Pasture Management Strategies for Sequestering Soil Carbon

Final Report

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Executive Summary

Pasturelands account for 51 of the 212 Mha of privately held grazing land in the USA. Tall fescue is the most important cool-season perennial forage for many beef cattle producers in the humid region of the USA. A fungal endophyte, *Neotyphodium coenophialum*, infects the majority of tall fescue stands with a mutualistic association. Ergot alkaloids produced by the endophyte have negative impacts on cattle performance. However, there are indications that endophyte infection of tall fescue is a necessary component of productive and persistent pasture ecology. The objectives of this research were to characterize and quantify changes in soil organic carbon and associated soil properties under tall fescue pastures with and without endophyte infection of grass. Pastures with high endophyte infection had greater concentration of soil organic carbon, but lower concentration of biologically active soil carbon than pastures with low endophyte infection. A controlled experiment suggested that endophyte-infected leaf tissue may directly inhibit the activity of soil microorganisms. Carbon forms of soil organic matter were negatively affected and nitrogen forms were

positively affected by endophyte addition to soil. The chemical compounds in endophyte-infected tall fescue (ergot alkaloids) that are responsible for animal health disorders were found in soil, suggesting that these chemicals might be persistent in the environment. Future research is needed to determine whether ergot alkaloids or some other chemicals are responsible for increases in soil organic matter. Scientists will be able to use this information to better understand the ecological impacts of animals grazing tall fescue, and possibly to identify and cultivate other similar associations for improving soil organic matter storage. Another experiment suggested that both dry matter production and soil microbial activity could be affected by the endophyte. Sampling of the cumulative effects of 20 years of tall fescue management indicated that soil organic carbon and nitrogen storage were greater with than without endophyte only under high soil fertility. This extra carbon and nitrogen in soil due to the presence of the endophyte was further found to be located in intermediately sized soil aggregates, which are important for reducing water runoff and improving water quality. These results suggest that well-fertilized tall fescue pastures with a high percentage of plants infected with the endophyte have the potential to help offset the rising carbon dioxide in the atmosphere. This research has also shown positive ecological implications of tall fescue-endophyte association.

Objectives and Accomplishments

Using a combination of field studies and controlled incubation studies, we were able to either meet or are continuing to address the following three objectives proposed. Accomplishments meeting these objectives are briefly described.

1. Determine the rate and magnitude of soil organic C sequestration, depth distribution of soil organic C, and biochemical quality of soil C during establishment of tall fescue pastures varying in plant genetic source (high endophyte–high alkaloid, high endophyte–low alkaloid, and low endophyte–low alkaloid), nutrient source (inorganic fertilizer and poultry litter), and harvest management (grazing and haying).

   Accomplishments: The established field study became completely operational in April 2002 and will enter the fifth year of treatment comparison during the spring of 2006. We are pleased with its current state of operation, despite the toll that several years of drought had on its early development. We have collected baseline soil samples, as well as biannual soil samples, and have analyzed them for surface residue and soil organic C at various depth increments to 1.5 m. In order to obtain high quality estimates of soil organic C sequestration under the treatments employed, we will need to continue sampling this study for a few more years.

2. Link rate of soil organic C sequestration in tall fescue pastures in a holistic manner with animal performance and productivity, plant stand and composition, alkaloid production, soil microbial biomass C, particulate organic matter, soil bulk density, surface residue accumulation, plant nutrient availability, soil pH, deep

profile nitrate concentration, water-stable aggregation, soil organic C protection in macroaggregates, water infiltration and total runoff, and quality of runoff.

Accomplishments: Pasture responses to treatments during the first 3 yr of field study have been described in the journal article "Pasture and Cattle Responses to Fertilization and Endophyte Association in the Southern Piedmont, USA", which will appear in print in 2006 in *Agriculture, Ecosystems and Environment.* Water runoff quantity and quality from experimental paddocks during the first 2.5 yr of field study has been described in the proceedings article "Hydrologic and Water Quality Implications of Management of Tall Fescue Pastures in a Southern Piedmont Environment", which appeared in *Proceedings of the 2005 Georgia Water Resources Conference*. Soil response variables from initial soil samples and from samples collected after 2 yr have been analyzed, but samples at 4 and 6 yr have not been collected yet. This objective can be most completely fulfilled through the further implementation of the field study for several more years. We are well equipped to evaluate each of these components and are beginning to link these components in a holistic manner. The simultaneous development of this recently established field study as intact water catchments will allow us to make very strong linkages among various soil properties (including soil organic C sequestration), water quality components, and agricultural production issues. Both poultry manure and ergot alkaloids produced by endophyte-infected tall fescue are potential endocrine disruptors, which from pastures in the southeastern USA could eventually become as important to water quality assessment as nutrient contamination. Associated field experiments at our location, not funded by this award, are allowing us to gather more mature experimental information regarding the holistic linkages between soil organic C sequestration and other production and environmental characteristics. We will continue to utilize these associated studies to make holistic assessments of the role of the endophyte in the environment. These studies continue to broaden our experimental perspectives by allowing more time to have elapsed for making inferences and creating complimentary, but unique experimental conditions. The current list of publications and several forthcoming publications from these studies will enhance the state of science on this topic.

