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Soil carbon under switchgrass stands and cultivated cropland

M.A. Liebig*, H.A. Johnson, J.D. Hanson, A.B. Frank

USDA-ARS, Northern Great Plains Research Laboratory, P.O. Box 459, Mandan, ND 58554-0459, USA

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Abstract

Switchgrass (*Panicum virgatum* L.) is considered to be a valuable bioenergy crop with significant potential to sequester soil organic carbon (SOC). A study was conducted to evaluate soil carbon stocks within established switchgrass stands and nearby cultivated cropland on farms throughout the northern Great Plains and northern Cornbelt. Soil from 42 paired switchgrass/cropland sites throughout MN, ND, and SD was sampled to a depth of 120 cm and analyzed for soil carbon in depth increments of 0–5, 5–10, 10–20, 20–30, 30–60, 60–90, and 90–120 cm. SOC was greater ($P<0.1$) in switchgrass stands than cultivated cropland at 0–5, 30–60, and 60–90 cm. Differences in SOC between switchgrass stands and cultivated cropland were especially pronounced at deeper soil depths, where treatment differences were 7.74 and 4.35 Mg ha^{-1} for the 30–60 and 60–90 cm depths, respectively. Greater root biomass below 30 cm in switchgrass likely contributed to trends in SOC between switchgrass stands and cultivated cropland. Switchgrass appears to be effective at storing SOC not just near the soil surface, but also at depths below 30 cm where carbon is less susceptible to mineralization and loss.
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Keywords: Carbon sequestration; Root biomass; On-farm research; Northern Great Plains; Northern Cornbelt

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1. Introduction

Concerns regarding negative social and environmental consequences of a fossil fuel-based economy have increased interest in developing a bioenergy industry in the USA. Bioenergy-based products have been purported to have significant environmental and economic benefits to society, including near-zero net emissions of greenhouse gases, improved soil and water quality, and increased net economic returns to rural communities [1,2]. Of the numerous cellulosic feedstocks considered for use as bioenergy crops, switchgrass (*Panicum virgatum* L.) has been identified as having significant potential in meeting these desired outcomes across a wide geographical range [1].

Switchgrass is a native warm season grass of the North American tallgrass prairie [3]. Switchgrass is

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*Corresponding author. Tel.: +1 701 667 3079; fax: +1 701 667 3054.
E-mail address: liebigm@mandan.ars.usda.gov (M.A. Liebig).

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highly productive, with net annual aboveground production in the range 17–35 Mg ha^{-1} in the southeastern USA [4], 8–10 Mg ha^{-1} in Texas [5], 10.6–12.6 Mg ha^{-1} in the western Corn Belt [6], and 3.2–9.5 Mg ha^{-1} in North Dakota (J.D. Berdahl, personal communication). Coupled with the production of significant amounts of aboveground biomass, switchgrass has a deep and productive root system. Switchgrass roots can extend over 2.5 m into the soil [7] and can account for over 80% of total plant biomass when crown tissue is included with roots [8]. Consequently, switchgrass is considered to be an effective crop for sequestering soil organic carbon (SOC). Previous evaluations have found switchgrass to increase SOC [5,8,9], although the rate of increase and soil depth at which C sequestration occurs is variable. Because of its capacity to increase SOC, use of switchgrass as a bioenergy crop can concurrently improve soil quality and mitigate the greenhouse effect through the uptake of atmospheric CO_2.

Although switchgrass has the capacity to increase SOC, more information is needed to better understand the quantity and depth distribution of SOC under switchgrass stands, especially across a range of soil types and growing conditions. In this study, we sought to evaluate soil C stocks within switchgrass stands on farms throughout the northern Great Plains and northern Cornbelt. As a basis for comparison, nearby cropland sites were also evaluated.

2. Materials and methods

Forty-two on-farm sites throughout MN, ND, and SD were selected for the study with the assistance of USDA-NRCS personnel. Presence of a monoculture switchgrass stand paired with nearby cultivated cropland on the same soil type was the primary criterion for site selection. Sites varied considerably with respect to soil type, length of time cropped, and age of switchgrass stands (Table 1). Sites were representative of the northern, central, and southern black glaciated plains, central dark brown glaciated plains, Red River valley, and the rolling and Minnesota till prairies; an area occupying approximately 30.2 Mha (Fig. 1). Long-term mean annual temperature and precipitation across the sampling region ranged from 3.9–9.4 °C and 36–74 cm, respectively [10].

