Carbon Sequestration by Biofuel Crop Switchgrass

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Under the macroenvironmental background of global warming, all countries are working to limit climate change. Internationally, biofuel plants are considered to have great potential in carbon neutralization. Several countries have begun using biofuel crops as energy sources to neutralize carbon emissions. Switchgrass (*Panicum virgatum*) is considered a resource-efficient low-input crop that produces bioenergy.

Keywords: biofuel crops ; carbon sequestration ; greenhouse gas emissions ; net ecosystem CO2 exchange

1. Introduction

In recent years, global climate change, especially global warming, has attracted widespread attention from all walks of life worldwide. Internationally, the United Nations Framework Convention on Climate Change (UNFCCC) reached The Paris Agreement at the Paris Climate Change Conference. The Paris Agreement aims to limit the increase in global average temperatures to 2 °C from pre-industrial periods and to limit temperature increases to 1.5 °C to constrain global temperature rise as soon as possible. The leading cause of global warming is the increase in greenhouse gases produced by human activities [1][2]; the main greenhouse gases are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) [3].

To limit temperature growth to 2 °C, the remaining global cumulative CO_2 emissions should not exceed 400–1000 Gt by the end of the century. Therefore, how to effectively control carbon emissions, especially human-induced carbon emissions, has attracted more attention from the international community. For non-CO_2 greenhouse gases, CH_4 and N_2O are of concern. According to the global warming potential (GWP) calculation, the GWP of CH_4 is about 23–25 times that of CO_2 and the GWP of N_2O is about 296 times that of CO_2 [4].

Carbon emitted from fossil fuels since the industrial revolution is about 420 Gt C [5]. Globally, CH_4 and N_2O emissions from agriculture exceed 610 million tons per year, accounting for 12% of total emissions [6]. Therefore, reducing agriculture's carbon emissions is a crucial issue. Biofuel crops are mainly perennial (herbaceous or woody) that improve soil quality, promote nutrient cycling and carbon fixation, and can produce large quantities of high-carbon biomass. Compared with fossil fuels, biofuel crops have greater advantages in energy utilization [7] (**Figure 1**). Furthermore, biofuel crops require less maintenance and input and can be adapted to marginal soils. Eggelston et al. [8] showed that 300–1300 Mt C fossil fuels can be replaced if 10–15% of agricultural land is used to grow biofuel crops. Moreover, under the circumstances, CH_4 emissions from agriculture can be reduced by 15–56% and N_2O emissions can be reduced by 9–26%.

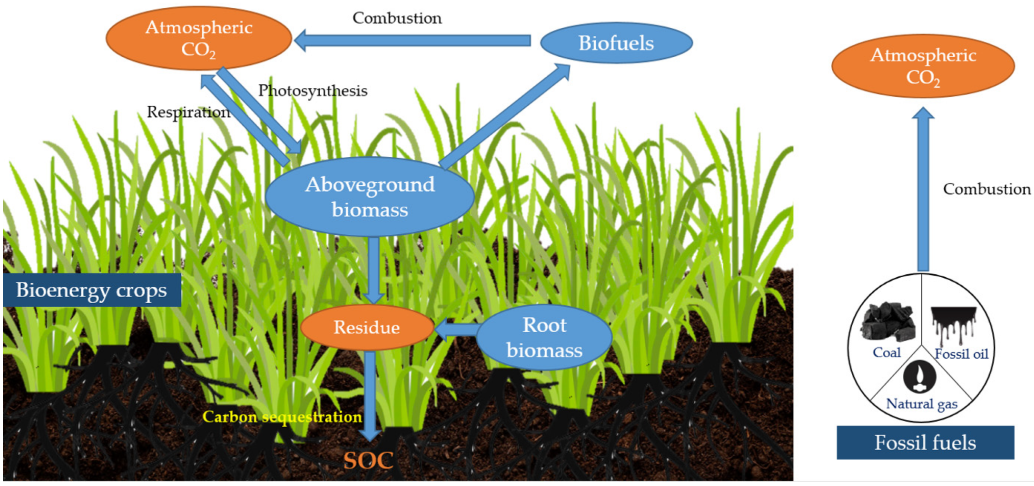

Figure 1. Carbon turnover process of biofuel crops vs. fossil fuels.

Switchgrass (*Panicum virgatum*), a species of grass in the family Poaceae, is an adaptable perennial herbaceous C4 plant native to North America. It is mainly distributed in several countries south of 55° north latitude. There are two ecotypes, including upland and lowland. In general, lowland types, which can grow up to more than 3 m, have larger biomass than upland types [9]. The tillers of the upland ecotype are usually shorter and better adapted to cold and dry habitats [10]. Since the mid-1980s, switchgrass has been mainly used as a renewable biofuel source for research. So far, switchgrass has been used in various forms of biofuel conversion processes, including cellulosic ethanol production, biogas, and direct combustion [11][12]. As a biofuel source, switchgrass has a lower demand for fertilizers and pesticides, which allows switchgrass to produce good yields on the land of the best part of soil types [13]. The climate benefits of biofuels are mainly manifested in (1) the use of alternative fossil fuels; (2) reducing greenhouse gas emissions during biofuel production, mainly through soil C accumulation and avoidance of greenhouse gas emissions.

