Assessment of Life Cycle Greenhouse Gas Emissions From Bioenergy Sorghum Production in Central Texas

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USDA United States Department of Agriculture National Institute of Food and Agriculture

Abstract

Estimating life cycle greenhouse gases (GHGs) from biofuel production scenarios are important for compliance with federally mandated reduction goals as well as quantifying the 'carbon footprint' of a bioenergy cropping system. Federal legislation has mandated increasing biofuel production to more than 136 billion liters of fuel by the year 2022 while minimizing overall carbon intensity. Both direct and indirect GHGs can have a significant impact on overall life cycle efficiency. Cellulosic biomass feedstocks, such as bioenergy sorghum, must reduce life cycle GHG emissions by 60% compared to the 2005 gasoline standard. The objective of this study was to quantify well-to-wheel greenhouse gas emissions from eight different bioenergy sorghum production scenarios using life cycle analysis. The effects of cropping sequence, N fertilization, and residue return on life cycle greenhouse gas emissions from bioenergy sorghum production in central Texas were examined from 2010 through 2011. Field measured values were combined with published and modeled GHG estimates to evaluate biofuel production efficiency. Nitrous oxide emissions from crop production contributed the greatest CO_2-eq emissions. Urea fertilizer production, ethanol production, and transportation and distribution were other major carbon-intensive activities. Net change in SOC to 90 cm was utilized to estimate net CO_2 emissions to the atmosphere. Large annual SOC accrual from sorghum led to more CO_2-eq sequestered than lost per MJ of theoretical ethanol produced. Nitrogen fertilization significantly increased life cycle GHG emissions across both years of study and fertilized treatments had lower biofuel production efficiency than unfertilized treatments. All treatments examined resulted in net negative life cycle GHG emissions and exceeded federally mandated reduction goals.

Background

- Federal legislation mandated an increase in production of domestic biofuels by 2022 with a reduction in life cycle GHGs relative to a 2005 petroleum standard.
- Bioenergy sorghum may play a significant role in future biofuel production as a high quality biomass feedstock.
- Life cycle analyses are used to evaluate biofuel efficiency by balancing the direct and indirect GHGs associated with production with total energy output.
- No studies to date have quantified life cycle GHGs from bioenergy sorghum production.

Objectives

- Quantify both direct and indirect GHG emissions associated with the production of bioenergy sorghum in central Texas.
- Identify which production scenario provides the greatest overall biofuel production efficiency.
- Determine if any production scenario meets the 60% life cycle GHG reduction mandated by the 2007 EISA.

Left: Measuring trace gas emissions from the soil early in the growing season. A LI-COR chamber was integrated with a photoacoustic gas analyzer for gas flux quantification.

Right: Bioenergy sorghum frequently exceeded 3 m in height and produced biomass yields in excess of 15 Mg ha^{-1} under drought conditions.

Materials & Methods

Site: Texas A&M AgriLife Research Farm near College Station, TX (mean annual temperature 20˚C and 978 mm precipitation). Soil at the site is a Weswood silty clay loam, pH 8.2, 0.8% SOC, and tests moderate to high in extractable P, K, Mg and Ca.

Experimental Design: Ongoing field study originated in 2008 to examine effects of various production scenarios on bioenergy sorghum cropping systems. The study is a RCBD with four replications (n = 3 for N_2O emissions) with 4.1 by 9.1 m plots subjected to two levels of each of the following three factors:

- Two crop sequences: continuous sorghum (SS) or sorghum rotated biannually with corn (CS).
- Two N application rates: zero (- N) or full fertilization (+ N) as granular urea-N fertilizer subsurface banded. N applied at rates of 280 kg ha^{-1} for sorghum and 168 kg ha^{-1} for corn.
- Two sorghum residue return rates: 0% (0%R) or 50% (50%R) of plot yield. All corn stover was returned.

Methods continued…

Theoretical Energy Yield: Yield of above-ground biomass and corn grain (when grown) was determined at the end of each growing season. Mass of sorghum residue returned to 50%R treatments was subtracted from total feedstock yield. Published conversion values were utilized to convert feedstock yield (Mg dry feedstock ha^{-1}) to volume of theoretical biofuel (L ethanol ha^{-1}); 452 L ethanol Mg^{-1} sorghum (Stefaniak et al., 2012) and 519 L ethanol Mg^{-1} corn grain (NREL, 2012). Volume of ethanol was multiplied by ethanol energy value (21.2 MJ L^{-1}) and converted to final energy yield units of GJ ha^{-1}. Due to exceptionally low corn yields in 2010, a conservative estimate of 75% of 2008 corn grain yields was utilized for this study.

