and clay particles. Semmel et al. (1990) reported that in wet soils, clay particles are repositioned to areas with the least amount of energy, and then the particles become chemically bound together upon contact with another clay particle, organic colloid, or salt. When the soil dries out, after the flood is released in the case of rice cropping, the bonds that were formed during this rearrangement strengthens the bonds between larger soil particles.
JUSTIFICATION

An applicable long-term experiment is necessary to effectively study the sustainability of rice cropping in the U.S. by enabling the direct quantification of SOM accumulation, which results from modified management practices (Greenland, 1994; Powlson and Olk, 2000; Pampolino et al., 2008). Given the increasing interest in global climatic conditions, it is important for North American rice producers and Earth scientists to understand the impacts and available measures that can be employed to reduce C and N gases from rice production. The proposed research will aim to evaluate the long-term impacts of rice-based crop rotations with continuous rice, corn, wheat, and soybeans under CT and NT management and two different soil fertility regimes (optimal and sub-optimal) on soil C and N storage and cycling. As part of this overall goal, the impacts of rice-based crop rotations on soil surface CO$_2$ flux and soil aggregate stability will specifically be investigated.

The results obtained from this long-term study can elucidate ways to remain profitable, produce similar yields, sustain a high level of production, and maintain essential soil physical, chemical, and biological properties of the soil while practicing these long-term management techniques. There is no single soil and/or crop management strategy that can be implemented to alter soil biotransformation processes and soil C storage. Practices must be tailored to individual environments based on the soil present, climatic conditions, land management practices, and social constraints (Karlen and Cambrella, 1996). Due to the unique climatic conditions that support rice production in the Mississippi Delta region, there is a need to find geographically adapted management techniques that promote SOM storage.
Hypotheses:

• No-tillage will result in greater SOM, SOC, total nitrogen (TN), water-stable aggregates (WSA), WSA C and N contents, and lower soil surface CO₂ flux compared to tillage.

• Optimal fertility treatments will result in greater SOM, SOC, and TN compared to sub-optimal fertility.

• High-residue rotations that include greater frequencies of rice, corn, and/or double-cropped with winter wheat will result in greater SOM, SOC, TN, WSA, WSA C and N contents, and soil surface CO₂ flux compared to lower-residue producing rotations.

• The Century model results are expected to correlate well with measured results for SOC and TN contents.
REFERENCES


57


CHAPTER 2

RICE ROTATION AND TILLAGE EFFECTS ON WATER-STABLE SOIL
MACROAGGREGATES AND THEIR ASSOCIATED CARBON AND NITROGEN
CONTENTS IN A SILT-LOAM SOIL
Rice rotation and tillage effects on water-stable soil macroaggregates and their associated carbon and nitrogen contents in a silt-loam soil

Abstract

Rice (Oryza sativa L.)-based cropping systems are different from other row crops due to the flood-irrigation scheme used from about one month after planting to a few weeks prior to harvest. The frequent cycling between anaerobic (i.e., flooding during the growing season) and aerobic (i.e., generally, the remainder of the year) conditions can influence the rate of soil organic matter (SOM) decomposition, which can subsequently affect water-stable soil aggregation and carbon (C) and nitrogen (N) storage and sequestration over time. A study was conducted on a silt-loam soil (fine, smectitic, thermic, Typic Albaqualf) in the Mississippi River Delta region of eastern Arkansas to evaluate the long-term effects of rice-based crop rotations [with corn (Zea mays L.), soybean (Glycine max L.), and winter wheat (Triticum aestivum L.)], tillage [conventional tillage and no-tillage (NT)], and soil depth (0- to 5-cm and 5- to 10-cm) and after 10 years of consistent management on water-stable soil aggregation and aggregate-C and -N concentrations, C:N ratios, and contents within and across five aggregate-size classes (0.25- to 0.5-mm, 0.5- to 1-mm, 1- to 2-mm, 2- to 4-mm, and > 4 mm). The total concentration of the soil that formed macroaggregates (> 0.25-mm in diameter) was 1.2 to 4 times greater under NT in the top 5 cm than in the other tillage-depth treatment combinations within all six crop rotations, with the 0.25- to 0.5-mm size class having a greater concentration of water-stable aggregates (WSA) than all other size classes. The concentration of total water-stable macroaggregates (TWSA) in the top 5 cm under NT was greater in continuous rice and rice rotations including corn than rotations that included wheat. The TWSA C concentration was similar under both tillage (38.2 g
kg⁻¹) and NT (41.8 g kg⁻¹) in the top 5 cm, but differed among tillage treatments in the 5- to 10-cm depth. The NT/0- to 5-cm treatment combination had 3 to 6 times greater TWSA C and N contents than all other tillage-depth combinations, which did not differ among one another. The frequency of periodic saturation did not appear to significantly affect soil aggregation and aggregate-C and -N contents compared to rotations that were flooded less frequently. Overall, results from this long-term experiment indicate that inputs from high-residue-producing crops and soil manipulation from tillage affect the dynamics of soil aggregation in rice-based crop rotations.
Introduction

Understanding cultural practices that affect soil aggregation, the ability to withstand water erosion, and the storage of carbon (C) and nitrogen (N) are crucial to developing management strategies that will increase C and N sequestration at a regional and global scale (Blanco-Canqui and Lal, 2004). Soil aggregates play an important role in maintaining soil aeration, water infiltration, soil structural stability, and provide the primary physical protection for soil organic matter (SOM) storage (Bird et al., 2002; Yoo and Wander, 2008; Hassink and Whitmore, 1997; Oades and Waters, 1991). Additionally, the formation of organo-mineral aggregates surrounds and physically protects soil organic carbon (SOC) from microbial attack (Lal, 2007; Kooistra, 1991).

The heterogeneous arrangement of particles and pores is important for microbial accessibility to SOC (Oades, 1993; De Gryze et al., 2006; Blanco-Canqui and Lal, 2004). Studies have shown that inter-aggregate pores < 1μm in diameter can prevent access by bacteria, and pores sizes between 1-2 μm allowed bacterial access, but blocked protozoa and nematodes (Juma, 1993). Research pertaining to the architecture of soil aggregates has demonstrated that the relatively stable organic fraction of the soil is predominantly present in the inner sections of microaggregates (Edwards and Bremer, 1967). The ability to retain sequestered SOC within aggregates relies on the architectural stability of the arrangement, which is determined by the quantity and quality of organic residues, the strength of the organic binding agents from microbial polysaccharides and organic mucilages, and the clay content of the soil (Jastrow and Miller, 1998; Blanco-Canqui and Lal, 2004; Tisdall, 1991, 1994; Carter, 1996). Water-stable aggregation, which is the ability of an aggregate to maintain its structure in the presence of wet conditions, of agriculturally managed soil is often directly affected by tillage practices, crop
rotation, fertilization treatments (Angers and Carter, 1996), and irrigation regimes (Tisdall, 1996; Tisdall and Oades, 2006).

Reduced- and no-tillage (NT) practices have been shown to increase the number and stability of soil aggregates, which are positively correlated with optimal soil structure (Chaney and Swift, 1986; Franzluebbers, 2004; Haynes and Knight, 1989; Douglas et al., 1986; Horne et al. 1992). Aggregate formation increases because of the overall increase in the SOM content in response to decreased soil disturbance from tillage (Wolf and Snyder, 2003). The increase in SOM contained in the soil sequentially supplies energy for the microbial production of mucus and cementing agents, which can serve as binding agents for soil particles (Haynes and Beare, 1996; Caesar-TonThat and Cochran, 2002). In addition to the quantity of water-stable aggregates (WSA), tillage has been shown to influence the chemical composition of the aggregates, where minimal tillage generally results in greater aggregate-C and -N concentrations in size classes greater than 0.25 mm in diameter and lower C:N ratios in larger size classes up to 1-mm in diameter when compared to more frequent tillage operations in agriculturally managed soil (Kasper et al., 2009).

The degree of soil aggregation in an agricultural crop rotation is highly dependent on the crop species being grown and the amount of residue that is returned to the soil from above- and below-ground biomass (Angers and Carter, 1996), which can be increased with optimal fertilization. Crop rotations which include legumes and/or grasses have been reported to promote the formation of WSA and favorable soil structure (Kay, 1990). The mean weight diameter of aggregates has been shown to be greater under more diverse rotations, which included a leguminous green-manure crop, than in a continuous wheat (Triticum aestivum L.)-soybean (Glycine max L.) rotation (Zotarelli et al., 2005). However, there has also been evidence that soil
aggregates are more stable in rotations that include corn (*Zea mays* L.) and wheat (wheat/soybean-corn, soybean-corn) than in soybean monoculture and soybean-sunflower (*Helianthus annus* L.) rotations (Arrigo et al., 1993). In general, the extent and stability of soil aggregation is dependent on the decomposition rate of a particular crop residue (Six et al., 2000a). Slower residue decomposition enables a greater number of stable microaggregates (≤ 0.25-mm in diameter) to form within macroaggregates (> 0.25-mm in diameter; Tisdall and Oades, 2006), which increases the overall stability of the macroaggregate (Six et al., 2000a).

In rotations that include rice (*Oryza sativa* L.), the maintenance of a semi-permanent flood on the soil surface during the cropping period can affect aggregate formation and stability. Saturated soil conditions not only affect the decomposition rate of organic matter, but the soil water content also affects the bonds between organic matter and clay particles (Tisdall, 1996). In wet soils, clay particles are repositioned to areas with the least amount of energy, and then the particles become chemically bound together upon contact with another clay particle, organic colloid, or salt (Semmel et al., 1990). When the soil dries out, after the flood is released in the case of rice cropping, the bonds that were formed during this rearrangement strengthens the bonds between larger soil particles (Semmel et al., 1990).

Since the nature of soil physical properties are generally of little concern during a rice-crop growing season due to the flooded-soil conditions, relatively few studies have examined the potential effects of rice rotations on soil physical properties (Motschenbacher et al., 2011), such as soil aggregation. However, with the recent and growing interest in greenhouse gas emissions, particularly methane (CH$_4$), and the carbon footprint of rice production, a need exists to investigate soil aggregation and the protection of SOC under rice production practices. In turn, the protection and sequestration SOC contributes to the minimization of gaseous losses of C as
CH₄ and/or carbon dioxide (CO₂). Therefore, the objective of this study was to evaluate the long-term effects of rice-based crop rotations (with corn, soybean, and winter wheat), tillage [conventional tillage (T) and NT], and soil depth (0- to 5-cm and 5- to 10-cm) after 10 years of consistent management in soil WSA and their associated C and N concentrations and contents within and across five aggregate-size classes (0.25- to 0.5-mm, 0.5- to 1-mm, 1- to 2-mm, 2- to 4-mm, and > 4-mm in diameter) on a silt-loam soil in the Mississippi River Delta region of eastern Arkansas. It was hypothesized that the total water-stable aggregate (TWSA) concentration (g aggregates kg⁻¹ soil) and TWSA C and N contents (g m⁻² soil) would be i) greater under NT than under tillage in the same soil depth, ii) greater in rotations with increased frequencies of high-residue-producing crops in both soil depths, iii) and greater in the top 5 cm than in the 5- to 10-cm depth. Furthermore, the aggregate concentration in various size classes and their C and N contributions to the TWSA C and N content were hypothesized to increase as aggregate diameter decreased.

Materials and Methods

Site Description

This study was conducted at the University of Arkansas’s Rice Research and Extension Center (RREC) near Stuttgart, AR (34°27’ N, 91°24’ W), which is located in the Mississippi River Delta region of eastern Arkansas in an area known as the Grand Prairie (NRCS, 2011). This study was initiated in 1999 in a 1.9-ha area on a Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf; NRCS, 2008) with an average soil pH of 5.6 in the top 10 cm, which is characteristic of Grand Prairie soils used for rice production (Brye and Pirani, 2005). In 1999, C
and N concentrations in the top 10 cm averaged 7.1 and 0.7 g kg\(^{-1}\) soil, respectively, throughout the study area.

Prior to 1999, the study area had been fallow for several years due to a lack of irrigation capability. Vegetation prior to the beginning of the study consisted of a mixture of grasses and weeds that were managed by periodic mowing during the summer. In preparation for this study, the site was land leveled to a 0.15% grade in fall 1998. Land leveling consisted of removing and piling the top 10 cm of soil off to the side of the area to be leveled, cutting the field to grade, and redistributing the topsoil uniformly over the field. Land leveling is a common practice in the Mississippi River Delta region, especially in areas where rice production dominates, to facilitate uniform distribution of flood-irrigation water (Brye et al., 2003).

The regional climate is warm and wet with a 30-yr mean annual temperature minimum of 0.2 °C in January and maximum of 33.1 °C in July. The 30-yr mean annual precipitation is 132 cm (SRCC, 2012).

**Experimental Design and Field Treatments**

This field study consisted of a randomized complete block design with four replications, where each block was 76-m wide by 120-m long. Each block was divided into two tillage treatments, striped into ten crop rotations, split into two depths, and for aggregate-size class differentiation, split into five aggregate-size classes. The ten crop rotations analyzed included continuous rice (R), rice-soybean (RS), soybean-rice (SR), rice-corn (RC), corn-rice (CR), rice (winter wheat) [R(W)], rice (winter wheat)-soybean (winter wheat) [R(W)S(W)], soybean (winter wheat)-rice (winter wheat), rice-soybean-corn, and rice-corn-soybean (RCS). Individual plots representing the tillage-rotation treatments were 6-m wide by 19-m long. For the purposes
of this experiment, only six of the 10 rotations where used due to the elimination of mirror image rotations. These rotations included R, RS, RC, R(W), R(W)S(W), and RCS.

Crop management practices for rice (Slaton, 2001), soybean (Ashlock, 2000), corn (Espinoza and Ross, 2003), and wheat (Kelley, 1999) closely followed the University of Arkansas Cooperative Extension Service recommendations for stand establishment, irrigation, weed management, and pest management. In the tilled treatment, crop residues were burned and then incorporated into the soil generally one to two months following harvest by disk ing twice. Prior to planting in the spring, plots were tilled by disking once to a typical depth of approximately 10 cm, followed by multiple passes with a light field cultivator (i.e., Triple-K) to achieve the desired seedbed for rice planting. In the NT treatment, crop residues were left on the surface after harvest and were not manipulated by any means prior to planting in the spring.

Crop varieties included in the rotation treatment of this study consisted of the major agronomic crops grown in Arkansas. ‘Wells’ was the rice cultivar grown based on its local popularity among rice producers. Rice, soybean, and wheat were sown into 19-cm rows using an Almaco NT drill (Almaco, Nevada, IA). Rice was drill-seeded at a rate of 100 kg seed ha$^{-1}$, soybean at a rate of 56 kg seed ha$^{-1}$, and wheat at a rate of 67 kg seed ha$^{-1}$. Corn was planted in 76-cm rows at a plant population of approximately 79,000 seeds ha$^{-1}$ (Schmid, 2008).

The soil fertility regime used on all plots followed a standard fertility recommendation based on the analysis of soil samples that were collected in spring 1999 (Table 1). The annual soil fertility scheme consisted of phosphorus applied as triple super phosphate and potassium applied as muriate of potash, with both fertilizers broadcast pre-plant and pre-tillage with a hand spreader. During the years rice was grown, zinc was applied as zinc sulfate, which was also broadcast pre-plant and pre-tillage with a hand spreader (Table 1). Phosphorous, potassium, and,
when applicable, zinc were incorporated into the soil in the tilled and were left at the surface in the NT treatment. Nitrogen as urea was applied with a hand spreader pre-flood at the 5-leaf stage of rice growth approximately one month after planting. For corn, N was applied after emergence and at the V4 vegetative growth stage. For wheat, N was applied shortly after emergence as well. Following N fertilization in rice, a 5- to 10-cm deep permanent flood was established, which was maintained annually until the rice reached physiological maturity. All other summer crops present in a given year were furrow-irrigated on an as-needed basis approximately three to four times annually, which was effectively based on the amount of recent rainfall received and visual assessment of the growth of the crop. Winter wheat was rain-fed only without irrigation.

As previously noted, weed management for rice, soybean, corn, and wheat followed recommendations made by the Arkansas Cooperative Service. Weed management for rice consisted of a pre-emergence application of 0.34 kg ha$^{-1}$ of clomazone [2-[(2-chlorobenzyl)methyl]-4,4-dimethyl-3-isoxaolidinone] and a post-emergent application of halosulfuron [3-chloro-5-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid] at 0.06 kg ha$^{-1}$ for both tillage treatments. Soybean and corn were treated with 2.3 L ha$^{-1}$ of glyphosate [N-(phosphonomethyl)glycine] in the spring and applications of paraquat [1,1’-dimethyl-4,4’-bipyridinium ion] and flumioxazin [2-[7-flurohydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione] in the fall following harvest and winter-wheat planting. Corn also received a treatment of 2.3 L ha$^{-1}$ of glufosinate-ammonium [2-amino-4-(hydroxymethylphosphinyl)butanoic acid monoammonium salt] and 0.07 L ha$^{-1}$ of halosulfuron [3-chloro-5-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid]. Wheat
was treated with 0.35 L ha\(^{-1}\) of mesosulfuron-methyl [methyl 2-[[[4,6-dimethoxy-2-pyrimidinyl]amino]carbonyl]amino]sulfonyl]-4-[[((methylsulfonyl)amino)methyl] benzoate].

**Soil Sampling and Analyses**

Soil aggregate samples were collected in mid-March 2009 from the 0- to 5-cm and 5- to 10-cm depth intervals using a 10-cm diameter, stainless steel core chamber that was beveled on the outside to minimize compaction upon sampling. Two core samples were collected from each plot at a random location between previously planted rows and combined into one composite sample for each depth (0- to 5-cm and 5- to 10-cm). Thus, one composite sample was collected from each depth per plot for a total of 96 samples.

At the time of sampling, the R and R(W) rotations had produced a total of 10 rice crops, the RS, RC, and R(W)S(W) rotations had produced five rice crops with five crops in the respective rotation with corn or soybean, and the RCS rotation had produced four rice crops with three crops in the respective rotations with corn and soybean (Table 2). Furthermore, the rotations with winter wheat produced a total of 10 wheat crops (Table 2). The tillage treatment was uniformly imposed on tilled plots five months (late-October 2008) prior to soil aggregate sampling.

Following collection, samples were manually broken up into pieces that were small enough to pass through a 6-mm sieve and air-dried for seven days at an approximate temperature of 22 °C. Sub-samples of air-dried soil (150 g) from each replicated treatment combination were separated into five aggregate-size classes (i.e., 0.25- to 0.5-mm, 0.5- to 1-mm, 1- to 2-mm, 2- to 4-mm, and > 4-mm in diameter) by wet sieving according to the procedure of Yoder (1936). Soil samples were wet-sieved for five minutes at approximately 130 cycles per minute. The water in
the column where the wet-sieving took place was emptied after each set of tillage-rotation-depth treatment replications. Thus, the four replications of each tillage-rotation-depth treatment combination were sieved in the same water and a composite-soil sample of the sediment (i.e., soil particles and aggregated soil ≤ 0.25-mm in diameter) deposited jointly from the tillage-rotation-depth replications was collected for C and N analysis. A total of 24 composite-soil samples were collected. Following wet-sieving, all samples were oven-dried for 24 hours at 70 °C, and the separated aggregates retained on the various sieves were weighed to determine the concentration of WSA by aggregate-size class based on the mass of the air-dried sample corrected for a 1.4% moisture difference between the air-dried and the oven-dried masses. The composite-soil mass, which was the sub-sample mass minus the total mass of macroaggregated soil (> 0.25-mm in diameter), was also corrected for moisture differences. After weighing, soil from the five aggregate-size classes and composite-soil samples were ground to pass a 2-mm mesh screen using a roller-mill procedure (Smith and Myung, 1990). During this procedure, the sample was placed in a glass vial along with six metal rods ranging in size from 3 to 6 mm. Samples were left on the roller-mill for approximately 12 hours, at which time the samples were considered uniformly ground for analyses.

In order to have enough physical mass of each aggregate-size class to chemically analyze, the four replications of aggregates were combined into one sample per tillage-rotation-depth-size treatment combination. The combined aggregate-size class samples and composite-soil samples were then analyzed for their total C and N concentration (g kg⁻¹) by high-temperature combustion (Flash 2000 NC Analyzer, Thermo Scientific, Waltham, MA). Carbon:N ratios were calculated from measured C and N concentrations for each tillage-rotation-depth-size or tillage-rotation-depth treatment combination.
Carbon and N contents (g m$^{-2}$ soil) for TWSA and WSA were calculated from C and N concentrations measured on aggregate samples combined across replicates, TWSA and aggregate-size class weights in each replicate, and the measured soil bulk density in each replicate from the 0- to 10-cm depth (Motschenbacher et al., 2011) in each tillage-rotation-depth (TWSA) or tillage-rotation-depth-size (WSA) treatment combination. Carbon and N contents for the composite-soil sample were also calculated from C and N concentrations measured on composite-soil samples, composite-soil sample weights in each replicate, and measured soil bulk density in each replicate. For TWSA, WSA, and composite-soil samples, the four replicates were assigned the same C and N concentration and treatment combination replication was obtained from the sample mass concentrations and soil bulk density values. Carbon and N contents for bulk soil in each tillage-rotation-depth treatment combination were calculated from the sum of the TWSA and composite-soil C and N contents.

Though soil WSA concentrations were not measured at the onset of the study in spring 1999, land-leveling activities uniformly affected the entire study area and 10 years of consistent management had elapsed prior to sampling in 2009. Therefore, it was reasonably assumed that any observed differences in soil aggregation, aggregate-associated C and N concentrations, and aggregate-associated C and N contents among treatment combinations from the 2009 sampling represented actual treatment effects rather than residual effects from inherent differences among plots prior to the beginning of the study.

**Data Analyses**

The effects of tillage, crop rotation, soil depth, and, where appropriate, aggregate-size class, on measured and calculated parameters (i.e., the mass concentration of TWSA and WSA
within various size classes, C and N concentrations of TWSA, WSA within size classes, and
composite-soil, C:N ratios, and C and N contents of TWSA, WSA within various aggregate-size
classes, composite-soil, and bulk-soil samples) were evaluated by analysis of variance (AVOVA)
of C and N concentrations and accompanying C:N ratios for the TWSA and composite-soil
samples were treated as three-factor treatment structures. Analyses of the C and N concentration
data and C:N ratios for WSA within various size classes were treated as four-factor treatment
structures. For all analyses related to the mass concentration of TWSA and their associated C and
N contents, as well as bulk-soil C and N contents, blocks were partitioned as a strip-split plot
design. For analyses evaluating the mass concentration of WSA within the various aggregate-size
classes and their associated C and N contents, a strip-split-split plot design was used. All factors
were considered as fixed effects for all analyses, and where applicable, blocks were a random
effect. When appropriate, means were separated using Fisher’s protected least significant
difference (LSD) at the 0.05 level.

Results and Discussion

Water-Stable Aggregation

Total Water-Stable Aggregates

After 10 years of consistent rotation management and nine years of T or NT, the TWSA
concentration (g aggregates kg⁻¹ soil) was affected by tillage, rotation, and soil depth \( P = 0.022; \)
Table 3). The total concentration of the soil that formed macroaggregates (i.e., > 0.25-mm in
diameter) was 1.2 to 4 times greater under NT in the top 5 cm than in the other tillage-depth
treatment combinations within all six crop rotations (Figure 1). A decreased concentration of
aggregates in the near-surface layer under T compared to reduced- or zero-tillage is commonly observed in agricultural systems (Six et al., 2000a; Six et al., 2000b; Bossuyt et al., 2002; Chaney and Swift, 1986; Franzluebbers, 2004; Haynes and Knight, 1989; Douglas et al., 1986; Horne et al. 1992; Anders et al., 2012) due to decreased soil disturbance and a greater concentration of organic matter. Although there was a considerable difference in the concentration of aggregated soil between tillage treatments in the top 5 cm (NT > T) within all crop rotations, ranging from two times greater in R(W)S(W) to four times greater in RCS, there were no differences between tillage treatments in the 5- to 10-cm depth within any crop rotation (Figure 1). These results are comparable to those of Anders et al. (2012), who conducted a similar study in rice-based crop rotations under sub-optimal fertility after six years of consistent management in a lit-loam soil. Anders et al. (2012) showed a greater concentration of macroaggregated soil (i.e., > 0.25 mm in diameter) in the NT/0- to 5-cm tillage-depth combination compared to the NT/5- to 10-cm combination and the T treatment in both the 0- to 5-cm and 5- to 10-cm depths when averaged across R, RS, RC, R(W), S(W)R(W), RSC, and RC(W)S rotations. Differences among tillage treatments in a R(W) rotation were also reported by Gathala et al. (2011) in the top 15 cm, in which the absence of tillage resulted in a greater concentration of WSA > 0.25-mm in diameter.

The concentration of TWSA under T in the top 5 cm did not differ among crop rotations. However, in the top 5 cm under NT, the R, RC, and RCS rotations had significantly greater concentrations of TWSA than the other rotations (Figure 1). This may be contributed to the increased frequency the high-residue-producing crops of rice [6.5 Mg above-ground dry matter (DM) ha\(^{-1}\) year\(^{-1}\)] and corn [8.0 Mg DM ha\(^{-1}\) year\(^{-1}\)] compared rice rotations that were only rotated with soybean [2.2 Mg/ha/year; USDA, 2011]. Results also suggest that the inclusion of
wheat (3.3 Mg DM ha\(^{-1}\) year\(^{-1}\)) into double-cropped rice rotations does not necessarily increase the quantity of WSA as much as mono-cropped continuous rice, despite the increase of annual inputs of crop residues (UDSA, 2011). The smaller concentration of WSA in the double-cropped rotation of R(W) compared to continuous rice may be attributed to greater soil disturbance in the near-surface soil from biannual planting. In contrast to NT, all rotations had numerically smaller TWSA concentrations in the 5- to 10-cm depth than in the top 5 cm under T. However, only the continuous rice cropping system had a significant difference in TWSA between depths under T, whereas the 5- to 10-cm depth had an 81% greater TWSA concentration (56.2 g kg\(^{-1}\)) than that in the top 5 cm (31.1 g kg\(^{-1}\)). Furthermore, the continuous rice rotation had a 13 to 67% greater TWSA concentration in the 5- to 10-cm depth under both T and NT treatments compared the same tillage-depth combinations in the R(W)S(W) and RCS rotations (Figure 1).

Water-Stable Aggregates among Size Classes

When separated into five aggregate-size classes, the concentration of WSA was affected by tillage, rotation, soil depth, and aggregate-size class (\(P = 0.004\); Table 4). Similar to Anders et al. (2012), the WSA concentration (g aggregates kg\(^{-1}\) soil) numerically increased as aggregate-size class decreased from the > 4.0-mm to the 0.25- to 0.5-mm size class in all tillage-rotation-depth combinations (Figure 1). The 0.25- to 0.5-mm size class had a greater concentration of WSA than all other size classes in each tillage-depth combination within a rotation. With the exception of the NT/5- to 10-cm combination in the R(W)S(W) rotation, the NT/0- to 5-cm combination had the greatest concentration of WSA in the 0.25- to 0.5-mm size class than any other size class across all rotations (Figure 1). Furthermore, most of the tillage-rotation-depth combinations had at least a numerically greater concentration of WSA in the 0.5- to 1-mm size
class than in the size classes above 1 mm (i.e., 1- to 2-mm, 2- to 4-mm, and > 4-mm in diameter), whereas all rotations, except R(W)S(W), had a significantly greater WSA concentration in the 0.5- to 1-mm size class than in the size classes above 1 mm under NT in the top 5 cm (Figure 1). This is comparable to results reported by Martins et al. (2009), where the majority of WSA were present in aggregate-size classes below 1 mm in rotations that included rice, corn, and/or soybean rotations. While numerically the quantities of WSA in the 1- to 2-mm and 2- to 4-mm size classes decreased as size class increased, only the NT/0- to 5-cm treatment combination in the R, RS, RC, R(W), and RCS rotations had any significant differences between the WSA concentration in the 1- to 2-mm size class and that in the 2- to 4-mm size class within tillage-rotation-depth combinations (Figure 1).

Although this study only examined macroaggregates (i.e., > 0.25 mm in diameter), the general trend of greater WSA concentrations in the smaller aggregate-size classes may be explained by the conceptual model of Six et al. (2000a) on the formation of microaggregates in a loam textured soil. In this model, the residue that forms intra-aggregate particulate organic matter, which induces macroaggregate formation, degrades into smaller fragments over time from microbial consumption (Six et al., 2000a; Six et al., 1998; Guggenburger et al., 1994). Clay particle accumulation on these smaller fragments forms smaller and more stable aggregated structures within the macroaggregate. These smaller aggregated structures are released when the binding agents of the macroaggregate eventually degrade due to decreased microbial activity (Six et al., 2000a). Although the smaller aggregate-size classes represented in the study do not classify as the microaggregates discussed in the Six et al. (2000a) model, the same basic principle should apply to the breakdown of larger macroaggregates into smaller macroaggregates. Although these smaller aggregated particles are susceptible to reintegration
into newly formed macroaggregates, a reasonable assumption would be that there is a greater accumulation of WSA in the smaller size classes than those in the size classes with larger diameters as a result of this soil aggregation cycle.

In the > 4-mm size class, only 70 out of the 160 samples had any measurable WSA mass after wet sieving, and all WSA concentrations did not differ from a concentration of zero. This lack of larger aggregated soil particles greater than 4 mm coincides with the assumption that larger aggregates are less water-stable and have the tendency to break down naturally in the soil overtime. Due to the small amount of WSA in the > 4-mm size class, there was an insufficient quantity of physical sample to chemically analyze after soil grinding procedures were conducted. Therefore, for the purposes of the subsequent discussions of aggregated C and N concentrations and contents, data for the > 4-mm aggregate-size class were not included in the analyses.