3. Elucidate the biological and/or environmental controls that might contribute to greater soil organic C sequestration in endophyte-infected tall fescue.

Accomplishments: Short-term decomposition of tall fescue leaves added to soil under controlled laboratory conditions has been described in the journal article "Soil Carbon, Nitrogen, and Ergot Alkaloids with Short- and Long-Term Exposure to Endophyte-Infected and Endophyte-Free Tall Fescue", which appeared in *Soil Science Society of America Journal* in 2005. Soil C and N and plant responses during a 60-week mesocosm experiment have been described in the journal article "Short-Term Responses of Soil C and N Fractions to Tall Fescue Endophyte Infection", which will appear in print in

2006 in *Plant and Soil*. Analysis of the soil bacterial changes associated with tall fescue-endophyte association has been described in the manuscript "Assessing Prokaryotic Communities in Bulk and Rhizosphere Soils of Endophyte-Infected and Endophyte-Free Tall Fescue with Fluorescence In Situ Hybridization", which has been submitted for consideration in *Soil Biology & Biochemistry*. Other laboratory analyses on soil microbial community structure and glomalin in soil aggregate fractions have been completed, but results are currently be summarized for presentation in a journal article. The short-term, controlled incubation and container studies conducted in this research program are creating a strong foundation to provide us with a mechanistic understanding of the effects of endophyte infection on soil properties. It is clear that soil functional capabilities of C and N cycling are being affected by endophyte infection. However, it is not yet clear whether ergot alkaloids, non-ergot alkaloids, or other metabolites secreted from the roots of endophyte-infected plants (e.g. phenolics) are the dominant sources of altered C and N cycling in soil. We have also seen evidence that soil microbial community structure may be altered in the presence of endophyte-infected tall fescue. We will need to continue our analyses of soil biological, chemical, and physical characteristics into the recently established field study in order to fully evaluate how medium- to long-term changes in soil properties (including soil C sequestration) are affected by the presence of the endophyte.

Project Summary

Project activities are summarized around some of the key questions and hypotheses that drove this project:

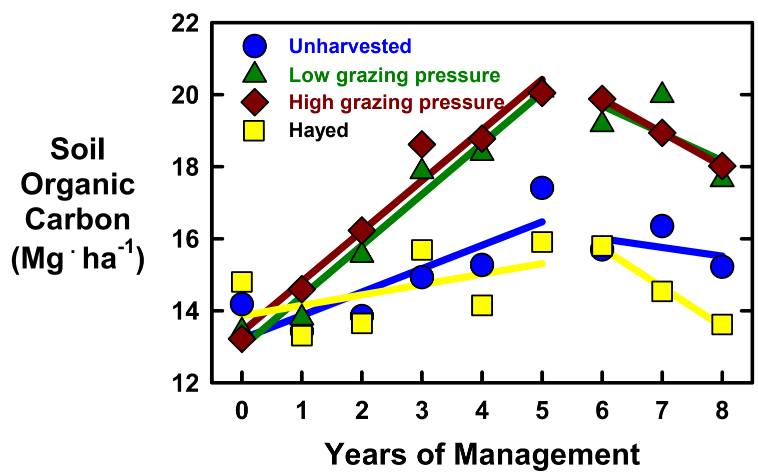
Question 1: What is the rate and magnitude of soil organic C sequestration following establishment of tall fescue? Is it more or less than that observed in previous studies on hybrid bermudagrass?
Hypothesis 1: Soil organic C sequestration will be rapid during establishment (i.e., first 5 yr) of tall fescue because of surface litter accumulation and senescent root deposition. Rate and magnitude of soil organic C sequestration in tall fescue (adaptable, cool-season perennial forage with major growth in spring and variable growth in fall and summer) will be more rapid than in hybrid bermudagrass (warm-season perennial forage with only growth in summer), because of much longer potential growth period and differences in plant morphology and forage quality.
Activity 1: A field study to provide the experimental conditions to meet this objective became fully functional in April 2002 and is continuing today. Soil samples prior to the implementation of treatments in 2002 were collected in Spring 1999, 2001, and 2002. These samples will provide us with detailed background information for this study. Soil samples were collected again in 2004 and will be collected in 2006 and 2008 to fully meet the goals of this objective. Although this field study is now functional, there were a

