Chapter 7

The Biofuel Crops in Global Warming Challenge: Carbon Capture by Corn, Sweet Sorghum and Switchgrass Biomass Grown for Biofuel Production in the USA

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Abstract

This research evaluates potential carbon capture of sweet sorghum, switchgrass, and corn grown in Portageville, Missouri, from 2007 to 2009. Our results showed that corn grain C content averaged 43%, whereas C grain captured was 1.3–4.7 Mg C ha^{-1} depending on year and N rate. N fertilization significantly increased C capture, but not C content of grain. C capture by switchgrass depended on cultivars and harvest date. Switchgrass cv. Alamo biomass contained 46% C compared to 44% C for Blackwell's. Alamo maximum C capture depended on year, being 9.8 Mg C ha^{-1} in 2008 and 13.4 Mg C ha^{-1} in 2009. C is equivalent to 32.3–49.6 Mg CO_2 ha^{-1}, while Blackwell captured 3.7–4.4 Mg C ha^{-1}. C in sweet sorghum biomass ranged from 42 to 45%, whereas total C capture ranged from 3.2 to 13.8 Mg ha^{-1} according to year, soil, and N rate. The highest C capture appeared in loam. Sweet sorghum aboveground biomass showed 82% C captured in the stalk. When converted into CO_2, C captured by sweet sorghum was equivalent to 12–51 Mg CO_2 ha^{-1}. In addition to their biofuel potential, corn, switchgrass, and sweet sorghum can substantially contribute to environmental cleaning by capturing a significant amount of CO_2.

Keywords: carbon, corn, sweet sorghum, switchgrass, global warming, CO_2

1. Introduction

For many decades, reports have increasingly proven that the climate of our planet is changing mostly because of anthropogenic effects that are increasing the global warming [1–3]. The increase of the concentration of certain molecules such as carbon dioxide (CO_2), methane, nitrous oxide, chlorofluorocarbons, aerosol, and sulfur in the atmosphere is one of the leading causes of the temperature increase. Actions are being taken to reduce the concentration of greenhouse gases in the atmosphere and to better protect the ozone layer [4]; one of these actions is the use of biofuel in engines [5–7]; [3].

Interestingly, plants have a unique ability to uptake CO_2 from the air through their stomata and use it for photosynthesis [8]. Therefore, plants help clean the environment by capturing the CO_2 [9, 11], and integrating it into the metabolic systems that make up carbohydrates and other carbon-containing compounds. When they die, plants return the carbon they sequestered in their roots and leaves to the soil [4]. The mechanism by which plants capture the atmospheric carbon and move it to a soil has been reviewed [12]. The previous author showed that grasses transfer more carbon to the soil than trees. However, because of the biological activity of microorganisms and some anthropogenic reasons, not all the carbon captured by plants is sequestered in the soil [12, 13]. Some carbon captured by plants returns to the atmosphere in the form of CO_2 [14, 8]. Although there is controversy about the impact of biofuel crops on the climate, the majority of the papers that have evaluated the environmental impact of these crops showed that each crop can significantly decrease the emission of greenhouse gases [15]. For instance, the greenhouse gas emitted by the cellulosic ethanol produced from switchgrass is 94% smaller than that from gasoline, so the production of ethanol from switchgrass is much cleaner than the production of gasoline [16].

Roots are the main carbon depositor in the soil, and they decompose very slowly [17, 8]. Unfortunately, it is difficult to study carbon sequestration in roots [8]. Nevertheless, Andress [18] proved that the amount of CO_2 sequestered by switchgrass in the soil is 138.1 kg of CO_2/Mg of aboveground biomass. In the northern plains of the US, switchgrass grown for biofuel production returned to the soil up to 4.42 Mg C $ha^{-1}year^{-1}$ [19]. Sorghum can capture 3.4–7.2 Mg of CO_2 per hectare [20]. In addition, these previous authors found that sorghum roots can accumulate up to 14% of the total carbon capture in the above and underground biomass. In general, roots can contribute from 7 to 43% of the total C sequestered by a plant [21]. In the case of corn, the amount of C sequestered in the roots is 60% more than that of the stover [22]. Residues from crops are a significant way to improve C sequestration into a soil [20]. Usually, plants that produce a lot of biomass capture the most C. One of the strategies currently used is to pay farmers a carbon credit to entice them to grow better crops that can help reduce global warming. In general, carbon dioxide costs $100 per metric ton [23, 24].