Sampling was conducted during the fall of 2000 and spring of 2001. Within each switchgrass stand or cropped field, two adjacent pseudoreplicates were established on the same landscape position. Four soil cores were collected to 120 cm in each pseudoreplicate using a truck-mounted, hydraulic-hammer-driven soil probe with a 25 mm (i.d.) probe tip (Model No. SS9350; Concord Environmental Equipment, Hawley, MN). Soil cores were kept intact in protective sampling sleeves and transported to the laboratory within 2 days of collection. Upon reaching the laboratory, soil cores were placed in cold storage at 5°C until processing.

Soil cores were separated into increments of 0–5, 5–10, 10–20, 20–30, 30–60, 60–90, and 90–120 cm. The four cores within each pseudo replicate were composited and gravimetric soil water content was determined for each sample using a 15–20 g subsample by measuring the difference in mass before and after drying at 105 °C for 24 h [11]. Whole samples were then dried at 35 °C for 3–4 days and ground to pass a 2.0 mm sieve. Identifiable root material was removed during sieving. Chemical analyses conducted on the soil samples included electrical conductivity (EC), pH, total C, and inorganic C. EC and pH were estimated from a 1:1 soil–water mixture [12,13]. Total soil C was determined by dry combustion on soil ground to pass a 0.106 mm sieve [14]. Using the same fine-ground soil, inorganic C was measured on soils with a pH $\geqslant 7.2$ by quantifying the amount of CO_2 produced using a volumetric calcimeter after application of dilute HCl stabilized with $FeCl_2$ [15]. SOC was calculated as the difference between total C and inorganic C. Gravimetric data were converted to a volumetric basis for each sampling depth using field measured soil bulk density [16]. All data were expressed on an oven-dry basis.

Soil properties were evaluated within and across sites by depth using PROC MIXED [17]. Mean values for switchgrass and cultivated treatments were compared at $P<0.1$. Stepwise regression was

Table 1
Background soil and management information for sites selected in study

State/ Site no.	County	Soil series	Soil classification	Years in production		Tillage on cropland	Vegetation removal method for switchgrass