2. Carbon Sequestration by Switchgrass

Soil and plant carbon sequestration is a practical way to mitigate CO_2 emissions [14][15]. As early as the 1990s, Ma et al. [16] studied the effects of soil management measures, including nitrogen (N) application, row spacing, and harvest frequency, on carbon sequestration in switchgrass fields established for 2–3 years. The results found that the soil management measures of switchgrass did not change the soil carbon concentration. Interestingly, they compared the soils of the switchgrass and their adjacent fallow soils that had been established for some time (10 years). The results showed that the soil organic carbon (SOC) of the switchgrass was significantly higher than that of the fallow land; the SOC of the 0–15 cm soil increased by 44.8% and in the 15–30 cm soil it increased by 28.2% [16]. Therefore, switchgrass soil can store more soil carbon, although detecting it may take several years. Carbon sequestration in the switchgrass field does not occur only in the topsoil. Liebig et al. [17] show that switchgrass soils below 30 cm can also effectively sequester SOC. C stored in deep soils is not prone to mineralization and erosion. According to a four-year measurement, after four growing seasons, the SOC produced by switchgrass is 9.45 Mg ha^{-1} [18]. Different ages of switchgrass have different changes in the underground 30 cm SOC. A prediction from Anderson et al. [19] of net changes in SOC indicated that the change of switchgrass to the underground SOC increases with time and the switchgrass cultivated for 15 years increases by about 6.49 Mg ha^{-1} (**Table 1**). Hong et al. [20] found that the biomass of switchgrass fields across locations in the USA increased significantly in the first three years after the establishment (**Figure 2**). The total yield in the third and fourth years was similar (**Figure 2**). At a soil depth of 1 m, the SOC of switchgrass soil was 9.4% higher than that of farmland and 8.1% higher than that of *Andropogon gerardi,* while the quality of soil N is basically the same as that of farmland [21].

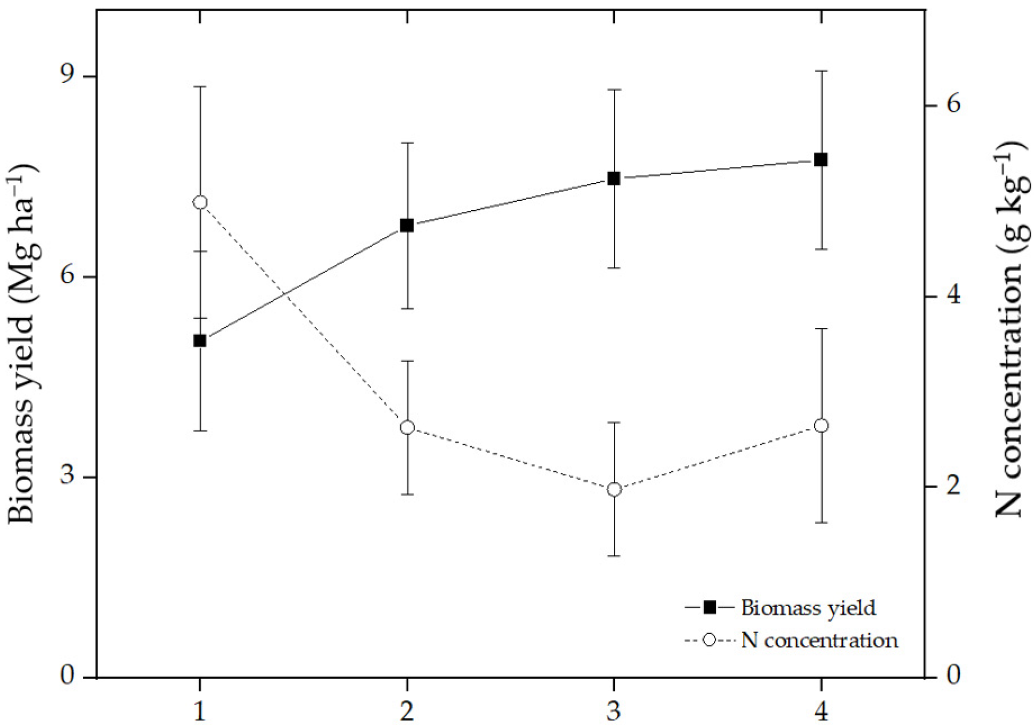

Figure 2. Average biomass yield and N concentrations in biomass of switchgrass across locations in the USA. Data were replotted from Hong et al. [20].

Table 1. Projected net changes in SOC (Mg C ha^{-1}) in the top 30 cm of soil under biofuel crops of various ages. Adapted from Anderson et al. [19].