couple of complicating factors during establishment that hindered our progress. First, precipitation during the 4-year period of 1999 to 2002 was well below normal. Low precipitation led to poor establishment of tall fescue during autumns of 1999 and 2000. Reseeding of pastures in autumn of 2001 was successful. Second, we initially planted an unreleased variety of novel endophyte-infected tall fescue (Experimental 961), but were advised by the plant breeder on our team (following new information collected that the selection might have poor survivability) to switch to a variety that became recently commercially available. The commercial variety had the same high endophyte-low alkaloid traits as the experimental variety. We made the decision to replant paddocks with this commercially available variety. The three grass treatments [all derivatives of 'Jesup', including endophyte-free, endophyte-infected with low alkaloid production (Max Q), and wild-type endophyte-infected with high alkaloid production] are factorially arranged with two fertilizer sources [inorganic fertilizer (180-20-75 kg N-P-K ha^{-1} yr^{-1}) and poultry litter (7 Mg ha^{-1} yr^{-1}; targeted to supply 225 kg N ha^{-1} yr^{-1})] with two replications each in 1-ha paddocks. Two additional control paddocks (not grazed, but harvested for hay) have been planted with Max-Q tall fescue and fertilized inorganically.

Total organic C and soil biochemical analyses have, for the most part, been completed on initial soil samples and those collected in 2004. Robust estimates of soil organic C sequestration could not be realistically achieved from this 2-yr period, and therefore, we plan to collect and analyze samples in 2006 and 2008. We hope to continue the field study with resources obtained from other sources.

To provide additional data on soil organic C sequestration potential of endophyte-infected tall fescue (Franzluebbers et al., 1999), a 20-year-old field study that was scheduled for termination due to a need for pasture renovation was sampled in May 2002. We report that soil organic C to a depth of 20 cm was greater in pastures with high endophyte infection (42.0 Mg ha^{-1}) compared with low endophyte infection (38.7 Mg ha^{-1}), but only with a high fertilization rate (Franzluebbers and Stuedemann, 2004b). Accumulation of C and N due to endophyte infection occurred preferentially in macroaggregates, suggesting a biophysical mechanism of protection that deserves further exploration.

Data from an associated long-term pasture study managed with bermudagrass only during the first 5 years and subsequently overseeded with tall fescue do not support our hypothesis of greater soil organic C with tall fescue than with bermudagrass. The shift in soil organic C from accumulation to decline



Soil organic C as a function of forage utilization during bermudagrass only (first 5 years) and subsequently with overseeding of tall fescue (Yeras 6 and onwards) (adapted from Franzluebbers et al., 2001 and unpublished data).

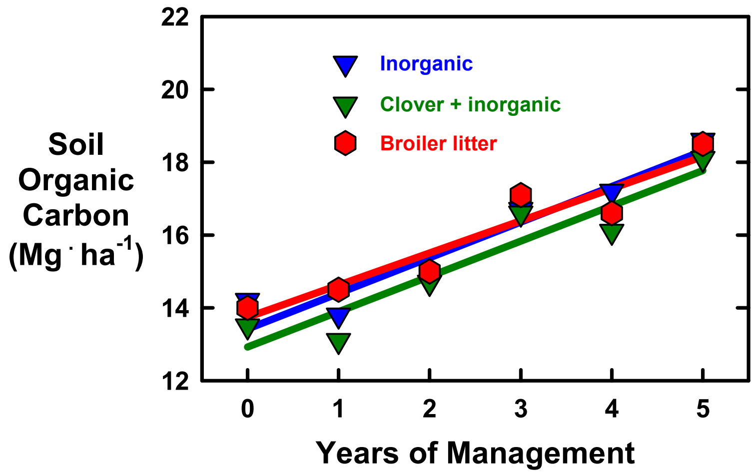
observed in this study coincided with extremely low rainfall during this period, which may have severely limited photosynthetic fixation of C by plants, but may not have greatly reduced soil organic matter decomposition. Additional soil samples to complete this associated experiment have been recently collected and analyses are underway to make conclusions about the impact of overseeding tall fescue into bermudagrass on soil organic C.