Net SOC Change: Composite soil samples from each plot were taken prior to planting each spring, using three soil cores/plot at depth increments of 0 – 5, 5 – 15, 15 – 30, 30 – 60, and 60 – 90 cm. A subsample of each composite sample was utilized to determine SOC concentration via combustion analysis, as described by Wight et al. (2012). Average (whole field) bulk densities from each depth were used with SOC concentration and soil volume to calculate mass of SOC for each depth annually. Mass of SOC at each depth in every plot was regressed across the first five years of study (2008 to 2012) to calculate a slope (net annual change). Slopes from each depth within each plot were summed to 90 cm to estimate net change in SOC annually (Mg C ha^{-1} yr^{-1}) to 90 cm.

Direct GHG Emissions: Cumulative N_2O emissions were calculated from chamber-based trace gas flux measurements in 2010 and 2011. Weekly sampling started shortly after fertilization and ended approximately a week prior to harvest each year; with a lower sampling frequency during the fallow season. A LI-COR 20-cm survey chamber (model 8100-103) was integrated with an Infrared Photoacoustic Spectroscopy (PAS) gas analyzer (INNOVA 1412) to measure N_2O concentrations. Cumulative fluxes were calculated by trapezoidal integration, assuming daily fluxes changed linearly between measurement dates. Cumulative CO_2-eq emissions were calculated by converting N_2O to CO_2-eq assuming N_2O is 298 times as potent as CO_2.

Indirect GHG Emissions: CO_2-eq values used to estimate emissions from production of urea fertilizer, diesel fuel, and herbicide (atrazine) inputs were calculated from GREET model (GREET1_2012), while irrigation inputs were estimated from Lal (2004). Post-field estimates of transportation & distribution, ethanol production, and fuel combustion were derived from Wang et al. (2012).

Life Cycle GHG emissions: Net change in SOC in 2010 and 2011 was subtracted from total (direct + indirect) life cycle CO_2-eq emissions associated with biomass production to estimate well-to-wheel life cycle GHG emissions.

Statistical Analysis: Cropping sequence, N fertilization, and residue return effects and their interactions on energy yield, net SOC change, and life cycle GHG emissions were tested using a mixed ANOVA in SAS (Version 9.2). Means separated by LSD when effects significant at ($P \leq 0.05$).