Our research proved that sweet sorghum and switchgrass can produce a significant amount of biomass, suggesting that their C capture will be high. Unfortunately, very little is known about the carbon capture potential of these crops in Missouri. Nevertheless, this kind of information is needed to make a complete economic and environmental assessment of these biofuel crops. The objectives of this research have been (1) to determine the carbon capture by corn grain, switchgrass, and sweet sorghum biomass, and (2) to determine the impact of nitrogen (N) application and the soil type on carbon capture. For sweet sorghum, we also studied the partitioning of the carbon capture between the leaves and the stalk. Our general goal is to show that in addition to producing biofuel, sweet sorghum, switchgrass, and corn have additional advantages in their ability to clean the environment and therefore help resolve the global warming challenge.

2. Methods

The research was carried out in South-eastern Missouri over a 2-year period (2008–2009) on Tiptonville silt loam soil (fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls). The test was located at Portageville (36°24′N, 89°41′W) in 2008 and Hayward (36°23′N, 89°39′W) in 2009. Weather data were obtained from Missouri Historical Agricultural Weather Database (www.agebb.missouri.edu/weather/history). Electronic weather stations (Campbell Scientific Inc., Logan, UT) were established at each test site to measure hourly air temperature, relative humidity, wind direction and speed, solar radiation, and rainfall.

The experimental design [25–27] was a four-replicate, randomized complete block. Each block consisted of seven N treatments. Each N treatment corresponded to a plot. Each plot was 8.30 m long and 3.05 m wide (four rows spaced 76.2 cm apart).

Corn (*Zea mays* cv. P33N58) was planted mid- to late April at 79,071 seeds ha^{-1} on a silt loam soil type and the sweet sorghum (*Sorghum bicolor* cv. M81E), in May at 296,516 seeds ha^{-1} on loamy, clayed, and sandy soils. The nitrogen rates applied were 0, 45, 90, 134, 179, 224, and 269 kg N ha^{-1} on the corn while 0, 22, 45, 67, 90, 112, and 135 kg N ha^{-1} on the sweet sorghum. Less than 2 weeks after planting, the field received two applications of atrazine (2-chloro-4-ethylamine-6-isopropyl amino-S-triazine) at 1.1 kg ha^{-1} active ingredient to control weeds. Additionally, the field was regularly hoed as needed to reduce weeds not controlled by the herbicides. Three weeks after planting, the appropriate N rate was broadcast by hand on each plot using ammonium nitrate (17% nitrate-N, 17% ammonium-N). Ammonium nitrate was chosen because it does not have urea's potential for ammonia volatilization, simplifying the test by minimizing and removing the uncertainty of ammonia losses. The field was irrigated as needed. The corn field was five furrow irrigated with 76-mm water applications per year. At maturity, the two middle rows in each plot were harvested using a plot combine. The grain yield was calculated per plot based on 15% moisture content. By the sorghum side, five furrow irrigations (76-mm water applications) per year were made on the loam and clay compared with six to eight sprinklers (25-mm applications) per year on the sand. The sandy soil was irrigated with linear move sprinkler irrigation, whereas the loam and the clay soils were furrow irrigated. The sweet sorghum heads were removed a month before the harvest of the stalk. This was done to maximize sugar in the stalk. Four and a half months after germination (**Table 1**), sweet sorghum was harvested using a hay sickle mower. The fields used in 2007 and 2008 had been previously planted in cotton and soybean, respectively. In 2009, the sorghum planted on the clay soil followed soybean, the sorghum planted on the loam followed corn, and the sorghum planted on the sand followed cotton.