Question 2: Will an endophyte-infected, low alkaloid genetic source lead to increased soil organic C sequestration much like that previously observed under endophyte-infected, high alkaloid genetic material compared with low endophyte material? Or will the lack of certain alkaloids in leaf tissue result in stand loss and decline in soil organic C sequestration?
Hypothesis 2: High endophyte–low alkaloid plant material (i.e., newly available genotype) will lead to SOC sequestration equal or greater than high endophyte–high alkaloid plant material and significantly greater than endophyte-free plant material, because of high productivity, stand persistence, and forage quality without negatively affecting animal performance and productivity, which would also reduce nutrient cycling.
Activity 2: The field study described in Activity 1 will also be used to answer this question. Data collection and sample analyses will have to be continued to provide an answer to this question. Data on pasture botanical composition have been collected yearly since April 2002. During the 3rd yr of experimentation, tall fescue composition of pastures was 79% in both high endophyte–high alkaloid and high endophyte–low alkaloid treatments and was 71% in low endophyte–low alkaloid treatment (Franzluebbers and Stuedemann, 2006). These early results suggest that the high endophyte–low alkaloid treatment may be able to maintain persistence and could contribute to high soil organic C sequestration.

Question 3: How long does it take to observe significant changes in soil organic C due to poultry litter application to and endophyte infection of tall fescue? Will poultry litter enhance the difference in soil organic C sequestration between low and high endophyte-infected tall fescue?
Hypothesis 3: Poultry litter application will enhance the rate of soil organic C sequestration in endophyte-infected tall fescue more than in endophyte-free tall fescue, because higher fertility with poultry litter (provides other essential elements that inorganic fertilizer typically does not) compared with inorganic fertilizer will increase stocking rate to maintain similar available forage and increase the cycling of C from plant tissue to soil via feces and senescent roots and plant litter.
Activity 3: The field study described in Activity 1 will also be used to answer this question. Data collection and sample analyses will have to be continued to provide an answer to this question. Animal manure application to crop and grazing lands was summarized in a review of soil organic C sequestration and agricultural greenhouse gas emissions in the southeastern USA (Franzluebbers, 2005). From a collection of six studies conducted for 2 yr only, soil organic C sequestration with poultry litter application was -0.12 ± 2.63 Mg ha^{-1} yr^{-1}. From eight studies conducted for 10 ± 8 yr, soil organic C sequestration with poultry litter application was 0.72 ± 0.67 Mg ha^{-1} yr^{-1}.

The greater and more consistent estimate of soil organic C sequestration with studies conducted for longer periods of time indicates the need for robust evaluations in long-term field studies, such as that being continued from this award.

From an associated field experiment with bermudagrass, there was no statistical change in soil organic C at a depth of 0 to 6 cm from initiation until the end of 5 yr in pastures fertilized with poultry litter (Franzluebbers et al., 2001). This associated experiment will soon have an evaluation of soil organic C sequestration at the end of 12 yr of poultry litter application, which should contribute to the question of how long it takes for animal manure application to significantly change soil organic C.



Soil organic C accumulation as affected by nutrient source when applied to bermudagrass (adapted from Franzluebbers et al., 2001).