				Cultivated site	Switchgrass site		
Minnesota							
4	Le Sueur	Mazaska	Vertic Argiaquoll	10	8	CT	None
5	Le Sueur	Hamel	Typic Argiaquoll	2	14	CT	None
6	Le Sueur	Mazaska	Vertic Argiaquoll	—	12	NT	None
7	Le Sueur	Le Sueur	Aquic Argiudoll	99	11	MT	None
8	Kerkhoven/ Swift	Buse	Typic Calciudoll	—	5	CT	None
9	Swift	Lamoure	Cumulic Endoaquoll	33	—	CT	None
10	Swift	Hamerly	Aeric Calciaquoll	36	10	NT	None
11	Blue Earth	Clarion	Typic Hapludoll	50	15	MT	Mowed
12	Blue Earth	Guckeen	Aquic Hapludoll	45	14	MT	Mowed
13	Blue Earth	Lester	Cumulic Haplaquoll	50	14	MT	Mowed
14	Blue Earth	Kilkenny	Mollic Hapludalf	55	14	MT	Mowed
15	Traverse	Hamerly	Aeric Calciaquoll	100+	2	CT	None
16	Traverse	Hamerly	Aeric Calciaquoll	100+	12	MT	None
17	Traverse	Fargo	Typic Epiaquert	100+	4	MT	None
18	Traverse	Hamerly	Aeric Calciaquoll	100+	3	CT	None
19	Stevens	McIntosh	Aquic Calciudoll	51	3	MT	None
20	Stevens	Hattie	Aquic Hapludert	100+	7	MT	None
21	Stevens	Hamerly	Aeric Calciaquoll	15	19	MT	Burned
22	Stevens	Hamerly	Aeric Calciaquoll	100+	4	MT	None
36	Brown	Lemond	Typic Endoaquoll	—	3	CT	None
37	Brown	Lemond	Typic Endoaquoll	100+	4	CT	None
38	Brown	Lemond	Typic Endoaquoll	40	5	MT	None
39	Brown	Lemond	Typic Endoaquoll	24	12	MT	None
40	Norman	Syrene	Typic Calciaquoll	—	11	CT	None
41	Norman	Arveson	Typic Calciaquoll	25	10	CT	None
42	Norman	Arveson	Typic Calciaquoll	4	9	CT	None
North Dakota							
1	Pierce	Embden	Pachic Hapludoll	40	11	CT	Grazed/hayed
2	Pierce	Emrick	Pachic Hapludoll	40	11	CT	Grazed/hayed
3	Pierce	Emrick	Pachic Hapludoll	—	11	NT	None
South Dakota							
23	Hutchinson	Clarno	Typic Haplustoll	50	13	MT	None
24	Hutchinson	Clarno	Typic Haplustoll	55	12	CT	None
25	Hutchinson	Prosper	Pachic Argiustoll	55	4	CT	None
26	Hutchinson	Prosper	Pachic Argiustoll	13	15	MT	None
27	Edmonds	Niobell	Glossic Natrustoll	16	12	CT	Hayed
28	Edmonds	Bowbells	Pachic Argiustoll	75	18	MT	Burned
29	Roberts	Peever	Vertic Argiudoll	1	10	MT	None
30	Roberts	Forman	Calcic Argiudoll	20	11	CT	None
31	Roberts	Sverdrup	Typic Hapludoll	100+	12	MT	None
32	Roberts	Sverdrup	Typic Hapludoll	100+	12	MT	None
33	Beadle	Hand	Typic Haplustoll	—	15	NT	None
34	Beadle	Bonilla	Pachic Haplustoll	8	7	NT	None
35	Beadle	Carthage	Pachic Haplustoll	32	5	CT	None