N rate (kg ha^{-1})	Carbon capture in corn grain (kg ha^{-1})†	
	2008	2009
0	2536.9 b	546.1 c
45	2513.1 b	1318. b
90	3591.6 ab	2471.4 a
134	4727.1 a	2690.2 a
179	4558.2 a	2886.2 a
224	3588.4 ab	2948.8 a
269	3884.5 ab	2917.0 a

†: Numbers followed by different letters are statistically different within the same column at p≤0.05.

Table 1. Mean separation of the carbon capture in corn grain.

Switchgrass (*Panicum virgatum* cv. Alamo) was drill planted in 6-m wide strips (east to west), spaced parallel 100 m apart and 450 m long by a cotton field near Portageville (MO, USA; 36.4253°N, 89.6994°W) [28, 29]. The main soil in the field was a Bosket fine sandy loam (bosket, fine loamy, mixed active, thermic, mollic, and Typic *Hapludales*) soil. The field was located in the upper Mississippi River Delta region where the topography is nearly flat and southwest winds in May and June sometimes cause damage to young crops. The farmer planted the switchgrass as a wind break to minimize blowing sand injury to cotton seedlings. An added benefit of the strips is habitat for birds and rabbits. The field is burned every 4 years in April and mowed annually in September or October, and switchgrass strips have not received any lime, pesticides, N, P, or K since establishment in 1990. This crop required fewer nutrients probably because it fixed the atmospheric N and had mycorrhizae activity. The optimal N fertilization rate applied in the US is not clear but ranged from 120 to 224 kg N ha^{-1} [29].

In 2008 and 2009, switchgrass biomass was monthly harvested from May to November. For each sampling date, four plots in the field were evaluated. The biomass was harvested from the center of the strips by hand in a floristically homogeneous subplot of 1.67 m^2 using a hay sickle mower. Total fresh biomass weight was separated into leaves, stem, and head and oven dried for constant weight. Switchgrass biomass was determined by extrapolation from the biomass obtained in the 1.67-m^2 subplot.

The biomass of four samples of each N treatment was dried in an oven and analyzed for carbon using the LECO SC 44 Carbon Analyser (Leco Corp, St Joseph, MI) adapted from NRCS [30]. The carbon content (%) was directly read from the machine. The carbon capture in the biomass was calculated as follows:

$$\text{Carbon capture } (\text{kg ha}^{-1}) = \text{dried Biomass } (\text{kg ha}^{-1}) \times \text{Carbon content } (\%) \tag{1}$$

The equivalent captured CO_2 was calculated based on the oxidation reaction of carbon:

$$C + O_2 \rightarrow CO_2 \quad (2)$$

Based on the molecular weight of carbon (14 g) and that of CO_2 (44 g), each gram of carbon sequestered by a plant is equivalent to 3.14 g of CO_2 uptake. The equivalent amounts of CO_2 captured by the plants were extrapolated considering that ratio.

The equivalent CO_2 sequestered switchgrass soil was extrapolated based on a previous study done by Andress [18] who proved that switchgrass sequestered 138.1 kg of CO_2/Mg of aboveground biomass. The data were analyzed using the Proc mixed model in SAS 9.2 (SAS Institute Inc., Cary, NC). Significant differences were assumed for $p \leq 0.05$. The year of the study, the soil type, and the N rate were considered the main fixed factors, whereas the block (repeat) was classified as a random variable. For the Proc mixed model, the estimation method was the restricted maximum likelihood (REML). Means were separated and grouped by letter by using the macro developed by Saxton [31]. Significant differences are assumed for $p < 0.05$.

3. Results

3.1. Carbon capture in corn grain

In general, the carbon content (%) and the amount of carbon captured (kg ha^{-1}) in corn grain depended on the year ($p < 0.0001$). In 2008, 43.8% of the grain was carbon compared to 42.9% in 2009. Additionally, N fertilization significantly affected the amount of C sequestered in the grain ($p < 0.0001$), but not the carbon content of the grain ($p = 0.4051$). Usually, the carbon capture in the grain increased as the N rate went up (**Table 1**).

