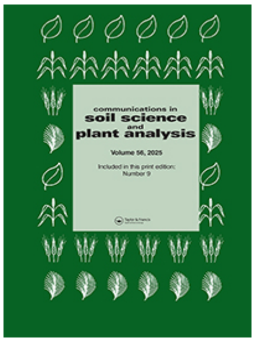

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Three Decades of Irrigated Sugarcane Cropping Increased the Soil Carbon Stock and Substituted Most of the Original Carbon in the Brazilian Drylands

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ABSTRACT
Soil carbon (C) dynamics are increasingly studied because of their role in the global C cycle and potential influence on atmospheric carbon dioxide concentrations and climatic changes. The substitution of native forests by crop fields usually decreases soil C stocks. However, C stocks may increase in irrigated fields of semiarid areas because high biomass production and litter incorporation may compensate for the fast turnover of organic matter. Using 13C isotopic techniques, we determined soil C dynamics in the 1 m superficial layer, in irrigated sugarcane fields established 10 and 30 years before. From 57% to 78% of the original C stock were lost after 10 years of cultivation and from 85% to 95% after 30 years. However, these high losses were more than compensated by sugarcane biomass inputs, and the total soil C stock increased from 94 to 169 Mg ha-1 between 10 and 30 years of cultivation. This last C stock is higher than any reported for soils in the Brazilian semiarid region. Therefore, substituting native dry deciduous forests by irrigated permanent sugarcane in semiarid areas may increase soil C stocks, contrary to most rain-fed and irrigated cropping systems with crops that accumulate less biomass than sugarcane.

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Carbon loss; land-use change; organic matter; soil C stock; stable isotope

Introduction

In the last decades, anthropic activities have increased atmospheric concentrations of carbon dioxide (CO_2) and other gases that produce greenhouse effects, leading to several climatic and ecological changes (IPCC 2018; Moitinho et al. 2021; Nong et al. 2020). As a result, most countries agreed to reduce emissions and increase the sequestration of greenhouse gases. Soil carbon (C) stocks play an important role in the efforts to reduce emissions, particularly in countries where most emissions come from the agricultural sector, such as in Brazil (SEEG 2019).

A large part of the greenhouse gas emissions is due to changes in land use and, in general, conversion of native vegetation areas to agricultural fields results in reduced soil C stocks and increased emissions (Oliveira et al. 2016; Crow and Sierra 2018; Gava et al. 2021; Medeiros et al. 2020; Menezes et al. 2021; Santana et al. 2019). However, information on the conversion of semiarid tropical deciduous forest areas into irrigated fields is scarce. In the only two published articles describing changes in C stocks in irrigated fields in the semiarid Brazilian region (Santana et al. 2022, 2024), the soil stocks also decreased in two short-cycle cultures (corn and beans) and two

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permanent crops (mango and grape). Increased soil humidity, together with high temperatures and ultraviolet radiation, accelerates organic matter decomposition (Choudhury et al. 2016; dos Santos et al. 2019; King, Brandt, and Adair 2012; Lee et al. 2014; Tan et al. 2020). On the other hand, higher water availability increases biomass productivity and may increase biomass incorporation into the soil. Gains or losses in the soil C stock depend on the balance of increases in incorporated biomass C and decomposition (Abbas et al. 2020; Moitinho et al. 2021; Silva Barros et al. 2021).

Several irrigation projects have been established in the Brazilian semiarid region (Santana et al. 2022, 2024), which was originally covered with the largest tropical dry forest in the world (Silva et al. 2017). Sugarcane is being cultivated in some of these projects, including large plantations. Sugarcane produces large amounts of below (Silva-Olaya et al. 2017) and aboveground biomass (Carvalho, Veiga, and Bizzo 2017; Crow et al. 2020), and all the belowground and part of the aboveground biomass is incorporated into the soil and contributes to the soil C stock. Therefore, the balance of incorporation and emissions may result in C sequestration into the soil C pool (Bohórquez-Sánchez et al. 2023; Umrit et al. 2014). However, few data have been published on the changes in the soil C pool under sugarcane in this or other semiarid irrigated areas in the world (Beza and Assen 2016).