CT, Conventional tillage; MT, Minimum tillage; NT, No tillage. —, Number of years in production unknown.

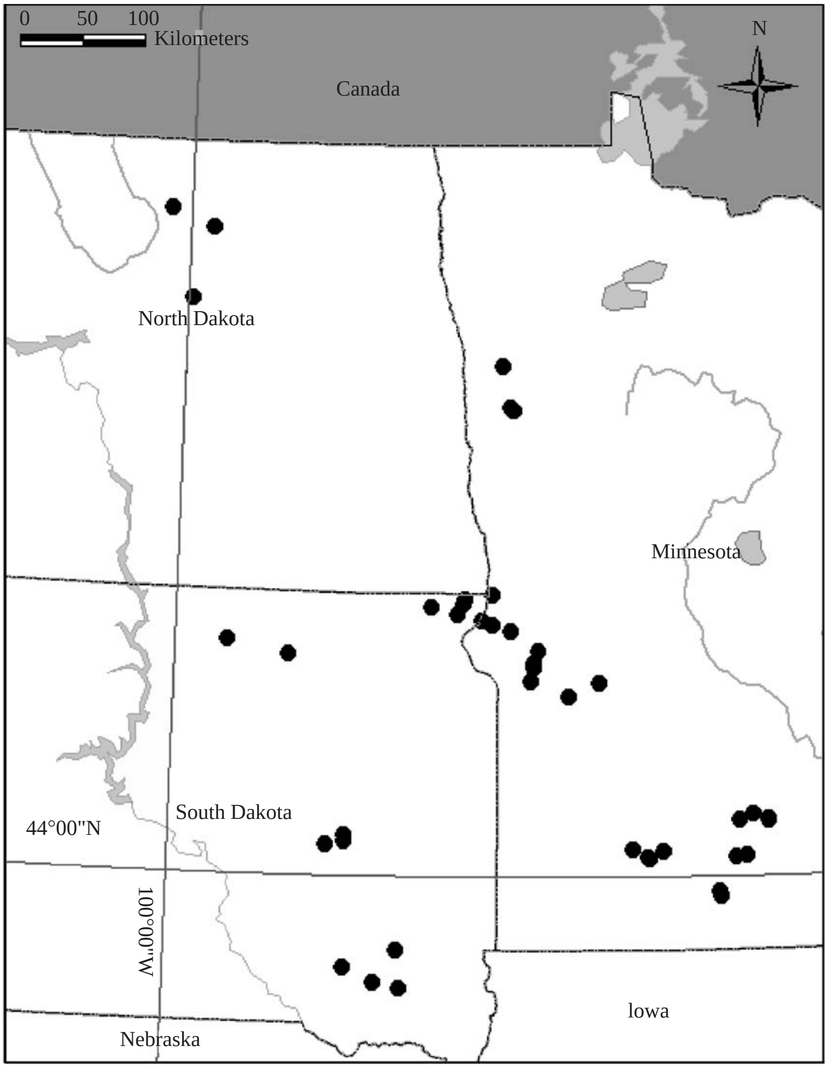

Fig. 1. Sampling sites included in study.

used to evaluate the contribution of age of switchgrass stand, vegetation removal (by either grazing, haying, mowing, or burning), average precipitation, and average air temperature to switchgrass SOC within and across soil depths [18].

3. Results

Background soil characterization of the sampling sites is presented in Table 2. Soil bulk density was lower in switchgrass stands than cultivated cropland at 0–5 cm. Perennial grasses tend to have a greater amount of biomass in surface soil than cropland, resulting in lower near-surface soil bulk density [19,20]. At 30–60 cm, cultivated cropland had lower soil bulk density relative to switchgrass stands by 60 kg m^{-3}. Mechanisms underlying the treatment difference in soil bulk density for this depth are unknown; field records indicate no use of deep (>30 cm) tillage or use of tractors with axle loads in excess of 20 ton in either treatment. There were no differences in EC between switch-

Table 2
Mean values of soil bulk density, electrical conductivity, and soil pH for switchgrass stands and cultivated cropland across sites

Depth (cm)	Switchgrass	Cropland
Soil bulk density ($Mg\,m^{-3}$)		
0–5	1.07	1.12*
5–10	1.33	1.35
10–20	1.34	1.34
20–30	1.43	1.40
30–60	1.49	1.43*
60–90	1.40	1.40
90–120	1.38	1.42
Electrical conductivity ($dS\,m^{-1}$)		
0–5	0.41	0.42
5–10	0.37	0.38
10–20	0.38	0.39
20–30	0.39	0.40
30–60	0.39	0.44
60–90	0.47	0.51
90–120	0.35	0.45
Soil pH ($-log[H^+]$)		
0–5	7.12	7.03
5–10	7.16	6.98*
10–20	7.26	7.11
20–30	7.45	7.30
30–60	7.77	7.63*
60–90	7.97	7.89
90–120	8.02	7.93

*Values within a depth significantly different at $P<0.1$.

grass stands and cultivated cropland at any depth, and all values were non-saline. Soil pH was lower in cultivated cropland than in switchgrass stands at 0–5 and 30–60 cm (Table 2). Lower soil pH in cultivated cropland is likely the result of acidification from long-term N fertilization [21]. Soil pH in both systems was neutral to slightly alkaline from 0 to 30 cm and slightly alkaline to moderately alkaline from 30 to 120 cm, indicating greater concentration of calcium carbonate with increasing soil depth.