Moreover, the impact of the N rate on the C capture in the grain was more pronounced in 2009 ($p < 0.0001$) than in 2008 ($p = 0.03$) (**Figure 1**).

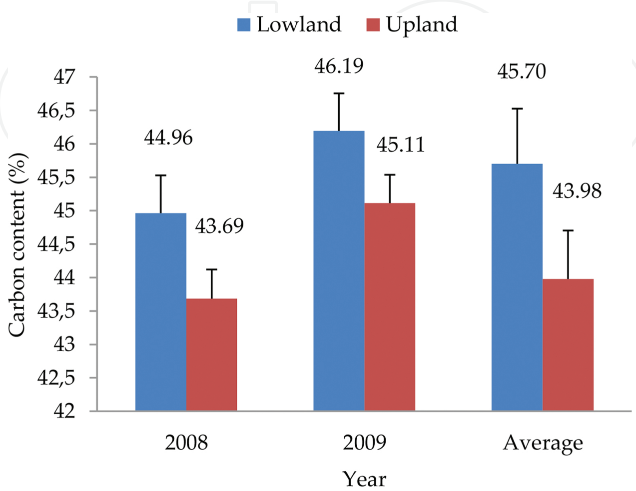

Figure 1. Carbon content of switchgrass biomass.

This confirmed the N need that the corn had on the loam in 2009, which was planted after corn in the rotation system. The corn was then unable to capture as much carbon from the air when compared to the previous year.

3.2. Carbon capture in switchgrass biomass

The carbon content in switchgrass biomass depended on the year of the study and the variety. Switchgrass var. Alamo contained more C (45.73%) than the Blackwell variety (44%). The carbon content of the underground biomass was similar to that of the aboveground. The amount of carbon sequestered in the aboveground biomass depended on the switchgrass variety, the year of the study ($p = 0.002$), and the date ($p < 0.0001$). The amount of C captured by the Alamo variety was more than three times that of the Blackwell one (**Table 2**).

Usually, the maximum carbon captured by the Alamo variety was reached in October (**Table 2**). In 2008, the Alamo variety captured a maximum of 9.8 Mg ha^{-1} compared to 13.4 Mg ha^{-1} in 2009. By contrast, the Blackwell variety captured 3.7 Mg ha^{-1} in 2008 as opposed to 4.4 Mg ha^{-1} in 2009. When the maximum carbon captured by the Alamo variety was converted into CO_2, it was equivalent to 32.3 and 49.6 Mg ha^{-1} in 2008 and 2009, respectively (**Table 2**). By contrast, the Blackwell variety captured 13.6 Mg CO_2 ha^{-1} in 2008 compared to 16.2 Mg CO_2 ha^{-1} in 2009. The amount of CO_2 sequestered to the soil by Alamo ranged from 3.03 to 4.02 Mg ha^{-1} according to the year (**Table 2**) compared to 1.17–1.34 Mg ha^{-1} for the Blackwell variety (**Table 2**).

Variables	Year	Alamo					Blackwell
		May	June	July	October	November	July
				kg ha^{-1} $year^{-1}$			
Carbon capture in aboveground biomass	2008	1571.6	4933.5	7823.7	9807.2	9276.3	3692.2
	2009	3816.5	8737.5	11074.3	13400.6	9560.8	4382.5
CO_2 capture by plant	2008	5815.0	18254.1	28947.8	36286.7	34322.2	13661.0
	2009	14121.0	32328.6	40974.9	49582.2	35375.0	16215.1
CO_2 sequestered to soil	2008	499.6	1556.6	2438.9	3031.2	2810.3	1174.1
	2009	1148.3	2628.9	3331.9	4024.7	2826.4	1342.8

Table 2. Carbon capture in switchgrass cv. Alamo.