**Aggregate C and N Concentrations and C:N Ratios**

*Total Water-Stable Aggregates*

Averaged across rotations, TWSA C concentration (g C kg\(^{-1}\) aggregated soil) combined across the four smallest aggregate-size classes (i.e., 0.25- to 4-mm in diameter range) was affected by tillage and soil depth \((P = 0.010; \text{Table 3})\). The TWSA C concentration was similar under both T (38.2 g kg\(^{-1}\)) and NT (41.8 g kg\(^{-1}\)) in the top 5 cm, but differed significantly among tillage treatments in the 5- to 10-cm depth, with the TWSA C concentration in the T/5-to 10-cm (20.8 g kg\(^{-1}\)) combination being nearly two times greater than that in the NT/5- to 10-cm (11.9 g kg\(^{-1}\)) combination (Figure 2A). This similarity among TWSA C concentrations under both T and NT in the top 5 cm of soil was unexpected because significantly greater C concentrations in macroaggregated soil (i.e., > 0.25 mm in diameter) have been reported in a sandy loam soil under
minimal tillage treatments when compared to more intensive tillage (Kasper et al., 2009). However, the greater C concentration in soil under T in the 5- to 10-cm depth compared to NT was similar to results reported in a 18-year R(W) rotation in a clay loam soil in China, whereas C and N concentrations in the whole soil (i.e., aggregated and non-aggregated) were generally greater in the 5- to 10- and 10- to 20-cm depths under T than under NT, despite greater C and N concentrations in the 0- to 5-cm depth under NT than that under T (Xu et al., 2007). Within the same tillage treatment, the TWSA C concentration in the top 5 cm was 1.8 times greater under T and 3.5 times greater under the NT than in the respective 5- to 10-cm depth, which can be explained by the annual accumulation of crop residues near the soil surface (Figure 2A).

Concentrations of TWSA N (g N kg$^{-1}$ aggregated soil) combined across the four smallest aggregate-size classes (i.e., 0.25- to 4-mm diameter range) was affected by tillage and soil depth when combined across rotations ($P < 0.001$; Table 3). The TWSA N concentration was 40% greater in the NT/0- to 5-cm (3.6 g kg$^{-1}$) combination than that in the T/0- to 5-cm (2.5 g kg$^{-1}$) combination, but was 51% greater in the T/5- to 10-cm (1.5 g kg$^{-1}$) combination than that in the NT/5- to 10-cm (1.0 g kg$^{-1}$) combination (Figure 2A). These results also coincide with the Xu et al. (2007) study that reported comparable results for N concentrations in these respective tillage-depth combinations (Figure 2A). Overall, the NT/0- to 5-cm combination had the largest and the NT/5- to 10-cm combination had the smallest concentration of N in the macroaggregated soil.

Similar to the C and N concentrations, the TWSA C:N ratios were affected by tillage and soil depth ($P = 0.031$; Table 3). The TWSA C:N ratio in the T/0- to 5-cm (15.2) combination was greater than that in the T/5- to 10-cm (14.0) combination, and the TWSA C:N ratio in both depths under T was greater than that in the NT/0- to 5-cm (11.7) and NT/5- to 10-cm (12.2) combinations (Figure 2B). However, the TWSA C:N ratios between soil depths did not differ
under the NT treatment. The lower C:N ratios in NT as opposed to T is similar to a previous study that reported lower C:N ratios in macroaggregates up to 1.0-mm in diameter under minimal tillage systems compared to that in frequent tillage operations (Kasper et al., 2009).

Water-Stable Aggregates among Size Classes

When separated among four aggregate-size classes (i.e., 0.25- to 4-mm range), WSA C concentrations (g C kg\(^{-1}\) aggregated soil) differed among soil depth and size class combinations \((P = 0.032; \text{ Table 4})\). Averaged across rotation and tillage, the WSA C concentration was significantly greater in the 0.5- to 1-mm (45.7 g kg\(^{-1}\)) and 1- to 2-mm (49.8 g kg\(^{-1}\)) size classes than in other size classes in the top 5 cm, with the 2- to 4-mm (27.3 g kg\(^{-1}\)) size class having the lowest WSA C concentration (Figure 3). The 2- to 4-mm size class also had the smallest WSA C concentration (9.2 g kg\(^{-1}\)) than the other size classes, which did not differ in the 5- to 10-cm depth (Figure 3). These results are similar to that reported in a R(W) rotation in a sandy loam soil in India, which showed the greatest concentration of WSA C in the 0.5-to 1-mm and 1- to 2-mm size classes in the top 10 cm under various rice-straw compost and fertilizer treatments (Sodhi et al., 2009). In another study conducted on a sandy loam soil in India on a rice-barley (\textit{Hordeum vulgare}) rotation, Kushwaha et al. (1999) reported that aggregates greater than 0.3 mm in diameter had a greater C concentration than aggregates with a smaller diameter in the top 10 cm of soil. In contrast to these results, a previous study examining dry-land crops in rotation for six years, including wheat, sugar beet (\textit{Beta vulgaris}), corn, and barley, reported that WSA C concentration in macroaggregates (i.e., > 0.25-mm) was negatively affected by tillage in size classes ranging from 0.25- to 1.0-mm (Kasper et al., 2009). However, there were no tillage
effects that were directly connected to C concentrations in various aggregate size-classes in this study.

Similar to the TWSA C concentrations, when averaged across rotations and aggregate-size classes, the WSA C concentration was also affected by tillage and soil depth ($P = 0.002$; Table 4). The WSA C concentration was unaffected by the tillage treatment imposed in the top 5 cm (T, 39.0 g kg$^{-1}$; NT 40.5 g kg$^{-1}$; Figure 4A). However, the WSA C concentration in the top 5 cm under both tillage treatments was 2 to 3.4 times greater than that in the 5- to 10-cm depth in each respective tillage treatment. In addition, the WSA C concentration was almost two times greater under T (20.8 g kg$^{-1}$) than under NT (11.9 g kg$^{-1}$) in the 5- to 10-cm depth (Figure 4A).

In contrast to the TWSA C concentration, the WSA C concentration was affected by crop rotation when averaged across tillage, depth, and aggregate-size classes ($P = 0.006$; Table 4). The WSA C concentration was greater under continuous rice (34.7 g kg$^{-1}$) than under all other rotations (23.2 to 28.8 g kg$^{-1}$) except RS (29.9 g kg$^{-1}$; Figure 4B). Numerically, the WSA C concentration was 16 to 49% greater under continuous rice than under the other crop rotations (Figure 4B).

When separated among four aggregate-size classes (i.e., 0.25- to 4-mm range) and averaged across tillage treatments, WSA N concentrations (g N kg$^{-1}$ aggregated soil) differed among rotation, soil depth, and aggregate-size classes ($P = 0.013$; Table 4). The WSA N concentration was greater in the R/2- to 4-mm combination in the top 5 cm (5.6 g kg$^{-1}$) than in all other rotation-depth combinations in the same aggregate-size class (0.5 to 2.1 g kg$^{-1}$; Figure 5). However, with the exception of the R/0- to 5-cm combination, the WSA N concentration was numerically smaller in the 2- to 4-mm size class within the other rotation-depth treatment combinations when compared to the other size classes. In general, the top 5 cm had a greater
WSA N concentration in all aggregate-size classes ranging from 0.25- to 2-mm than in the 5- to 10-cm depth (Figure 5).

Similar to TWSA N concentration, the WSA N concentration was also affected by tillage and soil depth treatment combinations \( (P < 0.001; \text{Table 4}) \). When averaged across rotations and aggregate-size classes, the WSA N concentration was greater in the NT/0- to 5-cm (3.5 g kg\(^{-1}\)) combination than in all other tillage-depth combinations (Figure 4A). The WSA N concentration in the T/0- to 5-cm (2.6 g kg\(^{-1}\)) combination was greater than that under both tillage treatments in the 5- to 10-cm depth, with the T/5- to 10-cm (1.5 g kg\(^{-1}\)) combination being greater than that in the NT/5- to 10-cm (1.0 g kg\(^{-1}\)) combination (Figure 4A).

In contrast to the TWSA N concentration, when averaged across depth and aggregate-size classes, the WSA N concentration was affected by tillage and rotation treatment combinations \( (P = 0.029; \text{Table 4}) \). The WSA N concentration was 36% greater under the RCS rotation and 31% greater under the R(W)S(W) rotation under NT than under T (Figure 6). However, WSA N concentration did not differ between tillage treatments within the other rotations. When comparing among rotations, continuous rice had a greater WSA N concentration under both T and NT than that in the R(W) rotation under both tillage treatments (Figure 6).

Carbon:N ratios differed among aggregate-size classes \( (P < 0.001; \text{Table 4}) \). When averaged across all other treatment factors, C:N ratios were greater in the 1- to 2-mm (14.6) and the 2- to 4-mm (14.1) size classes than in the other two smaller size classes, with the WSA C:N ratios decreasing as aggregate-size class decreased in the smaller two class sizes (Figure 7).

Similar to the TWSA C:N ratio, when averaged across rotations and aggregate-size classes, the C:N ratios also differed among tillage and depth treatment combinations \( (P = 0.014; \text{Table 4}) \). The C:N ratio was substantially greater in the T/0- to 5-cm (15.1) combination than in
all other tillage-depth combinations (Figure 8A). Furthermore, the C:N ratio in the T/5- to 10-cm
(14.0) combination was greater than that under NT in both depths, while the C:N ratios in the
NT/0- to 5-cm (11.7) and NT/5- to 10-cm (12.2) combinations did not differ (Figure 8A).

In contrast to the TWSA C:N ratio, when averaged across tillage, depth, and aggregate-
size classes, WSA C:N ratios also differed among crop rotations ($P = 0.050$; Table 4). Crop
rotations with wheat grown during the winter every year [i.e., R(W) and R(W)S(W)] had
significantly lower C:N ratios than all rotations except RS, whereas the double-cropped rotations
[i.e., R(W), R(W)S(W)] had C:N ratios of approximately 12.5 with all other crop rotations
having a mean C:N ratio of 13.6 (Figure 8B). This may be explained by the more recent
application of N fertilizer and the deposition of fresh plant residues into the soil from the winter
wheat rotations. Soil samples were collected in the spring following winter wheat harvest for
WSA assessment, whereas all other rotations had been fallow for the winter. This would provide
the microbial population a longer time period to utilize and tie up the inner-aggregate nitrogen
from crop residues left on the surface or incorporated into the soil from the previous fall.

**Composite-Soil C and N Concentrations and C:N Ratios**

Composite-soil, made up of soil particles and microaggregates ≤ 0.25-mm in diameter, C
and N concentrations differed between soil depths (C, $P = 0.007$; N, $P = 0.005$; Table 5). When
averaged across tillage and rotation treatments, composite-soil C concentration in the top 5 cm
(11.0 g kg$^{-1}$) was 75% greater than that in the 5- to 10-cm depth (6.3 g kg$^{-1}$). Composite-soil N
concentration was 65% greater in the top 5 cm (1.1 g kg$^{-1}$) than that in the 5- to 10-cm depth (0.7
g kg$^{-1}$). Carbon and N concentrations for the macroaggregated soil (i.e., > 0.25-mm in diameter)
and the non-macroaggregated soil (i.e., microaggregates and soil particles ≤ 0.25-mm in diameter) were generally greater in the top 5 cm.

Averaged across rotations and soil depths, composite-soil C:N ratios differed among tillage treatments \((P = 0.048; \text{ Table 5})\). The composite-soil C:N ratio under T (9.8) was 7% greater than that under the NT treatment (9.1). Similar to the TWSA and WSA C and N concentrations, composite-soil C:N also differed among soil depths when averaged across tillage and rotations \((P = 0.020; \text{ Table 5})\). Composite-soil C:N ratios were 10% greater in the top 5 cm (9.9) than that in the 5- to 10-cm depth (9.0). Carbon:N ratios for the macroaggregated soil (i.e., > 0.25-mm in diameter) and the non-macroaggregated soil (i.e., microaggregates and soil particles ≤ 0.25-mm) were both greater under T and in the top 5 cm than that under NT and in the 5- to 10-cm depth.

**Aggregate C and N Contents**

*Total Water-Stable Aggregates*

Averaged across rotations, TWSA C \((P = 0.002)\) and N \((P = 0.002)\) contents, summed across the four smallest aggregate-size classes (i.e., 0.25- to 4-mm range), differed between tillage and depth treatment combinations (Table 3). The TWSA C and N contents in the NT/0- to 5-cm treatment combination were 3 to 6 times greater than all other tillage-depth combinations, which did not differ among one another (Figure 9A). Results for TWSA C and N contents were similar to Six et al. (1999; 2000b) who reported that WSA C and N contents were greater in the top 5 cm rather than in the 5- to 20-cm depth across T and NT treatments of agriculturally managed soil, which is likely due to the concentration of annually added crop residues nearer the surface than at deeper soil depths. The differences between the C contents in the top 5 cm of soil
under T and NT practices can be explained by the accepted notion that soils degraded through excessive tillage tend to be lower in SOM, a key component in soil aggregation, in the near-surface soil due to an increased amount of exposed surface area, which facilitates aerobic decomposition (DeBusk et al., 2001). Since C makes up nearly half of the mass of SOM (Montgomery et al., 2000), cultivating the land greatly influences the dynamics and storage of SOC, including the amount of C that is emitted from the soil due to the aeration of the SOM (Paustian et al, 1995; Reicosky et al., 1995). Thus, the elimination of tillage results in an overall increase of C stored in the near-surface soil (Lal and Kimble, 1997; Doa, 1998; Kern and Johnson, 1993; Dick et al., 1998), which also influences N cycling (Shaffer and Ma, 2001). In an 18-year study on a R(W) rotation in China, SOC and N were also greater in the top 5 cm in NT compared with T (Xu et al., 2007).

Averaged across tillage and depth treatments, TWSA C content differed among crop rotations ($P = 0.021$; Table 3). The TWSA C content was greater in the RC (128 g m$^{-2}$) rotation than in the R(W) (102 g m$^{-2}$), R(W)S(W) (83 g m$^{-2}$), and RSC (97 g m$^{-2}$) rotations. Furthermore, TWSA C content in the R (113 g m$^{-2}$) and RS (109 g m$^{-2}$) rotations were greater than that in the R(W)S(W) rotation (Figure 9B). Total WSA C contents were greatly influenced by the actual mass of TWSA present in the rotation, whereas the inclusion of wheat into double-cropped rice rotations [i.e., R(W) and R(W)S(W)] did not necessarily increase the quantity of WSA as much as the respective mono-cropped systems (i.e., R and RS), despite the increase of annual inputs of crop residues. The double-cropped R(W)S(W) rotation had a smaller TWSA C content than that in the mono-cropped RS rotation. However, TWSA C concentration in the R(W) and R rotations did not differ (Figure 9B).
The TWSA N contents differed between tillage-rotation treatment combinations when averaged across soil depth ($P = 0.021$; Table 3). The TWSA N content was greater under NT than under T in all rotations, with rotations including corn (i.e., RC, 14.2 g m$^{-2}$; RCS, 13.3 g m$^{-2}$) displaying greater TWSA N contents than any other crop rotation under NT. Numerically, rotations including corn (i.e., RC and RCS) had the greatest TWSA N contents and rotations including wheat [i.e., R(W), 10.8 g m$^{-2}$; R(W)S(W), 10.1 g m$^{-2}$] displayed the lowest TWSA N contents under NT (Figure 9C). Few differences in TWSA N content were evident under T in the tillage-rotation treatment combinations. However, RS (5.9 g m$^{-2}$), RC (6.1 g m$^{-2}$), and R(W) (6.5 g m$^{-2}$) had greater TWSA N contents than RCS (3.4 g m$^{-2}$; Figure 9C).

Averaged across tillage treatments, TWSA N content also differed among rotation and soil depth treatment combinations ($P = 0.041$; Table 3). The TWSA N content was greater in the top 5 cm than the 5- to 10-cm depth in all rotations (Figure 9D). Among the crop rotations in the top 5 cm, RC (16.1 g m$^{-2}$) and RCS (14.1 g m$^{-2}$) rotations had greater TWSA N contents than any other rotation-depth treatment combination. The only difference in TWSA N content between rotations in the 5- to 10-cm depth was in the R and RCS rotations, where the TWSA N content under continuous rice (5.3 g m$^{-2}$) was two times greater than that under the RCS rotation (2.6 g m$^{-2}$).

Water-Stable Aggregates among Size Classes

When separated among the four aggregate-size classes, WSA C content (g C m$^{-2}$ soil) was affected by tillage, rotation, soil depth, and aggregate-size class ($P < 0.001$; Table 4). The WSA C content in the 0.25- to 0.5-mm size class was at least 51% greater in the NT/RS/0- to 5-cm than any other tillage-rotation-depth-size class treatment combination (Figure 10).
Furthermore, the NT/0- to 5-cm combination within each rotation had a greater WSA C content in the 0.25- to 0.5-mm size class than in any other tillage-depth-size class combination. In the 0.5- to 1-mm and 1- to 2-mm size classes, the RC and RCS rotations had a greater WSA C content in the NT/0- to 5-cm combination than in all other tillage-rotation-depth combinations (Figure 10). Under NT, size classes in the 0.25- to 2.0-mm range had a greater WSA C content within the top 5 cm compared to the 5- to 10-cm depth for all crop rotations. There were no differences in WSA C content for the 2- to 4-mm size class within and across tillage-rotation-depth treatment combinations.

Similar to WSA C content, WSA N content (g N m$^{-2}$ soil) was affected by tillage, rotation, soil depth, and aggregate-size class ($P < 0.001$; Table 4). The WSA N content was also greater in the NT/RS/0- to 5-cm/0.25- to 0.5-mm than in all other tillage-rotation-depth-size treatment combinations. Within each rotation, the 0.25- to 0.5-mm and 0.50- to 1.0-mm size classes under the NT/0- to 5-cm combination had greater WSA N contents than that in the same respective size classes in other tillage-depth treatment combinations. However, there were few significant differences in the remaining tillage-depth combinations within and across rotations for the two smallest size classes (Figure 11). In the 0.5- to 1-mm size class, the NT/RC/0- to 5-cm combination had the overall greatest WSA N content than that in the other tillage-rotation-depth combinations in the same size class. For the 1- to 2-mm size class, both the RC and RCS in the NT/0- to 5-cm combination had a greater WSA N content than that in the other tillage-rotation-depth treatment combinations. Similar to WSA C content, there were no differences in WSA N content in the 2- to 4-mm size class within or across tillage-rotation-depth treatment combinations.
Composite-Soil C and N Contents

Carbon contents (g C m$^{-2}$ soil) for the non-macroaggregated (i.e., ≤ 0.25-mm in diameter) composite-soil samples differed among tillage, rotation, and soil depths ($P < 0.001$; Table 5). Unlike the composite-soil C concentrations, which only differed between soil depths, the composite-soil C contents were generally greater under NT in the 0- to 5-cm depth and greater under T at the 5- to 10-cm depth (Figure 12A). Although composite-soil content under continuous rice and RC rotations did not differ between tillage treatments in the top 5 cm, C contents in the RS, R(W), R(W)S(W), and RCS rotations were approximately 1.5 times greater under NT than that in the same rotations under T (Figure 12A). With the exception of continuous rice, which had 1.3 times greater composite-soil C content under NT than that under T in the 5-to 10-cm depth, all rotations had a greater composite-soil C content under T than that in the same rotations under NT in the 5-to 10-cm depth. Also in the 5- to 10-cm depth, the RS, RC, R(W), R(W)S(W), and RCS rotations had approximately 1.4 times greater C contents under T than that in the same rotations under NT (Figure 12A). When comparing among rotations under the same tillage treatment and in the same depth, continuous rice (764 g m$^{-2}$) and R(W)S(W) (762 g m$^{-2}$) had greater composite-soil C contents than all other rotations (637 to 725 g m$^{-2}$) under NT and RC (718 g m$^{-2}$) had a greater C content than all other rotations (423 to 610 g m$^{-2}$) under T in the top 5 cm. Furthermore, R(W) (436 g m$^{-2}$), R(W)S(W) (413 g m$^{-2}$), and continuous rice (407 g m$^{-2}$) had greater composite-soil C contents when compared to the other rotations (367 to 385 g m$^{-2}$) under T in the 5- to 10-cm depth. However, with the exception of a greater composite-soil C content in the continuous rice rotation (773 g m$^{-2}$), there were no differences among any other rotations in the NT/5- to 10-cm treatment combination (276 to 300 g m$^{-2}$; Figure 12A). These results suggest that while rotations including wheat [i.e. R(W) and R(W)S(W)] had at least
numerically lower macroaggregate (> 0.25-mm in diameter) C contents, it appears that these rotations may contain more microaggregate (≤ 0.25-mm in diameter) C than other rotations. Consequently, the results also suggest that double-cropped rice-based crop rotations have a greater concentration of microaggregates, and associated microaggregate C, than the other monocropped systems.

Similar to composite-soil C contents, N contents (N m\(^{-2}\) soil) for the non-macroaggregated (i.e., ≤ 0.25-mm in diameter) soil also differed among tillage, rotation, and soil depths (\(P < 0.001\); Table 5). Also similar to composite-soil C contents, N contents were generally greater under NT in the 0- to 5-cm depth and greater under T at the 5- to 10-cm depth (Figure 12B). All rotations had a significantly greater N content under NT than that under T in the top 5 cm. With the exception of continuous rice, in which composite-soil N content was 1.8 times greater under NT than that under T in the 5-to 10-cm depth, all rotations had a greater composite-soil N content under T than that in the same rotations under NT in the 5-to 10-cm depth. When comparing among rotations under the same tillage treatment and in the same depth, R(W)S(W) (76.9 g m\(^{-2}\)) and RC (76.0 g m\(^{-2}\)) had greater N contents than the RS (72.0 g m\(^{-2}\)) and RCS (68.7 g m\(^{-2}\)) rotations under NT and RC (71.8 g m\(^{-2}\)) had a greater N content than all other rotations (42.9 to 55.7 g m\(^{-2}\)) under T in the top 5 cm. In the 5- to 10-cm depth, R(W) (45.3 g m\(^{-2}\)) and R(W)S(W) (44.2 g m\(^{-2}\)) had greater N contents than all other rotations (39.6 to 40.6 g m\(^{-2}\)) under T. Similar to composite-soil C contents, with the exception of a greater N content in the continuous rice rotation (72.1 g m\(^{-2}\)), there were no differences among any of the other rotations in the NT/5- to 10-cm treatment combination (33.9 to 36.9 g m\(^{-2}\); Figure 12B).
Bulk-Soil C and N Contents and Content Partitioning

Bulk Soil C and N Contents

Bulk-soil C content (g C m$^{-2}$ soil), which represents the sum of both the TWSA and the composite-soil C contents, differed among tillage, rotation, and soil depths ($P < 0.001$; Table 6). The NT/0- to 5-cm combination had greater bulk-soil C content in all rotations than other tillage-depth treatment combinations, with the greatest C content in the RC (997 g m$^{-2}$), R (996 g m$^{-2}$), and RS (963 g m$^{-2}$) rotations and the smallest C content in the RCS (903 g m$^{-2}$) and R(W) (897 g m$^{-2}$) rotations (Figure 13). In the T/0- to 5 cm combination, the RC (812 g m$^{-2}$) rotation had the greatest bulk-soil C content and the RCS (481 g m$^{-2}$) rotation had the smallest. When comparing tillage-depth combinations in the top 5 cm, the R, RC, and RS rotations generally had the greatest bulk-soil C content under both T and NT, whereas the R(W), R(W)S(W), and RCS rotations generally had the smallest C contents. In the T/5- to 10-cm combination, the R(W) (511 g m$^{-2}$) rotation had the greatest C content when compared to other crop rotations, and like the NT/0- to 5-cm and T/0- to 5-cm combinations, the RCS (406 g m$^{-2}$) rotation had the smallest bulk-soil C content in the T/5- to 10-cm combination. With the exception of continuous rice (830 g m$^{-2}$), the NT/5- to 10-cm combination had the smallest bulk-soil C content in all rotations than in any other tillage-depth combination. When comparing between depths under NT, the bulk-soil C content in the top 5 cm was roughly three times greater than that in the 5- to 10-cm depth in all rotations but continuous rice, which was only two-fold greater in the top 5 cm. Other than in continuous rice, there were no differences in bulk-soil C content among any other rotation (305 to 335 g m$^{-2}$) in the NT/5- to 10-cm combination (Figure 13).

Similar to bulk-soil C content, the bulk-soil N content (g N m$^{-2}$ soil), which represented the sum of both the TWSA and the composite-soil N contents, also differed among tillage,
rotation, and soil depths \((P < 0.001; \text{Table 6})\). The NT/0- to 5-cm treatment combination showed a greater N content in all rotations when compared to other tillage-depth combinations (Figure 14). In the NT/0- to 5-cm combination, RC \((101 \text{ g m}^{-2})\) had a greater bulk-soil N content than all other rotations \((91.0 \text{ to } 93.4 \text{ g m}^{-2})\), which did not differ among one another. In the T/0- to 5 cm combination, bulk-soil N content was greater in the RC \((78.6 \text{ g m}^{-2})\) rotation and smallest in the RCS \((47.0 \text{ g m}^{-2})\) rotation when compared to the other crop rotations. In the T/5- to 10-cm combination, the R(W) \((51.6 \text{ g m}^{-2})\) and R(W)S(W) \((48.2 \text{ g m}^{-2})\) rotations had the greatest bulk-soil N content compared to other crop rotations \((42.4 \text{ to } 46.2 \text{ g m}^{-2})\), which did not differ from one another. With the exception of continuous rice \((77.1 \text{ g m}^{-2})\), the NT/5- to 10-cm combination had the smallest bulk-soil N contents in all rotations than in any other tillage-depth combination.

When comparing between depths under NT, bulk-soil N content in the top 5 cm was roughly 2.5 times greater than that in the 5- to 10-cm depth in all rotations but continuous rice, which was only 1.2 times greater in the top 5 cm. Other than the continuous rice, there were no differences in N content among any other rotation \((37.0 \text{ to } 40.2 \text{ g m}^{-2})\) in the NT/5- to 10-cm combination (Figure 14).

**Bulk-Soil C and N Content Partitioning**

The macroaggregated-soil (i.e., TWSA; \(> 0.25 \text{ mm in diameter}\)) C content represented between 7 (NT/R/5- to 10-cm) and 30\% (NT/RCS/0- to 5-cm) of the total C content of bulk-soil for each tillage-rotation-depth treatment combination (Figure 13). In all rotations, the NT/0- to 5-cm combination had the greatest percentage of macroaggregated soil contributing to the bulk-soil C content when compared to other tillage-depth combinations. The TWSA C content in the NT/0- to 5-cm combination represented between 19 \([R(W)S(W)]\) and 30\% (RCS) of the bulk-
soil C content across rotations, whereas all other tillage-rotation-depth treatment combinations represented between 7 (NT/R/5- to 10-cm) to 20% (T/RC/5- to 10-cm) of the bulk-soil C content (Figure 13). In general, the contribution of the TWSA to bulk-soil C content followed the pattern of NT/0- to 5-cm > T/5- to 10-m > T/0- to 5-cm > NT/5- to 10-cm within rotations (Figure 13).

Similar to the magnitude of TWSA C content partitioning, the TWSA N content represented between 6 (T/RCS/5- to 10-cm) and 26% (NT/RCS/0- to 5-cm) of the bulk-soil N content for each tillage-rotation-depth treatment combination (Figure 14). In all rotations, the NT/0- to 5-cm combination represented 18 [R(W)S(W)] to 26% (NT/RCS/0- to 5-cm) of the bulk-soil N content and all other tillage-rotation-depth combinations represented between 6 (T/RCS/5- to 10-cm) and 12% [T/R(W)/0- to 5-cm] of the bulk-soil N content within rotations (Figure 14). Also similar to TWSA C content partitioning, the contribution of TWSA N content to bulk-soil N content generally followed the pattern of NT/0- to 5-cm > T/5- to 10-m > T/0- to 5-cm > NT/5- to 10-cm within rotations (Figure 14).

**Summary and Conclusions**

This study demonstrated that after 10 years of consistent soil and crop management, the concentration of soil macroaggregates and their associated C and N contents were affected by tillage, rice-based crop rotation, and soil depth. In contrast to that hypothesized, only the NT treatment had a greater TWSA concentration in the top 5 cm. However, the TWSA concentration in the top 5 cm under T was often at least numerically greater than that in the 5- to 10-cm depth within a rotation. The TWSA C and N contents were both greater under NT in the top 5 cm than the same depth under T. However, there were no differences in the C and N contents between tillage treatments in the 5- to 10-cm depth. Since crop residues are concentrated at the surface
under NT, macroaggregate formation appears to be proportional to the quantity of crop residue at or near the soil surface, which subsequently increases the content of aggregated soil C and N. However, the mixing action caused from tillage clearly has increased the decomposition of crop residues to result in more uniformity of aggregated soil C and N contents in the top 10 cm.

As hypothesized, rotations that included corn and increased frequencies of rice, with the exception of R(W), had a greater TWSA concentration in the top 5 cm under NT compared to that in the other crop rotations. However, no differences in TWSA concentration were noticeable in the 5- to 10-cm depth in any crop rotation. Furthermore, only the RC rotation had a greater TWSA C content than the R(W), R(W)S(W), and RCS rotations when averaged across tillage and depth, whereas R, RC, and RCS rotations had a greater TWSA N content under NT compared to the other rotations.

The WSA concentration in the various size classes and their C and N contents generally increased as aggregate diameter decreased, particularly in the smaller size classes. Aggregate C and N concentrations were greatest in the aggregates ranging from 0.25- to 2-mm in diameter in both the top 5 cm and the 5- to 10-cm depths compared to aggregates > 2-mm.

Overall, this long-term experiment indicated that inputs from high-residue producing crops and soil manipulation from tillage significantly affect the dynamics of soil aggregation and C and N storage in rice-based crop rotations. However, there was not strong evidence to suggest that the frequency of periodic saturation of agronomic soils (i.e., continuous rice rotation) greatly affected the frequency of soil aggregates and their associated C and N contents when compared to crop rotations which were flooded less frequently (i.e., 2- and 3-year rice rotations with other upland crops). The results obtained from this study can help contribute to the ongoing effort of
studying the sustainability of rice cropping in the United States by enabling the direct quantification of C and N storage within soil aggregates.