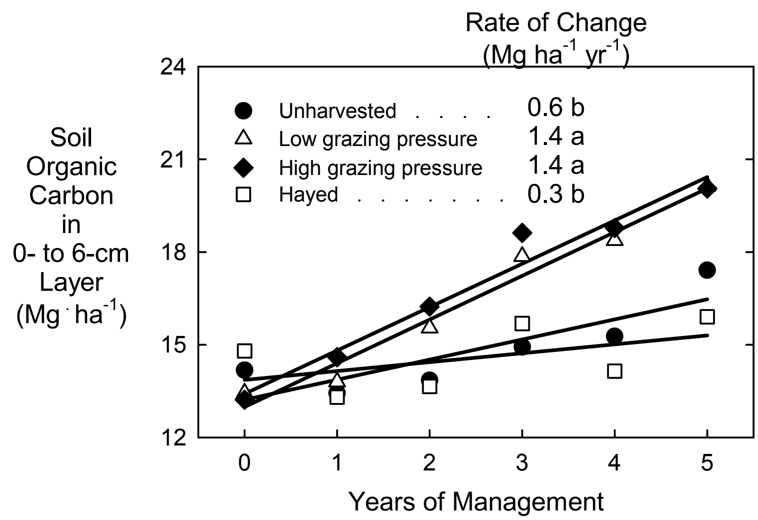
<u>Question 4</u>*:* What is the rate and magnitude of soil organic C sequestration with application of poultry litter to tall fescue pastures?
<u>Hypothesis 4</u>*:* Poultry litter application will enhance soil organic C sequestration compared with inorganic fertilizer, because 3 Mg · ha^{-1} · yr^{-1} of organic C will be applied via organic fertilizer.
<u>Activity 4</u>*:* The field studies described in Activities 1 and 3 will also be used to answer this question. Data collection and sample analyses will have to be continued to provide an answer to this question.

From an associated field experiment with bermudagrass, soil organic C sequestration during 5 yr of poultry litter application compared with inorganic fertilizer was 0.40 $\pm$ 0.61 Mg ha^{-1} yr^{-1} at a depth of 0 to 20 cm among four harvest management systems (Franzluebbers et al., 2001). This associated experiment will have an evaluation of soil organic C sequestration with 12 yr of poultry litter application available during the next year.

<u>Question 5</u>*:* What is the effect of harvesting forage by grazing cattle versus haying on soil organic C sequestration? Does harvest management of forage affect rooting depth and subsequent deep C storage?
<u>Hypothesis 5</u>*:* Cattle grazing will increase soil organic C sequestration compared with hay removal, because more of the plant-fixed C is returned to the soil via feces and senescent plant litter. Also, grazing animals may actually stimulate plant growth via saliva-controlled hormonal interactions with grass.
<u>Activity 5</u>*:* The field study described in Activity 1 will also be used to answer this question. Data collection and sample analyses will have to be continued to provide an

answer to this question. Both surface (0-3, 3-6, 6-12, and 12-20 cm) and deep (0-15, 15-30, 30-60, 60-90, 90-120, and 120-150 cm) soil samples have been collected at initiation in 2002 and in 2004 and will be collected in 2006 and beyond.

From an associated field study with bermudagrass, soil organic C sequestration with cattle grazing was greater than with haying or not harvesting grass (Franzluebbers et al., 2001). Other studies at the research station in Watkinsville support the conclusion of a positive effect of grazing on soil organic C sequestration. In a survey of bermudagrass pastures that were either harvested for hay or grazed by cattle, soil organic C averaged 31.1 Mg ha^{-1} with haying and 38.0 Mg ha^{-1} with cattle grazing (Franzluebbers et al., 2000).



Soil organic C during the first 5 yr of bermudagrass management as affected by forage utilization (adapted from Franzluebbers et al., 2001).

Products and Technology Transfer

New research collaborations, renewed previous collaborations, and initially developing collaborations were established as a direct result of this research award, between the principal investigator and the following individuals:

- Bacon, Charles W., USDA – Agricultural Research Service, 950 College Station Road, Athens GA 30604
- Bouton, Joseph H., Samuel Roberts Noble Foundation, 2510 Samuel Noble Parkway, Ardmore OK 73401
- Burke, Roger A., US – Environmental Protection Agency, Ecosystems Research Division, 960 College Station Road, Athens GA 30605
- Buyer, Jeffrey S., USDA – Agricultural Research Service, 10300 Baltimore Avenue, Building 001, BARC-West, Beltsville MD 20705
- Endale, Dinku M., USDA – Agricultural Research Service, 1420 Experiment Station Road, Watkinsville GA 30677
- Hill, Nicholas S., University of Georgia, Department of Crop and Soil Sciences, Athens GA 30602
- Humayoun, Shaheen B., USDA – Agricultural Research Service, 1420 Experiment Station Road, Watkinsville GA 30677
- Jenkins, Michael B., USDA – Agricultural Research Service, 1420 Experiment Station Road, Watkinsville GA 30677