3.3. Sweet sorghum carbon capture

In addition to its biofuel potential, sweet sorghum captured 3.2–13.8 Mg ha^{-1} according to the year, the soil, and the N rate (**Table 3**). The highest carbon capture was recorded in the loam. Usually, the carbon content of the aboveground biomass ranged from 41.9 to 44.6% (**Table 3**). Unlike in the loam and the sand, the carbon in the clay was not affected by the N rate (**Table 4**). This suggested that the lack of available N in the soil reduced the ability of sweet sorghum to assimilate atmospheric CO_2 into its metabolic systems to build organic compounds. The fact that in 2009 (year where sweet sorghum was planted after corn in the loam) the impact of the N rate on the C content was significant only in the loam confirmed that sweet sorghum had difficulty taking up the amount of N it needed from the soil to perform photosynthesis. In general, the application of N improved the C content of the biomass.

Variables	**Year**	**Soil type**	**N rate (kg ha^{-1})†**							
			0	**22**	**45**	**67**	**90**	**112**	**134**	**Mean**
Whole biomass carbon content (%)	2007	Loam	42.8	42.9	42.9	42.9	42.9	42.9	42.5	42.8
	2008	Clay	42.9	43.1	43.2	43.5	43.2	43.2	43.3	43.2
		Loam	43.2	43.3	43.3	43.4	43.3	33.8	43.3	41.9
		Sand	44	43.4	43.4	44.5	43.4	43.4	44.3	43.8
	2009	Clay	42.9	42.9	43	43.1	43.2	43	43.1	43
		Loam	44.3	44.8	44.4	44.6	44.8	43.8	45.2	44.6
		Sand	44.4	44.4	44.5	44.6	44.4	44.5	44.5	44.5
Total carbon yield (Mg ha^{-1})	2007	Loam	6.8	5.8	7.5	8.6	6.6	7.9	6.1	7
	2008	Clay	4.9 b	5.1 b	5.9 ab	8.4 a	7.8 a	7.1 ab	8.0 a	6.7
		Loam	11.4	10.6	13.8	11.5	11	10	11.7	11.4
		Sand	4.5	3.7	5.1	4	5.1	6.2	5	4.8
	2009	Clay	3.3 c	5.6 abc	5.6 abc	6.9 ab	7.2 ab	7.8 a	7.7 ab	6.3
		Loam	3.2 c	4.7 bc	4.4 bc	6.3 ab	5.3 abc	6.4 ab	7.7 a	5.6
		Sand	4.8 c	5.1 c	7.6 a	7.1 ab	5.0 c	6.2 abc	5.4 bc	5.8
Equivalent CO_2 captured by biomass (Mg ha^{-1})	2007	Loam	25.3	21.5	27.6	31.8	24.2	29.2	22.5	26
	2008	Clay	18.1	19	21.8	31	29	26.1	29.6	24.9
		Loam	42.2	39.3	51.1	42.5	40.7	36.9	43.4	42.3
		Sand	16.8	13.8	18.8	14.9	19	23	18.7	17.9
	2009	Clay	12.2	20.8	20.6	25.7	26.8	29.1	29.6	23.4
		Loam	11.9	17.6	16.5	23.4	19.7	23.7	28.3	20.9
		Sand	17.8	18.9	28.1	26.2	18.5	23	20.1	21.6

†Numbers followed by different letters are statistically different within the same column at $p \leq 0.05$.

Table 3. Carbon content and capture by sweet sorghum aboveground biomass.

Variable†	2007	2008			2009		
	Loam	Clay	Loam	Sand	Clay	Loam	Sand
Carbon content whole biomass	*	ns	ns	***	ns	**	ns
Leaves C content	*	ns	ns	ns	ns	ns	ns
Stalk content stalk	ns	ns	ns	ns	ns	*	ns
Total capture yield	ns	*	ns	ns	**	*	*
Carbon capture leaves (kg ha^{-1})	ns	ns	ns	ns	ns	ns	*
Carbon capture stalk (kg ha^{-1})	ns	*	ns	ns	**	*	ns

†The values (i.e., symbols) in the table are the probability associated with the test of the impact of *N*; $^{*}p < 0.05$; $^{**}p < 0.01$, and $^{***}p < 0.001$.