**Acknowledgments**

This research was partially funded by the Arkansas Rice Research and Promotion Board. Field assistance provided by Terry Sells and Daniel McCarty is gratefully acknowledged.
Literature Cited


Table 1. Summary of the annual nitrogen (N), phosphorous (P), and potassium (K) added to corn, soybean, rice, and wheat to comprise the optimal soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Soil Amendment (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Corn</td>
<td>337</td>
</tr>
<tr>
<td>Soybean</td>
<td>0</td>
</tr>
<tr>
<td>Rice †</td>
<td>168</td>
</tr>
<tr>
<td>Wheat</td>
<td>168</td>
</tr>
</tbody>
</table>

† Rice also received 11 kg ha⁻¹ of zinc at each fertility level.
Table 2. Summary of the crop rotations and the number of crops grown in the respective rotations during the 10-yr study period (1999-2009) at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Number of Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rice</td>
</tr>
<tr>
<td>Continuous Rice</td>
<td>10</td>
</tr>
<tr>
<td>Rice-Soybean</td>
<td>5</td>
</tr>
<tr>
<td>Rice-Corn</td>
<td>5</td>
</tr>
<tr>
<td>Rice-(Wheat)</td>
<td>10</td>
</tr>
<tr>
<td>Rice-(Wheat)-Soybean-(Wheat)</td>
<td>5</td>
</tr>
<tr>
<td>Rice-Corn-Soybean</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 3. Analysis of variance summary of the effects of tillage, crop rotation, and soil depth on total water-stable aggregate (TWSA; > 0.25-mm) concentration (g aggregates kg\(^{-1}\) soil), TWSA carbon (C) concentration (C Conc.; 0.25- to 4-mm diameter; g C kg\(^{-1}\) aggregated soil), TWSA nitrogen (N) concentration (N Conc.; 0.25- to 4-mm diameter; g N kg\(^{-1}\) aggregated soil), C:N ratio, and TWSA C and N contents (0.25- to 4-mm diameter; g m\(^{-2}\) soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Interactions that were not significant at the 0.05 level are represented by NS.

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>TWSA</th>
<th>C Conc.</th>
<th>N Conc.</th>
<th>C:N</th>
<th>C Content</th>
<th>N Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>0.014</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>0.011</td>
<td>0.006</td>
</tr>
<tr>
<td>Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.022</td>
<td>NS</td>
</tr>
<tr>
<td>Tillage*Rotation</td>
<td>0.031</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.021</td>
</tr>
<tr>
<td>Depth</td>
<td>0.015</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>NS</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Depth*Tillage</td>
<td>0.007</td>
<td>0.010</td>
<td>&lt; 0.001</td>
<td>0.031</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Depth*Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.041</td>
</tr>
<tr>
<td>Depth<em>Tillage</em>Rotation</td>
<td>0.022</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 4. Analysis of variance summary of the effects of tillage, crop rotation, soil depth, and aggregate-size class (0.25- to 0.5, 0.5- to 1-, 1- to 2-, 2- to 4-, and > 4-mm diameter) on water-stable aggregate (WSA) concentration (g aggregates kg⁻¹ soil), WSA carbon (C) concentration (C Conc.; g C kg⁻¹ aggregated soil), WSA nitrogen (N) concentration (N Conc.; g N kg⁻¹ aggregated soil), WSA C:N ratio, and WSA C and N contents (g m⁻² soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Interactions that are not significant at the 0.05 level are represented by NS.

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>WSA</th>
<th>C Conc.</th>
<th>N Conc.</th>
<th>C:N</th>
<th>C Content</th>
<th>N Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>0.014</td>
<td>0.019</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>0.010</td>
<td>0.005</td>
</tr>
<tr>
<td>Rotation</td>
<td>NS</td>
<td>0.006</td>
<td>0.012</td>
<td>0.050</td>
<td>0.033</td>
<td>NS</td>
</tr>
<tr>
<td>Tillage*Rotation</td>
<td>0.031</td>
<td>NS</td>
<td>0.029</td>
<td>NS</td>
<td>NS</td>
<td>0.036</td>
</tr>
<tr>
<td>Depth</td>
<td>0.015</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>NS</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Depth*Tillage</td>
<td>0.007</td>
<td>0.002</td>
<td>&lt; 0.001</td>
<td>0.014</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>Depth*Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.041</td>
</tr>
<tr>
<td>Depth<em>Tillage</em>Rotation</td>
<td>0.022</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Size</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Size*Tillage</td>
<td>&lt; 0.001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Size*Rotation</td>
<td>&lt; 0.001</td>
<td>NS</td>
<td>0.025</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Size*Depth</td>
<td>&lt; 0.001</td>
<td>0.032</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Size<em>Tillage</em>Rotation</td>
<td>0.002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Size<em>Tillage</em>Depth</td>
<td>&lt; 0.001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Size<em>Rotation</em>Depth</td>
<td>0.001</td>
<td>NS</td>
<td>0.013</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Size<em>Tillage</em>Rotation*Depth</td>
<td>0.004</td>
<td>- †</td>
<td>- †</td>
<td>- †</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

† P-values for the C concentration, N concentration, and C:N ratios were unable to be determined due an insufficient number of samples to conduct the four-factor analysis.
Table 5. Analysis of variance summary of the effects of tillage, crop rotation, and soil depth on composite-soil (≤ 0.25-mm diameter) carbon (C) concentration (C Conc.; g C kg\(^{-1}\) soil), nitrogen (N) concentration (N Conc.; g N kg\(^{-1}\) soil), C:N ratio, C content (g C m\(^{-2}\) soil), and N content (g N m\(^{-2}\) soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Interactions that are not significant at the 0.05 level are represented by NS.

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>C Conc.</th>
<th>N Conc.</th>
<th>C:N</th>
<th>C Content</th>
<th>N Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>NS</td>
<td>NS</td>
<td>0.048</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Tillage*Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Depth</td>
<td>0.007</td>
<td>0.005</td>
<td>0.020</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Depth*Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Depth*Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Depth<em>Tillage</em>Rotate</td>
<td>- (^\dagger)</td>
<td>- (^\dagger)</td>
<td>- (^\dagger)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

\(^\dagger\) P-values for the C concentration, N concentration, and C:N ratios were unable to be determined due an insufficient number of samples to conduct the three-factor analysis.
Table 6. Analysis of variance summary of the effects of tillage, crop rotation, and soil depth on bulk-soil carbon (C) and N contents (g C m\(^{-2}\) soil) after 10 years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>C Content</th>
<th>N Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Tillage</td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Rotation</td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Tillage*Rotation</td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Depth</td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Depth*Tillage</td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Depth*Rotation</td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Depth<em>Tillage</em>Rotation</td>
<td>(&lt; 0.001)</td>
<td>(&lt; 0.001)</td>
</tr>
</tbody>
</table>
Figure 1. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregates (WSA) in various size classes (>0.25-mm diameter). The total water-stable aggregate (TWSA) concentration for each tillage-rotation-depth treatment combination is represented by the top of each bar [standard error = 7.9; least significant difference (LSD) = 18.8 to 23.0]. Individual WSA concentrations by size class are represented by the shaded segments within each bar (standard error = 2.4; LSD = 5.5 to 6.9). The LSD values for TWSA and WSA concentrations by size class vary depending on the treatment combinations being compared.
Figure 2. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) effects on the carbon (C) and nitrogen (N) concentration [A] and C:N ratio [B] of the total water-stable aggregates (TWSA; > 0.25-mm diameter). Different letters on bars within each panel for the same variable are significantly different at the 0.05 level.
Figure 3. Soil depth (0- to 5- and 5- to 10-cm) and aggregate-size class (0.25- to > 4-mm) effects on water-stable aggregate (WSA) carbon (C) concentration. Different letters on each bar are significantly different at the 0.05 level.
Figure 4. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) effects on WSA carbon (C) and nitrogen (N) concentration [A] and rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects on water-stable aggregate (WSA) C concentration [B]. Different letters on bars within each panel for the same variable are significantly different at the 0.05 level.
Figure 5. Rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregate (WSA) nitrogen (N) concentration [standard error = 0.28; least significant difference (LSD) = 0.60].
Figure 6. Tillage [conventional tillage (T) and no-tillage (NT)] and rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects on water-stable aggregate (WSA) nitrogen (N) concentration. Different letters on each bar are significantly different at the 0.05 level.
Figure 7. Soil aggregate-size class effects on the water-stable aggregate (WSA) carbon and nitrogen (C:N) ratio. Different letters on each bar are significantly different at the 0.05 level.
Figure 8. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) treatment combination [A] and rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects [B] on the water-stable aggregate (WSA) carbon and nitrogen ratio (C:N). Different letters on each bar within each panel are significantly different at the 0.05 level.
Figure 9. Tillage [conventional tillage (T) and no-tillage (NT)] and soil depth (0- to 5- and 5- to 10-cm) effects on total water-stable aggregate (TWSA) carbon (C) and nitrogen (N) content [A]; rotation [rice (R), soybean (S), wheat (W), and corn (C)] effects on TWSA C content [B]; tillage and rotation effects on TWSA N content [C]; and rotation and soil depth effects on TWSA N content [D] after 10 years of consistent management. Different letters on bars within each panel for the same variable are significantly different at the 0.05 level.
Figure 10. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregate (WSA) carbon (C) content. The total water-stable aggregate (TWSA) C content for each tillage-rotation-depth treatment combination is represented by the top of each bar. The WSA C content by size class is represented by the shaded segments within each bar [standard error = 5.7; least significant difference (LSD) = 11.9 to 16.0]. The LSD values vary depending on the treatment combinations being compared.
Figure 11. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], soil depth (0- to 5- and 5- to 10-cm), and aggregate-size class effects on water-stable aggregate (WSA) nitrogen (N) content. The total water-stable aggregate (TWSA) N content for each tillage-rotation-depth treatment combination is represented by the top of each bar. The WSA N content by size class is represented by the shaded segments within each bar [standard error = 0.5; least significant difference (LSD) = 1.0 to 1.4]. The LSD values vary depending on the treatment combinations being compared.
Figure 12. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], and soil depth (0- to 5- and 5- to 10-cm) effects on composite-soil (≤ 0.25-mm in diameter) carbon (C) [A] and nitrogen (N) [B] contents. The composite-soil C and N contents are represented by the shaded segment within each bar [standard error = 11.4 (C) and 1.2 (N); least significant difference (LSD) = 19.4 to 32.5 (C) and 1.9 to 3.3 (N)]. The LSD values vary depending on the treatment combinations being compared.
Figure 13. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], and soil depth (0- to 5- and 5- to 10-cm) effects on bulk-soil carbon (C) content. The bulk-soil C content for each tillage-rotation-depth treatment is represented by the top of each bar [standard error = 13.8; least significant difference (LSD) = 31.3 to 44.6]. The total water-stable aggregated soil (> 0.25 mm in diameter; TWSA) and composite-soil (≤ 0.25 mm in diameter) C contents are represented by the shaded segments within each bar. The LSD values for the bulk-soil vary depending on the treatment combinations being compared.
Figure 14. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), wheat (W), and corn (C)], and soil depth (0- to 5- and 5- to 10-cm) effects on bulk-soil nitrogen (N) content. The bulk-soil N content for each tillage-rotation-depth treatment is represented by the top of each bar [standard error = 1.2; least significant difference (LSD) = 2.5 to 3.9]. The total water-stable aggregated soil (> 0.25 mm in diameter; TWSA) and composite-soil (≤ 0.25 mm in diameter) N contents are represented by the shaded segments within each bar. The LSD values for the bulk-soil vary depending on the treatment combinations being compared.
CHAPTER 3

LONG-TERM RICE ROTATION, TILLAGE, AND FERTILITY EFFECTS ON CHEMICAL PROPERTIES IN A SILT-LOAM SOIL
Long-Term Rice Rotation, Tillage, and Fertility Effects on Chemical Properties in a Silt-Loam Soil

Abstract

A majority of the rice (*Oryza sativa* L.) produced in the United States is produced on alluvial soils in the Mississippi River Valley and adjacent areas in the lower coastal plain of Louisiana and Texas, or in the Sacramento River Valley of California. Over 40% of the total rice area harvested and rice grain produced in the United States occurs in the Mississippi River Delta region of eastern Arkansas. Rice is a staple grain of global importance, so ensuring the sustainability of rice production systems is vital to feeding a large portion of the world’s population and protecting their economic livelihoods. One of the key factors to accomplishing viable food-production systems is through the continual management and maintenance of proper soil fertility. Therefore, a study was conducted to evaluate the long-term effects of rice-based crop rotations [with corn (*Zea mays* L.), soybean (*Glycine max* L.), and winter wheat (*Triticum aestivum* L.)], tillage [conventional and no-tillage (NT)], and fertility treatments (optimal and sub-optimal) after 11 years (1999-2010) of consistent management on soil organic matter (SOM) content and a suite of other soil chemical properties [electrical conductivity (EC), pH, and Mehlich-3 extractable nutrient contents] in the top 10 cm of a Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf). The field study was conducted at the Rice Research and Extension Center near Stuttgart, Arkansas. Results revealed increases in SOM (14%) and extractable manganese (68 to 220%), iron (82%), and sodium (37 to 76%) contents in most tillage-fertility-rotation treatments over time. Furthermore, increases over time were also observed in phosphorous (four- to eight-fold) and potassium (two- to three-fold) contents in rotations with
wheat, and soil pH (9%) in the sub-optimal fertility regime. However, decreases over time were observed in soil EC (36 to 70%) and extractable sulfur (30%), calcium (22%), and copper (27%) contents in all treatment combinations, and zinc contents decreased two-fold for continuous rice. Soil organic matter was also 9% greater in NT and in the continuous rice-winter wheat rotation than in all other rotations evaluated after 11 years. Understanding the decadal effects of rice-based crop rotations and the associated management practices have on soil fertility will give insight to the longer-term sustainability of these systems so that they remain highly productive without detrimental effects to the environment and the soil resource.
Introduction

Rice (*Oryza sativa* L.) crops occupy 156 million hectares (USDA-FAS, 2012a) of soil around the world, which accounts for approximately 20% of the total grain production worldwide (USDA-FAS, 2012a). Rice cultivation in the United States gained popularity in the late 19th century when it was discovered that rice could be cultivated profitably by machinery on the prairies in the south-western part of Louisiana (Grist, 1959). After this discovery, rice agriculture continued to spread throughout the Mississippi River Delta region, and in the early 20th century commercial rice production began in California’s Sacramento Valley (Flach and Slusher, 1978; Maclean et al., 2002). Although rice only comprises less than 1% of the total cropland harvested in the US and roughly 2% of the global production (USDA-FAS, 2012b; USDA-NASS, 2012), rice generates roughly 3 billion dollars in revenues annually in the United States (USDA-NASS, 2012) and makes up 11% of the global rice export market (USDA-FAS, 2012b). Of the 1 million ha of rice planted and 8.4 million Mg of rice grain produced in the United States annually, over 44% of the total rice area (454,330 ha) and over 42% of the total grain production (3.5 million Mg) occurs in the Mississippi River Delta region of eastern Arkansas (USDA-NASS, 2012). In Arkansas, rice is grown in 40 of the 75 counties (Slaton, 2001), and with a production value of around 1 billion dollars, rice is ranked as the number one cash-crop commodity for farmers in the state (USDA-ERS, 2012; USDA-NASS, 2012). Therefore, ensuring the sustainability of rice production systems is vital to protecting the economic livelihood of the state of Arkansas and the rice production areas of the United States.

One of the key factors to accomplishing viable food production systems is through the continual management and maintenance of proper soil fertility. Rice production is unique from other agricultural row-crops in that the crop is usually grown under flood-irrigated conditions.
after about one month post-emergence, where the upper-most part of the soil profile is nearly to completely saturated (Norman et al., 2003). The management of flooded conditions during the growing period can greatly influence soil nutrient availability and cycling in the soil (Norman et al., 2003). Saturated conditions also substantially affect the decomposition rate of soil organic matter (SOM), in that the decomposition is slower during times of flooding. All SOM is predisposed to undergo decomposition in the soil, which is primarily attributed to breakdown processes conducted by bacteria and fungi (Scow, 1997; Wolf and Snyder, 2003). However, the rate at which microbes can decompose and cycle SOM depends on the location in the soil, type and age of the SOM, soil particle-size distribution, and nutrient content (Wolf and Snyder, 2003; Seiter and Horwath, 2004). These characteristics are added to the already present environmental factors influencing decomposition, such as soil moisture, temperature, aeration, and soil pH (Bayer, 1996; Alvarez and Lavado, 1998; Filcheva and Mitova, 2002).

Soil organic matter content is directly correlated with the organic nutrient content of the soil, which contains 90 to 95% of the nitrogen (N), 90% of sulfur (S) and 40% of the phosphorus (P) in the soil, and smaller quantities of other soil nutrients (Smith et al., 1993). These nutrients serve as a source of replenishment to the plant-available soil nutrient pool after mineralization from microbes (Weil and Magdoff, 2004). Therefore, the storage of SOM results in the storage of these organic constituents and is essentially a reserve of plant-essential nutrients. Another important attribute of SOM is that the material adds to the colloidal fraction, which increases the soil’s cation exchange capacity (CEC). Increases in the CEC influences the ability of the soil to adsorb and exchange nutrient cations with those in the soil solution (Havlin et al., 2005). The exchange of cations between soil particles and the soil solution is important in agricultural production because it allows plant-essential nutrients, such as potassium (K), calcium (Ca),
magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) to be readily available for plant uptake, and adsorption of the cations onto the exchange site deters nutrient leaching, or downward movement of nutrients in the soil profile with water, which carries the nutrients away from the root zone (Havlin et al., 2005; McCauley et al., 2009). The exchange sites associated with SOM also buffer soil pH, which affects nutrient transformations and the solubility of many plant-essential nutrients, and soluble organic compounds have the ability to chelate micronutrient metals, which allows them to stay in solution and be readily available for plant uptake (Nichols, 1984; Weil and Magdoff, 2004; Havlin et al., 2005).

Flood-irrigated conditions not only affect the organic constituents of the soil, but flooding also affects soil pH and inorganic nutrient availability in the system. During the flooded period, soil pH shifts closer to neutral, which allows for greater nutrient availability due to the dissolution of precipitated forms associated with more acidic or more alkaline pH (Scott et al., 1998; Havlin et al., 2005). Over a long period of time of irrigation with less acidic irrigation water, the overall pH of the soil can be increased due to the addition of Ca, Mg, and bicarbonates (HCO₃⁻; Snyder and Slaton, 2002), which essentially act as liming materials. Depending on the quality of water used in irrigation, the addition of nutrients in the irrigation water can also greatly influence the nutrient pool and soil salinity. Water sources vary with location, but most of the rice in the Arkansas is irrigated with groundwater (83%), while 9% of the area utilizes water from surface reservoirs, and 8% use streams, rivers, and other natural water sources (Wilson et al., 2010).

In addition to water management, other management practices that can greatly affect nutrient availability and cycling include tillage practices, crop rotation, and fertilizer applications (DeBusk et al., 2001; Follett, 2001, Dick et al., 1998). The impact that tillage treatments and
crop rotation have on soil fertility is primarily related to their influence on the amount of SOM stored in the soil. Soils that have been degraded through excessive tillage tend to be low in SOM due to an increased amount of exposed surface area, which facilitates aerobic decomposition (DeBusk et al., 2001). Fertility treatments influence the quantities of managed nutrients that are added to the soil and can influence the amount of biomass produced, which affects the quantity and quality of crop residues returned to the soil as organic matter (Follett, 2001). However, other influences on soil fertility are associated with nutrient uptake of the crop being grown, the removal of grain during harvest, and the nutrient composition of the plant biomass being returned to the soil. In Arkansas rice production systems, soils are primarily managed using some type of tillage. However, approximately 12% of the rice is produced using no-tillage (NT) practices (Wilson et al., 2010). A majority of the land in production is rotated every other year with soybean [Glycine max (L.) Merr.] (68%), while some is kept in continuous rice production (28%) (Wilson et al., 2010). Other rotations that make up the remaining 4% of the planted rice area include corn (Zea mays L.), wheat (Triticum aestivum L.), cotton (Gossypium hirsutum L.), grain sorghum (Sorghum bicolor L.), oats (Avena sativa L.), and some fields are kept fallow (Wilson et al., 2010).

Therefore, the objective of this study was to evaluate the long-term effects of rice-based crop rotations (with corn, soybean, and winter wheat), tillage [conventional tillage (T) and NT], and soil fertility (optimal and sub-optimal) after 11 years (1999-2010) of consistent management on SOM and other chemical properties [pH, electrical conductivity (EC), Mehlich-3 extractable nutrients] in the top 10 cm of a silt-loam soil. It was hypothesized that: (1) NT and optimal fertility practices would have greater SOM, which would lead to generally greater extractable soil nutrient contents, than that under T and sub-optimal fertility regimes over time; (2) SOM
would be greater in higher-residue producing crop rotations of rice and corn, and in double-cropped continuous rice rotations with wheat, than in rotations which included soybean as a result of greater plant biomass being incorporated into the soil; (3) extractable nutrients of P and K would be greater in the optimal fertility regime than in the sub-optimal fertility regime due to greater inputs of the nutrients in fertility treatments; (4) extractable micronutrients (i.e., Fe, Mn, Zn, and Cu) were expected to decrease overtime from plant uptake and removal of grain during harvest; and (5) soil pH, EC, and extractable Ca and Na were expected to increase overtime as a result of long-term flood-irrigation.

**Materials and Methods**

**Site Description**

This study was conducted at the University of Arkansas Rice Research and Extension Center (RREC) near Stuttgart (34°27' N, 91°24' W), which is located in the Mississippi Delta Region of eastern Arkansas in an area known as the Grand Prairie. The Grand Prairie is located between the White and Arkansas Rivers in east-central Arkansas (USACE, 2000). The relatively flat topography is primarily made up of alluvial soils from the major land resource areas (MLRA) of the Southern Mississippi River Alluvium and Terraces and the Arkansas River Alluvium (NRCS, 2006), which consist mainly of silt-loam and clay-textured soils (NRCS, 2008). The climate of the region is warm and wet with a 30-yr mean annual temperature minimum of 0.22 °C in January and maximum of 33.1 °C in July. The 30-yr mean annual precipitation is 131.6 cm (SRCC, 2012).

A long-term tillage-fertility-rotation study was initiated in 1999 on a Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf; NRCS, 2008), which is characteristic of Grand Prairie
soils. The Dewitt series present in this area consists of very deep, poorly drained, slowly permeable soils that formed in alluvium (NRCS, 2008). The top 10 cm of soil are primarily dark grayish brown (10YR 4/2) in color with a moderate medium granular and weak medium and course subangular blocky structure. The 10- to 18-cm depth has a more compacted and dense layer that is a distinct dark brown (7.5YR 3/2) color and commonly contains iron-manganese concretions (NRCS, 2008).

The study site had been fallow for a number of years prior to the initiation of the study, with the vegetation including a combination of grasses and weeds. The study site was leveled to a 0.15% grade in Fall 1998. This process involved removal of the top 10 cm of soil, cutting the field to grade, and redistributing to topsoil uniformly over the field. The practice of land-leveling is common in the rice producing areas in the Mississippi River Delta region because the level field conditions allow a uniform distribution of flood-irrigation water (Brye et al., 2003).

**Experimental Design and Field Treatments**

The experimental design for this study was a randomized complete block, with each block partitioned as a split-strip-split plot. Blocks consisted of four rectangular sections 76-m long by 120-m wide (9120 m²) within the 1.9-ha experimental site. Each block was divided into two tillage treatments (T and NT) and each tillage treatment was split into two fertility treatments (optimal and sub-optimal). Ten crop rotations were stripped across the tillage-fertility treatment combinations, and for the evaluation between years, split across time (1999 and 2010). The 10 crop rotations in the field design included continuous rice (R), rice-soybean (RS), soybean-rice (SR), rice-corn (RC), corn-rice (CR), rice (winter wheat) [R(W)], rice (winter wheat)-soybean (winter wheat) [R(W)S(W)], soybean (winter wheat)-rice (winter wheat), rice-
soybean-corn, and rice-corn-soybean (RCS). However, for the purposes of this experiment, only six of the 10 rotations where used due to the elimination of mirror-image rotations. The six rotations chosen for this study included R, RS, RC, R(W), R(W)S(W), and RCS. All rotations started with rice in 1999 and followed the respective rotations in successive years (Table 1). Individual plots comprising the 96 tillage-fertility-rotation treatment had dimensions of 6- by 19-m. Crops included in the study consisted of the major agronomic crops grown in Arkansas. Rice, soybean, and wheat were sown into 19-cm rows in both tillage treatments using an Almaco NT drill (Almaco, Nevada, IA). During the duration of the study, rice was drill-seeded at a rate of 100 kg seed ha$^{-1}$, soybean at a rate of 56 kg seed ha$^{-1}$, and wheat at a rate of 67 kg seed ha$^{-1}$. Corn was planted in 76-cm rows at a plant population of 79,040 seeds ha$^{-1}$. Residue management in T treatments consisted of burning the surface residue prior to tillage, whereas residue in NT plots was left undisturbed.

The soil fertility treatments consisted optimal and sub-optimal fertilizer treatments based on the soil analyses in the top 10 cm from the beginning of the study in Spring 1999 (Table 2). Soil fertility treatments consisted of P applied as triple super phosphate and K applied as muriate of potash, with both fertilizers broadcast pre-plant and pre-tillage with a spreader. During years rice was grown, Zn was applied as zinc sulfate (ZnSO$_4$), which was also broadcast pre-plant and pre-tillage with a hand spreader. Nitrogen as urea was applied with a hand spreader pre-flood at the 5-leaf stage of rice growth approximately one month after planting. For corn, N was applied after emergence and at the V4 vegetative growth stage. For wheat, N was applied soon after emergence as well. Phosphorous, K, and Zn were incorporated into the soil with the T treatment and were left on the surface for the NT treatment. After N was applied to rice, a 5- to 10-cm permanent flood was established and maintained until the rice reached physiological maturity.
All other crops present in a given year were furrow-irrigated on an as-needed basis approximately three to four times annually, which was effectively based on the amount of precipitation received and the growth of the crop. Irrigation water originated from a nearby surface reservoir, with water additions mainly from an adjacent stream channel and some groundwater. All other crop management practices for rice (Slaton, 2001), soybean (Ashlock, 2000), corn (Espinoza and Ross, 2003), and wheat (Kelley, 1999) closely followed University of Arkansas Cooperative Extension Service recommendations for stand establishment, irrigation, weed management, and pest management (Motschenbacher et al., 2012).

**Soil Sampling and Analyses**

Soil samples were collected from the top 10 cm in March 1999 and 2010 for each tillage-fertility-crop rotation treatment combinations. The 1999 samples were collected after land-leveling practices had occurred and prior to any treatment being imposed. The 2010 samples were collected prior to the spring planting of rice, corn, or soybean. Rotations with winter wheat had wheat in the ground during sampling, whereas all other rotations had been fallow for the winter.

After collection, samples were dried at 70°C for 48 hours. In 2010, soil samples were acquired using a 4.7-cm diameter stainless steel cylinder, resulting in an approximate 203-cm³ collected volume. Following drying, samples were weighed for bulk density determination. In 1999, bulk density was not measured. Therefore, particle-size analyses were conducted on all of the 2010 soil samples. The measured fractions of sand and clay from the 2010 soil samples were combined with SOM concentrations in the top 10 cm from 1999 soil samples, which were used to estimate bulk density on a plot-by-plot basis for 1999 using the Soil-Plant-Atmosphere-Water
(SPAW) Model (USDA-NRCS, 2012). Soil samples in both years were crushed to pass a 2-mm mesh screen for soil chemical property analyses. In 1999, extractable soil P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu were determined using the Mehlich-3 extraction method with a 1:7 soil mass to solution volume dilution ratio as per standard University of Arkansas laboratory procedures at the time. In 2010, extractable soil P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu were determined using the Mehlich-3 extraction method with a 1:10 soil mass to solution volume dilute ratio, which are the current standard University of Arkansas laboratory procedures. For the purposes of this experiment, 1999 concentrations determined with the 1:7 dilute ratio were converted to a 1:10 dilute ratio in order to compare between the two time periods. For both years, soil pH and electrical conductivity (EC) were determined potentiometrically with an electrode in a paste based on a 1:2 (m/v) soil to water ratio and SOM concentration was measured by loss on ignition (LOI). Measured SOM and nutrient concentrations (mg kg\(^{-1}\)) were converted to kg ha\(^{-1}\) using a 10-cm sample depth and measured soil bulk densities (g cm\(^{-3}\)).

At the time of the 2010 sampling, the R and R(W) rotations had produced a total of 11 rice crops; the RS, RC, and R(W)S(W) rotations had produced six rice crops with five crops in the respective rotation with corn or soybean; and the RCS rotation had produced four rice crops, four corn crops, and three soybean crops (Table 3). Furthermore, rotations with winter wheat produced a total of 11 wheat crops (Table 3). In 2010, the tillage treatment was uniformly imposed on tilled plots five months (late-October 2008) prior to soil sampling.

**Data Analyses**

The inherent soil properties at the initiation of the study (1999) and the effects of tillage, fertility, crop rotation, and time (1999 to 2010), and their interactions on SOM content, soil pH
and EC, and extractable soil nutrient contents, were evaluated by analysis of variance (ANOVA) using the PROC MIXED procedure in SAS® (version 9.2, SAS Institute, Inc., Cary, NC). When appropriate, means were separated using Fisher’s protected least significant difference (LSD) at the 0.05 level.

**Results and Discussion**

**Initial Soil Properties**

Soil in the top 10 cm at the initiation of the study in 1999, characterized after land-leveling, but prior to the implementation of tillage, fertility, and rotation treatments, was as uniform throughout the study area as could reasonably be expected. Soil organic matter, soil pH, and extractable soil P, K, S, Ca, Mg, Fe, Mn, Cu, and Na contents did not differ among pre-assigned tillage-fertility-rotation treatment combinations (Table 4). Furthermore, soil particle-size distribution did not differ among any pre-assigned treatment combinations. However, there were a few minor inherent differences in calculated soil bulk density ($P = 0.005$) and soil EC ($P < 0.001$) among pre-assigned rotations and soil Zn content ($P = 0.026$) among pre-assigned tillage-rotation treatment combinations (Table 4).