Results

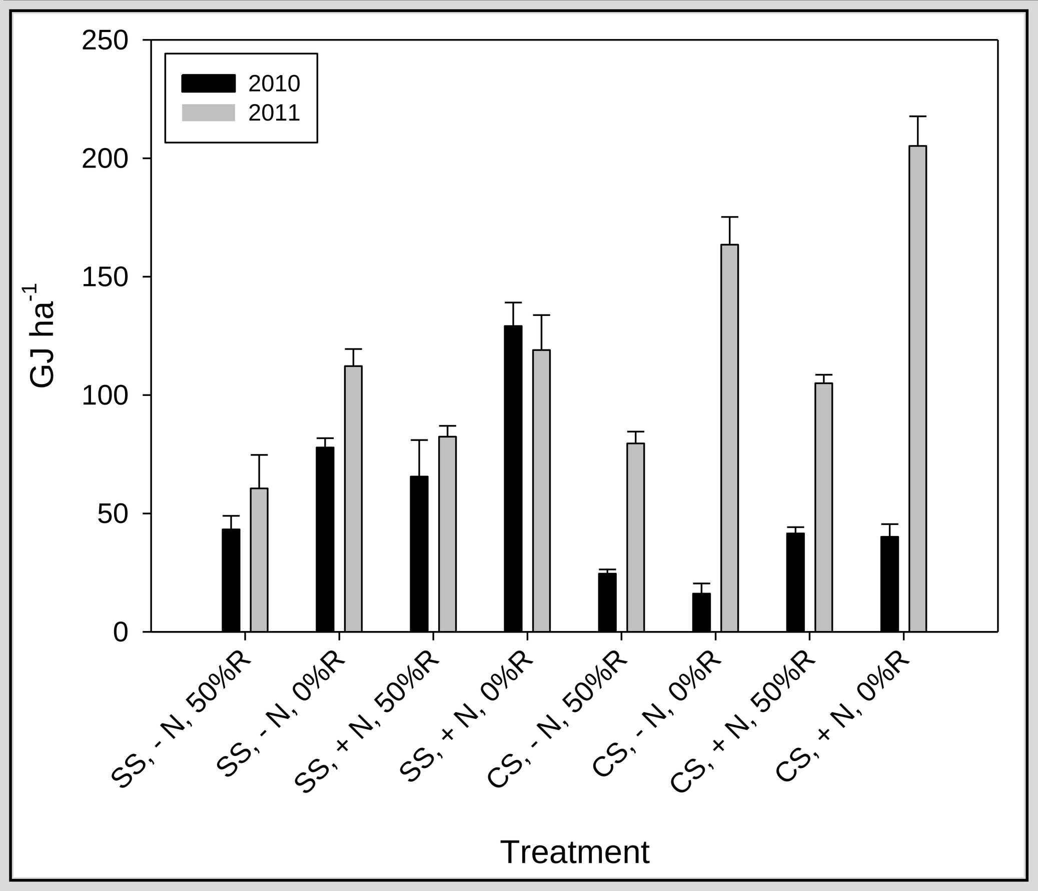

Figure 1. Mean energy yields in 2010 and 2011 for treatment combinations of crop sequence (SS or CS), N fertilization rate (- N or + N), and residue return rate (0%R or 50%R) are reported with one SE (n = 4).

- 50%R treatments return half the harvested feedstock to the soil as an amendment; thus less yield was available for biofuel production.
- Energy yield was significantly increased by N fertilization in 2010 and 2011.
- CS had 'feast or famine' characteristics in energy yield across years; when corn was grown, CS < SS, but when sorghum was grown the next year, CS > SS.

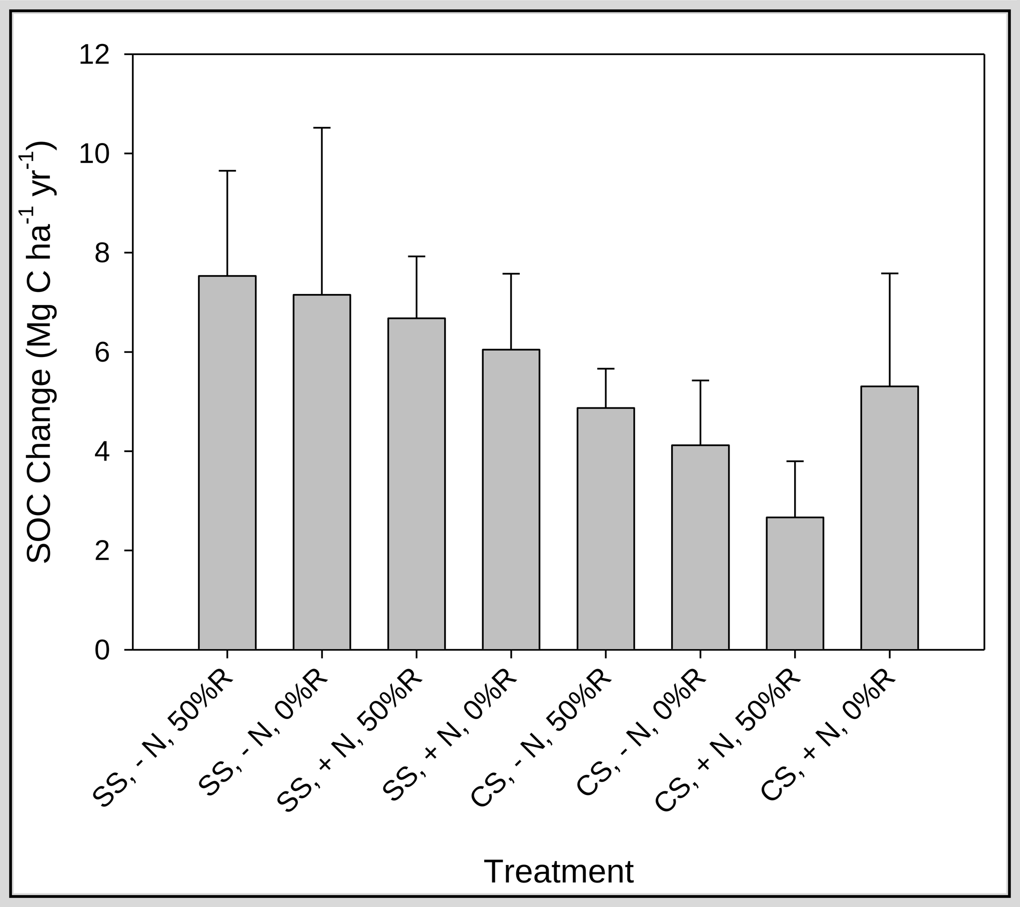

Figure 2. Mean net annual change in SOC from 2008 to 2012 from treatment combinations of crop sequence (SS or CS), N fertilization rate (- N or + N), and residue return rate (0%R or 50%R) are reported with one SE (n = 4). Means are the sum of net change in SOC from 5 sampling depths to 100 cm.