Table 4. Impact of *N* on the carbon content and capture in sweet sorghum aboveground biomass.

However, the impact of N on the biomass C content depended on the organ. Indeed, in both years, the C content of the leaves did not depend on the N rate (**Table 4**). However, in 2009, the impact of the N rate on the carbon content of the stalk was significant ($p = 0.0135$). These results suggested that the accumulation of organic compounds in the stalk was affected by the lack of N. The predominant organic molecules in sweet sorghum stalks are sugars. Therefore, the decrease of the sugar content in the stalk may explain why its carbon content decreased as N is lacking. In other words, the lower C content means less C available to make the sugars so less sugar.

Nitrogen fertilization affected the C capture in sweet sorghum biomass depending on the soil and the year. Unlike the carbon content, the carbon capture in the clay was significantly affected by the N rate (**Table 4**). These results showed that the application of N is required in the clay if an increase of N capture by sweet sorghum is persuaded. Similarly, on the loam, when sweet sorghum is grown after corn, its ability to sequester the atmospheric carbon is limited by N ($p = 0.03$) (**Table 4**). Except in the loam 2009 ($p = 0.016$), the N rate did not affect the amount of carbon captured in the leaves (**Table 2**). By contrast, the N fertilization improved the sequestration of the C in the stalk in the clay in both years and in the loam in 2009. The C accumulation in the stalk and in the sand was never affected by the N rate (**Figure 2**). These results suggested that the significant impact of the N rate on the total C capture in the sand was due to its effect on the leaves. Therefore, in sand, the leaves are more sensitive to the C capture than the stalk in cases when the N is lacking. By contrast, in the clay and in the loam, when N is deficient, the carbon accumulation in the stalk is highly affected. In general, 82% of the carbon captured in the biomass is found in the stalk (**Figure 2**). When converted into equivalent CO_2, the amount of C captured by sweet sorghum was 11.9–51.1 Mg ha^{-1} according to the soil type and the N rate (**Table 3**).