- Lang, David J., Mississippi State University, P.O. Box 9555, Mississippi State MS 39762
- Nichols, Kristine A., USDA – Agricultural Research Service, 1701 10th Avenue SW, P.O. Box 459, Mandan ND 58554
- Omacini, Marina, University of Buenos Aires, Buenos Aires, Argentina
- Poore, Matt, North Carolina State University, P.O. Box 7621, Raleigh NC 27695
- Steiner, Jean L., USDA – Agricultural Research Service, Grazinglands Research Laboratory, 7207 W. Cheyenne, El Reno OK 73036
- Stuedemann, John A., USDA – Agricultural Research Service, 1420 Experiment Station Road, Watkinsville GA 30677
- Timper, Patricia, USDA – Agricultural Research Service, 108 Plant Science Drive, Tifton GA 31793
- Waller, John C., University of Tennessee, Department of Animal Science, Knoxville TN 37901
- West, Charles P., University of Arkansas, Department of Crop, Soil, and Environmental Sciences, Fayetteville AR
- Zuberer, David A., Texas A&M University, Department of Soil and Crop Sciences, College Station TX 77843

Information products available to the public that were derived directly from this research award, include:

- Franzluebbers AJ, Stuedemann JA. 2006. Pasture and cattle responses to fertilization and endophyte association in the Southern Piedmont USA. *Agriculture, Ecosystems and Environment* (in press). [Submitted to E-Link as DOE/ER/63021-1].
- Franzluebbers AJ. 2006. Short-term responses of soil C and N fractions to tall fescue endophyte infection. *Plant and Soil* (in press). [Submitted to E-Link as DOE/ER/63021-2].
- Franzluebbers AJ, Hill NS. 2005. Soil carbon, nitrogen, and ergot alkaloids with short- and long-term exposure to endophyte-free and -infected tall fescue. *Soil Science Society of America Journal* 69, 404-412. [Submitted to E-Link as DOE/ER/63021-3].
- Franzluebbers AJ, Stuedemann JA. 2005. Soil carbon and nitrogen pools in response to tall fescue endophyte infection, fertilization, and cultivar. *Soil Science Society of America Journal* 69, 396-403. [Submitted to E-Link as DOE/ER/63021-4].
- Franzluebbers AJ, Hill NS, Jenkins MB, Zuberer DA, Humayoun SB, Stuedemann JA. 2004. How does soil respond to wild-type endophyte infection? In: Proceedings of the 5th International Symposium on Neotyphodium/Grass Interactions, 23-26 May 2004, Fayetteville AR. [Submitted to E-Link as DOE/ER/63021-5].
- Endale DM, Franzluebbers AJ, Stuedemann JA, Hill NS, Frankling DH. 2005. Hydrologic and water quality implications of management of tall fescue pastures in a Southern Piedmont environment. In: Proceedings of the Georgia Water

Resources Conference, 25-27 April 2005, Athens GA. [Submitted to E-Link as DOE/ER/63021-6].
- Franzluebbers AJ. 2003. Pasture management strategies for sequestering soil carbon. US-DOE Carbon Cycle and Carbon Sequestration Program Annual Meeting, 16-17 October 2003, Boulder CO. [Submitted to E-Link as DOE/ER/63021-7].
- Franzluebbers AJ, Jenkins MB, Zuberer DA, Hill NS. 2003. Soil responses to tall fescue endophyte infection. ASA-CSSA-SSSA Annual Meetings, 2-6 November 2003, Denver CO. [Submitted to E-Link as DOE/ER/63021-8].
- Franzluebbers AJ, Jenkins MB, Zuberer DA, Hill NS. 2002. Belowground responses to tall fescue endophyte infection. USDA Symposium on Natural Resource Management to Offset Greenhouse Gas Emissions. 19-21 Nov 2002, Raleigh NC. [Submitted to E-Link as DOE/ER/63021-9].
- Franzluebbers AJ, Stuedemann JA, Endale DM, Franklin DH, Jenkins MB, Hill NS, Bouton JH, Kaplan RM, Zuberer DA. 2003. Production and environmental quality of tall fescue pastures: Cattle performance and production during first 18 months. Tall Fescue Toxicosis Workshop of SERAIEG-8, 26-28 October 2003, Wildersville TN.
- Jenkins MB, Franzluebbers AJ. 2003. Soil microbial community structure under endophyte-free and endophyte-infected tall fescue as determined by FISH analysis. ASA-CSSA-SSSA Annual Meetings, 2-6 November 2003, Denver CO.