Most of what reports exists on tropical soil C changes upon irrigation compared only bulk stocks, lacking information on the dynamics of the process (Corrêa et al. 2021; de Oliveira et al. 2015; Menezes et al. 2021). In areas where the native forest, consisting almost exclusively of plants with the C3 photosynthetic metabolism, is substituted by crops with the C4 photosynthetic metabolism, it is possible to use ^{13}C isotope techniques to follow the progressive disappearance of the original organic matter and the accumulation of new organic matter derived from the C4 crop (Bernoux et al. 1998; Loss et al. 2012, 2016). The ^{13}C isotope technique has been used in cane fields established in previous forest areas (Bernoux et al. 1998; Umrit et al. 2014) but not in irrigated cane fields, substituting tropical deciduous forests under semiarid conditions. Determining the dynamics of this land-use change is essential to calculate national and global C balances and frame proper agriculture and C stocks management policies.

Considering the importance of soil C stocks and the scarcity of data on its dynamics in tropical semiarid areas converted from native vegetation to irrigated fields, we compared the soil C stocks in sugarcane fields that have been cropped for 10 and 30 years, determining how much of the stocks originated from the previous native C3 vegetation and how much originated from the C4 sugarcane, using the $\delta^{13}C$ isotopic technique. Our hypothesis is that the high incorporation of biomass in irrigated sugarcane fields may compensate the high soil organic matter losses and the soil C stocks may not decrease or even increase.

Material and methods

Six large fields cultivated with sugarcane, three for 10 and three for 30 years, were selected in Agroindústria do Vale do São Francisco (Lat. −9.4980 S and Long. −40.3647 W; 370 masl), in Juazeiro municipality, Bahia state, Brazil (Figure 1). Temperatures are above 24 °C, potential evapotranspiration above 2000 mm, and average yearly rainfall is 472 mm, mainly during the summer months, characterizing a semiarid climate, BSh according to the Köppen classification (Alvares et al. 2013). All fields have soils classified as Vertisols (WRB 2006), with similar characteristics (Table 1) and were initially covered by the native deciduous dry forest, called Caatinga, composed mainly of short trees and shrubs classified as C3 photosynthesis system species. Some of the most abundant species belong to the genera *Mimosa*, *Bauhinia*, *Poincianella*, *Cnidoscolus*, and *Manihot* (Silva et al. 2017). All fields have been managed similarly after the forest plants were cut, being plowed and disked, planted with sugarcane culm-pieces, fertilized with nitrogen (N), phosphorus (P), and potassium (K), furrow irrigated, and harvested after being set on fire to burn the dry leaves. Harvests of the ratoon crops, similarly fertilized and irrigated, were proceeded for 4 to 8 more yearly cycles, when the fields were once more plowed, disked, and planted. Fertilizer was applied each year, based on the soil analyses, usually in the range of 100–140 kg of N, 60–100 kg of P, and 60–70 kg of K. Over the 10 years, culm