Averaged across pre-assigned tillage and fertility treatments, calculated soil bulk density in the R(W) (1.44 g cm$^{-3}$) rotation was 2 to 4% greater than that in the R (1.41 g cm$^{-3}$), RC (1.40 g cm$^{-3}$), and RCS (1.38 g cm$^{-3}$) rotations. Furthermore, calculated soil bulk density was 3% greater in the R(W)S(W) and RS (both 1.42 g cm$^{-3}$) rotations than the RCS rotation. Though statistically different, differences were ≤ 0.06 g cm$^{-3}$, which are not large enough to cause substantial differences in crop production or SOM and nutrient contents. Similar to bulk density, averaged across pre-assigned tillage and fertility treatments, soil EC was 44 to 77% greater in the
R(W) (0.24 dS m\(^{-1}\)) and R(W)S(W) (0.21 dS m\(^{-1}\)) rotations than that in the R, RS, RC rotations (0.13 to 0.14 dS m\(^{-1}\)). Furthermore, soil EC was greater in the R(W) (0.24 dS m\(^{-1}\)) than that in the RCS (0.16 dS m\(^{-1}\)) rotation.

Averaged across pre-assigned fertility regimes, the soil Zn content in the NT/R (0.24 kg ha\(^{-1}\)) treatment combination was 86% greater than that in the T/R (0.13 kg ha\(^{-1}\)) treatment combination, and NT/R had twice the soil Zn content than in all other tillage-rotation treatment combinations (0.08 to 0.12 kg ha\(^{-1}\)) evaluated. With the exception of the NT/R combination, soil Zn content in the T/R combination was 8 to 62% greater than that in other tillage-rotations combinations, which did not differ.

**Soil Organic Matter**

Considering soil physical and chemical properties throughout the 1.9 ha study area were as uniform as reasonably could be expected, SOM, which is the soil’s natural source of essential plant nutrients, in the top 10 cm was affected by tillage ($P = 0.048$), rotation ($P = 0.008$), and changed over time ($P = 0.006$) after 11 years of consistent management (Table 5). However, contrary to that hypothesized, SOM content (kg m\(^{-2}\)) was unaffected by fertility regime ($P > 0.050$; Table 5).

As anticipated, SOM content in the top 10 cm was 9% greater under NT (2.9 kg m\(^{-2}\)) than that under T (2.6 kg m\(^{-2}\)) when averaged across fertility, rotation, and time. This result was expected because the elimination of tillage enables a greater quantity of above- and below-ground biomass to be stored in the soil, whereas tillage aerates the soil and promotes a greater rate of aerobic SOM decomposition (DeBusk et al., 2001). The relationship between soil cultivation and a decline in SOM has been extensively reported, especially during the initial
years of soil disturbance and in the near-surface layers of the soil (Lal et al., 1999; Balesdent et al., 2000). An integrated analysis by Kern and Johnson (1993) compared the effects of tillage management in 17 different research studies in the United States ranging from 3 to 44 years in duration. On average, the organic fraction of the soil, primarily in the top 8 cm, was greater under NT than under tilled treatments, whereas there were no differences among tillage treatments below 15 cm (Kern and Johnson, 1993). Differences in SOM in the top layers of the soil among tillage treatments can be directly related to the depth of tillage, in that the mechanical mixing action of tillage and the resulting soil aeration primarily affects the near-surface layers where physical disturbance occurs.

Averaged across tillage, fertility, and time, SOM content differed among crop rotations. The R(W) rotation had 5 to 13% greater SOM in the top 10 cm (3.0 kg m$^{-2}$) than that in any of the other crop rotations (2.7 to 2.9 kg m$^{-2}$), which did not differ among one another. This may be due to the annual inputs of crop residue from the high-residue-producing continuous rice (6.5 Mg biomass ha$^{-1}$ yr$^{-1}$) combined with annual inputs of wheat residue [3.3 Mg biomass ha$^{-1}$ yr$^{-1}$; R(W) totaling approximately 9.8 Mg biomass ha$^{-1}$ yr$^{-1}$ and 19.6 Mg biomass ha$^{-1}$ over two years], whereas the other wheat-containing rotation of R(W)S(W) only had biennial inputs of rice residue and had biennial inputs of low-residue-producing soybean [2.2 Mg biomass ha$^{-1}$ yr$^{-1}$; R(W)S(W) totaling 15.3 Mg biomass ha$^{-1}$ over two years; USDA-NASS, 2011]. Likewise, the R(W) also had greater annual biomass inputs than any other annually mono-cropped rotations evaluated in this study (i.e., R, RS, RC, RCS). Surprisingly, the RC and RCS rotations, which included high-residue-producing corn (8.0 Mg biomass ha$^{-1}$ yr$^{-1}$; USDA-NASS, 2011), did not have greater SOM content than the other non-wheat crop rotations (i.e., R and RS) over the 11
years of consistent management, which suggests some degree of equilibrium in tillage-fertility-rotation combinations had been achieved.

Previous studies have reported stable or increased SOM concentrations in annually double-cropped irrigated rice rotations (i.e., two rice crops grown per year), whereas rice annually double-cropped with an upland crop (i.e., one rice crop and one upland crop grown per year) generally had lower SOM concentrations than double-cropped rice (Cheng, 1984; Olk et al., 1996). Olk et al. (1996) reported that annually double-cropped rice in a silty-clay soil and an annually triple-cropped, irrigated rice rotation in a clay soil had 69 to 112% greater SOM concentration in the top 15 cm than that in an annually double-cropped RS rotation in a silty-clay-loam soil in the Philippines. Based on a comprehensive evaluation of several rice rotation studies in south China on annually double-cropped rice and rice rotated with dry-land crops (ISSAS, 1961), Cheng (1984) primarily accredited greater SOM concentrations in double-cropped rice than that in rice rotated with dry-land crops to the prolonged periods of anaerobic soil conditions when compared with those containing intermittent aerobic soil conditions. Although anaerobic conditions greatly influence SOM contents, in this study, all rice crops in the rotations evaluated were grown once a year in the summer, as opposed to double-cropped rice commonly conducted in Asia, and the rotations were either fallow or produced wheat in the winter. Therefore, the reason R(W) had greater SOM than R in this study can presumably be a result of increased quantities of annual biomass returned to the soil from the winter wheat because both rotations had comparable flooding regimes in the summer and comparable lengths of aerobic conditions in the winter.

Averaged across tillage, fertility, and rotation treatments, SOM content in the top 10 cm increased 14% from 1999 (2.6 kg m⁻²) to 2010 (3.0 kg m⁻²). Therefore, the sequestration rate of
SOM in rice-based rotations averaged less than 0.04 kg m$^{-2}$ yr$^{-1}$ (364 kg ha$^{-1}$ yr$^{-1}$), when averaged across all treatment factors. Crop management practices, such as tillage, fertility, and crop rotations, affect the SOM pool by providing continual changes in the soil climate, disruption of the soil structure, and through the incorporation of new plant material into the soil matrix (Balesdent et al., 2000). When the soil climate and vegetation system changes, the SOM content shifts toward a new equilibrium that is characteristic of the newly imposed combination of influential factors (Powlson and Olk, 2000). Therefore, a change in SOM over time was expected due to the annual (i.e., mono-cropped rotations) or biannual (i.e., double-cropped rotations with winter wheat) inputs of crop residues in all treatment combinations over the 11-year study period, whereas the land had been fallow for a number of years prior to the initiation of the study. Thus, the only plant biomass added to the soil in previous years was from low-residue-producing grasses and weeds that were periodically mowed and left uniformly on the surface. It appears that, over time, the addition of above- and below-ground biomass from field crops, combined with the maintenance of at least minimal additions of inorganic nutrients (i.e., N, P, K, and Zn), substantially increased SOM contents, regardless of the tillage treatment imposed.

The results observed in this study are similar to increases in SOM content reported in the top 20 cm in four intensive continuous rice rotations after 15 years of uninterrupted management (Pampolino et al., 2008). Pampolino et al. (2008) evaluated four biannual or triannual, paddy-grown, continuous rice rotations at three different locations in the Philippines on silty-clay to clay soil, which ranged from 32 to 36 years in duration by the end of the evaluation period. Results showed that SOM content was at least maintained or increased in the top 20 cm over time in all locations regardless of the N-P-K fertilizer regime (Pampolino et al., 2008).
Soil pH

Similar to SOM content, soil pH differed between tillage treatments ($P = 0.043$; Table 5). However, unlike SOM content, soil pH also differed between fertility regimes over time ($P = 0.032$) and was unaffected by rotation ($P > 0.050$; Table 5).

Averaged across rotation, fertility, and time, soil pH was greater under T (pH = 5.8) than under NT (pH = 5.5). This can be explained by greater SOM present under NT, which in turn increases the buffering capacity of the soil due to the greater amount of negatively charged surface area in the colloidal fraction of the soil (Skjemstad et al., 2008). Thus, greater buffering capacity under NT can prevent the potential increase in soil pH associated with the repeated application of less acidic irrigation water.

Averaged across tillage and rotation, soil pH increased by 0.5 units under sub-optimal fertility over time, but did not change over time under optimal fertility (Figure 1A). The only difference between fertility treatments was the quantity of fertilizer applied. It appears that the acidity produced from the nitrification process associated with a greater input of fertilizer-N in the optimal treatment offset the likely increased pH associated with long-term irrigation from less acidic irrigation water (Snyder and Slaton, 2002; Havlin et al., 2005), in which the pH of the irrigation water used in this study was approximately 7.2. It has been reported that long-term irrigation with groundwater has increased soil pH in some rice fields due to the elevated concentrations of Ca, Mg, and bicarbonates ($\text{HCO}_3^-$) in groundwater compared to surface water (Snyder and Slaton, 2002). The carbonates present in the irrigation water dissipate and neutralize acidity on CEC sites and in the soil solution, which in turn increases the soil pH. The magnitude of the effects of irrigation water on soil pH depends on the amount of water applied and the buffering capacity of the soil, which enables the soil to resist changes in pH and is determined
based on the mineral and organic components in a soil (Havlin et al., 2005; Skjemstad et al., 2008).

In the case of this study, the changes in pH among treatments were relatively small (≤ 0.5 units); therefore, the influence of soil fertility over time and influences of tillage treatments were likely not large enough to cause substantial differences in nutrient availability. Furthermore, soil pH generally ranged from 5.5 to 6.0 in all treatment combinations throughout the course of this study, which is close to the optimal range for row crops of 5.8 to 6.5 (Espinoza et al., 2007). Thus, any changes in soil pH were essentially not agronomically significant.

**Soil Electrical Conductivity**

In contrast to SOM and pH, soil EC was affected by all treatments evaluated in this study ($P = 0.036$; Table 5). Between 1999 and 2010, soil EC in all tillage-fertility-rotation treatment combinations decreased 36 [T/sub-optimal (SO)/RC] to 70% [NT/optimal (O)/RCS] (Figure 2). However, there were no particular patterns in the magnitude of EC decreases over time in relation to individual tillage, fertility, or rotation treatments (Figure 2). Electrical conductivity can vary greatly across time and space, and the primary factors that influence soil EC include soil moisture content and soluble salt accumulation, particularly for the cations Na$^+$, K$^+$, Ca$^{2+}$, and Mg$^{2+}$ and the anions chloride (Cl$^-$), sulfate (SO$_4^{2-}$), HCO$_3^-$, and carbonate (CO$_3^{2-}$; Havlin et al., 2005). Irrigating crops can cause an increased risk for elevated accumulations of soluble salts in the near-surface soil due to the upward movement of dissolved salts with the evaporation of water from the soil surface. However, an increased accumulation of soluble salts in the near-surface soil layers does not appear to be the case in this study. Instead, soluble salts appear to have leached with the infiltration and movement of applied irrigation water. Despite significant
changes in EC over time in all the treatment combinations, accumulated soluble salt levels were never above the threshold (> 4.0 dS m\(^{-1}\)) that would classify the soil as saline or saline-sodic at an acidic pH (Havlin et al., 2005) or above levels that would be detrimental to crop growth.

When examining each year separately, 1999 soil EC values did not differ among treatment combinations, except for the rotations double-cropped with winter wheat [i.e., R(W) and R(W)S(W)] under both tillage treatments and both fertility regimes, which were greater than that in the R, RS, and RC rotations under both tillage treatments and both fertility regimes and the RCS rotation under T and both fertility regimes (Figure 2). However, due to the fact that the 1999 samples were collected from tillage-fertility-rotation treatment combinations after land leveling had been performed uniformly on the entire study site and prior to any treatments being imposed, elevated soil EC in the double-cropped rotations in 1999 could possibly be a result of sampling or laboratory error. Theoretically, all treatments should have been similar due to uniform field conditions and the randomized field design. However, this was not the case, and reevaluation of the 1999 dataset does not indicate any specific outliers that could potentially skew the data. In 2010, R(W) and R(W)S(W) rotations also generally had greater EC than other crop rotations, which did not differ (Figure 2). Although elevated EC in rotations that included winter wheat in both years could be related to inherent differences, the likelihood of this happening in all four replications in 1999 seems unlikely. The 2010 values can potentially be explained by the elevated K contents in rotations double-cropped with winter wheat from K-fertilizer applications in the fall, whereas all other rotations did not receive a fall application because they were fallow for the winter (Table 2). These results indicate that long-term flood irrigation in the Grand Prairie region of eastern Arkansas causes a relatively uniform decrease in
soil EC over time as a result of nutrient leaching from the top 10 cm to deeper in the soil profile regardless of tillage, fertility, or rotation management.

**Extractable Soil Nutrients**

**Phosphorous**

Phosphorus is important for energy storage and transformation processes in plants, so inadequate soil P results in restricted plant growth and development (Havlin et al., 2005). For this reason, relatively large quantities of P-fertilizers are usually essential for sustainable intensive rice production systems and enhancing soil fertility (Sahrawat, et al., 2001). As expected, extractable soil P content (kg ha\(^{-1}\)) differed among tillage-rotation combinations over time (\(P = 0.030\)) and differed among fertility-rotation combinations over time (\(P = 0.006\); Table 5).

Averaged across fertility, extractable soil P content increased over time under NT in RS, RC, R(W), R(W)S(W), and RCS and under T in R(W), R(W)S(W), and RCS (Figure 3A). The other tillage-rotation combinations (i.e., R under optimal fertility and R, RS, and RC under sub-optimal fertility) were numerically greater in 2010 than in 1999, but did not differ significantly between years (Figure 3A). In 1999, all tillage-rotation combinations were similar in extractable P content (Figure 3A). In 2010, the greatest extractable P content was under NT in the rotations that included winter wheat [i.e., R(W) and R(W)S(W); Figure 3A]. Increased soil P in wheat rotations can be explained by the timing of the last P-fertilizer application. Rotations with wheat had fertilizer applied in the fall for the winter crop, whereas all other rotations were unfertilized prior to the winter. Thus, the last application of P-fertilizer for non-wheat rotations was in the spring of the previous year prior to the summer crop in rotation (i.e., rice, soybean, or corn). The
generally greater amounts of SOM present in the NT, when averaged across fertility, rotation, and time, could have been responsible for the overall greater increases over time of extractable soil P content in the RC, R(W), R(W)S(W), and RCS rotations under NT from 1999 to 2010, compared with that under T. A pattern of greater extractable soil P content in R(W), R(W)S(W), and RCS rotations over time was also observed under T, but not to the same extent as was present under NT (Figure 3A).

Similar to patterns of tillage-rotation treatments, extractable soil P content increased over time under optimal fertility in RS, RC, R(W), R(W)S(W), and RCS and under sub-optimal fertility in R(W), R(W)S(W), and RCS (Figure 4A) when averaged across tillage treatments. Other fertility-rotation combinations (i.e., R under optimal fertility and R, RS, and RC under sub-optimal fertility) had numerically greater extractable soil P content in 2010 than in 1999, but did not differ significantly between years (Figure 4A). In 1999, extractable soil P was similar in all fertility-rotation treatment combinations (Figure 4A), as would be expected due to the uniform field conditions after land leveling and prior to imposed field treatments. In 2010, the greatest extractable soil P content was under optimal fertility in rotations which included winter wheat [i.e. R(W) and R(W)S(W); Figure 4A]. Like the tillage-rotation combination effects, this result can be attributed to the P fertilizer application in the fall versus application in the previous spring. A pattern of greater extractable P content in winter wheat rotations was also observed under the sub-optimal treatment (Figure 4A). The RCS rotation under optimal fertility had greater extractable soil P than that in R, RS, and RC in both fertility regimes, whereas RCS under sub-optimal fertility was greater only than the RS rotation under sub-optimal fertility in 2010 (Figure 4A). Elevated extractable soil P in the RCS rotation under optimal fertility in 2010 can be explained by the larger rate of P-fertilizer applied to the corn crop during the previous spring.
(90 kg P$_2$O$_5$ ha$^{-1}$), whereas all other rotations had rice in 2009 with an application of 67 kg P$_2$O$_5$ ha$^{-1}$ (Table 2).

Prior to the addition of any P-fertilizer in 1999, extractable soil P concentrations (mg kg$^{-1}$) for all treatment combinations were below an expected field crop yield potential of 65% without fertilization (< 16 mg kg$^{-1}$ for Mehlich-3 extraction methods; Espinoza et al., 2007). After 11 years of consistent P-fertilizer management, extractable soil P concentrations generally ranged from 65 to 100% of expected field crop yield potential prior to spring P-fertilizer applications (Espinoza et al., 2007).

**Potassium**

Potassium is a component of biochemical compounds in the plant and is important for plant water relations, charge balance, and osmotic pressure in cells and across membranes (Havlin et al., 2005). When there is deficiency of K in the plant, lodging and susceptibility to plant diseases can occur (Havlin et al., 2005). Like P, K is a macronutrient that is usually required in relatively large quantities in intensive rice production systems in order to remain sustainable and maintain adequate soil fertility. As expected, extractable soil K content (kg ha$^{-1}$) differed between tillage treatments ($P = 0.019$) and differed among fertility-rotation combinations over time ($P = 0.001$; Table 5).

Averaged across fertility, rotation, and time, extractable soil K content was 8% greater in NT (125 kg ha$^{-1}$) than that under T (115 kg ha$^{-1}$). Greater extractable soil K in the top 10 cm under NT could be influenced by the physical location of K in the profile. In that, tillage helps distribute applied K fertilizer uniformly throughout the plow layer, whereas K fertilizer applied to NT primarily remains on the surface. Furthermore, NT had greater SOM contents in the upper
top 10 cm than T, which has the ability to decrease the leaching potential of K from upper layers of the profile due to overall increases in CEC from SOM (Skjemstad et al., 2008). The increased SOM content allows a greater amount of K$^+$ ions to be adsorbed to the CEC sites on the organic material, which allows a greater quantity of K$^+$ ions to be readily available for plant uptake as opposed to being leached below the top 10 cm.

Averaged across tillage, extractable K content increased over time in the rotations that included winter wheat [i.e., R(W) and R(W)S(W)] under both optimal and sub-optimal fertility and increased over time in RCS under optimal fertility (Figure 4B). There were no differences in extractable soil K content over time in the R, RS, and RC under either optimal or sub-optimal fertility or in RCS under sub-optimal fertility (Figure 4B). Like extractable soil P content, all fertility-rotation treatment combinations were similar in extractable soil K content in 1999, and the greatest increase in extractable soil K content over time was in the winter wheat rotations [i.e., R(W) and R(W)S(W)] under optimal fertility (Figure 4B). Unlike what was expected in 2010, only the R(W), R(W)S(W), and RCS rotations showed greater extractable soil K in the optimal versus sub-optimal fertility regimes, whereas there were no differences in soil fertility regimes in R, RS, and RC (Figure 4B). Similar to extractable P contents, the increased extractable soil K contents in double-cropped rotations appear to be directly related to the K-fertilizer treatment in the fall for winter wheat as opposed to the previous spring for summer crops. Furthermore, increased extractable soil K contents in the RCS rotation under optimal fertility as opposed to R, RS, and RC in both fertility regimes can be explained by the quantity of K fertilizer applied during the 2009 growing season to corn (168 kg ha$^{-1}$) as opposed to rice (101 kg ha$^{-1}$; Table 1; Table 2).
Before K fertilizer was applied in 1999, soil extractable K concentrations (mg kg\(^{-1}\)) for all treatment combinations generally ranged from 65 to 85% of the expected field crop yield potential without fertilization (< 61 to 90 mg kg\(^{-1}\) for Mehlich-3 extraction methods; Espinoza et al., 2007). After 11 years of consistent fertilizer management, extractable K concentrations in all tillage-fertility-rotation treatment combinations generally had an expected field crop yield potential of 100% prior to the spring K-fertilizer application (Espinoza et al., 2007).

**Sulfur**

Sulfur is needed by plants for the synthesis of the amino acids cystine, cysteine, and methionine, which are components of proteins that make up 90% of the S in plants, and S is also needed by plants for the synthesis of chlorophyll (Havlin et al., 2005). In Arkansas, S fertilization is not usually needed in rice-based systems due to the adequate concentrations present in water used for irrigation (Wilson et al., 2001). As expected, extractable soil S content (kg ha\(^{-1}\)) was affected by tillage (\(P = 0.015\)) and time (\(P = 0.011\); Table 5). Neither fertility nor rotation affected extractable S content (\(P > 0.05\); Table 5).

Averaged across fertility regimes, crop rotations, and time, the extractable soil S content under NT (19.0 kg ha\(^{-1}\)) was 4% greater than that under T (18.3 kg ha\(^{-1}\)). This dissimilarity can be explained by the replenishment of the plant-available S pool through the mineralization of organic S contained in SOM. Approximately 90% of all S contained in non-calcareous soils is present in the organic form (Havlin et al., 2005). Therefore, increased SOM contents present under NT in this study would allow a greater potential for the mineralization of SOM, which is consistent with greater extractable S under NT.
Averaged across tillage, fertility, and rotation, extractable soil S content decreased 30% from 1999 (21.9 kg ha\(^{-1}\)) to 2010 (15.4 kg ha\(^{-1}\)). Despite an increase in SOM over time, the addition of S through ZnSO\(_4\) fertilizer during the years rice was grown, and the addition of S in irrigation water (0.3 kg ha\(^{-1}\) cm\(^{-1}\) irrigation water applied; Table 5), it appears that nutrient leaching below the top 10 cm of the soil profile and plant uptake and the removal of grain during harvest were greater than the quantity added to treatment combinations during routine fertility treatments and irrigation.

Despite substantial decreases over time, extractable soil S concentrations only decreased slightly below the general guidelines for an expected yield potential of at least 65% without fertilization (\(\leq 10\) mg kg\(^{-1}\) for Mehlich-3 extraction methods; Espinoza et al., 2007) under the T/R treatment combination in the sub-optimal fertility regime (9.9 mg kg\(^{-1}\)) in 2010. All other tillage-fertility-rotation treatment combinations were at or remained above a 65% expected crop yield potential.

**Calcium**

Calcium is needed by plants for cell wall membrane structure, N metabolism, protein formation, cell elongation and division, and the translocation of carbohydrates and nutrients (Havlin et al., 2005). When plants are not able to take up enough Ca from the soil, plant tissues become deformed and death of the buds, blossoms, and roots can occur (Havlin et al., 2005). As expected, extractable soil Ca content (kg ha\(^{-1}\)) was affected by time \((P = 0.008;\) Table 5). In contrast, extractable soil Ca content was not affected by tillage, fertility, or rotation treatments \((P > 0.05;\) Table 5).
Averaged across tillage treatments, fertility regimes, and crop rotations, extractable soil Ca content decreased 22% from 1999 (1305 kg ha\(^{-1}\)) to 2010 (1024 kg ha\(^{-1}\)). In this study, there were no inputs of Ca from supplemental fertilizer treatments for any treatment combination, but there were additions into the system from Ca deposited from irrigation water (1.10 kg ha\(^{-1}\) cm\(^{-1}\) irrigation water applied; Table 5). Therefore, the decreased Ca values from downward leaching from the top 10 cm of the soil profile and plant uptake and the removal of grain during harvest were greater than the inputs of Ca from irrigation water or the return of crop residues to the soil.

Although there was a decrease in extractable soil Ca over time, Ca concentrations did not fall below the general guidelines for an expected yield potential of at least 65% without fertilization (≤ 400 mg kg\(^{-1}\) for Mehlich-3 extraction methods; Espinoza et al., 2007). According to Espinoza et al. (2007), as long as soil pH remains in the range of recommended crop growth, then a Ca deficiency is unlikely to occur. Therefore, although there were decreases in concentrations, those decreases were not agronomically significant after 11 years of consistent management.

**Magnesium**

Magnesium is an important component of chlorophyll, ribosome structure, and is associated with transfer reactions involving phosphate reactive groups within plants (Havlin et al., 2007). In this study, there were no differences in extractable soil Mg content (kg ha\(^{-1}\)) for any treatment imposed over the 11-year time period (\(P > 0.05\); Table 5). It appears that plant uptake of Mg from the soil could have been replenished by deposits from irrigation water (0.36 kg ha\(^{-1}\) cm\(^{-1}\) irrigation water applied; Table 5). Furthermore, extractable Mg concentrations in the soil were well-above the general guidelines for an expected yield potential of at least 65% without
fertilization (≤ 30 mg kg\textsuperscript{-1} for Mehlich-3 extraction methods; Espinoza et al., 2007) for the duration of the study.

**Iron**

Iron is a structural component of the porphyrin molecules, which are involved in oxidation-reduction reactions during respiration and photosynthesis in plants (Havlin et al., 2007; Schulte, 2004). Iron also provides electrochemical potential for many enzymes within the plant, and a deficiency in Fe can affect chlorophyll production (Havlin et al., 2007; Schulte, 2004). Similar to Ca content, extractable soil Fe content (kg ha\textsuperscript{-1}) was affected by time ($P = 0.002$), but was unaffected by tillage, fertility, or rotation treatments ($P > 0.05$; Table 5).

Averaged across tillage, fertility, and rotations, extractable soil Fe content increased 82% from 1999 (287 kg ha\textsuperscript{-1}) to 2010 (522 kg ha\textsuperscript{-1}). This large increase in extractable Fe content could be from inputs into the system from irrigation water, increased availability of Fe from the mineralization of SOM, and/or influences of repeated wetting and drying cycles on the recrystallization of precipitated forms of Fe. Water used for irrigation during this study contained elevated concentrations of Fe (> 5 mg L\textsuperscript{-1}; Robbins, 2010; Table 5), which may have influenced extractable Fe in the soil. Based on samples acquired from the water used for irrigation, the irrigation water added roughly 0.85 kg Fe ha\textsuperscript{-1} cm\textsuperscript{-1} irrigation water applied to the soil (Table 5). It has been estimated that rice fields in the Mississippi Delta region of Arkansas use approximately 76 cm of irrigation water a year (Wilson et al., 2001). If this estimation holds true, then roughly 65 kg Fe ha\textsuperscript{-1} yr\textsuperscript{-1} could theoretically be added to the soil through irrigation in the years rice was produced, with less Fe added during the years non-flooded crops of corn or soybean were produced.
However, not all of this Fe would remain in the soil due to losses through nutrient leaching from the top 10 cm with irrigation water movement, as may have occurred with other extractable nutrients in this study (i.e., Ca, S, and Cu). The mineralization of SOM also influences Fe cycling in the soil (Schulte, 2004; Havlin, et al., 2007). Therefore, increased SOM contents over time may have led to increased plant-available Fe from microbial mineralization. Another explanation for the increase of extractable Fe over time is related to the cycling of elemental forms and precipitated forms of Fe as a result of pH changes and the oxidation-reduction status changes associated with periodic flooding (Havlin et al., 2007; Ponnamperuma, 1972). After repeated cycles of wetting and drying, the secondary Fe minerals may not be able to recrystallize completely back to their precipitated forms, which could result in greater extractable Fe in the soil over time.

Although there was an increase in extractable Fe over time, there are currently no recommendations for extractable soil Fe concentrations in relation to plant growth and development in Arkansas (Espinoza et al., 2007). However, it has been noted that elevated levels of Fe (i.e., > 200 mg kg$^{-1}$ for Mehlich-3 extraction methods) in the soil, such as those in this study, do not necessarily mean that plant toxicities will occur (Espinoza et al., 2007).

**Manganese**

Manganese is essential in photosynthesis and lignin production, and deficiencies in Mn can negatively affect plant growth and disease resistance (Havlin et al., 2007). Similar to extractable P, extractable soil Mn content (kg ha$^{-1}$) was affected by tillage treatment, crop rotation, and time ($P < 0.001$), but was unaffected by fertility ($P > 0.05$; Table 5).
Averaged across fertility regimes, extractable Mn content increased over time in all rotations under T and in RS, R(W), R(W)S(W) and RCS rotations under NT (Figure 3B). There were no differences among any of the tillage-rotation treatment combinations in 1999. In 2010, the R and RC rotations had greater Mn contents under T than NT, but the RS, R(W), R(W)S(W), and RCS rotations did not differ among tillage treatments (Figure 3B). In 2010, T/RC had greater Mn content than T/RCS, but there were no differences among other crop rotations under T. Furthermore, there were no differences among the any rotation under NT in 2010 (Figure 3B).

Groundwater used for irrigation did not contain high levels of Mn (0.02 kg ha\(^{-1}\) cm\(^{-1}\) irrigation water applied; Table 5; Robbins, 2010), and there were no inputs of Mn through inorganic fertilizers. Therefore, increases in extractable soil Mn over time may have also been affected by the cycling of precipitated and elemental forms of Mn in relation to pH changes and oxidation-reduction status changes related with periodic flooded conditions (Havlin et al., 2007; Ponnamperuma, 1972). The repeated cycles of wetting and drying could potentially deter the complete recrystallization of Mn as precipitated forms, which, in turn, can result in greater extractable Mn in the soil over time. Furthermore, extractable Mg concentrations in the soil were well above the general guideline recommendations for crop growth (≤ 30 mg kg\(^{-1}\) for Mehlich-3 extraction methods; Espinoza et al., 2007) for the duration of the study.