Ages (Year)	Net Change in SOC (Mg ha^{-1} per 30 cm)		
	Switchgrass	Sugarcane	*Miscanthus*
5	2.66	−34.21	2.31
10	4.64	−31.57	2.97
15	6.49	−28.93	3.63

Although the effects of switchgrass soil management measures on soil carbon sequestration did not have a significant effect in the study of Ma et al. [16], some studies have shown that fertilizer management measures and harvesting methods have essential effects on switchgrass carbon sequestration [22][23][24][25]. On the Conservation Reserve Program (CRP) land dominated by switchgrass in South Dakota, there is no benefit if the N applied exceeds 56 kg ha^{-1} [24]. The application of NH_4NO_3 and manure can effectively increase switchgrass's soil carbon sequestration, especially at soil depths of 30–90 cm [23]. Switchgrass is a perennial herb whose roots can grow deep in the soil. It has considerable root biomass, which is more than the aboveground biomass [16]. The root biomass of switchgrass in different soil types at different depths is shown as follows (**Table 2**). Zan et al. [26] showed that switchgrass has a biomass 4–5 times that of maize and can store 2.2 Mg C ha^{-1} yr^{-1}. Liebig et al. [17] found that the cumulative rate of C was 1.1 Mg C ha^{-1} yr^{-1}, most of which occurred at depths of 30 cm underground. Tulbure et al. [27] used RF (Random Forest packet in R) to analyze the effects of multiple factors such as fertilizer, genetics, and precipitation on yield. The results showed that the total variance of RF interpretation was 75%, with N fertilizer being the most important explanatory variable, followed by genetics, precipitation, and management measures.

Table 2. The root biomass (kg m^{-2}) of switchgrass in different soil types [28].

Depth (cm)	Clay Loam	Sandy Loam
	Root Biomass (kg m^{-2})	
0–20	7.28 ± 0.44	7.44 ± 0.39
20–40	2.66 ± 0.10	1.97 ± 0.43
40–60	1.75 ± 0.07	1.84 ± 0.33
60–80	1.25 ± 0.08	3.23 ± 0.31
80–100	1.16 ± 0.07	2.26 ± 0.25

3. Net Ecosystem CO_2 Exchange of Switchgrass

Net ecosystem CO_2 exchange (NEE) is the result of imbalances between total primary production (GPP) and ecosystem respiration (Re), which can affect carbon dynamics and budgets [29]. A better understanding of switchgrass's NEE changes will help assess switchgrass's potential for climate change mitigation. Some NEE of biofuel crops are shown below (**Table 3**). Zeri et al. [30] found that switchgrass has a stronger carbon sink capacity at the initial establishment stage than *Miscanthus* × *giganteus* (giant miscanthus, a sterile hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus*). Compared with corn, switchgrass absorbs more carbon. The NEE of switchgrass is −336 ± 40 g C m^{-2} and that of corn is 64 ± 41 g C m^{-2} [31]. From 2012 to 2013, the analysis of the NEE of switchgrass [32][33][34] showed that it had a stronger carbon sink capability than sorghum land. This may be because that switchgrass has a net carbon sink of about 4–5 months (April/May–August) and sorghum has only 3 months of net carbon sink (June–August).

Table 3. Four energy crops' net ecosystem CO_2 exchange (NEE) of biofuel crops since 2005.

Location	Year	Crop	NEE (g C m^{-2} yr^{-1})	Citation
Urbana, IL, USA	2009	Switchgrass	−453 ± 20	[30]
		Miscanthus	−281 ± 30	
		Corn	−307 ± 40	
	2010	Switchgrass	−485 ± 20	

Location	Year	Crop	NEE (g C m^{-2} yr^{-1})	Citation
Guelph, ON, Canada	2014	Switchgrass	−336 ± 40	[31]
		Corn	64 ± 41	
Chickasha, OK, USA	2012	Switchgrass	−490 ± 59	[33]
		Sorghum	−261 ± 48	
	2013	Switchgrass	−406 ± 24	
		Sorghum	−330 ± 45	
Cadriano, Italy	2014–2016	Switchgrass	−733	[18]
Guelph, ON, Canada	2012	Switchgrass	−380 ± 25	[35]
	2013		−430 ± 30	
Ligonier, PA, USA	2005–2006	Switchgrass	−118	[36]
	2006–2007		−248	
	2007–2008		−189	

Surprisingly, in a study by Zenone et al. [37], the switchgrass field did not exist as a carbon sink but produced CO_2 emissions. However, their measurements were only carried out for 2 years. In contrast, in the 4-year study [18], CO_2 can be fixed each year and NEE stabilized at higher values from the second year, although the cumulative biomass in the first year was relatively low. Zenone et al. [37] and Virgilio et al. [18] conducted studies on a newly established switchgrass field. For mature switchgrass fields, Eichelmann et al. [35] conducted two years of data collection and found that NEE is 106 ± 45 g C m^{-2} in the first year, which was represented as a carbon source, while the NEE in the second year was −59 ± 45 g C m^{-2}, which was manifested as a carbon sink. Previous four-year studies of mature switchgrass fields [36] showed that the first three years of switchgrass forests served as a sink of net CO_2, while the following year became a source of CO_2 emissions. These results suggest that switchgrass may be able to act as a powerful carbon sink in its establishment years, then its benefits will be reduced or even transformed into a carbon source.

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