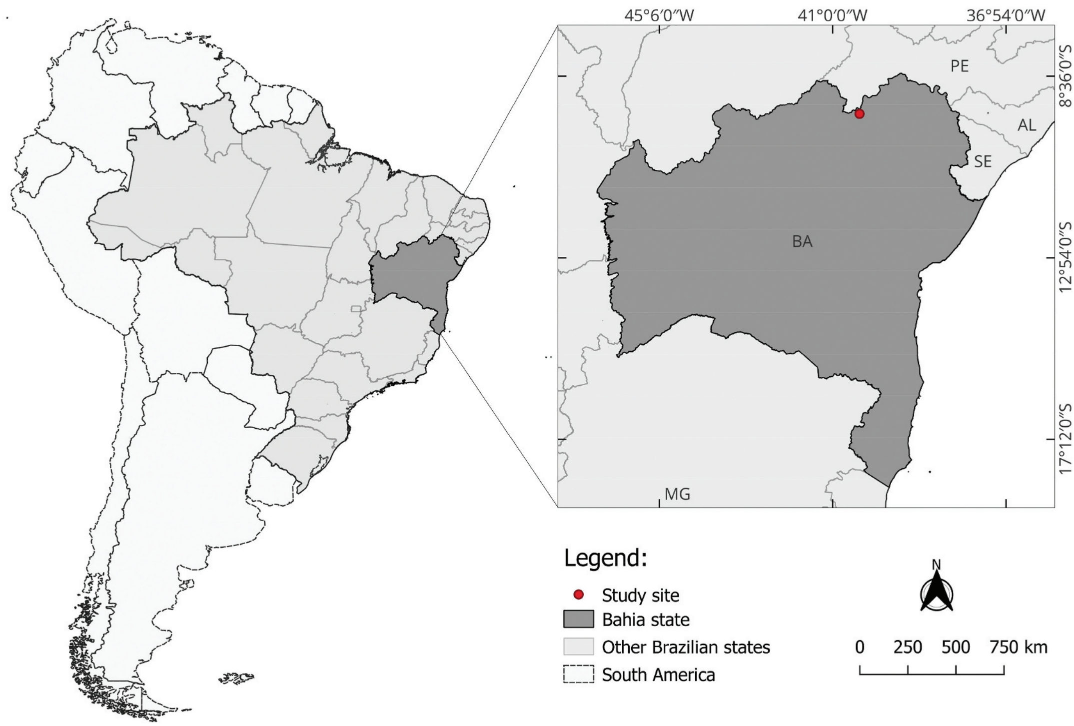

Figure 1. Map of the studied areas in Bahia (BA) state, Brazil.

Table 1. Soil physical and chemical characteristics of the 1 m depth layer of a vertisol cultivated with irrigated sugarcane for 10 and 30 years, in Juazeiro municipality, Bahia state, Brazil.

	10 years	30 years
Soil density (g cm^{-3})	1.85 a	1.89 a
Sand (%)	42.1 a	41.0 a
Silt (%)	20.1 a	21.5 a
Clay (%)	37.8 a	37.5 a
pH in water (1:2.5)	7.97 a	8.66 a
Extractable Ca^{+2} (mmolc kg^{-1})	255 b	33 a
Extractable Mg^{+2} (mmolc kg^{-1})	7.39 b	13.68 a
Extractable K^{+} (mmolc kg^{-1})	0.36 a	0.31 a
Extractable Na^{+} (mmolc kg^{-1})	1.50 a	1.64 a
Extractable P (mg kg^{-1})	0.71 a	0.79 a
Electrical conductivity (dS m^{-1})	0.41 a	0.51 a

Averages in the row followed by the same small letter are not significantly different by the Tukey test at the 0.05 probability level.

productivities averaged 95.4 Mg ha^{-1} and along the 30 years 88.4 Mg ha^{-1}, tending to decrease from the planting year to the following ratoon crops.

One 1.5 m × 1.2 m trench was dug down to 1 m depth in each of the six fields (three for 10 and three for 30 years), at least 10 m from the field border. Undisturbed and disturbed soil samples were collected in the layers 0–10, >10–20, >20–40, >40–80, and > 80–100 cm deep. The undisturbed samples (three paraffined soil blocks in each layer of each trench) were used to determine soil density (Teixeira et al. 2017). The disturbed samples were taken after removing all the soil in each layer of the trench and were air-dried, sieved (2 mm), and used to analyze texture, chemical characteristics, and C and N isotopic composition. Mineral particles larger than 2 mm were weighted to correct the calculation of soil C stocks (Veldkamp 1994).

Soil texture was determined by densitometry, electrical conductivity with a conductivity meter, and pH (water 1:2.5) with a pH meter (Teixeira et al. 2017). Phosphorus was extracted with sodium bicarbonate 0.5 mol L^{-1} at pH 8.5 and determined by Olsen et al. (1954) method. Potassium, sodium, calcium, and magnesium were extracted with 1 mol L^{-1} ammonium acetate, and the first two were determined by flame photometry and the last two by atomic absorption spectrophotometry.