**Zinc**

Zinc is an important component of some proteins and is involved in the production of growth hormones and other enzymatic activities in plants (Havlin et al., 2005). Deficiencies in Zn can cause the shortening of internodes and dwarfed leaf area (Havlin et al., 2005). In Arkansas, Zn deficiencies commonly occur on silt- and sandy-loam soils and on precision-
graded fields (Wilson et al., 2001). Decreased Zn availability can be caused by increases in pH from calcareous irrigation water and, when applicable, over-liming (Wilson et al., 2001). Similar to extractable P and Mn, extractable soil Zn content (kg ha\(^{-1}\)) was affected by tillage, crop rotation, and time \((P = 0.047; \text{Table 5})\), but was unaffected by fertility \((P > 0.05; \text{Table 5})\).

Averaged across fertility regimes, extractable soil Zn content in both the NT/R and T/R treatment combinations decreased over time, but extractable soil Zn did not change in any other tillage-rotation treatment combination changed after 11 years of management (Figure 3C). In 1999, the NT/R treatment combination had an abnormally greater Zn content than any other tillage-rotation treatment combination, whereas there were no differences among any other tillage-rotation treatment combinations at the beginning of the study (Figure 3C). Being that the Zn content in the NT/R treatment combination was two to three times greater than that in any of the other combinations in 1999, there may have been discrepancies in the sampling and/or laboratory analyses in 1999 (Figure 3C). In 2010, the only extractable soil Zn difference among tillage-rotation treatments was that the NT/R(W) rotation was greater than the T/R rotation (Figure 3C). All other treatment combinations had similar extractable soil Zn contents.

With the exception of NT/R under optimal fertility in 1999, soil Zn concentrations were below the expected field crop yield potential of less than 65% without fertilization (< 1.6 mg kg\(^{-1}\) for Mehlich-3 extraction methods; Espinoza et al., 2007) during both 1999 and 2010 in all tillage-fertility-rotation treatment combinations. In the years rice was not grown, ZnSO\(_4\) was added prior to spring planting. However, during the periods that corn, soybean, or wheat were grown, these small concentrations of Zn may have affected optimal plant growth.
Copper

Copper is an important component in photosynthesis and respiration, lignin formation, and carbohydrate and lipid metabolism (Havlin et al., 2005). Similar to extractable Ca and S, extractable soil Cu content (kg ha\(^{-1}\)) was affected by time (\(P = 0.007\)), but was not affected by tillage, fertility, or rotation treatments (\(P > 0.050\); Table 5).

Averaged across tillage treatments, fertility regimes, and crop rotations, Cu content decreased 27% from 1999 (1.1 kg ha\(^{-1}\)) to 2010 (0.8 kg ha\(^{-1}\)). This result was expected because there were no inputs of Cu from fertilizer treatments for any treatment combination. Thus, the decreased values are presumably a result of plant uptake and the removal of grain during harvest and from nutrient leaching down the soil profile. Unlike other soil nutrients discussed, and with the exception of NT/R under optimal and sub-optimal fertility in 1999, soil Cu concentrations were below the general recommended concentration for an expected field crop yield potential of 65% without fertilization (< 1.0 mg kg\(^{-1}\) for Mehlich-3 extraction methods; Espinoza et al., 2007). Therefore, stand establishment could have been affected for the duration of the study.

Sodium

Though not classified as an essential plant nutrient, the primary concern with row crop production is that the accumulation of Na, in combination with other soil salts, can increase the salinity of the soil (Havlin et al., 2005). Extractable soil Na content (kg ha\(^{-1}\)) was affected by fertility regime and time (\(P = 0.022\)), but was unaffected by tillage or rotation treatments (\(P > 0.05\); Table 5).

Averaged across tillage treatments and crop rotations, extractable soil Na increased over the 11-year time period in both fertility regimes, with a greater increase in the sub-optimal
fertility regime than that in the optimal fertility regime (Figure 1B). Extractable soil Na content increased 76% from 1999 (44.9 kg ha\(^{-1}\)) to 2010 (78.9 kg ha\(^{-1}\)) in the sub-optimal fertility regime and 37% from 1999 (44.3 kg ha\(^{-1}\)) to 2010 (60.8 kg ha\(^{-1}\)) in the optimal fertility regime. There were no differences between fertility treatments in 1999, but in 2010, the sub-optimal fertility regime had roughly 30% greater Na content than that in the optimal fertility regime (Figure 1B). Increases in soil Na content over time are expected due to the continuous addition of Na through irrigation water (3.36 kg ha\(^{-1}\) cm\(^{-1}\) irrigation water). Considering the fact that SOM content was unaffected by the fertility regime imposed, the greater quantity of extractable Na in sub-optimal as opposed to optimal fertility in 2010 could be related to the more neutral pH in sub-optimal fertility (6.0) as opposed to the optimal fertility (5.7). The higher pH value in the sub-optimal fertility would have led to a greater CEC due to the neutralization of hydrogen ions (H\(^+\)). This would allow a greater quantity of Na to adsorb onto the exchange sites, which, in turn, would increase the exchangeable Na in the soil.

Although the groundwater used for irrigation had elevated Na concentrations, the sodium adsorption ratio (SAR), which provides an estimate of the concentration of Na in the water relative to Ca and Mg, was at a maximum value of 0.95 under the sub-optimal treatment in 2010. The maximum SAR value of 0.95 is well-below the general irrigation water quality guidelines of < 10 (University of Arkansas, 2006). Therefore, sodic soils are not likely to occur with long-term use of the irrigation water that was used for the duration of the study (University of Arkansas, 2006).
Summary and Conclusions

This study was meant to provide a comprehensive look at the longer-term sustainability of rice-based crop rotations and field management practices that are commonly used in the United States. After 11 years of consistent production management, SOM and extractable Mn, Fe, and Na contents generally increased over time for most treatment combinations, and P and K contents generally increased over time as a result of managed nutrient inputs. Soil pH also increased over time, but only in the sub-optimal fertility treatment. However, soil EC and extractable S, Ca, and Cu contents decreased over time for all treatment combinations, and Zn contents decreased for continuous rice. Furthermore, it appears that long-term flood irrigation affects soil chemical properties by decreasing the EC through nutrient leaching from the top 10 cm despite increases of soil Na from flood irrigation water deposits.

The general pattern of nutrient availability over time demonstrated in this study suggests that managed fertilizer applications increase plant-available soil nutrient contents of the respective nutrients applied. However, the increased biomass production associated with optimum fertility may essentially deplete the soil of non-managed nutrients over time due to plant uptake and the removal of grain during harvest and leaching associated with flood irrigation.

Today’s rice production systems are under pressure to achieve increasingly greater crop yields. However, the long-term sustainability of rice production systems is not possible unless there is a balance of nutrient inputs and nutrient removal. Increasing the SOM is one way to combat nutrient losses from leaching and is a way to essentially reuse nutrients that were taken up and stored in the above-ground biomass. The evaluated parameters of this long-term study show decadal effects of tillage, fertility, and rotation management, which will expectantly reveal
ways to remain profitable and produce similar yields while using conservation management techniques. Furthermore, the results should help demonstrate ways to maintain essential soil chemical properties in rice-based cropping system soils, which can help assure the sustainability of rice production in the United States for years to come.

Acknowledgments

This research was partially funded by the Arkansas Rice Research and Promotion Board. Field assistance provided by Terry Sells, Daniel McCarty, and Tara Moss Clayton is gratefully acknowledged.
Literature Cited


Table 1. Summary of crop rotations by year with all rotations tilled prior to planting in 1999 and the no-tillage treatment starting in 2000. Crops used in the rotations include rice (R), soybean (S), corn (C), and winter wheat (W). Crops in parentheses were grown in the winter.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
</tr>
<tr>
<td>RS</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
</tr>
<tr>
<td>RC</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
</tr>
<tr>
<td>R(W)</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
</tr>
<tr>
<td>R(W)S(W)</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
</tr>
<tr>
<td>RCS</td>
<td>Rice</td>
<td>Corn</td>
<td>Soybean</td>
<td>Rice</td>
<td>Corn</td>
<td>Soybean</td>
<td>Rice</td>
<td>Corn</td>
<td>Soybean</td>
<td>Rice</td>
<td>Corn</td>
</tr>
</tbody>
</table>
Table 2. Summary of the annual nitrogen (N), phosphorous (P), potassium (K), and zinc (Zn) added to corn, soybean, rice, and winter wheat to comprise the soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Nutrient</th>
<th>Sub-Optimal</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>N</td>
<td>224</td>
<td>337</td>
</tr>
<tr>
<td></td>
<td>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>67</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>112</td>
<td>168</td>
</tr>
<tr>
<td>Soybean</td>
<td>N</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>45</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>67</td>
<td>135</td>
</tr>
<tr>
<td>Rice</td>
<td>N</td>
<td>112</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>45</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>67</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>ZnSO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Wheat</td>
<td>N</td>
<td>112</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>34</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>34</td>
<td>67</td>
</tr>
</tbody>
</table>
Table 3. Summary of the crop rotations and the number of crops grown in the respective rotations during the 11-yr study period (1999-2010) at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Number of Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rice</td>
</tr>
<tr>
<td>Continuous Rice</td>
<td>11</td>
</tr>
<tr>
<td>Rice-Soybean</td>
<td>6</td>
</tr>
<tr>
<td>Rice-Corn</td>
<td>6</td>
</tr>
<tr>
<td>Rice-(Wheat)</td>
<td>11</td>
</tr>
<tr>
<td>Rice-(Wheat)-Soybean-(Wheat)</td>
<td>6</td>
</tr>
<tr>
<td>Rice-Corn-Soybean</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 4. Analysis of variance summary of the inherent differences of soil properties in plots prior to tillage, fertility, and crop rotation treatments being imposed. Soil particle-size (PS) measurements presented were measured in 2010 and used to calculate bulk density (BD) for 1999. Soil properties and their interactions related to the inherent soil differences in the assigned treatment combinations on soil organic matter (SOM) content, soil pH, electrical conductivity (EC), and extractable phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and sodium (Na) contents prior to any treatment being imposed in 1999. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>PS</th>
<th>BD</th>
<th>SOM</th>
<th>pH</th>
<th>EC</th>
<th>P</th>
<th>K</th>
<th>S</th>
<th>Ca</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Zn</th>
<th>Cu</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility* Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation</td>
<td>NS</td>
<td>0.005</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation<em>Tillage</em>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 5. Analysis of variance summary of the effects of tillage, fertility, crop rotation, time, and their interactions on soil organic matter (SOM) content, soil pH, electrical conductivity (EC), and extractable phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and sodium (Na) contents after 11 years of consistent management. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.050$ are considered non-significant (NS).

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>SOM</th>
<th>pH</th>
<th>EC</th>
<th>P</th>
<th>K</th>
<th>S</th>
<th>Ca</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Zn</th>
<th>Cu</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>0.048</td>
<td>0.043</td>
<td>NS</td>
<td>0.014</td>
<td>0.019</td>
<td>0.015</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.018</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.016</td>
<td>0.015</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility* Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation</td>
<td>0.008</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.032</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.022</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.002</td>
<td>0.019</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.007</td>
<td>0.003</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation<em>Tillage</em>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>0.025</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time</td>
<td>0.006</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>0.006</td>
<td>0.033</td>
<td>0.011</td>
<td>0.008</td>
<td>NS</td>
<td>0.002</td>
<td>0.007</td>
<td>0.034</td>
<td>0.007</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Time*Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.016</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time*Fertility</td>
<td>NS</td>
<td>0.032</td>
<td>NS</td>
<td>0.014</td>
<td>0.015</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time*Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.001</td>
<td>0.003</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.005</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Tillage</em>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Tillage</em>Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.030</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt;0.001</td>
<td>0.047</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Fertility</em>Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.006</td>
<td>0.001</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Tillage</em>Fertility*Rotation</td>
<td>NS</td>
<td>NS</td>
<td>0.036</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 5. Summary of irrigation water element concentrations at the Rice Research and Extension Center near Stuttgart, AR.

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration (g L(^{-1}) irrigation water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>0.05</td>
</tr>
<tr>
<td>Potassium</td>
<td>5.28</td>
</tr>
<tr>
<td>Sulfur</td>
<td>3.00</td>
</tr>
<tr>
<td>Calcium</td>
<td>11.0</td>
</tr>
<tr>
<td>Magnesium</td>
<td>3.64</td>
</tr>
<tr>
<td>Iron</td>
<td>8.46</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.24</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.01</td>
</tr>
<tr>
<td>Copper</td>
<td>0.01</td>
</tr>
<tr>
<td>Sodium</td>
<td>33.6</td>
</tr>
</tbody>
</table>
Figure 1. Fertility (optimal and sub-optimal) and time (1999 and 2010) effects on soil pH [A] and extractable soil sodium (Na) content [B] in the top 10 cm. Different letters atop bars are significantly different at the 0.05 level.
Figure 2. Tillage [conventional tillage (T) and no-till (NT)], fertility [optimal (O) and sub-optimal (SO)], rotation [rice (R), soybean (S), corn (C) and winter wheat (W)], and time (1999 and 2010) effects on soil electrical conductivity (EC) in the top 10 cm (standard error = 0.015). Least significant difference values vary depending on the treatment combinations being compared (0.023 to 0.042 dS m\(^{-1}\)).
Figure 3. Tillage [conventional tillage (T) and no-tillage (NT)], rotation [rice (R), soybean (S), corn (C) and winter wheat (W)], and time (1999 and 2010) effects on extractable soil phosphorus (P) [A], manganese (Mn) [B], and zinc (Zn) [C] contents in the top 10 cm. Different letters atop bars within the same panel are significantly different at the 0.05 level.
Figure 4. Fertility [optimal (O) and sub-optimal (SO)], rotation [rice (R), soybean (S), corn (C) and winter wheat (W)], and time (1999 and 2010) effects on extractable soil phosphorus (P) [A] and potassium (K) [B] contents in the top 10 cm. Different letters atop bars within the same panel are significantly different at the 0.05 level.
CHAPTER 4

LONG-TERM CROP ROTATION, TILLAGE, AND FERTILITY EFFECTS ON SOIL CARBON AND NITROGEN IN DRY-SEEDED, DELAYED-FLOOD RICE PRODUCTION SYSTEMS
Long-Term Crop Rotation, Tillage, and Fertility Effects on Soil Carbon and Nitrogen in Dry-Seeded, Delayed-Flood Rice Production Systems

Abstract

Rice (Oryza sativa L.) production systems occupy nearly 156 million hectares of soil around the world, and rice makes up approximately 20% of worldwide grain production. In the United States, nearly 80% of the land area used for domestic rice production occurs in the Mississippi Delta region in the south-central portion of the country. In this geographic area, rice is primarily produced using drill-seeding methods into dry soil followed by delayed flooding, as opposed to wet- or transplant-seeding into flooded soil, which are the most common methods used in other rice-producing areas throughout of the world. Since the cycling between dry and water-logged soil conditions greatly influences the storage and turnover of soil organic matter, drill-seeded rice production systems can play an influential role in the biogeochemical cycling of carbon (C) and nitrogen (N) in current agriculturally managed systems. A study was conducted to evaluate the long-term effects of six rice-based crop rotations [with corn (Zea mays L.), soybean (Glycine max L.), and winter wheat (Triticum aestivum L.), tillage [conventional and no-tillage (NT)], and fertility treatments (optimal and sub-optimal) after 11 years (1999 to 2010) of consistent management on soil organic carbon (SOC) and total nitrogen (TN) contents, the partitioning of SOC and TN within SOM, and C:N ratios in the top 10 cm of a silt-loam soil at the Rice Research and Extension Center near Stuttgart, Arkansas. In addition to field measurements, SOC and TN contents modeled using the Century model compared with measured SOC and TN. Results showed that SOC and TN contents increased more than 30% over time in rotations which included winter wheat. Soil OC contents increased ($P < 0.05$) 16% and TN contents increased ($P$
< 0.05) 19% in the rice-soybean rotation over time, whereas there were no differences ($P > 0.05$) in SOC or TN over time in the other crop rotations evaluated. Furthermore, SOC content was 14% greater ($P < 0.05$) under NT and TN was 9% greater ($P < 0.05$) under NT after the 11-year period in the top 10 cm. Century model predictions generally overestimated SOC and TN contents over time. The linear relationship between Century-modeled and observed SOC ($P = 0.010$) and TN ($P = 0.024$) was significant, but there was not a strong predictive relationship between them modeled and observed SOC ($r^2 = 0.137$) and TN ($r^2 = 0.105$) contents when evaluated after 11 years of management. Because soil moisture conditions have such a large impact on the overall storage of SOC and the cycling of N in the soil, examining crop production systems that contain periods of both aerobic and anaerobic conditions is an important step in obtaining a more accurate global estimate of SOC and N storage in agricultural production systems.
Introduction

Rice (*Oryza sativa* L.) production systems occupy 156 million hectares of soil around the world (USDA-FAS, 2012), and rice is considered the world’s most important staple food crop due to its prevalence and societal longevity. As a result of human activities, such as cultivation, domestication, dispersal, and diversification, rice is now grown in more than 100 countries across the latitudinal span of 40°S to 53°N (Chang, 2003), which contributes to 20% of the annual worldwide grain production (USDA-FAS, 2012). In the United States, 82% of the land area used for domestic rice production (1.1 million hectares) occurs in Arkansas (44%), California (22%), and Louisiana (16%), but smaller quantities of rice are also produced in Texas (8%), Mississippi (7%), and Missouri (6%; USDA-NASS, 2012). Rice production in the Mississippi Delta region of the United States is primarily drill-seeded during dry conditions as opposed to wet-seeded or transplant-seeded during flooded conditions, which are the two most common methods used in most rice-producing areas of the world (De Datta, 1981).

Drill-seeded rice production systems are unique from other row-crop production systems in that the crop is grown under flood-irrigated conditions from about one month post-emergence until a few weeks prior to harvest, where the upper-most part of the soil profile is nearly to completely saturated (Norman et al., 2003). Drill-seeded rice production systems are also unique from wet-seeded or transplant-seeded rice production systems because they provide shorter periods of saturated soil conditions and longer periods of dry soil conditions as a result of delayed flooding and time allowed between cropping periods. Since the cycling of water-logged and dry soil conditions have been known to greatly influence the storage and cycling of soil organic matter (SOM) (IPCC, 2007), drill-seeded rice production systems can play an influential
role in the biogeochemical cycling of carbon (C) and nitrogen (N) in agriculturally managed systems.

Soil organic matter is one of the main reservoirs of C in the biosphere (Bernsten et al., 2006). The actual C content in SOM is approximately 57% by weight (Sundermeiser et al., 2005), with the remaining components made up of oxygen (O$_2$), hydrogen, N, and smaller amounts of other nutrients (Bot and Benites, 2005). Follett (2001) estimated that there are about 1550 petagrams (Pg) of organic C stored in the world’s soils. This is more than twice the estimated C contained in living vegetation (560 Pg) or in the atmosphere (750 Pg; Sunquist, 1993). Information on the dynamics of SOM, and the associated soil organic carbon (SOC) and N, storage in agricultural soils has gained interest over recent years because of its influences on global climate change and crop productivity (Majumder et al., 2007; IPCC, 2007). The concept of global warming is primarily attributed to three C and N greenhouse gases that are present both naturally and from anthropogenic sources: carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O; IPCC, 2007). According to Lal (2004), land management practices have the potential to enhance SOC accumulation, thereby easing the gaseous C load to the atmosphere and enriching the soil. The decomposition of SOM, and thus the loss of C from the soil through the conversion of SOC into the gaseous compounds of CO$_2$ under aerobic conditions and CH$_4$ under anaerobic conditions, is promoted by an array of factors, such location in the soil, fibrous composition of the substrate, nutrient content, soil texture, soil pH, moisture conditions, and soil temperature (Denman et al, 2004; Wolf and Snyder, 2003; Seiter and Horwath, 2004; Alvarez and Lavado, 1998; Bayer, 1996; Filcheva and Mitova, 2002).

Soil organic matter present in the soil is a reflection of a long-term balance between additions and losses, so the SOM content is greater when there is a high annual plant
productivity rate and a low decomposition rate (Weil and Magdoff, 2004). Therefore, crops that produce large amounts of above-ground biomass have a greater contribution to the overall SOM content. The length of time SOC can be stored in the soil is controlled by the chemical composition of the biomass, which in turn determines the microbial breakdown potential of the substrate (Debusk et al., 2001; Farquhar et al., 2001). In relation to nutrient content, a large portion of the N within soil (90 to 95%; Smith et al. 1993) occurs along with SOC in the constituents of SOM, and the ratio of N available in the substrate directly affects the rate of microbial SOM decomposition (McGill and Cole, 1981; Weil and Magdoff, 2004). Consequently, the C and N cycles are directly linked, thus the C cycle of an ecosystem cannot be properly examined or modeled without giving reference to N cycling (McGill and Cole, 1981; Weil and Magdoff, 2004). Furthermore, the presence or absence of O$_2$ plays an important role in the process dynamics and management responses of decomposition systems. Generally, an abundant O$_2$ supply promotes rapid decomposition, whereas a deficiency in O$_2$ results in a substantially lower decomposition rate (DeBusk et al., 2001; Shaffer and Ma, 2001). Under extremely wet conditions, decomposition can become limited by O$_2$ availability (Wolf and Snyder, 2003). Decreased decomposition results in greater accumulations of SOM in saturated soils, which essentially increases the amount of stored SOC and N (DeBusk et al., 2001).

An important aspect of soil management practices is to maintain soil physical properties in a way that supports crop growth and ensures an adequate amount of the biomass gets recycled back to the soil to serve as a long-term organic nutrient source (Lal, 2007). A number of studies have been conducted on the changes in SOC due to different production practices. In a large-scale, intensive cropping system, the long-term balance of SOC is altered from natural conditions due to larger accumulations from crop residues and the increased oxidative losses from
continuous cultivation, which can lead to either a net build up or reduction of SOC stock (Kong et al., 2005). Reicosky et al. (1995) showed that there is a strong relationship between the quantity of crop residue inputs and SOM accumulation in the top 15 mm of soil, and that SOM accumulation is controlled by crop variety, tillage, fertilization, and climate.

Because soil moisture conditions have such a large impact on the overall storage of SOC and the cycling of soil N, examining crop production systems that contain periods of both aerobic and anaerobic conditions is important to obtaining a more accurate global estimate of SOC and N storage in agricultural production systems. Therefore, the objective of this study was to evaluate the long-term effects of rice-based crop rotations (with corn, soybean, and winter wheat), tillage [conventional tillage (T) and NT], and soil fertility (optimal and sub-optimal) after 11 years (1999 to 2010) of consistent management on SOC and total N (TN) contents, the partitioning of SOC and TN in SOM, and C:N soil ratios in the top 10 cm of a silt-loam soil. Furthermore, SOC and TN contents were modeled for the 11 year period and into the future using the Century soil organic model (Parton et al., 1987; NREL, 2006). It was hypothesized that: (1) NT practices would have greater SOC and TN than that under T over time as a result of decreased aeration and soil disturbance; (2) rotations with increased frequencies of high-residue-producing crops, such as rice, corn, and those double-cropped with wheat, would have a greater SOC and TN from greater amounts of biomass returned to the soil than lower-residue producing crop rotations, such as those with greater frequencies of soybean; (3) the optimal fertility regime would have greater SOC and TN than that in the sub-optimal fertility regime over time as a result of increased biomass production related with greater fertility inputs of fertilizer; (4) the partitioning of SOC and TN in SOM would not vary greatly as a result of treatment combinations; (5) soil C:N ratios would be greater in high-residue-producing rotations, such as
rice and corn, and would be lower in rotations including soybean, as a result of crop residue
inputs and (6) the Century model outcomes are expected to be correlated with measured SOC
and TN obtained in the study. The Century model is expected to show that systems with high-
residue-producing crops, NT, and optimal fertility result in greater amounts of SOM in the soil,
thus increasing the SOC and N contents over time.

Materials and Methods

Site Description

This field study was conducted at the University of Arkansas’ Rice Research and
Extension Center (RREC) near Stuttgart (34°27' N, 91°24' W), which is situated in the
Mississippi Delta Region of eastern Arkansas in an area known as the Grand Prairie (USACE,
2000). The geographic area is made up of silt-loam and clay-textured soils from the Southern
Mississippi River Alluvium and Terraces and the Arkansas River Alluvium (USDA-NRCS,
2008). The 30-yr mean monthly air temperature ranges from a minimum of 0.22 °C in January to
a maximum of 33.1 °C in July, and the 30-yr mean annual precipitation is 131.6-cm (SRCC,
2012).

The study began in 1999 on a Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf;
USDA-NRCS, 2008), which is a common soil present in the Grand Prairie region. The Dewitt
series is made up of very deep, poorly drained, slowly permeable soils that formed in alluvium
(USDA-NRCS, 2008). The top 10 cm are primarily dark grayish brown (10YR 4/2) in color with
a moderate medium granular and weak medium and course subangular blocky structure. The 10-
to 18-cm depth has a more compacted and dense layer that is a distinct dark brown (7.5YR 3/2)
color and commonly contains iron-manganese concretions (USDA-NRCS, 2008).
Prior to the initiation of the study in 1999, the study area had been fallowed for numerous years due to a lack of irrigation capability. Vegetation present consisted of a mixture of grass and weeds that were mowed in the summer. In preparation for the study, the site was land leveled to a 0.15% grade in Fall 1998, which is common practice in the area in order to facilitate uniform distribution of flood-irrigation water (Brye et al., 2003). Top soil was first removed, piled off to the side of the area, and then spread back over the area that was land leveled.

Experimental Design and Field Treatments

The experimental design for this study was a randomized complete block, with each block partitioned as a split-strip-split plot. The blocks included four rectangular sections 76-m long by 120-m wide (9120 m²) within the 1.9-ha experimental site. Each block was divided into two tillage treatments (T and NT) and each tillage treatment was split into two fertility regimes (optimal and sub-optimal). Each of the tillage-fertility combinations were stripped across with 10 crop rotations and split across time (1999 and 2010). The 10 crop rotations present included continuous rice (R), rice-soybean (RS), soybean-rice (SR), rice-corn (RC), corn-rice (CR), rice (winter wheat) [R(W)], rice (winter wheat)-soybean (winter wheat) [R(W)S(W)], soybean (winter wheat)-rice (winter wheat), rice-soybean-corn, and rice-corn-soybean (RCS). However, for the purposes of this experiment, only six of the 10 rotations were used due to the elimination of mirror-image rotations. Consequently, the six rotations used in this study included R, RS, RC, R(W), R(W)S(W), and RCS. The rotations evaluated started with rice during the first year of the study and followed the respective rotations in successive years (Table 1). There were 96 plots evaluated and each plot representing a tillage-fertility-rotation treatment combination measured 6- by 19-m. Residue management in T treatments consisted of burning the surface residue after
harvest, whereas residue in NT plots was left undisturbed. Rice, soybean, and wheat were sown into 19-cm rows in both tillage treatments using an Almaco NT drill (Almaco, Nevada, IA). Rice was drill-seeded at a rate of 100 kg seed ha$^{-1}$, soybean at a rate of 56 kg seed ha$^{-1}$, and wheat at a rate of 67 kg seed ha$^{-1}$. Corn was planted in 76-cm rows at a plant population of 79,000 seeds ha$^{-1}$.

Fertility treatments applied were based on soil analyses from the study site at the beginning of the study in 1999 (Table 2). Each year, phosphorus (P) was applied as triple super phosphate and potassium (K) was applied as muriate of potash, which were broadcast pre-plant and pre-tillage with a hand-spread. During the years rice was grown, zinc (Zn) was applied as zinc sulfate, which was also broadcast pre-plant and pre-tillage with a hand spreader. Nitrogen was applied as urea with a hand-spread pre-flood approximately one month after planting. Phosphorous, K, and Zn were incorporated into the soil in the T treatment and were applied to the surface in the NT treatment. Following N fertilization in rice, a 5- to 10-cm permanent flood was established, which was maintained on all of the rice plots throughout the growth period. Corn and soybean were furrow-irrigated on an as-needed basis during the summer growth period, with the irrigation amount varying based on the rainfall received and the growth of the crop. Irrigation water originated from a nearby surface reservoir, with water additions mainly from an adjacent stream channel and some groundwater. Wheat grown during the winter was rainfed only. All recommendations for stand establishment, irrigation, weed management, and pest management for rice (Slaton, 2001), soybean (Ashlock, 2000), corn (Espinoza and Ross, 2003), and wheat (Kelley, 1999) followed the University of Arkansas Cooperative Extension Service recommendations for the duration of the study (Motschenbacher et al., 2012b).
Soil Sampling and Analyses

Soil samples were collected in March from the top 10 cm in each tillage-fertility-rotation treatment combination prior to spring planting during both evaluation years. The 1999 samples were collected after land-leveling practices had occurred and prior to any actual field treatment being imposed. The 2010 samples were collected prior to the spring planting of rice, corn, or soybean. During the time of sampling in 2010, the wheat was present in the R(W) and R(W)S(W) rotations, whereas the R, RS, RC, and RCS rotations were still fallow from the winter.

Soil samples for both years were dried at 70°C in an oven for 48 hours. In 2010, soil samples were acquired using a 4.7-cm diameter stainless steel cylinder, resulting in an approximate 203-cm³ collected volume. Following drying, samples were weighed for bulk density determination. However, in 1999 bulk density was not measured. Therefore, particle-size analyses were conducted on all of the 2010 soil samples from the top 10 cm. The percentages of sand and clay measured from the 2010 samples were combined with measured SOM concentrations from 1999 (Motschenbacher et al., 2012a) to estimate bulk density for the 1999 samples on a plot-by-plot basis using a bulk density prediction equation incorporated in the Soil-Plant-Atmosphere-Water (SPAW) Model (Saxton and Rawls, 2006).

In both 1999 and 2010, total carbon (TC) and TN were measured by high-temperature combustion after samples were crushed to pass a 2-mm mesh screen. All measured soil C was assumed to be associated with the organic fraction of the soil because, upon treatment with concentrated hydrochloric acid (HCl), there was no effervescence. Therefore, measured TC is hereafter referred to as SOC. Measured SOC and TN concentrations (mg kg⁻¹) were converted to contents (kg m⁻²) using a 10-cm sampling depth and measured or estimated soil bulk densities (g
cm$^{-3}$). The partitioning of SOC and TN within SOM, in addition to C and N ratios (C:N), were calculated from SOM (Motschenbacher et al., 2012a), SOC, and TN concentrations from each tillage-fertility-rotation treatment combination.