- Measured annual change in SOC was much higher than anticipated.
- SOC accrual rates were slightly ($p = 0.064$) higher in SS than in CS.
- Soil C accrual has a major impact on net CO_2 emissions, as each Mg C is approximately 3.7 Mg CO_2-eq.

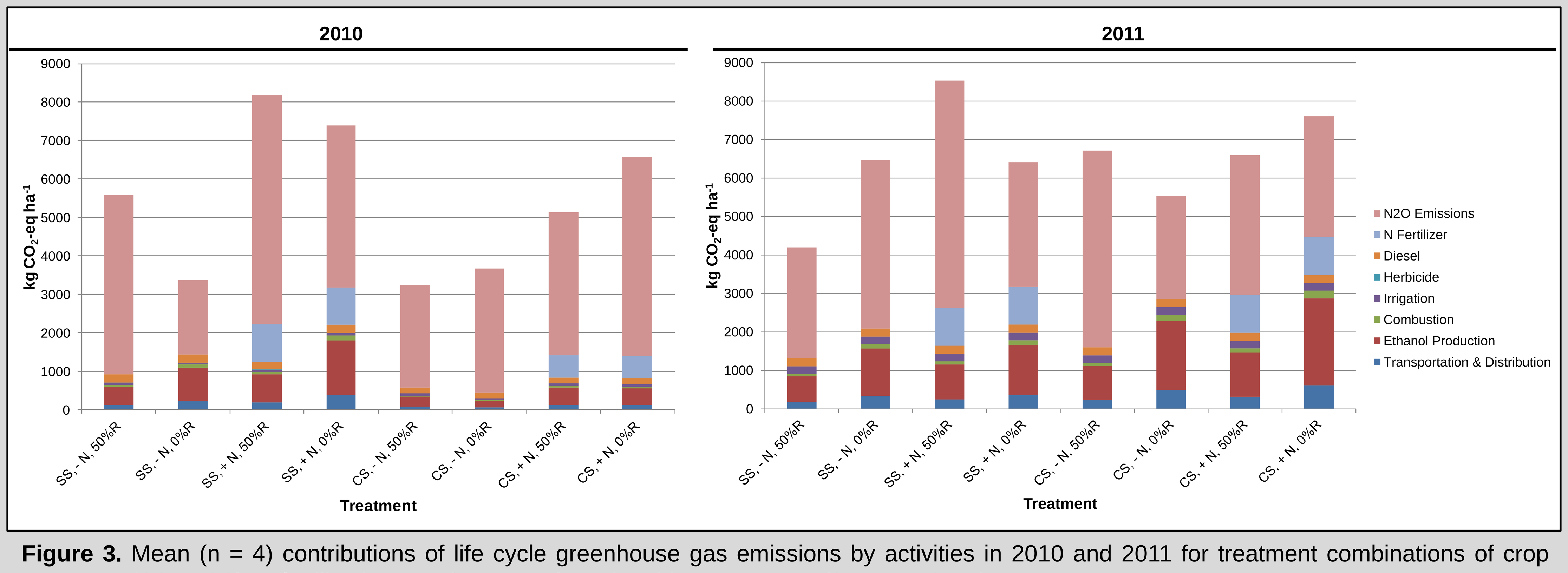

Figure 3. Mean (n = 4) contributions of life cycle greenhouse gas emissions by activities in 2010 and 2011 for treatment combinations of crop sequence (SS or CS), N fertilization rate (- N or + N), and residue return (0%R or 50%R).

- N_2O emissions were much higher than anticipated in this study and accounted for over half of life cycle GHGs for all production scenarios.
- Cumulative N_2O emissions ranged from 4 to 13 kg N_2O-N ha^{-1} across all production scenarios.
- N fertilization significantly ($p < 0.05$) increased N_2O emissions in 2010 and 2011.
- Emissions from combustion, ethanol production, and transportation & distribution were directly proportional to feedstock yield, thus higher yield caused higher emissions from these activities.
- Urea fertilizer and ethanol production were other major contributors to total life cycle GHG emissions.