Other recent information products that developed indirectly as a result of collaborations and similar scientific interests derived from this research award, include:

- Derner JD, Schuman GE, Jawson M, Shafer SR, Morgan JA, Polley HW, Runion GB, Prior SA, Torbert HA, Rogers HH, Bunce J, Ziska L, White JW, Franzluebbers AJ, Reeder JD, Venterea RT, Harper LA. 2005. USDA-ARS global change research on rangelands and pasturelands. *Rangelands* 27 (5), 36-42.
- Franzluebbers AJ. 2002. Endophyte grasses. p. 94-96. In: *2002 Yearbook of Science and Technology*, McGraw-Hill Inc., New York.
- Franzluebbers AJ. 2003. Mechanical renovation of bermudagrass for interseeding tall fescue. 16th International Conference of the Soil Tillage Research Organization, 13-18 July 2003, Brisbane, Australia.
- Franzluebbers AJ. 2003. Soil organic carbon in livestock and cropping systems in the southesastern USA. First meeting of principal investigators of the North American Carbon Program. 12-14 May 2003, Arlington VA.
- Franzluebbers AJ. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. *Soil and Tillage Research* 83, 120-147.
- Franzluebbers AJ, Follett RF. 2005. Greenhouse gas contributions and mitigation potential in agricultural regions of North America: Introduction. *Soil and Tillage Research* 83, 1-8.
- Franzluebbers AJ, Nazih N, Stuedemann JA, Fuhrmann JJ, Schomberg HH, Hartel PG. 1999. Soil carbon and nitrogen pools under low- and high-endophyte-

infected tall fescue. *Soil Science Society of America Journal* 63:1687-1694.

- Franzluebbers AJ, Stuedemann JA. 2001. Bermudagrass management in the Southern Piedmont U.S. IV. Soil-surface nitrogen pools. *The Scientific World* 1 (S2), 673-681.
- Franzluebbers AJ, Stuedemann JA. 2001. Carbon cycling and sequestration in humid grazinglands. Presented in the symposium AThe Carbon Cycle of Grazinglands: Is it Worth Managing?@ at the annual meeting of the ASA-CSSA-SSSA, 21-25 Oct 2001, Charlotte NC.
- Franzluebbers AJ, Stuedemann JA. 2002. Managing grazinglands for soil organic C sequestration in the southeastern USA. USDA Symposium on Natural Resource Management to Offset Greenhouse Gas Emissions. 19-21 Nov 2002, Raleigh NC.
- Franzluebbers AJ, Stuedemann JA. 2002. Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. *Environmental Pollution* 116:S53-S62.
- Franzluebbers AJ, Stuedemann JA. 2002. Temporal and spatial responses in soil carbon pools under grass. Presented at the symposium AThe Greenhouse Effect, Carbon Sequestration, and the Role of Forages@ at the annual meeting of the Southern Association of Agricultural Scientists, 2-4 Feb 2002, Orlando FL.
- Franzluebbers AJ, Stuedemann JA. 2003. Bermudagrass management in the Southern Piedmont USA. III. Particulate and biologically active soil carbon. *Soil Science Society of America Journal* 69, 1455-1462.
- Franzluebbers AJ, Stuedemann JA. 2005. Bermudagrass management in the Southern Piedmont USA: VII. Soil-profile organic carbon and total nitrogen. *Soil Science Society of America Journal* 69, 1455-1462.
- Franzluebbers AJ, Stuedemann JA, Schomberg HH. 2000. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. *Soil Science Society of America Journal* 64, 635-639.
- Franzluebbers AJ, Stuedemann JA, Schomberg HH, Wilkinson SR. 2000. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. *Soil Biology and Biochemistry* 32, 469-478.
- Franzluebbers AJ, Stuedemann JA, Wilkinson SR. 2001. Bermudagrass management in the Southern Piedmont USA: I. Soil and surface residue carbon and sulfur. *Soil Science Society of America Journal* 65, 834-841.
- Franzluebbers AJ, Wright SF, Stuedemann JA. 2000. Soil aggregation and glomalin under pastures in the Southern Piedmont USA. *Soil Science Society of America Journal* 64, 1018-1026.
- Schnabel RR, Franzluebbers AJ, Stout WL, Sanderson MA, Stuedemann JA. 2001. The effects of pasture management practices. p. 291-322. In: Follett RF, Kimble JM, Lal R (Editors), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton FL.
- Schomberg HH, Stuedemann JA, Franzluebbers AJ, Wilkinson SR. 2000. Spatial distribution of extractable P, K, and Mg as influenced by fertilizer and tall fescue endophyte status. *Agronomy Journal* 92:981-986.