When the 2010 samples were collected, R and R(W) rotations had produced 11 rice crops, and the RS, RC, and R(W)S(W) rotations had produced six rice crops with five crops in the respective rotation with corn or soybean (Table 3). Furthermore, the RCS rotation had produced four rice crops, four corn crops, and three soybean crops, and the R(W) and R(W)S(W) rotations with had produced 11 winter wheat crops (Table 3). Tillage had occurred in the tilled plots five months prior (late-October 2009) to the collection of samples in March 2010.

**Century Model Simulation**

For comparison to measured data over time, simulations using the Century model were conducted for each tillage-fertility-rotation treatment combination. Century is a SOM model that simulates C and N cycling in different plant production systems based on a monthly time step (Parton et al., 1987, 1988; Parton and Rasmussen, 1994). The model works by allocating various plant components and animal excreta into different SOM pools with varying timescales of decomposition, which include the active (a few months to a few years), slow (20 to 50 years), or passive (400 to 2000 years) pools. This is done by partitioning plant residues as either structural or metabolic organic pools based on their lignin:N ratio (Shibu et al., 2006), in that plant parts with a larger ratio take longer to decompose. The model works by dividing the structural pool into lignin and cellulose components (NREL, 2006). The lignin is moved to the slow decomposition pool, whereas the cellulose and metabolic C (i.e., microbial biomass) is added to the active pool. The actual decomposition rates of the SOM from the active pool are calculated
based upon the soil texture, soil temperature, and soil moisture, and the decomposition rates of the structural pool are determined based upon the lignin content of the plant material. In the Century model, the nitrification process is not incorporated because there is no distinction made within the mineral-N pool between nitrate and ammonium (Shibu et al., 2006).

The limitations of the model in relation to rice-based cropping systems are that the model was originally designed for grassland, arable land, forests, and savanna ecosystems under aerobic conditions (NREL, 2006; Parton et al., 1988), not periodically flooded ecosystems. This has resulted in the Century model not being extensively used to simulate rice-based crop rotations. However, Bhattacharyya et al. (2007) used Century to model a jute (Cochoro capsularis L.)-rice-wheat rotation in West Bengal, India and Milne et al. (2008) modeled a three year rice-soybean, wheat-soybean rotation in eastern Arkansas, United States, in which the field was flooded for rice production once every three years. Bharracharyya et al. (2007) reported that the model overestimated SOC content, but was able to simulate trends in SOC cycling over the 30-year study period, and while Milne et al. (2008) reported that the model underestimated the increase of SOC content in the first year, but could be used to more accurately to predict the long-term SOC dynamics in rice-based crop rotations that are flooded every three years.

Parameters for the Century soil organic matter model (Parton et al., 1987; NREL, 2006) simulation in this study were adjusted using a combination of recorded historic climatic data, measured plant properties and responses, and measured data in the top 10 cm and adjusted to a depth of 20 cm. In 1999, soil samples were only acquired from the top 10 cm, whereas 2010 samples were collected from both the 0- to 10- and 10- to 20-cm depths. In order to model trends over time using Century, which only simulates C and N cycling in a fixed depth of the top 20 cm, depth adjustments had to be made from the measured 0- to 10-cm sampling depth in both
years. In order to calculate the percentage of C and N that was contained in the top 10 cm of the 0- to 20-cm depth interval, the average percent content was calculated from the 2010 soil samples. Based on 160 samples from both the top 10- and 10- to 20-cm depths, the top 10 cm contained an average of 66% of the SOC and 61% of the TN in the top 20 cm of soil. To facilitate comparison to measured data from the top 10 cm, output values from Century from the top 20 cm were adjusted to SOC and TN contents for the top 10 cm based on the average calculated percentages from observed data.

Different simulated model designs for field treatments and crop rotations were set up for each tillage-fertility-rotation treatment combination. However, the input file used in all model designs used the same values for monthly average maximum and minimum air temperature (SRCC, 2012), monthly precipitation (SRCC, 2012), soil texture, soil bulk density, soil pH, and initial SOC and TN contents from 1999. In order to establish a uniform starting point in time for comparisons between the modeled treatment combinations over time, initial conditions were set uniformly across all treatment combinations. This approach was justified because there were no substantial variations in soil physical properties (Motschenbacher et al., 2012a) and SOC and TN contents in 1999. Therefore, initial values for soil texture, soil bulk density, and SOC and TN contents were fixed based on the average values across all pre-assigned tillage-fertility-rotation treatment combinations. All model input files started with the same site and control parameters for the model. Any observed differences among tillage-fertility-rotation treatment combinations over time were assumed to be a result of the imposed treatments instead of inherent differences in soil physical and chemical properties. Anaerobic conditions associated with flooding during the rice growing season, which results in slower decomposition rates, were accounted for by adjusting the drainage potential of the soil and the irrigation frequency.
Data Analyses

Initial soil properties in 1999 and the effects of tillage, fertility regime, crop rotation, and time (1999-2010) on SOC and TN contents, the partitioning of SOC and TN in SOM, and C:N ratios were evaluated by analysis of variance (ANOVA) using the PROC MIXED procedure in SAS® (version 9.2, SAS Institute, Inc., Cary, NC). When appropriate, means were separated using Fisher’s protected least significant difference (LSD) at the 0.05 level. Modeled results for SOC and TN storage trends over time were compared to direct observations via a linear regression analyses using Minitab (version 15, Minitab, Inc., State College, PA).

Results and Discussion

Initial Soil Properties

Samples collected at the initiation of the study in 1999, which were collected after land leveling and prior to the implementation of tillage, fertility, and rotation treatments, showed soil properties in the top 10 cm were generally uniform among pre-assigned tillage-fertility-rotation treatment combinations (Motschenbacher et al., 2012a). Statistical analyses performed exclusively on 1999 soil properties did not show differences among SOC and TN contents, the partitioning of SOC and TN within SOM, and soil C:N ratios among pre-assigned tillage, fertility, and/or rotation treatments ($P > 0.05$; Table 4). Furthermore, soil particle-size distribution did not differ among any among treatment combinations when measured in 2010 ($P > 0.05$; Table 4; Motschenbacher et al., 2012a).

Although there were no differences among other soil properties in 1999, there were a few minor inherent differences in estimated soil bulk density ($P = 0.005$) among pre-assigned
rotations (Table 4). Estimated soil bulk density in the R(W) (1.44 g cm\(^{-3}\)) rotation was 2 to 4% greater than that in the R (1.41 g cm\(^{-3}\)), RC (1.40 g cm\(^{-3}\)), and RCS (1.38 g cm\(^{-3}\)) rotations, when averaged across pre-assigned tillage and fertility treatments. Furthermore, estimated soil bulk density was 3% greater in the R(W)S(W) and RS (both 1.42 g cm\(^{-3}\)) rotations than in the RCS rotation. Though statistically different, all differences in soil bulk density were ≤ 0.06 g cm\(^{-3}\), which are not large enough to cause substantial differences in SOC and TN contents.

Analyses conducted on the effects of tillage, fertility, and/or rotation treatment combinations over time (i.e., 1999 and 2010) on SOC and TN contents did not have two- or three-way interactions among field treatments (i.e., tillage, fertility, or rotation) used in this study. Furthermore, results showed that the effects on SOC and TN contents were either an interaction between tillage or rotation and time [i.e., tillage-time (TN) or rotation-time (SOC and TN)] or a solitary field treatment effect of tillage (SOC), but SOC and TN contents did not differ between fertility treatments. Therefore, the following results for SOC and TN is based on the effects of each individual field treatment (i.e., tillage, fertility, or rotation), with differences or lack of differences in each field treatment over time (i.e. 1999 to 2010).

The partitioning of both SOC and TN in SOM were both affected by tillage-rotation interactions, but soil C:N ratios were not affected by tillage, fertility, rotation, or time. Therefore, the partitioning of SOC and TN in SOM and the soil C:N ratios are each discussed separately from each other and from the results for SOC and TN contents.

**Tillage Effects on SOC and TN**

Similar to hypothesized, averaged across fertility regimes, crop rotations, and time, SOC content (kg m\(^{-2}\)) was affected by tillage \((P = 0.012)\), and when averaged across fertility regimes
and crop rotations, TN content (kg N m\(^{-2}\)) differed over time between tillage treatments (\(P = 0.019;\) Table 5). Soil OC content was 14% greater under NT (1.14 kg m\(^{-2}\)) than under T (1.00 kg m\(^{-2}\); Figure 1), but unlike what was expected, SOC content did not differ between the tillage treatments over time (i.e. 1999 to 2010; \(P = 0.075\)). However, as expected, TN content increased 34% from 1999 (0.10 kg m\(^{-2}\)) to 2010 (0.13 kg m\(^{-2}\)) under NT, but did not differ over time under T (Figure 2). Consequently, NT management resulted in a net TN sequestration rate of about 0.003 kg m\(^{-2}\) yr\(^{-1}\) from 1999 to 2010.

Tillage effects on SOC and TN contents appear to be directly related to SOM content differences, whereas the SOM content was 9% greater under NT (2.88 kg m\(^{-2}\)) than under T (2.64 kg m\(^{-2}\)), when averaged across all other treatments (Motschenbacher et al., 2012a). Although SOC content did not differ over time, the increase in TN content over time under NT corresponds to the 14% increase in SOM content over the same time period [1999 (2.58 kg m\(^{-2}\)) to 2010 (2.95 kg m\(^{-2}\))], when averaged across all other treatments (Motschenbacher et al., 2012a). Similar to results observed in this study, greater SOC under NT as opposed to that under T is a common occurrence which has been reported heavily in past agronomic studies (West and Post, 2002; McCarty et al., 1998; Xu et al., 2007). Soils that have been degraded through excessive tillage tend to have less SOM due to an increased amount of exposed surface area, which facilitates aerobic decomposition (DeBusk et al., 2001). Carbon makes up more than half the mass of SOM (Montgomery et al., 2000), and it has been shown that cultivating the land influences the dynamics of SOC and, in turn, the amount of C emitted from the soil as CO\(_2\) due to the oxidation or decomposition of SOM (Paustian et al, 1995; Reicosky et al., 1995).

Although flooded-soil conditions in rice-based crop rotations alter the environmental conditions contributing to C and N sequestration and cycling, due to slower decomposition rates
and increased CH$_4$ emissions as opposed to CO$_2$ emissions, studies on long-term effects of different tillage regimes implemented in non-flooded upland soils can also provide insight on the impacts of soil disturbance from tillage. Salinas-Garcia et al. (1997) reported that a decrease in tillage increased SOM, microbial biomass C, inorganic N, and labile C and N content pools when compared to plowed systems in a long-term quadrennial corn-cotton rotation on a sandy-clay-loam soil in Texas. Furthermore, West and Post (2002) showed that among 67 non-flooded long-term studies located on various soil textures in countries throughout the world, the average sequestration rate was $57 \pm 14$ g C m$^{-2}$ yr$^{-1}$ on land converted from T to NT systems, with the exclusion of wheat-fallow systems. West and Post (2002) also estimated that C sequestration reaches a maximum between 5 and 10 years after conversion from T to NT, and after 15 to 20 years, the soil reaches a greater equilibrium C concentration.

In a study evaluating a wheat-soybean double-cropping system on a silt-loam soil in east-central eastern Arkansas, SOC content was greater under NT in the top 10 cm than that under T after two years of continuous cultivation (Byre et al., 2006a) and C lost as CO$_2$ flux from soil respiration was 38% greater from T than from NT (Brye et al., 2006b). Reicosky and Lindstrom (1993) attributed the large initial rate of soil surface CO$_2$ flux after tillage to the release of CO$_2$ in newly exposed soil pores and from dissolution or direct oxidation of C substrates, which further demonstrates the loss of C through increased decomposition rates as a result of aeration from tillage. Furthermore, SOM is made up of approximately 5% N, which is mineralized into NH$_4^+$ during the decomposition process. Mineralized N is susceptible to removal from or translocation within the soil after nitrification through the leaching of nitrate (NO$_3^-$) and through gaseous losses during denitrification (Havlin et al., 2005; Schlesinger, 1997).
The reduction of tillage intensity by switching from T to NT has been widely recognized as management practice that increases the amount of C storage in soils (Lal and Kimble, 1997; Doa, 1998; Kern and Johnson, 1993; Dick et al., 1998) and influences N cycling (Shaffer and Ma, 2001) in the near-surface soil. McCarty et al. (1998) reported increased SOC (38%), microbial biomass C (33%), TN (30%), and microbial biomass N (87%) concentrations in the top 2.5 cm of a silt-loam soil three years after the transition from T to NT on a continuous corn rotation in the United States, whereas SOC (7%), microbial biomass C (15%), TN (6%), and microbial biomass N (35%) concentrations in the 12.5 to 20 cm depth decreased. An 18-year study of a rice-wheat rotation in a clay-loam soil in China also showed greater SOC, TN, and microbial biomass C and N concentrations in the top 5 cm under NT compared with T, whereas SOC and TN concentrations were greater in the 5- to 10-cm and 10- to 20-cm depths under T compared with NT (Xu et al., 2007). The results of previous studies suggest the elimination of tillage greatly influences the stratification of SOC and TN on the near-surface soil layers, whereas there are greater quantities of less-decomposed residue in the upper-most soil layers under NT and that the SOC and TN contents decrease with depth.

In contrast, SOC and TN contents are commonly unstratified and similar throughout the plow layer under T because the mechanical mixing action of tillage distributes reside more evenly. Tillage also allows for the incorporation of SOM deeper into the soil by mixing plant residue and microbial biomass that usually remains in the upper-most layers under undisturbed conditions. This mixing action in the plow layer can result in greater SOC and TN contents in soil depths immediately below the plow depth under T than that under NT due to the placement of the SOM near the bottom of the plow layer under full-inversion tillage (Angers and Eriksen-Hamel, 2008).
**Fertility Regime Effects on SOC and TN**

In contrast to that hypothesized, SOC and TN contents did not differ between fertility regimes imposed in the study ($P > 0.05$; Table 5). Fertilization of the soil has been well-documented as being directly correlated to the quantity of biomass produced, which, in turn, is directly correlated with the amount of crop residues that are returned to the soil to become SOM, thus contributing to the SOC and TN pools (Follett, 2001). However, in this study, the differences among optimal and sub-optimal fertility treatments (Table 2) were likely not great enough to significantly affect SOC and TN contents even after 11 years of consistent management. The lack of fertility treatment differences in SOC and TN contents between optimal and sub-optimal fertility directly correspond to the lack of differences in SOM contents that were also observed in this study, when averaged across all other treatment factors ($P > 0.05$; Motschenbacher et al., 2012a). However, the lack of SOC and TN content differences under optimal and sub-optimal fertility do not insinuate soil fertilizer treatments failed to increase the overall input of crop residues added to the soil when compared to the quantity that would be added upon the elimination of N-P-K treatments. For the purposes of this, only the effects of commonly recommended fertilizer rates provided to producers in the Mississippi Delta area of Arkansas were evaluated (Table 2; Espinoza et al., 2007). Therefore, the design of this study did not include a control treatment in which no fertilizer was applied, as that would not be a common recommendation for field-crop production in the geographic study area.

Furthermore, there is a chance that differences in the fertility treatments over time might have existed if soil at a greater soil depth interval was compared. Electrical conductivity (EC) values evaluated in Motschenbacher et al. (2012a) showed a substantial decrease in EC values
over the 11-year time period evaluated, which suggest that nutrient leaching through the profile with the infiltration and movement of applied irrigation water occurred. Therefore, it is reasonable to assume that some of the SOC and TN could have also leached further in the profile with irrigation water. Therefore, differences between fertilizer treatments might have been too small to be significant in analyses on the top 10 cm, but lower soil depths could potentially show differences related to fertility.

Based on past studies, it can be assumed that both fertilization treatments allowed a greater quantity of above-ground biomass to be returned to the soil than would have been returned without fertilization. Halvorson et al. (2002) reported that N fertilization increased the quantity of crop residue returned to the soil after 12 years in two dryland cropping systems located in North Dakota, which included spring wheat-winter wheat-sunflower (*Helianthus annuus* L.) and spring wheat-fallow rotations in the top 30.5 cm of a loam soil under different tillage treatments. Clapp et al. (2000) had similar findings in a 13-year study with corn in the 15- to 30-cm depth of a silt-loam soil in Minnesota, which showed that adding N fertilizer increased SOC content when residues were returned to the soil in NT systems. Lal et al. (1998) reported that on average, soil fertility management practices add roughly 50 to 150 kg SOC ha\(^{-1}\) to the soil every year, depending on the cropping system.

Most rice cultivars grown in the United States require 135 to 200 kg ha\(^{-1}\) of N fertilizer to produce profitable grain yields (Norman et al., 2003). Shen et al. (2007) indicated that when compared to untreated plots, chemical-fertilizer-treated plots produced a net gain of 16 to 18 g SOC kg soil\(^{-1}\) in rice-wheat agroecosystems in China. In an 18-year study of a rice-wheat rotation in China by Xu et al. (2007) reported greater SOC and TN concentration increases in the top 10 cm when a combination of organic and inorganic N-P-K fertilization treatments were
applied to a clay-loam soil than with no fertilization. Pampolino et al. (2008) reported that after 17 to 21 years of continuous rice production, several studies producing two to three rice crops per year on silty-clay or clay soils in the Philippines had greater SOC and TN concentrations in the top 20 cm with N-K, N-P, and N-P-K fertilization than in areas with no fertilization.

**Crop Rotation Effects on SOC and TN**

As hypothesized, SOC ($P < 0.001$) and TN ($P = 0.003$) contents (kg m$^{-2}$) were affected by crop rotation and time, when averaged across tillage treatments and fertility regimes (Table 5). The SOC content in rotations that included winter wheat [i.e., R(W) and R(W)S(W)] increased more than 30% for a sequestration rate of 0.028 kg$^{-1}$ SOC m$^{-2}$ yr$^{-1}$ and the R rotation increased 16% for a sequestration rate of 0.014 kg$^{-1}$ SOC m$^{-2}$ yr$^{-1}$ from 1999 to 2010, whereas SOC contents in the RS, RC, and RCS rotations did not differ over the 11-year time period (Figure 1A). Likewise, TN contents increased 36 to 46% in the R(W) rotation for a sequestration rate of 0.003 kg$^{-1}$ TN m$^{-2}$ yr$^{-1}$ and in the R(W)S(W) rotation for a sequestration rate of 0.004 kg$^{-1}$ TN m$^{-2}$ yr$^{-1}$, respectively, and the RS rotation increased 19% for a sequestration rate of 0.002 kg$^{-1}$ TN m$^{-2}$ yr$^{-1}$ from 1999 to 2010, whereas the TN contents in R, RC, and RCS rotations did not differ over time (Figure 1B). The greater increase of SOC and TN over time in rotations with wheat could be partially due to greater quantities of annual biomass from the double-cropped rotations, as opposed to rotations that were fallow in the winter, and partially due to the presence of wheat in the ground during sampling. The presence of the wheat crop would suggest that there were greater concentrations of fresh root biomass and increased microbial activity in the near-surface soil compared to rotations that were fallow during the winter.
The increases in SOC and TN correspond to similar observed differences in SOM among rotations and increases in SOM content over time. Soil organic matter content increased 14% from 1999 (2.58 kg m\(^{-2}\)) to 2010 (2.95 kg m\(^{-2}\)), when averaged across all tillage, fertility, and rotation treatment combinations, and SOM content was 5 to 13% greater in R(W) (3.01 kg m\(^{-2}\)) than in all other crop rotations (2.67 to 2.78 kg m\(^{-2}\)), when averaged across tillage, fertility, and time (Motschenbacher et al., 2012a). However, SOC contents only increased in the R(W), R(W)S(W), and R rotations and TN contents only increased in the R(W), R(W)S(W), and RS rotations over the 11 year period, whereas SOM content changes over time were unaffected by individual crop rotations (Motschenbacher et al., 2012a).

Increasing the amount of SOC, and associated N, in the soil requires the addition of enough crop residue to exceed the losses from SOM decomposition, erosion, and leaching (Follett, 2001). This can be accomplished by using crop rotation systems that can influence the volume, distribution, and turnover of the active and passive pools of SOC (Franzluebbers et al., 1994). Examining each year separately and averaged across tillage and fertility regimes, SOC content in the RCS (1.04 kg m\(^{-2}\)) rotation was 14% greater than that in the R(W)S(W) (0.91 kg m\(^{-2}\)) rotation at the beginning of the study in 1999, while SOC contents in all other rotations did not differ (Figure 1A). For TN content, there were no differences among crop rotations in 1999 (Figure 1B). However, after 11 years of continuous management, the R(W) (1.32 kg m\(^{-2}\)) and R(W)S(W) (1.22 kg m\(^{-2}\)) rotations had 15 to 28% greater SOC contents than rotations that included corn [i.e. RC (1.03 kg m\(^{-2}\)) and RCS (1.06 kg m\(^{-2}\))] (Figure 1A). Furthermore, the R(W) rotation had 15 to 28% greater SOC content in 2010 than that in the R, RS, RC, and RCS rotations (1.03 to 1.15 kg m\(^{-2}\)), which did not differ among one another (Figure 1A). In 2010, TN content was 14 to 27% greater in the R(W) (0.14 kg m\(^{-2}\)) and R(W)S(W) (0.13 kg m\(^{-2}\)) rotations.
than that in any of the other crop rotations (0.11 to 0.12 kg m$^{-2}$), whereas TN content among the R, RS, RC, and RCS rotations in 2010 did not differ (Figure 1B). Greater TN contents in winter-wheat rotations [i.e., R(W) and R(W)S(W)] compared to the R, RS, RC, and RCS rotations could partially be due to the timing of the last fertilizer-N application prior to the 2010 sampling date in mid-March. The R(W) and R(W)S(W) rotations received N fertilization at the beginning of March 2009 for the winter-wheat crop, whereas the last application of N fertilizer was in the previous spring (i.e., Spring 2009) for all other crop rotations (Table 2).

Dick et al. (1998) concluded that crop rotation and cover crops are an effective way to facilitate C sequestration, especially when combined with NT and optimal fertilization. After evaluating 67 long-term agricultural studies, West and Post (2002) estimated that enhancing the rotation complexity, including changing from monoculture to continuous rotation cropping, crop-fallow to continuous monoculture or rotation cropping, or increasing the number of crops in a rotation system, can sequester an average of $0.020 \pm 0.012$ kg C m$^{-2}$ yr$^{-1}$ in the top 30 cm of dryland systems, with the exclusion of a change from continuous corn to corn-soybean, which may not lead to a significant change in SOC. This rate is comparable to the SOC sequestration rate of $0.028$ kg$^{-1}$ m$^{-2}$ yr$^{-1}$ in the top 10 cm for rotations which included winter wheat [i.e., R(W) and R(W)S(W)] in this study compared to continuous rice ($0.014$ kg$^{-1}$ m$^{-2}$ yr$^{-1}$) and other rotations, which did not significantly sequester SOC over time.

In this study, crop rotation appeared to be a major contributor to the quantity of SOC present in the top 10 cm. Rice and corn are two high-residue-producing crops that are capable of producing 6.5 Mg ha$^{-1}$ (rice) to 8.0 Mg ha$^{-1}$ (corn) of above-ground dry matter per crop produced under adequate fertilization, whereas soybean is only capable of producing around 2.2 Mg ha$^{-1}$ of above-ground dry matter during a cropping season (USDA-NASS, 2012). The above-ground
biomass quantities produced annually can also be increased by double-cropping a system with wheat (West and Post, 2002), which is capable of producing an additional 3.3 Mg dry matter ha\(^{-1}\) per year (USDA-NASS, 2012), as opposed to keeping the rotation fallow for the winter. For this study, rotations that produced rice and wheat during a year [i.e., R(W) and R(W)S(W)] were capable of producing 9.8 Mg dry matter ha\(^{-1}\) per year, and during the years soybean and wheat were grown, the R(W)S(W) rotation produced roughly 5.5 Mg dry matter ha\(^{-1}\) per year (USDA-NASS, 2012). Therefore, a greater SOC content in the R(W) rotation after 11 years of rotation management was expected due to the consistent input of at least 23% more inputs of above-ground dry matter annually than that from the RS, RC, and RCS rotations, and the R(W)S(W) rotation during the years soybean and wheat were produced (Figure 1A).

In addition to large above-ground biomass inputs, rice is a unique crop to add to a crop rotation because it is unlike all other row crops in that rice is grown under nearly to completely saturated soil conditions (Norman et al., 2003), which slows the rate of SOM decomposition and affects N cycling dynamics. Thus, flooding the soil during the period rice is produced greatly affects SOM, and consequently SOC, accumulation in the soil, which is then susceptible to rapid decomposition when the field is drained for harvest and during the fallow period. Although crop rotations involving high-residue-producing crops like corn typically facilitate substantial increases in SOC, the anaerobic conditions under which rice is grown also affect the breakdown of crop residues in the soil. Witt et al. (2000) demonstrated that soils continuously cropped with flooded rice had 11 to 12% more C sequestration and 5 to 12% more N accumulation than soils which supported a dry-season, maize-flooded-rice rotation. The results were attributed to a 33 to 41% increase in the estimated amount of mineralized C and decreased input of N from biological N fixation during the dry-season, maize-cropping period (Witt et al., 2000). Aulakh et al. (2001)
reported that C sequestration in a sandy-loam soil in India was 69 to 107% greater when wheat residues were added to flooded rice. Furthermore, Aulakh et al. (2001) also showed that adding wheat residue immobilized mineral-N during the fallow period, but the amount of mineral-N increased rapidly at the start of the flooded rice season when green manure or urea-N were applied.

The increase in TN in the RS rotation over time in this study can be explained by the increased frequency of an N-fixing legume crop in the rotation, whereas the R, RC, and RCS did not result in increased TN over time (Figure 1B). This is because the *Rhizobia* bacteria present in the nodules on legume roots are able to absorb dinitrogen gas (N$_2$) from the air and convert it to ammonium (NH$_4^+$), which can either be excreted into the soil or taken up by the plant and returned to the soil as residue at a later time (Havlin et al., 2005). The R(W)S(W) rotation also had a biennial rotation with soybean, but it is unclear whether the increase in TN content over time was a result of having a leguminous crop present in the rotation or related to the application of fertilizer-N in the fall. The R(W)S(W) rotation had a similar TN content as the R(W) rotation in 2010, which also had fertilizer-N applied in the fall, but did not include a leguminous crop (Figure 1B). These results are similar to those by Granatstein et al. (1987) from a 10-year study on winter wheat-legume rotations using different tillage regimes, which reported the greatest increase in TN in the top 5 cm was in rotations with greater frequencies of N-fixing legume crops in the rotation.

**Partitioning of SOC and TN within SOM**

Similar to SOC and TN contents, the fraction of SOM made up by SOC in the top 10 cm differed by tillage ($P = 0.007$), when averaged across fertility, rotation, and time. Also similar to
SOC and TN contents, the fraction of SOM made up by SOC ($P = 0.047$) and TN ($P = 0.037$) differed by rotation and time, when averaged across tillage and fertility regimes, but SOC and TN fractions of SOM were unaffected by fertility regime ($P > 0.05$; Table 5).

The fraction of SOM made up of SOC was 5% greater under NT (39.7%) than that under T (37.7%). Furthermore, the fraction of SOM made up of SOC was roughly 1.4% greater in the RS rotation in 1999 (40.7%) and R(W)S(W) rotation in 2010 (40.4%) than the R(W)S(W) rotation in 1999 (35.6%), whereas there were no differences in SOC among any other rotation-time combinations. Therefore, the fraction of SOM made up of SOC increased 13% over 11 years in the R(W)S(W) rotation, but no other rotations’ SOC fraction of SOM changed over time. The fraction of SOM made up of TN was 2% greater in the R(W)S(W) rotation in 2010 (4.4%) than in the R, RC, R(W), R(W)S(W), and RCS rotations in 1999 and the R and RC rotations in 2010 (both years ranged from 3.7 to 3.9%). Similar to SOC, the TN fraction of SOM in the R(W)S(W) increased 21% from 1999 (3.6%) to 2010 (4.4%).

Although there were differences in the SOC and TN fractions of SOM, these differences only ranged from 1 to 5%. With the exception of the RS rotation in 1999, which had a greater fraction of SOC in SOM, only the R(W)S(W)/2010 treatment combination had greater SOC and TN fractions of SOM than a majority of the other rotation-time combinations. Furthermore, the R, RC, R(W), R(W)S(W), and RCS rotations in 1999 and the R, RS, RC, R(W), and RCS rotations in 2010 did not differ in the SOC and TN fractions of SOM. Therefore, there is a possibility that the greater SOC and TN fractions of SOM in R(W)S(W) in 2010 could be an isolated sampling or laboratory discrepancy instead of a true rotation effect over time.
Soil C:N Ratio

The soil C:N ratio in the top 10 cm was unaffected by tillage, fertility, rotation, or time ($P > 0.05$; Table 5). Carbon:N ratios ranged from 8.1 to 14.0 in both 1999 and 2010. The C:N ratio of the soil is important because N is essential to microbial growth and reproduction, so the microorganisms must obtain N either from the material being decomposed or an external source (i.e., inorganic N fertilizer compounds in the soil) in order to continue consuming SOM (Wolf and Snyder, 2003). If the SOM being decomposed has a high C:N ratio, then soil microbes have to either acquire N from the surrounding soil or decrease the rate of decomposition (Havlin, 2005). A common rule of thumb is that a C:N ratio of 20 to 30 in crop residues maintain an equilibrium mineral-N level in the soil, whereas any C:N ratio above 30 results in a net loss of NH$_4^+$- and NO$_3^-$-N, and a C:N ratio below 20 results in a net gain of NH$_4^+$- and NO$_3^-$-N (Stevenson and Cole, 1999). However, in this study, there were no differences in soil C:N ratios among treatment combinations evaluated.