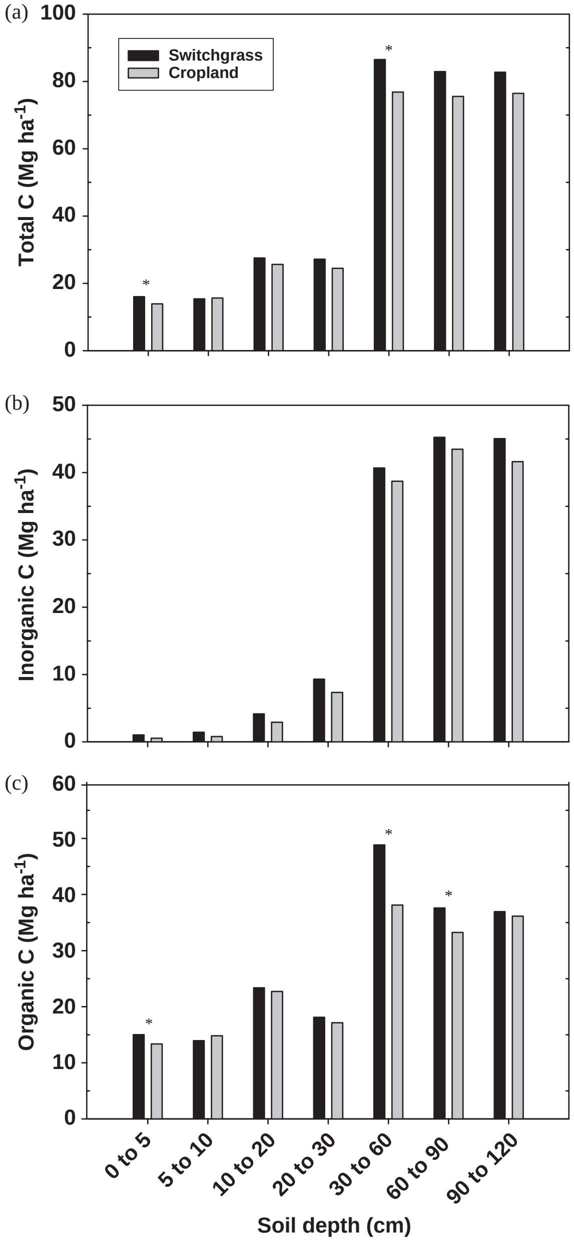

Fig. 2. Mean values of total C (a), inorganic C (b), and SOC (c) for switchgrass stands and cultivated cropland across sites. Treatments within a depth designated with an asterisk (*) are significantly different at $P<0.1$.

Total soil C was greater in switchgrass stands than cultivated cropland at the near-surface and deeper soil depths (Fig. 2). Total soil C was greater in switchgrass stands than cultivated cropland at 0–5 and 30–60 cm. No differences in soil inorganic C were observed between treatments, although there was a clear trend toward more inorganic C in switchgrass stands relative to cropland throughout the sampled soil depth. Switchgrass stands had greater SOC than cultivated cropland at 0–5, 30–60, and 60–90 cm. Differences in SOC between switchgrass stands and cultivated cropland were greatest at the deeper soil depths, where treatment differences were 7.74 and 4.35 Mg ha^{-1} for the 30–60 and 60–90 cm depths, respectively. Over the 120 cm sampling depth, switchgrass stands averaged 15.3 Mg ha^{-1} more SOC than cultivated cropland.

On a concentration basis, SOC was greater in switchgrass stands than cultivated cropland at 0–5 cm (switchgrass = 28.8 g kg^{-1}, cropland = 24.5 g kg^{-1}; $P = 0.0100$) and at 60–90 cm (switchgrass = 8.9 g kg^{-1}, cropland = 7.9 g kg^{-1}; $P = 0.0786$) (data not shown). At 30–60 cm, where SOC was greater in switchgrass stands than cultivated cropland when expressed on a volumetric basis, SOC on a concentration basis was not different between treatments (switchgrass = 10.3 g kg^{-1}, cropland = 9.2 g kg^{-1}; $P = 0.2107$).

Individual site analyses indicated that a greater number of sites had significantly more SOC in switchgrass stands than cultivated cropland at all depths except at 20–30 and 90–120 cm (Table 3). Differences in the number of sites with significantly greater levels of SOC were most pronounced at 0–5 cm. Within this depth, 21% of the sites sampled had greater SOC in switchgrass stands compared to cultivated cropland, whereas 7% of the sites sampled had greater SOC in cultivated cropland relative to switchgrass stands. A similar trend was observed at 30–60 cm, where 14% of the sites had greater SOC in switchgrass stands compared to cultivated cropland, while 2% of the sites had greater SOC in cultivated cropland relative to switchgrass stands.

Parameters included in stepwise regression were weakly related to SOC in switchgrass stands, with model r^2 not exceeding 0.4 at any depth (Table 4). Age of switchgrass stand was most frequently included in the model across depths (5–60 cm) followed by average precipitation (20–60 cm), average air temperature (60–120 cm), and vegetation removal (0–5 cm). Two parameters (age of switchgrass stand and average precipitation) were included in the model for the 20–60 cm depths, but with cumulative $r^2 \leqslant 0.25$.