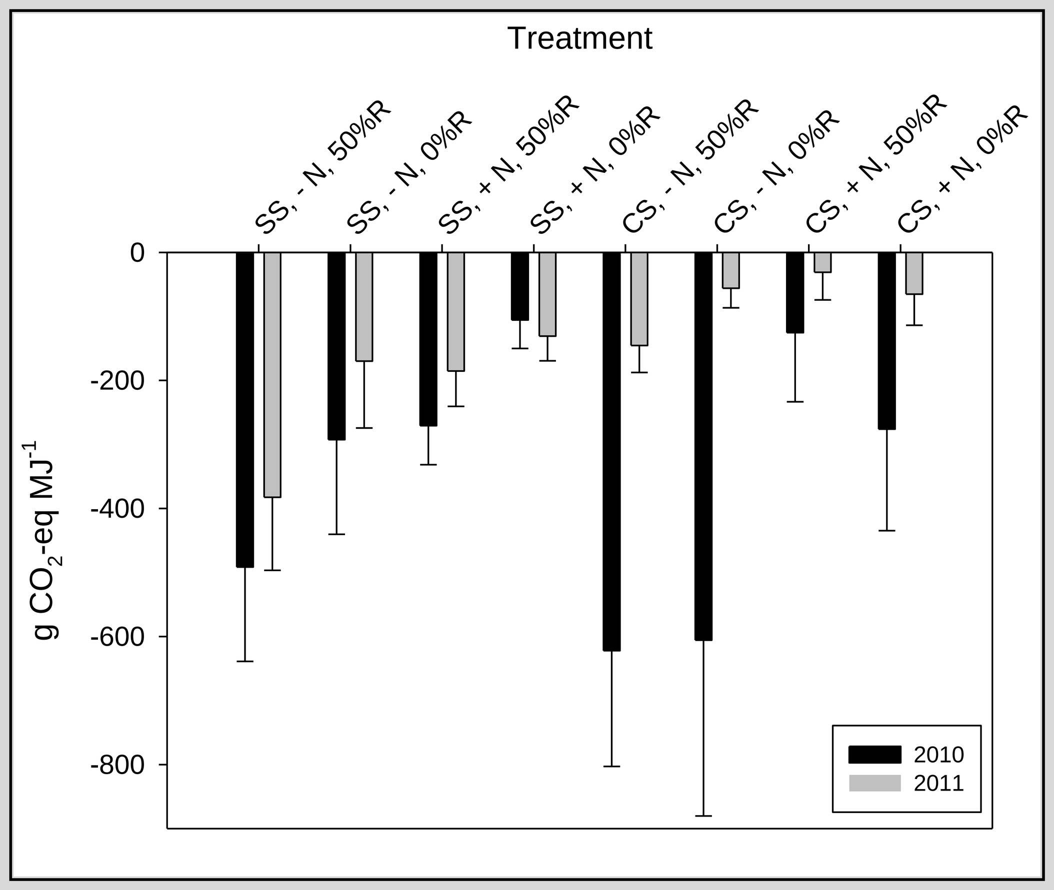

Figure 4. Mean net well-to-wheel GHG emissions associated with bioenergy sorghum production in 2010 and 2011 for treatment combinations of crop sequence (SS or CS), N fertilization (- N or + N), and residue return rate (0%R or 50%R) are reported with one SE (n = 4).

- To comply with the federally mandated 60% reduction in life cycle GHGs, cellulosic biofuels must not exceed emissions of 38 g CO_2-eq MJ^{-1}.
- All treatment means were negative, indicating net C sequestration per MJ energy produced.
- Well-to-wheel GHG emissions ranged from -622 to -105 g CO_2-eq MJ^{-1} in 2010 and from -383 to -31 g CO_2-eq MJ^{-1} in 2011.
- N fertilization increased well-to-wheel GHG emissions (reducing production efficiency) in 2010 and 2011, likely due to increased N_2O emissions, increased energy yield, and emissions from urea production.
- Crop sequence influenced well-to-wheel emissions in 2011, but not 2010, potentially due to lower yield and slight increase in SOC accrual by SS treatments.
- Residue return had a marginal effect ($p = 0.084$) in 2011 and was most likely related to direct impact on energy yield.

Conclusions

- Bioenergy sorghum may be a promising biomass feedstock, particularly in drought-prone areas of the southern U.S.
- SS, - N, 50%R had the greatest overall biofuel production efficiency based on GHG emissions savings. However, crop rotation and fertilization would be recommended to minimize pest pressure and sustain long term crop yield.
- All production scenarios examined complied with the life cycle GHG reductions established by the Energy Independence and Security Act of 2007.
- Future research is needed to verify whether sorghum belowground C inputs were the source of significant SOC accrual.

Above: Bioenergy sorghum plots post-harvest. An illustration of a plot with 100% biomass removal (left) and a plot with 50% biomass residue returned (right).

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Acknowledgements

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