Century Model SOC and TN Contents

The linear relationship between Century-modeled and measured SOC ($P = 0.010$) and soil TN ($P = 0.024$) after 11 years of consistent management was significant, but there was a relatively weak predictive relationship between modeled and measured SOC ($r^2 = 0.137$; Figure 3A) and TN ($r^2 = 0.105$; Figure 3 B) contents. For the analyses of SOC and soil TN contents, all modeled estimations for the 24 tillage-fertility-rotation treatment combinations were evaluated against mean direct observation values for 2010. The mean values of the direct observations were used in order to get a direct comparison analyses between modeled and measured SOC and soil TN contents.
A numerical evaluation of Century-estimated values and direct observations over the 11-year study period (1999 to 2010) indicated that the Century estimated greater SOC (Figure 4A) and TN (Figure 4B) contents than that observed in soil samples collected in 2010 (Table 6). Century-modeled SOC contents were numerically greater than measured SOC contents by 6 (0.08 kg SOC m\(^{-2}\)) to 56% (1.10 kg SOC m\(^{-2}\)) in all tillage-fertility-rotation treatment combinations except the NT/Optimal/R(W), NT/Sub-optimal/R(W), and the NT/Optimal/R(W)S(W) treatment combinations, which were slightly underestimated by 1 (0.01 kg SOC m\(^{-2}\)) to 8% (0.12 kg SOC m\(^{-2}\); Table 6).

On average, Century modeled SOC contents overestimated SOC by 26%. Estimated SOC in eight of the 24 treatment combinations differed less than 14% from direct measured SOC observations in 2010, while the other 16 treatment combinations exceeded a 23% difference from measured SOC observations (Table 6). It appears that this overestimation by Century would increase into the future if management practices continued (Figure 3A). The overestimation of SOC during a longer time period in this study is similar to modeling results reported by Bhattacharyya et al. (2007) in a jute (*Cochorus capsularis* L.)-rice-wheat rotation over a 30-year period. Bhattacharyya et al. (2007) reported that SOC was generally overestimated by 15% in the top 20 cm when modeled in Century. Therefore, if the model were to be used for more accurate prediction in the rice-based rotations, such as those used in this study, a more in depth evaluation and further adjustments of the Century modeling environment for flood-irrigation would be recommended.

Similar to modeled SOC contents, Century-modeled soil TN contents were also generally greater than the direct observations after 11 years of management. Soil TN was greater by 1 (1 g SOC m\(^{-2}\)) to 45% (78 g SOC m\(^{-2}\)) in most treatment combinations except NT/Optimal/R(W),
T/Optimal/RS, T/Optimal/R(W), T/Optimal/R(W)S(W), T/Sub-Optimal/RS, T/Sub-Optimal/R(W), and T/Sub-Optimal/R(W)S(W), which were underestimated by 1 (< 0.01 kg TN m\(^{-2}\)) to 26% (0.03 kg TN m\(^{-2}\); Table 6). On average, modeled soil TN content was overestimated by 10% across all tillage-fertility-rotation treatment combinations, which was a more accurate value than that of the average estimated SOC content over time. Century-modeled soil TN in 14 of the 24 treatment combinations had a range of less than 19% from measured observations, whereas the other 10 treatment combinations exceeded a 23% difference from measured observations (Table 6). Similar to the pattern of modeled SOC contents, it appears that this overestimation of soil TN by Century would continue to increase slightly over time if management practices continued into the future (Figure 3B).

Based on numerical values for modeled estimations and direct observations, it appears that Century can predict SOC and TN contents more accurately for certain tillage-fertility-rotation treatment combinations when compared to other modeled treatment combinations (Table 6). The closest estimations of SOC to direct observation were for treatment combinations that included rotations with winter wheat [i.e., R(W) and R(W)S(W)] during the study period, and the closest estimations for soil TN over time occurred in treatment combinations that included the R(W)S(W) rotation (Table 6). The least accurate estimations of SOC to direct observation were for treatment combinations that included rotations with corn (i.e. RC and RCS), and the closest estimations for soil TN was in treatment combinations that included the R(W) rotation (Table 6). The prediction estimates of SOC and soil TN contents for rotations that included wheat could be a result of overestimating or underestimating the inputs from the winter wheat crop, which was in the ground during the time of sampling. The overestimations of SOC contents for rotations with corn could be a result of reduced yields at the study site compared to common yield values.
produced in the local geographic area, which is the yield value simulated in the Century model. This could be a result of many factors, but the more likely scenario is the size of the research plot resulted in essentially an edge effect that would not be present in larger production fields.

The inaccuracies associated with the modeling results suggest that a few input parameters could be adjusted in the Century model to more accurately predict SOC and TN cycling in rice-based crop rotations which are frequently flooded for a majority of the growing season. Perhaps incorporation of the measured plant nutrient composition of the specific crop varieties grown during the study period and specific yields in each research area sampled over the 11-year period would improve the accuracy of specific input variables. Furthermore, soil sampling at a greater soil depth for comparison in Century might not only create a greater understanding of soil cycling in the near-surface soil, but sampling at a greater soil depth could help improve the accuracy of the overall model.

**Summary and Conclusions**

This study demonstrated SOC and soil TN contents in the top 10 cm were affected by tillage, rotation, and/or time after 11 years of consistent management. As hypothesized, soil TN contents increased overtime under NT, but SOC contents did not differ under either tillage treatment (i.e., NT and T) over the 11-year study period. Furthermore, high-residue producing rotations double-cropped with winter wheat [i.e. R(W) and R(W)S(W)] had greater increases in both SOC and soil TN contents over time when compared to all other crop rotations. The only high-residue mono-cropped rotation with greater SOC over time was continuous rice, whereas SOC contents in all other crop rotations (i.e., RS, RC, and RCS) did not differ during the 11-year study period. Similar to the double-cropped rotations, the RS rotation also had an increase of soil
TN over time. However, other crop rotations (i.e., R, RC, and RCS) did not differ in soil TN contents over time. In contrast to that hypothesized, fertility treatments had no effect on SOC and TN contents. The primary difference in SOC and TN contents among treatment combinations included the presence or absence of a winter wheat crop.

The Century model is a predictive tool for future environmental nutrient cycling estimations. Results from this study suggested that Century could be used to predict general trends in SOC and TN cycling in rice-based crop rotations over time, but further adjustment of the model would be needed to increase accuracy. The direct measured observations and the modeled estimations of this study are important because there has not been a great amount of research conducted on SOC and TN storage in dry-seeded, delayed-flooded rice production systems. A majority of C and N research in agricultural systems has either been conducted on non-flooded crops or in paddy-grown rice. Relatively few studies have actually evaluated long-term SOC and soil TN storage using dry-seeded rice, delayed-flooded production practices commonly used in the United States.

This study is essentially meant to provide a long-term evaluation of SOC and TN storage in soil used for flood-irrigation rice-based crop rotations. Because soil moisture conditions have such a large impact on the overall storage of SOC and the cycling of N in the soil, examining crop production systems that contain periods of both aerobic and anaerobic conditions is an important component in obtaining a more accurate global estimate of SOC and TN storage in agricultural production systems. The results obtained from this study can help contribute to the on-going effort of studying the sustainability of rice cropping in the United States by enabling the direct quantification of C and N storage in the soil over time.
Acknowledgments

This research was partially funded by the Arkansas Rice Research and Promotion Board. Field assistance provided by Terry Sells, Daniel McCarty, and Tara Moss Clayton is gratefully acknowledged.
Literature Cited


213


Table 1. Details of spring crop rotations by year with all rotations tilled prior to planting in 1999 and no-tillage treatments starting in 2000. Crops used in the rotations include rice (R), soybean (S), corn (C), and winter wheat [(W)].

<table>
<thead>
<tr>
<th>Rotation</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
</tr>
<tr>
<td>RS</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
</tr>
<tr>
<td>RC</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
<td>Corn</td>
<td>Rice</td>
</tr>
<tr>
<td>R(W)</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
<td>Rice</td>
</tr>
<tr>
<td>R(W)S(W)</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
<td>Soybean</td>
<td>Rice</td>
</tr>
<tr>
<td>RCS</td>
<td>Rice</td>
<td>Corn</td>
<td>Soybean</td>
<td>Rice</td>
<td>Corn</td>
<td>Soybean</td>
<td>Rice</td>
<td>Corn</td>
<td>Soybean</td>
<td>Rice</td>
<td>Corn</td>
</tr>
</tbody>
</table>
Table 2. Summary of the annual nitrogen (N), phosphorous (P), potassium (K), and zinc (Zn) added to corn, soybean, rice, and winter wheat to comprise the optimal soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Nutrient</th>
<th>Soil Fertility Treatment (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sub-Optimal</td>
</tr>
<tr>
<td>Corn</td>
<td>N</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td>P₂O₅</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>K₂O</td>
<td>112</td>
</tr>
<tr>
<td>Soybean</td>
<td>N</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P₂O₅</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>K₂O</td>
<td>67</td>
</tr>
<tr>
<td>Rice</td>
<td>N</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>P₂O₅</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>K₂O</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>ZnSO₄</td>
<td>11</td>
</tr>
<tr>
<td>Wheat</td>
<td>N</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>P₂O₅</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>K₂O</td>
<td>34</td>
</tr>
</tbody>
</table>
Table 3. Summary of the crop rotations and the number of crops grown in the respective rotations during the 11-yr study period (1999 to 2010) at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Rice</th>
<th>Corn</th>
<th>Soybean</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Rice</td>
<td>11</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rice-Soybean</td>
<td>6</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rice-Corn</td>
<td>6</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rice-(Wheat)</td>
<td>11</td>
<td>-</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td>Rice-(Wheat)-Soybean-(Wheat)</td>
<td>6</td>
<td>-</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Rice-Corn-Soybean</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4. Analysis of variance summary of inherent differences among tillage, fertility, and crop rotation treatments on soil particle-size (PS) distributions, estimated soil bulk density (BD), soil organic carbon (SOC) content, total nitrogen (TN) content, SOC fraction of the soil organic matter (SOM), TN fraction of the SOM, and soil carbon to nitrogen ratios (C:N) prior to any treatment being imposed in 1999. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>PS</th>
<th>BD</th>
<th>SOC</th>
<th>TN</th>
<th>SOC/SOM</th>
<th>TN/SOM</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility* Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation</td>
<td>NS</td>
<td>0.005</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation<em>Tillage</em>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 5. Analysis of variance summary of the effects of tillage, fertility, crop rotation, and time on soil organic carbon (SOC) content, total nitrogen (TN) content, SOC fraction of the soil organic matter (SOM), TN fraction of the SOM, and soil carbon to nitrogen ratios (C:N) after 11 years of consistent management. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>SOC</th>
<th>TN</th>
<th>SOC/SOM</th>
<th>TN/SOM</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tillage</td>
<td>0.012</td>
<td>0.002</td>
<td>0.007</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fertility* Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation</td>
<td>NS</td>
<td>0.010</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation<em>Tillage</em>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time</td>
<td>0.039</td>
<td>0.036</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time*Tillage</td>
<td>NS</td>
<td>0.019</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time*Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time*Rotation</td>
<td>&lt; 0.001</td>
<td>0.003</td>
<td>0.047</td>
<td>0.037</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Tillage</em>Fertility</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Tillage</em>Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Fertility</em>Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time<em>Tillage</em>Fertility*Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 6. Measured and Century-model-estimated values for soil organic carbon (SOC) and total nitrogen (TN) contents under different tillage [tillage (T) and no-tillage (NT)], fertility [optimal (O) and sub-optimal (SO)], and crop rotation [with soybean (S), corn (C), and/or wheat (W)] treatment combinations after an 11-yr study period (1999 to 2010). The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Values presented are from the 2010 sampling period measured and model predictions. Crops in parentheses were grown during the winter.

| Rotation | SOC (kg m\(^{-2}\)) | | | TN (kg m\(^{-2}\)) | | |
|----------|---------------------|---------------------|---------------------|---------------------|---------------------|
|          | Measured            | Modeled             | Measured            | Modeled             | Measured            | Modeled             |
|          | T O SO              | NT O SO             | T O SO              | NT O SO             | T O SO              | NT O SO             |
| R        | 1.11 0.97 1.28      | 1.22                | 1.72 1.67 1.95      | 1.67                | 0.12 0.12 0.11      | 0.09                | 0.15 0.13 0.17      | 0.14                |
| RS       | 0.96 0.93 1.24      | 1.26                | 1.42 1.38 1.38      | 1.34                | 0.14 0.13 0.10      | 0.10                | 0.12 0.11 0.12      | 0.11                |
| RC       | 0.84 0.90 1.19      | 1.18                | 1.94 1.86 1.95      | 1.84                | 0.13 0.12 0.09      | 0.10                | 0.17 0.15 0.17      | 0.15                |
| R(W)     | 1.20 1.21 1.45      | 1.43                | 1.38 1.38 1.43      | 1.42                | 0.15 0.15 0.13      | 0.12                | 0.12 0.13 0.13      | 0.12                |
| R(W)S(W) | 1.08 1.08 1.49      | 1.22                | 1.46 1.41 1.37      | 1.37                | 0.17 0.13 0.12      | 0.12                | 0.13 0.13 0.13      | 0.12                |
| RCS      | 1.01 1.06 1.10      | 1.07                | 1.74 1.66 1.72      | 1.62                | 0.12 0.12 0.11      | 0.10                | 0.15 0.13 0.15      | 0.13                |
Figure 1. Tillage [conventional tillage (T) and no-tillage (NT)] and time (1999 and 2010) effects on total nitrogen (TN) in the top 10 cm. Different letters atop bars are significantly different at the 0.05 level.
Figure 2. Rotation [rice (R), soybean (S), corn (C) and winter wheat (W)] and time (1999 and 2010) effects on soil organic carbon (SOC) [A] and total nitrogen (TN) [B] in the top 10 cm. Different letters atop bars within a panel are significantly different at the 0.05 level.
Figure 3. Century-modeled verses measured soil organic carbon (SOC) [A] and total nitrogen (TN) [B] content in the top 10 cm after 11 years of management for 24 different tillage-fertility-rotation treatment combinations.
Figure 4. Century-modeled and measured soil organic carbon (SOC) [A] and total nitrogen (TN) [B] contents in the top 10 cm over time (1999 and 2010) for 24 different tillage-fertility-rotation treatment combinations. The regression equations on each graph represent the average modeled and measured SOC and TN contents across all treatment combinations over time.
CHAPTER 5

LONG-TERM RICE CROP ROTATION AND TILLAGE EFFECTS ON SOIL RESPIRATION
Long-Term Rice Crop Rotation and Tillage Effects on Soil Respiration

Abstract
The flux of carbon dioxide (CO₂) from the soil, as a result of root and microorganism respiration, is a major process in the global carbon (C) cycle and is a portion of the terrestrial C budget. Since the 1750s, the global CO₂ concentration in the atmosphere has steadily increased from an average of 280 parts per million (ppm) to 389 ppm in 2011. Furthermore, CO₂ emissions represent roughly 77% of the total anthropogenic greenhouse gas emissions annually. The unnatural enrichment of CO₂ in the atmosphere is partly due to fossil fuel combustion and in part due to land-use changes, such as soil cultivation, expansion into natural ecosystems, and the mineralization of soil organic C. A study was conducted on a silt-loam soil (fine, smectitic, thermic, Typic Albaqualf) in the Mississippi River Delta region of eastern Arkansas to evaluate the long-term effects of rice (Oryza sativa L.)-based crop rotations [with corn (Zea mays L.), soybean (Glycine max L.), and winter wheat (Triticum aestivum L.)] and tillage [conventional tillage (T) and no-tillage (NT)] after 10 and 11 years of consistent management on soil surface CO₂ flux. Soil respiration measurements were made six and 10 times throughout the 2009 and 2010 growing seasons, respectively, for a total of 16 sampling days. Soil surface CO₂ flux was measured using a static-chamber procedure. In addition, soil temperature at the 2- and 10-cm depths and soil volumetric water content (VWC) in the top 6-cm were measured and their correlations to soil surface CO₂ flux were evaluated. Soil respiration differed among tillage-rotation treatment combinations on two days [T/RS and NT/RS 84 to 99% greater than T/R(W), NT/R(W), T/R(W)S(W), and NT/R(W)S(W)], between tillage treatments on one day (NT 47% greater than T), and among rotations on four (varied between 2- and 3-fold depending on
sampling date) of the 16 dates sampled over two years. Results showed soil surface CO$_2$ flux did not differ in rotations growing rice before flooding and after the flood was released, nor in rotations that contained corn every other year compared to rotations with soybean. As expected, soil temperature and VWC were directly related with soil surface CO$_2$ flux. Knowing the influences different rice management practices have on the quantity of CO$_2$ emitted from the soil is critical for formulating innovative agricultural practices, economic policies, and energy conservation strategies that will affect the sustainability of rice production in the future.
Introduction

The concept of global warming is attributed to an array of different factors, but is primarily attributed to three main greenhouse gases (GHG) that are present both naturally and from anthropogenic influences: carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O) (IPCC, 2007). The most influential of these components contributing to this worldwide phenomenon is CO$_2$ (IPCC, 2007; Le Treut et al., 2007; Weil and Magdoff, 2004). Since the 1850s, the global concentration of CO$_2$ in the atmosphere has steadily increased from 280 parts per million (ppm) to 389 ppm in 2011 (Kimble and Follett, 2002; NOAA-ESRL, 2011). Annual emissions of CO$_2$ have risen by 80% between 1970 and 2004 (21 to 38 Pg yr$^{-1}$), and in relation, CO$_2$ emissions represent approximately 77% of the total anthropogenic GHG emissions (ICPP, 2007). The unnatural enrichment of CO$_2$ in the atmosphere is partly due to elevated fossil fuel combustion since the Industrial Revolution and in part due to land-use changes associated with agriculture. Agricultural operations contribute roughly 25% of the total anthropogenic CO$_2$ emissions (Duxbury, 1995), and a sizeable portion of this percentage is attributed to soil cultivation, expansion into natural ecosystems, and the mineralization of soil organic carbon (SOC) (Kimble et al., 2002). With the knowledge that the increase in CO$_2$ concentration is unnaturally affecting the global climate, the need to find agricultural production practices that decrease CO$_2$ gas emissions are essential to society’s future.

The flux of CO$_2$ from the soil is a major process in the global C cycle and is a significant portion of the terrestrial C budget (Bajracharya et al., 2000). Soil aeration pertains to the condition and bioavailability of gases in the soil and the exchange of these gases between the soil and the atmosphere (Scott, 2000). Generally, soil air is greater in CO$_2$ (1-10%) and lower in O$_2$ (5-10%) than the atmosphere, which is a result of the decomposition of organic material in the
soil and by the respiration of roots and microbes (Montgomery et al., 2000; Castelle and Galloway, 1990; Piñol et al., 1995). Soil organic matter (SOM) is a one of the main reservoirs of SOC in the biosphere (Bernsten et al., 2006). Follett (2001) estimated approximately 1550 petagrams (Pg) of organic C are stored in the world’s soils, which is more than twice the C contained in living vegetation (560 Pg) or in the atmosphere (750 Pg) (Sunquist, 1993).

Information on the dynamics of SOC storage in agricultural soils has gained interest over the years because of its influences on global climate change and crop productivity (Majumder et al., 2007). According to Lal (2004), land management practices have the potential to enhance C accumulation, thereby easing the gaseous C load to the atmosphere and enriching the soil. Net C sequestration can be accomplished with any practice that returns large amounts of plant biomass to the soil, decreases soil disturbance, maintains soil structure, and conserves nutrient and water usage (McCarl et al., 2007; Follett, 2001; Paustian et al., 2000). Agricultural practices that can accomplish this include conservation tillage, decreasing or ceasing fallow periods, discontinuing residue burning, winter cover cropping, switching from monoculture to rotation cropping, and altering fertilizer applications to increase production (Farquhar et al., 2001; Karlen and Cambardella, 1996; West and Post, 2002).

One of the key factors in the process dynamics and management responses of SOM is the presence or absence of oxygen (O2). Generally, an abundant O2 supply promotes rapid SOM decomposition, whereas a deficiency in O2 results in a substantially lower decomposition rate (DeBusk et al., 2001; Shaffer and Ma, 2001), with the C mineralization rates in aerobic conditions being as much as three times faster than under anaerobic conditions (DeBusk and Reddy, 1998). Therefore, the presence of saturated soil conditions can affect the release rates and patterns of C gas emissions from the soil. In agricultural row-cropping systems, flood-irrigated
rice (*Oryza sativa* L.) is unique as it is grown under nearly to completely saturated soil
conditions (Norman et al., 2003). However, flood-irrigated rice is different from common
wetland soils, in that the soil is dry between harvesting and planting periods and between crop
rotations. Rice is also one of several high-residue-producing crops grown in the United States
and is capable of producing 6.5 Mg ha\(^{-1}\) of above-ground biomass under optimal N fertilization
(USDA-NASS, 2012). Crop rotations involving high-residue-producing crops, such as rice and
corn (*Zea mays* L.; 8.0 Mg ha\(^{-1}\)), typically show a substantial increase in SOC, and the anaerobic
conditions under which rice is grown affects the breakdown and retention of these crop residues,
which in turn impacts the total SOC content in the soil (USDA-NASS, 2012; Witt et al., 2000).
Soils continuously cropped with flood-irrigated rice have been reported to sequester 11 to 12% more C than soils that supported a dry-season, maize-flooded rice rotation within the top 15 cm of a clay soil in the Philippines (Whitt et al., 2000).

While there have been numerous studies conducted on C gas emissions, predominantly
CH\(_4\), in rice during the flooded period, there have been fewer studies conducted on soil
respiration from rice-based crop rotations during the non-flooded periods (i.e., pre-flood, post-
flood release, and between crop rotations). Most of the studies that have been performed to
investigate the long-term effects of crop rotations on CO\(_2\) emissions have been evaluated in crops
such as soybean (*Glycine max* L.), corn, and wheat (*Triticum aestivum* L.; Al-Kaisi and Yin,
2005; Omonode et al., 2007; Brye et al., 2006b); however, due to the cyclic anoxic conditions
that result from rice production, these dry-land crop studies do not pertain to crop rotations that
include flood-irrigated rice. Furthermore, a majority of the rice research on soil C storage and C
gas emissions that is available has been conducted on paddy-grown rice in Asia, which varies
from upland rice by the planting techniques used (i.e., transplant water-seeded as opposed to dry-
seeded), flooding regimes, harvesting methods, and residue management (De Datta, 1981). These production differences, combined with the information that climatic differences account for a large variation in the amount of C gas loss due to SOM decomposition (Carter, 1996), results in findings from paddy rice not being applicable to the geographic area of the Mississippi River Delta region of the southern and mid-southern United States, which is where 81% of the rice production occurs in the United States (USDA-NASS, 2012).

Therefore, the objectives of this study were to i) evaluate the effects of tillage [conventional tillage (T) and no-tillage (NT)] and rice-based crop rotations (i.e., with corn, soybean, and winter wheat) on soil surface CO$_2$ flux after 10 and 11 years of consistent management, and ii) since soil CO$_2$ respiration rates have shown to be positively correlated with both soil temperature and soil moisture (Franzluebbers et al., 1995; Raich and Schlesinger, 1992; Raich and Potter, 1995; Wang et al., 2000), evaluate the degree to which environmental variables (i.e., soil temperature and soil moisture) control soil respiration in the Mississippi River Delta region of eastern Arkansas. It was hypothesized that soil surface CO$_2$ flux would be: 1) greater from T than NT in response to greater soil disturbance and aeration cause from tillage, 2) greater in rice during the post-flood than pre-flood period due to the accumulation of SOM during the cropping period, 3) greater in corn than soybean crop rotations during the growing period due to larger biennial inputs of SOM from crop residues, 4) greater in rotations that are double-cropped with winter wheat compared to single-cropped rotations due to an overall greater annual contribution to the SOM pool from biannual inputs of crop residues, and 5) positively correlated with both soil temperature and soil moisture levels.
Materials and Methods

Site Description

This field study was conducted during 2009 and 2010 at the University of Arkansas Rice Research and Extension Center (RREC) near Stuttgart, AR (34°27′ N, 91°24′ W), which is located in the Mississippi River Delta region of eastern Arkansas in an area known as the Grand Prairie (USACE, 2000). Measurements were performed in a long-term experiment that was initiated in 1999 on a Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf; NRCS, 2008), which is characteristic of Grand Prairie soils used for rice production.

Prior to 1999, the study site had been fallow for a number of years due to the absence of irrigation capabilities. Vegetation covering the site consisted of a mixture of grasses and weeds that were managed by periodic mowing during the growth period. To prepare for the study, the site was land-leveled to a 0.15% grade in fall 1998. Land-leveling consisted of removing the top 10 cm of soil, mechanically leveling the field to grade, and redistributing the topsoil evenly over the field. This land-leveling procedure is a common practice in the Mississippi River Delta region, especially in areas that are heavily concentrated in rice production, to enable an even distribution of flood-irrigation water (Brye et al., 2003).

The climate of the region is warm and wet with a 30-yr mean annual temperature minimum of 0.22 °C in January and maximum of 33.1 °C in July. The 30-yr mean annual precipitation is 132 cm (SRCC, 2012).

Field Treatments and Experimental Design

This field study was comprised of two tillage treatments [tillage (T) and no-tillage (NT)] and 10 rice-based cropping systems arranged in a randomized complete block design with four
replications. Each replicate block occupied an area of 120 by 76 m ($9120 \text{ m}^2$) within the 1.9-ha experimental site, and was partitioned as a strip-plot, whereas each block was divided into two tillage treatments and the 10 rice-based crop rotations were stripped across each tillage treatment. There were a total of 80 individual plots (6- by 19-m) evaluated, with each tillage-rotation combination under optimal fertility and unchanged annual crop varieties representing an experimental unit.

Crop varieties included in the rotation treatment of this study consisted of the major agronomic crops grown in Arkansas. Crop rotations included: continuous rice (R), rice-soybean (RS), soybean-rice (SR), rice-corn (RC), corn-rice (CR), rice (winter wheat) [R(W)], rice (winter wheat)-soybean (winter wheat) [R(W)S(W)], soybean (winter wheat)-rice (winter wheat) [S(W)R(W)], rice-soybean-corn (RSC), and rice-corn-soybean (RCS). Early season rice and soybean crops included the rotations which were fallow during the winter, whereas late-season rice and soybean crops included rotations with wheat during the winter growth period (Table 1). Planting generally occurred in mid-April for long-season crops (i.e., rice, corn, and soybean) and mid-June for short-season crops (i.e., rice and soybean). During the 2009 sampling period, there were an even number of rice crops and dry-land crops (i.e., corn and soybean) produced throughout the summer growing season in two-crop rotations, while there were an uneven number produced in 2010 (Table 2). Rice, soybean, and wheat were sown into 19-cm rows using an Almaco NT drill (Almaco, Nevada, IA). Rice was drill-seeded at a rate of $100 \text{ kg seed ha}^{-1}$, soybean at a rate of $56 \text{ kg seed ha}^{-1}$, and wheat at a rate of $67 \text{ kg seed ha}^{-1}$. Corn was planted in 76-cm rows at a plant population of $79,000 \text{ seeds ha}^{-1}$ (Schmid, 2008). Long-season rice and soybean, in addition to corn, was planted in April, and late-season rice and soybean were planted in June (Table 1).
Crop fertilization followed an optimal fertility recommendation based on the analysis of soil samples that were collected in spring 1999 (Table 3). The annual soil fertility treatment consisted of P$_2$O$_5$ applied as triple super phosphate and K$_2$O applied as muriate of potash, with both fertilizers broadcast pre-plant and pre-tillage with a spreader. Urea was used as the nitrogen (N) fertilizer source, which was applied with a hand-spreader pre-flood at the 5-leaf stage of rice growth approximately one month after planting. Phosphorous and potassium were incorporated into the soil under tillage and were left at the surface under NT. Following N fertilization, a 5- to 10-cm deep permanent flood was established on the rice, which was maintained annually on all of the rice plots until the crop reached physiological maturity. All other summer crops present in a given year were furrow-irrigated on an as-needed basis approximately three to four times annually, which was based on the amount of rainfall received and the growth of the crop. Winter wheat was rain-fed only without irrigation.

Crop management practices for rice (Slaton, 2001), soybean (Ashlock, 2000), corn (Espinoza and Ross, 2003), and wheat (Kelley, 1999) followed the University of Arkansas Cooperative Extension Service recommendations for stand establishment, irrigation management, weed control, and pest management (Motschenbacher et al., 2012c). In tillage plots, crop residues were burned and incorporated into the soil generally one to two months following harvest by diskng twice. Prior to planting in the spring, plots were tilled by diskng once, followed by multiple passes of a light field cultivator (i.e., Triple-K) to achieve the desired seedbed for rice planting. In NT plots, crop residues were left on the surface after harvest and were not manipulated by any means prior to planting in the spring.
Soil CO₂ Sampling

Similar to Brye et al. (2006a), soil surface CO₂ flux was measured on the tillage-rotation treatment combinations using a portable photosynthesis system (LI-6400XT) equipped with a 10-cm diameter CO₂ flux soil chamber (LI-6400-09; LiCor, Inc., Lincoln, NE). Measurements were conducted six times during the 2009 growing season and 10 times during the 2010 growing season, with the first measurement each year made prior to spring planting in May and the last measurement made following harvest in November. For rotations that had rice planted, measurements were made up until the plots were flooded and after the flood was released, whereas rotations with corn or soybean planted had measurements made throughout the entire growing season. Soil surface CO₂ flux was measured along with the 2- and 10-cm soil temperatures using a pencil-type thermometer and the volumetric water content (VWC) in the top 6-cm using a Theta Probe (Model TH20, Dynamax, Houston, TX). In order to uniformly measure the soil surface CO₂ flux in each plot, the soil chamber was placed vertically on a 10-cm diameter plastic collar that was previously inserted into the ground to an approximate depth of 2-cm. The collars were placed in-between rows and were moved to another location in each plot every month to ensure an accurate representation of the plot. Measurements were generally made between the hours of 0700 and 1400 Central Time.