Table 3
Sites with significant differences in SOC between switchgrass stands and cultivated cropland

Site	Soil depth (cm)						
	0–5	5–10	10–20	20–30	30–60	60–90	90–120
1	C[a]	—	C	C	—	S	C
3[b]	—	—	S	—	—	—	—
4	—	—	C	—	—	C	C
5	—	—	—	C	C	—	S
6	S	—	—	—	—	C	—
8	—	—	—	—	S	S	—
9	S	—	—	—	S	S	—
10	S	—	—	S	—	—	—
12	—	S	—	—	—	—	—
14	S	—	C	—	—	S	—
15	—	—	S	—	—	—	—
16	—	—	S	—	—	—	—
19	—	S	S	—	—	—	—
21	—	C	C	—	—	—	—
22	S	—	—	—	—	—	—
23	—	—	—	S	—	—	—
24	S	—	—	—	—	—	—
26	S	—	—	C	—	—	—
27	—	—	—	C	—	—	—
28	—	—	—	—	S	—	—
31	C	—	—	C	—	—	—
32	S	S	—	S	—	—	—
33	—	—	—	—	—	—	C
34	—	—	—	C	—	—	—
35	—	—	—	—	S	—	—
36	—	—	—	—	—	C	—
37	—	—	S	—	—	—	—
38	—	—	S	S	—	—	—
39	C	—	—	—	—	—	—
41	S	—	—	—	S	—	—
42	—	C	S	S	S	—	—

[a] C, SOC significantly greater ($P<0.1$) in cropland; S, SOC significantly greater ($P<0.1$) in switchgrass; —, not significant at $P<0.1$.

[b] No differences in SOC across all depths for 11 sites (2, 7, 11, 13, 17, 18, 20, 25, 29, 30, 40).

4. Discussion

Greater SOC within switchgrass at 0–5 cm is likely due to a combination of positive inherent and management-related factors within switchgrass relative to cropland. Specifically, accrual of SOC within switchgrass near the soil surface is likely because switchgrass is a perennial plant with abundant aboveground and root biomass, the

Table 4

Model r^2 from stepwise regression analysis: Switchgrass SOC = age of switchgrass stand, vegetation removal, average precipitation, average air temperature

Variable	Soil depth (cm)							
	0–5	5–10	10–20	20–30	30–60	60–90	90–120	All depths
Age of switchgrass stand		0.24	0.30	0.10	0.25			0.05
Vegetation removal	0.10							
Avg. precipitation				0.17	0.20			
Avg. temperature						0.08	0.38	0.03

production of which can be enhanced by grazing and/or haying [8,22]. Conversely, SOC loss from cropland in near-surface soil is probable when tillage is utilized, which contributes to C mineralization and increased soil erosion [23]. Of the 42 cropland sites included in the study, some form of tillage was used during each growing season at 37 sites (Table 1).

Differences in the quantity of root biomass with depth may account for greater SOC at 30–90 cm within switchgrass stands relative to cultivated cropland. Annual production of root biomass by switchgrass has been estimated at approximately 6.7 Mg ha^{-1} for well-adapted varieties within the northern Great Plains, over half of which is found below 30 cm [8]. In contrast, wheat and corn—the two major crops in the study region—have lower levels of annual root biomass production and possess a lower proportion of roots below 30 cm than switchgrass [24–29]. Consequently, there is at least indirect evidence for potential increased SOC below 30 cm within switchgrass relative to cropland based on root biomass levels. Additionally, rhizodeposition of photosynthetically fixed C may also be a contributing factor to increased SOC levels below 30 cm within switchgrass [30]. Support for increased SOC at depths below 30 cm under switchgrass was found by Frank et al. [8], where the majority of an increase in SOC (1.01 kg C m^{-2} yr^{-1}) was found between 30 and 90 cm.

5. Conclusion

Results from this study indicate that switchgrass is effective at storing SOC not just in near-surface depths as found in other evaluations [5,9], but also at depths below 30 cm. Deep storage of SOC is particularly beneficial from the standpoint of C sequestration, because C stored at deeper soil depths is less susceptible to mineralization and loss. Further research is needed to determine if deep storage of C by switchgrass is possible in other regions of the USA where previous evaluations have focused on SOC dynamics above a depth of 30 cm.

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