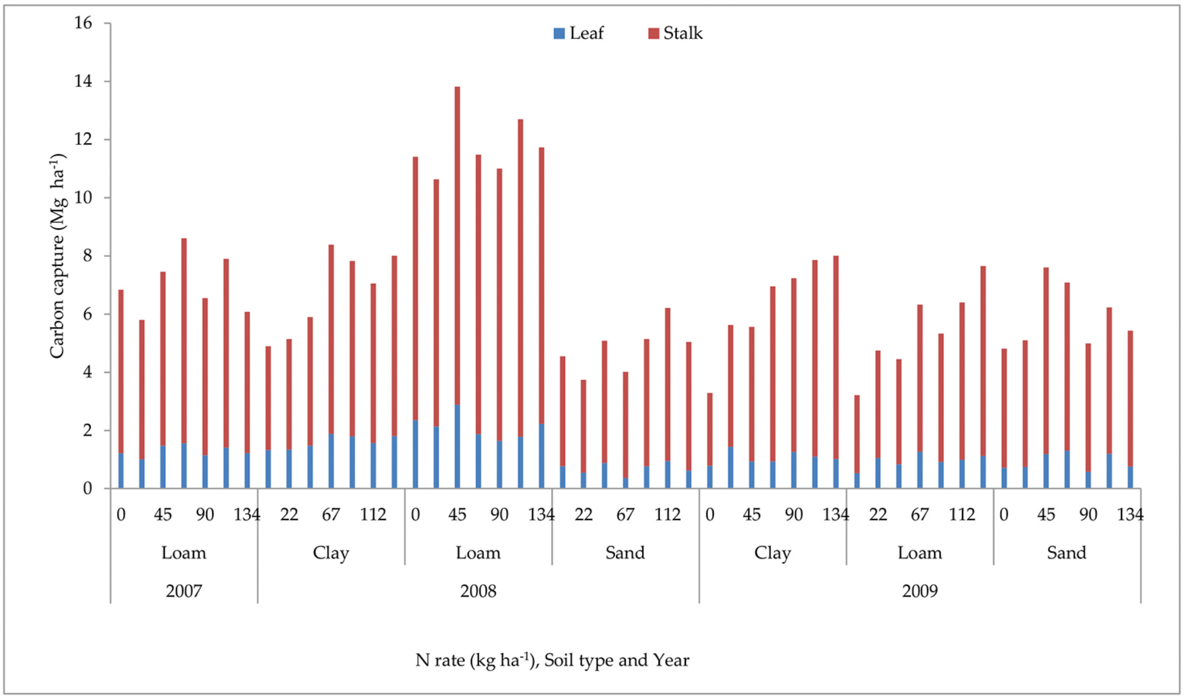

Figure 2. Impact of the soil type, the year, and the N rate on the partitioning of the C capture in sweet sorghum leaves and stalk.

4. Discussion

Our results proved that the carbon content ranged from 42.9 to 43.8% in corn grain, 44–45.7% in switchgrass and 41.9–44.6% for sweet sorghum biomass. Generally, the carbon capture by corn depended on the N rate. The maximum C capture by corn grain was recorded with the application of 134 kg N ha^{-1} in 2008 (4.7 Mg C kg ha^{-1}) compared to 2.9 Mg C ha^{-1} in 2009 with 224 kg N ha^{-1}.

We observed that the maximum C capture by switchgrass cv. Alamo was reached in October, ranging from 9.8 Mg C ha^{-1} (in 2008) to 14.4 Mg C ha^{-1} (in 2009). That is three to four times higher than what corn put in its grain. However, the C capture is smaller with switchgrass var. Blackwell (3.7 Mg ha^{-1} in 2008 compared to 4.4 Mg C ha^{-1} in 2009) which is the same range as what corn had in its grain. Furthermore, sweet sorghum captured 3.2–13.8 Mg C ha^{-1} (**Table 3**), suggesting that switchgrass can sequester more C than sweet sorghum. The amount of C sequestered by sweet sorghum in our study was higher than the 3–7 Mg of CO_2 per hectare recorded by [20].

The high ability of switchgrass to capture atmospheric carbon was also recorded [32]. In most cases, sweet sorghum captured two to three times the amount of C that corn put in its grain. We found that switchgrass captured more carbon than sweet sorghum and corn grain. These results showed the additional environmental impact that switchgrass and sorghum may have over corn grain. Because of their high C capture, sweet sorghum and switchgrass can clean the environment from CO_2 as has been shown feasible with other crops [9–11]. The C sequestered in the soil will also significantly increase the positive environmental effects of these crops. Other authors also pointed to the potential C sequestration in crop roots as an important component of the fight against climate change. The theoretical maximum C sequestered in the soil by switchgrass in our study was about 4 Mg ha^{-1}, a little less than the 4.42 Mg C $ha^{-1}year^{-1}$ observed by previous authors in the northern plains of the US [19].

Finally, farmers that grow these crops should be compensated with carbon credit. However, if not well managed, the captured carbon can return to the air. To avoid that scenario, farming techniques that disturb the soil less should be encouraged [12, 13]. Farming techniques that minimize soil disturbance (e.g., non-tillage and use of cover crops) can help sequester C in the soil, and consequently reduce the effects of global warming [20]. While non-tillage is ideal, it is also impractical. Still, it is important to point out that in contrast to tillage that increases the rate of soil C mineralization, non-tillage improves the storage of soil C [33, 34, 21].

5. Conclusion

Our results showed that since the carbon capture by sweet sorghum, switchgrass, and corn are statistically significant, these crops can help reduce the concentration of CO_2 in the environment and therefore contribute to the reduction of global warming.

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