Data Analyses

The effects of tillage and crop rotation on soil surface CO₂ flux, soil temperature, and soil moisture were evaluated by analysis of variance (ANOVA) using the GLM procedure in SAS® (version 9.2, SAS Institute, Inc., Cary, NC). Data were analyzed separately for each measurement date. A single comprehensive analysis for all crop rotations over the two-year
study period was not practical because only the tillage-rotation combinations not flooded during the dates measured were included in the data set for statistical analyses. Due to the combination of annual, biannual, and triannual crop rotations evaluated in the study (Table 1), combined with the two-year duration of the study, only the RSC and RCS rotations could be measured throughout the entire study period. All other rotations were either flooded during the growing season every year [i.e., R, R(W)] or during one of the two years [i.e., RS, RC, R(W)S(W), RSC] evaluated (Table 1). The field treatment of tillage and rotation were considered as fixed effects for all analyses and blocks were a random effect.

For analyses on dates before flooding (pre-flood), during the growing period (dry-crop growing season), and after the flood was released (post-flood release), both years were combined in order to have enough measurements for a statistical analysis. The pre-flood measurements were made prior to any flooding on rice, the measurements during the dry-crop growing season were only made on the non-flooded rotations growing soybean or corn during the growth period, and the post-flood release period was when floods were released in all treatments (Table 1). The effects of volumetric moisture content (VWC) and 2- and 10-cm soil temperatures on soil surface CO$_2$ flux were also evaluated using the SAS® linear regression analysis. When appropriate, means were separated using Fisher’s protected least significant difference (LSD) at the 0.05 level on all statistical analyses.

For annual estimations of CO$_2$ flux during summer growing period, CO$_2$ flux (µmol CO$_2$ m$^{-2}$ s$^{-1}$) readings from each measurement date (Figure 1A and 1B) were used to calculate daily CO$_2$ flux (g CO$_2$ m$^{-2}$ day$^{-1}$). Daily CO$_2$ values on dates not sampled during each annual evaluation period (25 May 2009 to 10 November 2009 and 16 April 2010 to 13 November 2010; Figure 1A and 1B) were calculated by taking the difference between two of the closest
measurement dates, and then calculating a running average of increases or decreases in flux over time using an Excel spreadsheet (version 10, Microsoft, Inc. Redmond, WA). Annual CO₂ fluxes emitted during the growing period were calculated for each tillage-rotation treatment combination. Due to the presence of anoxic conditions during the growing period in rice, values were set as 0 g CO₂ m⁻² day⁻¹ from the date flooding occurred until the flood was released.

**Results and Discussion**

**Initial Soil Properties**

Similar to Motschenbacher et al. (2012a, 2012b), which examined six of the 10 crop rotations in this study, soil samples collected in 1999 prior to any tillage or rotation treatment imposed showed that soil properties in the top 10 cm were generally uniform among the 20 pre-assigned tillage-rotation treatment combinations evaluated. Statistical analyses performed exclusively on 1999 soil properties tillage-rotation treatment combinations did not differ among soil bulk density, SOM contents, soil organic carbon (SOC) contents, total nitrogen (TN) contents, the partitioning of SOC and TN within SOM, and carbon to nitrogen (C:N) ratios among pre-assigned treatments (P > 0.05; Table 4). Furthermore, soil particle-size distribution did not differ among any of the treatment combinations when measured in 2010 (P > 0.05; Table 4).

**Tillage and Rotation Effects on Soil Respiration within Sampling Dates**

After 10 and 11 years of consistent crop rotation and nine and 10 years of T or NT management, soil surface CO₂ flux was infrequently affected by tillage and/or crop rotation. Of the 16 measurement dates across two years of observations, soil respiration was affected by a
tillage-rotation interaction (two dates in 2010), tillage alone (one date in 2009), and rotation alone (two dates in 2009 and two dates in 2010), for a total of seven dates (Table 5). However, there were no individual tillage or rotation treatment effects occurred on the same date. Variability of all readings within the same sampling date generally increased throughout the cropping season until after harvest, which may be associated with crop maturity and soil temperature (Amos et al., 2005).

Tillage-Rotation Interaction Effects on Soil Respiration

The tillage-rotation combinations differed in soil surface CO₂ flux on 23 June 2010 ($P = 0.031$) and 15 July 2010 ($P = 0.004$; Table 5). On 23 June 2010, soil surface CO₂ flux was greater in the RS rotation under both T (8.76 µmol CO₂ m⁻² s⁻¹) and NT (7.54 µmol CO₂ m⁻² s⁻¹) than that in the late-season cropping systems (late-rice and late-soybean) rotated with wheat [i.e., R(W), R(W)S(W), S(W)R(W)] under both tillage treatments (ranging from 0.11 to 1.19 µmol CO₂ m⁻² s⁻¹) and NT/RC (1.49 µmol CO₂ m⁻² s⁻¹; Figure 1B). With the exception of the RS rotation under both T and NT, all other rotations [i.e., RC, RSC, RCS, R(W), R(W)S(W), and S(W)R(W)] under both tillage treatments (i.e., T and NT) measured during this date did not differ ($P > 0.05$; Table 5). During the time of sampling, early-season rice rotations (i.e., R, SR, and CR) were not measured because rice had already been flooded for the growing season.

Although the T/RS and NT/RS tillage-rotation combinations were the only treatment combinations to show statistically greater CO₂ flux on 23 June 2010 compared to R(W), R(W)S(W), and S(W)R(W) rotations under T and NT, the other non-flooded early-season tillage-rotation combinations (i.e., T/RC, T/RSC, T/RCS, NT/RC, NT/RSC, and NTRCS) had numerically greater CO₂ flux (ranging from 3.65 to 5.08 µmol CO₂ m⁻² s⁻¹). The lower soil
surface CO$_2$ flux in the late-season crops of rice and soybean [i.e., R(W), R(W)S(W), S(W)R(W)] may be explained by the different growth stages of crops during the time of sampling (Amos et al., 2005). Root respiration was estimated to make up 40 to 60% of the CO$_2$ emitted from the soil (Raich and Schlesinger, 1992), so soils containing more mature crops have the ability to produce greater soil CO$_2$ emissions due to increased root respiration from greater photosynthetic rates (Kuzyakov and Cheng, 2001; Amos et al., 2005). During the 23 June 2010 measurement date, late-season crops [i.e., R(W), R(W)S(W), and S(W)R(W)] had just been planted three days prior to CO$_2$ flux measurements, whereas the non-flooded early-season rotations (i.e., RS, RC, RSC, and RCS) had been planted approximately three weeks prior to measurement on this date (Table 1).

On 15 July 2010, soil surface CO$_2$ flux was also lower in some of the late-season cropping systems containing wheat, including R(W), R(W)S(W), S(W)R(W) under T (ranging from 3.16 to 4.08 µmol CO$_2$ m$^{-2}$ s$^{-1}$) and R(W) under NT (3.07 µmol CO$_2$ m$^{-2}$ s$^{-1}$), than T/RS, T/RC, and T/RCS NT/RSC (ranging from 6.74 to 9.01 µmol CO$_2$ m$^{-2}$ s$^{-1}$) tillage-rotation combinations (Figure 1B). Like the 23 June 2010 sampling date, lower soil surface CO$_2$ flux in late-season crops could be associated with crop maturity during the time of measurement (Raich and Schlesinger, 1992; Kuzyakov and Cheng, 2001; Amos et al., 2005). In that, the late-season rice and soybean crops were less mature than the early-season rice, soybean, and corn crops.

**Tillage Effects on Soil Respiration**

Tillage can affect CO$_2$ loss from the soil by aerating the soil through physical disturbance from mechanical manipulation (West and Post, 2002). However, averaged across all rotation treatments, there was only one out of the 16 sampling dates that differed in tillage as a single
effect, which was 10 November 2009 ($P = 0.025$; Table 5). On this date, NT (1.07 µmol CO$_2$ m$^{-2}$ s$^{-1}$) was 47% greater in soil surface CO$_2$ flux than that under T (0.73 µmol CO$_2$ m$^{-2}$ s$^{-1}$; Figure 1A). Results from this sampling date are different from what was expected based on past studies that reported greater CO$_2$ flux under T than under T in reduced and NT treatments (Reicosky and Lindstrom, 1993; Reicosky et al., 1997; West and Marland, 2002). Contrary to the results of this study, a study evaluating a wheat-soybean double-cropping system on a silt-loam soil in a similar geographic location of east-central Arkansas reported a 38% greater soil surface CO$_2$ flux under T than from that under NT (Brye et al., 2006b). However, greater soil surface CO$_2$ flux under NT than under T observed in this study during the 10 November 2009 measurement date was similar to tillage effects on CO$_2$ emissions in a sorghum ($Sorghum$ $bicolor$ $L.$)-based cropping system study conducted in Georgia (Hendrix et al., 1988). The greater CO$_2$ flux under NT than under T reported by Hendrix et al. (1988) was expected to be a result of measurement timing. In that, tillage effects the time at which CO$_2$ is released from the soil rather than the total CO$_2$ production of the measurement, meaning the CO$_2$ emission is expected to be greater immediately following disturbance in tillage and not necessarily during the time of measurement. Thus, a reasonable assumption for the results on the 10 November 2009 sampling date may also be related to the actual timing of CO$_2$ measurements following tillage.

Despite CO$_2$ flux differences reported in previous studies in relation to tillage, there was only one out of the 16 measurement dates actually showed differences in soil surface CO$_2$ flux as a single effect between T and NT treatments. Thus, the measured soil surface CO$_2$ flux in each sampling date over time does not provide strong support that tillage was the main contributing factor influencing daily soil surface CO$_2$ flux across the two years of measurements. While there would expectantly be larger CO$_2$ flux under T immediately after tillage, these loses would occur
rather rapidly. Therefore, measurement from this study suggests that increases in soil surface CO₂ flux under tillage are not constant throughout the season.

*Rotation Effects on Soil Respiration*

Rotation can affect soil surface CO₂ flux by increasing the plant and microbial biomass content in the soil and through root respiration of the crops being grown (Kuzyakov and Cheng, 2001; Al-Kaisi and Yin, 2005; Brye et al., 2006b; Omonode et al., 2007). However, averaged across tillage treatments, rotations differed in only four of the 16 sampling dates, which were 30 June 2009 \( (P = 0.007) \), 06 September 2009 \( (P < 0.001) \), 16 April 2010 \( (P = 0.015) \), and the 01 July 2010 \( (P < 0.001; \) Table 5). 

During the 2009 measurement dates, patterns of soil surface CO₂ flux among rotations varied within each measurement date. On 30 June 2009, rotations growing corn (i.e., CR and RCS) had greater soil surface CO₂ flux (ranging from 4.69 to 5.71 μmol CO₂ m⁻² s⁻¹) than those growing soybean [i.e., RSC, S(W)R(W), and SR; ranging from 2.34 to 2.79 μmol CO₂ m⁻² s⁻¹] when compared among all rotations not flooded during the measurement date [i.e. SR, CR, S(W)R(W), RSC, and RCS; Figure 1A]. Rotations that were flooded and not compared during the 30 June 2009 measurement date included R, RS, RC, R(W), and R(W)S(W) (Figure 1A). However, on 06 September 2009, rotations growing soybean [i.e., SR, S(W)R(W), and RSC] had greater CO₂ flux (ranging from 4.10 to 5.18 μmol CO₂ m⁻² s⁻¹) than rotations growing corn (i.e. CR and RCS; ranging from 1.61 to 1.82 μmol CO₂ m⁻² s⁻¹), when compared among rotations not flooded during the time of measurement [i.e. R, RS, SR, RC, CR, S(W)R(W), RSC, and RCS; Figure 1A]. Rotations flooded and not compared during the 30 June 2009 measurement date included R(W), and R(W)S(W) (Figure 1A).
Like measurements conducted in 2009, patterns of soil surface CO$_2$ flux among rotations in 2010 varied among measurement dates. On 16 April 2010, the R(W) and R(W)S(W) rotations had greater CO$_2$ flux (ranging from 3.02 to 3.39 µmol CO$_2$ m$^{-2}$ s$^{-1}$) than that in all other rotations [i.e., R, RS, SR, RC, CR, S(W)R(W), RSC, and RCS; ranging from 0.99 to 1.96 µmol CO$_2$ m$^{-2}$ s$^{-1}$; Figure 1B]. Furthermore, the S(W)R(W) rotation (1.96 µmol CO$_2$ m$^{-2}$ s$^{-1}$) had greater CO$_2$ flux than the R, RS, RS, SR, RSC, and RCS rotations (0.99 to 1.44 µmol CO$_2$ m$^{-2}$ s$^{-1}$; Figure 1B). Because the 16 April 2010 measurement date was early in the season, early-season crop rotations (i.e., R, RS, SR, RC, CR, RSC, and RCS) had been planted just prior to the measurement date and the late-season crop rotations [i.e., R(W), R(W)S(W), and S(W)R(W)] still had winter wheat planted during the time of measurement. Thus, greater soil respiration would be expected due to the influence of root respiration from wheat as opposed to the absence of crop growth in rotations fallow for the winter. However, on the 01 July 2010 measurement date, early-season rotations growing soybean (i.e., RS and RCS; 7.38 and 8.35 µmol CO$_2$ m$^{-2}$ s$^{-1}$) had a greater CO$_2$ flux than all late-season rice or soybean rotations [i.e., R(W), R(W)S(W), and S(W)R(W); ranging from 2.61 to 3.07 µmol CO$_2$ m$^{-2}$ s$^{-1}$; Figure 1B].

**Pre-Flood and Post-Flood Release Soil Surface CO$_2$ Flux in Rice**

For an analysis of the rotations that grew rice during the summer growing period, comparisons were made between the pre-flood and the post-flood-release sampling dates for each tillage-rotation combination (Table 1). When sampling years were combined, there were no differences in CO$_2$ flux between pre-flood or post-flood-release periods in the rotations growing rice for any of the tillage, rotation, or tillage-rotation combinations ($P > 0.05$; Table 1; Figure 1A and 1B). These results suggest that the buildup of SOM, and thus, SOC, during the anaerobic
period when the rice field is flooded and the input of fresh crop residues following harvest did not result in a difference of soil surface CO₂ flux in rice rotations among the dates sampled pre-flood or post-flood release.

**Soil Surface CO₂ Flux in Rotations with Soybean and Corn Planted during the Growth Period**

When compared across both sampling years, there were no differences in rotations that contained soybean and/or corn during biennial or triennial time periods (P > 0.05). Furthermore, there were no differences in soil surface CO₂ flux when comparing the crop grown during the growth period (Figure 1A and 1B). These results are unexpected considering the varied quantities of biomass inputs from crop residues, which add to the SOC pool, in rotations with greater frequencies of corn as opposed to soybean (Motschenbacher et al., 2012a, 2012b) and the differences associated with root respiration (Kuzyakov and Cheng, 2001; Al-Kaisi and Yin, 2005; Brye et al., 2006b; Omonode et al., 2007).

**Soil Moisture and Temperature effects on Soil Surface CO₂ Flux**

When combined across measurement dates, tillage treatments, and crop rotations, soil surface CO₂ flux was significantly affected by soil moisture (VWC) and soil temperature at both the 2- and 10-cm soil depths (P < 0.001). Despite the significant relationship, the predictive relationship between these measured environmental variables was not as accurate as expected (r² = 0.311). The association between soil moisture and soil temperature on soil surface CO₂ flux has been well-documented throughout the years, whereas warmer temperatures and adequate soil moisture with proper drainage increase soil surface CO₂ flux (Schlesinger, 1997; Davidson et al.,
2002). However, though significant enough to be included in the regression equation, soil moisture was not as strong of a predictive variable as soil temperature when evaluating each variable separately within the model equation. In general, the numerical values for soil moisture content were similar among sampling days, despite large variations in CO₂ flux during the sampling days. Soil surface CO₂ flux was also greater in 2009 than 2010, which could be associated with above normal rainfall amounts during the 2009 sampling year and below average rainfall amounts during the 2010 sampling year (USDA-ARS, 2011). The weakness of the soil moisture variable relative to soil temperature in the predictive value of soil surface CO₂ flux has been evaluated in a previous CO₂ study conducted in a similar geographic location. Brye et al. (2006a) reported a reduced connection between soil moisture content and CO₂ flux in a soybean-wheat double-cropped system, which was assumed to be contributed to climatic factors during the years of observation.

For this analysis on the measured environmental variables, 2- and 10-cm soil temperatures and VWC were the only variables used to determine the predictive relationship between soil surface CO₂ flux. The treatment effects of tillage and rotation were eliminated from the model due to a lack of consistent differences in measured CO₂ flux within individual sampling dates that were associated with tillage and/or rotation treatment effects. Furthermore, the inability to measure rice during the flooded period limited the ability to fully evaluate all tillage-rotation treatment combinations over a large fluctuation of soil temperature and moisture throughout the year. Thus, the rationale behind the elimination of managed treatment effects was to get a predictive equation of soil surface CO₂ flux based solely on environmental factors.
Estimation of Soil Surface CO$_2$ flux during the Growth Period

Estimations of soil surface CO$_2$ flux during summer growing period displayed substantially greater CO$_2$ emissions under rotations not flooded during the estimation period, which ranged from 25 May to 10 November in 2009 and 16 April to 13 November in 2010 (Table 6). However, dissimilarities in these values were expected due to pre-establishing daily CO$_2$ flux values as 0 g CO$_2$ m$^{-2}$ day$^{-1}$ during times when flooded conditions were present. Rotations not flooded during the growing season ranged from 1434 (NT/CR) to 2530 [NT/S(W)R(W)] g CO$_2$ m$^{-2}$ growing season$^{-1}$ in 2009 and from 1614 [T/R(W)S(W)] to 3362 (T/RS) g CO$_2$ m$^{-2}$ growing season$^{-1}$ in 2010 (Table 6). Rotations that were flooded at some period during the growing season had much lower estimated rates of 121 [T/R(W)] to 949 (NT/RC) g CO$_2$ m$^{-2}$ growing season$^{-1}$ in 2009 and 575 (T/R) to 993 [T/R(W)S(W)] g CO$_2$ m$^{-2}$ growing season$^{-1}$ in 2010 (Table 6).

Conclusions

After 10 and 11 years of consistent soil management, this study demonstrated that soil surface CO$_2$ flux was not substantially and consistently affected by tillage and rice-based crop rotations. Based on 16 sampling dates over the course of two growing seasons, only seven dates showed any differences in tillage and/or crop rotation. However, with the exception of the tillage treatment differences on two of the sampling dates, there were no consistent patterns in tillage-rotation combinations or rotation related to the tillage treatment, rotated crops, or the crops being grown during the time of measurement in any of the individual sampling dates or when compared between the sampling dates. However, this lack of consistent significance in the data is
in itself significant because the results seem to indicate that over the course of time, the cropping systems appear to have reached a somewhat equilibrium state.

In relation to the CO$_2$ flux in rice cropping systems, there were not any differences seen in this study between pre-flood and post-flood release sampling dates. Furthermore, the rice crops in rotation could not be measured during the flooded period. While there might have been differences in CO$_2$ flux in the days after flooding and immediately following the post-flood release, the inability to use the equipment in flooded soil conditions prevented this segment of time from being measured. Further research with semi-permanently installed monitoring devices would be necessary to investigate these periods further. Although this CO$_2$ measuring situation would be ideal, the expense of machinery to conduct these analyses with replicated date could hinder this procedure from being conducted in future observations. While NT, high-residue producing crops, double-cropped systems, and rice-based rotations may have the ability to sequester an overall greater amount of C in the soil overtime, results from this study suggest that emission rates of soil CO$_2$ flux over the summer growing period may not be consistent. This might especially be the case if conservation management procedures have been conducted over a longer period of time due to the potential of these management practices to establish new equilibrium levels of stored soil C over time.

Acknowledgments

This research was partially funded by the Arkansas Rice Research and Promotion Board. Field assistance provided by Taylor Adams, Kevin Rorex, Terry Sells, Daniel McCarty, and Richard McMullen is gratefully acknowledged.
Literature Cited


Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, and M.


Table 1. Summary of the crop rotations and planting, rice flooding, rice flood-release, and harvest dates during the 2009 and 2010 study period at the Rice Research and Extension Center near Stuttgart, Arkansas. Crop management dates are summarized for the crops grown during the summer growing period. Crops in parentheses were grown during the winter. Rotations with flooding and flood-release dates represent rotations that had rice planted during the growing season.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Plant</th>
<th>Flood&lt;sup&gt;‡&lt;/sup&gt;</th>
<th>Release</th>
<th>Harvest</th>
<th>Plant</th>
<th>Flood&lt;sup&gt;‡&lt;/sup&gt;</th>
<th>Release</th>
<th>Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice-Soybean</td>
<td>07 Apr.</td>
<td>02 June</td>
<td>24 Aug.</td>
<td>03 Sep.</td>
<td>23 Apr.</td>
<td>-</td>
<td>-</td>
<td>26 Aug.</td>
</tr>
<tr>
<td>Rice-Corn</td>
<td>07 Apr.</td>
<td>02 June</td>
<td>24 Aug.</td>
<td>03 Sept.</td>
<td>21 Apr.</td>
<td>-</td>
<td>-</td>
<td>04 Oct.</td>
</tr>
<tr>
<td>Soybean-(Wheat)-Rice-(Wheat)&lt;sup&gt;†&lt;/sup&gt;</td>
<td>28 June</td>
<td>-</td>
<td>-</td>
<td>04 Nov.</td>
<td>18 June</td>
<td>28 July</td>
<td>20 Sep.</td>
<td>15 Oct.</td>
</tr>
<tr>
<td>Rice-Corn-Soybean</td>
<td>07 Apr.</td>
<td>-</td>
<td>-</td>
<td>29 Sep.</td>
<td>23 Apr.</td>
<td>-</td>
<td>-</td>
<td>26 Aug.</td>
</tr>
</tbody>
</table>

<sup>‡</sup> Rotations that include wheat were planted/harvested on 13 November 2008/16 June 2009 and 28 October 2009/08 June 2011.

<sup>‡</sup> Flooding dates listed are approximate flooding dates.
Table 2. Summary of the crop rotations and the number of crops that had consistently been produced in the respective rotations during the 10- (2009) and 11-year (2010) study period at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Crops in parentheses were grown during the winter.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Rice</th>
<th>Corn</th>
<th>Soybean</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Rice</td>
<td>10/11</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rice-Soybean</td>
<td>5/6</td>
<td>-</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Soybean-Rice</td>
<td>5</td>
<td>-</td>
<td>5/6</td>
<td>-</td>
</tr>
<tr>
<td>Rice-Corn</td>
<td>5/6</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Corn-Rice</td>
<td>5</td>
<td>5/6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rice-(Wheat)</td>
<td>10/11</td>
<td>-</td>
<td>-</td>
<td>10/11</td>
</tr>
<tr>
<td>Rice-(Wheat)-Soybean-(Wheat)</td>
<td>5/6</td>
<td>-</td>
<td>5</td>
<td>10/11</td>
</tr>
<tr>
<td>Soybean-(Wheat)-Rice-(Wheat)</td>
<td>5</td>
<td>-</td>
<td>5/6</td>
<td>10/11</td>
</tr>
<tr>
<td>Rice-Soybean-Corn</td>
<td>4</td>
<td>3</td>
<td>3/4</td>
<td>-</td>
</tr>
<tr>
<td>Rice-Corn-Soybean</td>
<td>4</td>
<td>3/4</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3. Summary of the annual nitrogen (N), phosphorous (P), and potassium (K) added to corn, soybean, rice, and wheat to comprise the optimal soil fertility treatments in a long-term, rice-based rotation study at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Soil Amendment (kg ha⁻¹)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Corn</td>
<td>337</td>
<td>39</td>
</tr>
<tr>
<td>Soybean</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>Rice</td>
<td>168</td>
<td>29</td>
</tr>
<tr>
<td>Wheat</td>
<td>168</td>
<td>29</td>
</tr>
</tbody>
</table>
Table 4. Analysis of variance summary of inherent differences among tillage and crop rotation treatments on soil particle-size (PS) distributions, estimated soil bulk density (BD), soil organic matter (SOM) content, soil organic carbon (SOC) content, total nitrogen (TN) content, SOC fraction of the SOM, TN fraction of the SOM, and soil carbon to nitrogen ratios (C:N) prior to any treatment being imposed in 1999. The study site was located at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

<table>
<thead>
<tr>
<th>Treatment Effect</th>
<th>PS</th>
<th>BD</th>
<th>SOM</th>
<th>SOC</th>
<th>TN</th>
<th>SOC/SOM</th>
<th>TN/SOM</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rotation*Tillage</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 5. Analysis of variance summary of the effects of tillage, crop rotation, and their interaction on soil surface CO$_2$ flux, 2- and 10-cm soil temperature, and 0- to 6-cm volumetric water content (VWC) within sampling dates after 10 (2009) and 11 (2010) years of consistent management at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Treatment effects with $P > 0.05$ are considered non-significant (NS).

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>CO$_2$ Flux (µmol m$^{-2}$ s$^{-1}$)</th>
<th>2-cm Temperature (°C)</th>
<th>10-cm Temperature (°C)</th>
<th>VWC (cm$^3$ water cm$^{-3}$ soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Till*</td>
<td>Rotate</td>
<td>Till*</td>
<td>Rotate</td>
</tr>
<tr>
<td>2009 25 May</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>30 June</td>
<td>NS</td>
<td>0.007</td>
<td>NS</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>13 July</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>27 July</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.002</td>
</tr>
<tr>
<td>06 Sep.</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>10 Nov.</td>
<td>0.025</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>2010 16 Apr.</td>
<td>NS</td>
<td>0.015</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>07 May.</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.036</td>
</tr>
<tr>
<td>23 June</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>01 July</td>
<td>NS</td>
<td>&lt; 0.001</td>
<td>NS</td>
<td>0.003</td>
</tr>
<tr>
<td>15 July</td>
<td>NS</td>
<td>0.027</td>
<td>NS</td>
<td>0.004</td>
</tr>
<tr>
<td>27 July</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.003</td>
</tr>
<tr>
<td>11 Aug.</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>18 Aug.</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.002</td>
</tr>
<tr>
<td>04 Sep.</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>13 Sep.</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Note: Treatment effects with $P > 0.05$ are considered non-significant (NS).
Table 6. Summary of estimated soil carbon dioxide (CO$_2$) flux over annual summer growing seasons under different tillage and rice (R) based crop rotations during a 10- (2009) and 11-year (2010) study period at the Rice Research and Extension Center near Stuttgart, AR on a silt-loam soil. Tillage treatments included conventional tillage (T) and no-tillage (NT). Rice was rotated with soybean (S) and/or corn (C), with some rotations also including winter wheat [(W)]. Crops in parentheses were grown during the winter.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
<td>NT</td>
</tr>
<tr>
<td>Continuous Rice</td>
<td>514</td>
<td>663</td>
</tr>
<tr>
<td>Rice-Soybean</td>
<td>824</td>
<td>873</td>
</tr>
<tr>
<td>Soybean-Rice</td>
<td>1976</td>
<td>2189</td>
</tr>
<tr>
<td>Rice-Corn</td>
<td>743</td>
<td>949</td>
</tr>
<tr>
<td>Corn-Rice</td>
<td>2239</td>
<td>1434</td>
</tr>
<tr>
<td>Rice-(Wheat)</td>
<td>121</td>
<td>521</td>
</tr>
<tr>
<td>Rice-(Wheat)-Soybean-(Wheat)</td>
<td>239</td>
<td>424</td>
</tr>
<tr>
<td>Soybean-(Wheat)-Rice-(Wheat)</td>
<td>2161</td>
<td>2530</td>
</tr>
<tr>
<td>Rice-Soybean-Corn</td>
<td>1945</td>
<td>2241</td>
</tr>
<tr>
<td>Rice-Corn-Soybean</td>
<td>1509</td>
<td>1867</td>
</tr>
</tbody>
</table>

† Flooding occurred in the R, RS, RC,R(W), and R(W)S(W) rotations in 2009 and the R, SR, CR, R(W), and S(W)R(W) rotations in 2010.
Figure 1. Soil surface carbon dioxide (CO$_2$) flux during the 2009 [A] and 2010 [B] growing seasons under different tillage regimes and rice (R) based crop rotations. Tillage treatments included conventional tillage (T) and no-tillage (NT). Rice was rotated with soybean (S) and/or corn (C) on a biennial or triennial cropping cycle, with some rotations also including a biannual rotation with winter wheat [(W)]. Lines within the graph represent when the all rice plots were flooded early in the growing season and when all floods were released prior to fall harvest.
OVERALL DISSERTATION CONCLUSIONS

This long-term experiment demonstrated that the dynamics of soil C and N cycling in flood-irrigated, rice-based cropping systems were affected by inputs from high-residue producing crops and soil manipulation from tillage over time. After 11 years of consistent management, NT had greater soil C and N contents than that under tillage, but fertility treatments used in this study did not influence C and N contents during the time period evaluated. Furthermore, rotations double-cropped with winter wheat had greater total soil C and N contents over time when compared to rotations that were fallow during the winter. However, rotations with corn had greater WSA C and N contents than rotations that included winter wheat over time. This suggests that rice rotated with the high-residue producing crop of corn may lead to greater C and N sequestration over time due to physical protection provided by macroaggregated soil. Results from this study also suggest that rice-based cropping systems reach equilibrium in soil surface CO$_2$ gas emissions over time regardless of the management system practices. Soil surface CO$_2$ flux did not differ consistently among tillage treatments or rice-based crop rotations during the summer growing period after 10 and 11 years of management, despite measured increases in soil C and N contents. Therefore, NT and higher-residue producing systems did appear to sequester C and N over time.

This study was meant to provide a comprehensive look at the long-term C and N storage and the sustainability of flood-irrigated, rice-based crop rotations under the field management practices commonly used in the United States. Today’s rice production systems are under pressure to achieve increasingly greater crop yields. However, the longer-term sustainability of rice production systems will not be possible unless there is a balance of nutrient inputs and nutrient removal, in addition to conservation of the soil resource. Increasing SOM is the most
efficient method to combat nutrient losses from leaching, reuse nutrients that were taken up and stored in the above-ground biomass, and protect the physical, chemical, and biological properties of the soil. Evaluated parameters of this long-term study show the decadal effects of tillage, fertility, and rotation management, which can help reveal ways for producers to remain profitable without detrimental effects to the environment. Finding a balance between production efficiency and soil health will assure the sustainability of rice production in the United States for years to come.
APPENDIX 1: Aerial view of study site and plot plan.