Soil subsamples were sent to the Laboratory of Isotope Ecology (CENA-USP, Brazil), where they were treated with 1N HCl to eliminate carbonate deposits and dried. Aliquots were weighted using analytical high precision scales, placed into tin capsules, and had their ^{13}C and ^{15}N abundances determined by mass spectrometry, using a Thermo Quest-Finnigan Delta Plus isotope ratio mass spectrometer (Finnigan-MAT; CA, USA) interfaced with an Elemental Analyzer (Carlo Erba model 1110; Milan, Italy). The isotope ratios were measured relative to the Pee Dee Belemnite standard for ^{13}C and to the atmospheric N_2 standard for ^{15}N. Internal reference materials (atropine, yeast, and soil standard no. 502–308 from LECO Corporation) were included in every analytical run. The concentrations of ^{13}C and ^{15}N were expressed in δ units (‰), based on the equation $\delta^{13}C$ or $\delta^{15}N$ = (Rsample/Rstandard − 1) × 1000, were Rsample and Rstandard are the ratio ^{13}C:^{12}C or ^{15}N:^{14}N of the sample and the standard (Pee Dee Belemnite or air), respectively.

Isotopic analyses were run in aboveground and root samples from sugarcane and plants from the nearby native vegetation, which were previously oven-dried at 60 °C and ground to a fine powder. Considering that all native vegetation on Vertisols had been disturbed to a large degree since the beginning of the sugarcane cultivation and that several soil trenches opened in areas of this vegetation revealed much shallower soils, the soil C and N stocks in these native vegetation areas were not considered to be representative of the original stocks. These marginal areas were probably left without cultivation because they were not considered appropriate for sugarcane cultivation.

Soil C and N stocks in each layer were calculated considering the C and N concentrations, the layer's height, and the soil density, which was corrected for compaction according to Carvalho et al. (2009). To calculate the contribution of the C4 sugarcane to the soil organic C, we used the mass equation described by Bernoux et al. (1998): f = (δT − δrefA)/(δvegA − δrefA), where f is the fraction of soil C derived from the sugarcane, δT is the isotopic signal of the soil C in the sugarcane fields (δ^{13}Csoil), δrefA is the isotopic signal of the C3 native vegetation (δ^{13}Ccaatinga), and δvegA is the isotopic signal of the C4 sugarcane (δ^{13}Csugar cane). The contribution of the previous C3 native vegetation to soil C in the sugarcane fields was equal to 1 − f.

The data on the soil C and N concentrations, $\delta^{13}C$ and $\delta\ ^{15}N$ values and C/N ratios were submitted to analyses of variance considering a split plot design in which the main plots were the two cultivation periods (10 and 30 years) and the subplots were the six soil layers (0–10, >10–20, >20–40, >40–80, and > 80–100 cm deep). The C and N stocks were analyzed considering only the main plots because the deeper soil layers had double the volume of the shallower layers. The data on C and N concentration and $\delta^{13}C$ and $\delta^{15}N$ values of sugarcane and native plants aboveground and root samples were also submitted to analysis of variance, following a completely randomized design. The averages were compared by the Tukey test ($p < .05$).

Results and discussion

After the first decade, the cultivation of sugarcane for the subsequent 20 years resulted in increases in the C stocks in all soil layers (Table 2), especially in the topsoil layers. Down to 1 m of depth, the stock increased from 94.2 to 168.6 Mg ha^{-1}, corresponding to an average annual addition of 3.72 Mg C ha^{-1}. Most of this addition likely originated from the roots and underground shoots since the dry leaves were burned and the cane culms were harvested, eliminating most of the aboveground biomass, except for part of the green leaves that escaped burning and the short culm stumps below the cutting height (about 10–20 cm).

The underground biomass, considering the average cane production in these fields, is estimated to be around 10 Mg ha^{-1} (Otto et al. 2009; Salata, Armene, and Demattê 1987), equivalent to about 4.0

Table 2. Soil carbon concentration, stock, and isotopic signal in a vertisol cultivated with irrigated sugarcane for 10 and 30 years, in Juazeiro municipality, Bahia state, Brazil.

	C concentration (%)		C stock (Mg ha^{-1})		$\delta^{13}C$ (‰)	
Layer depth (cm)	10 years	30 years	10 years	30 years	10 years	30 years
0–10	0.97 bA	1.45 aA	14.54 b	21.87 a	−15.5 bA	−13.5 aA
>10–20	0.93 bA	1.43 aA	12.98 b	19.35 a	−15.2 bA	−13.3 aA
>20–40	0.67 bB	1.23 aAB	21.02 b	36.81 a	−15.4 bA	−13.4 aA
>40–60	0.57 bBC	0.98 aBC	18.32 b	30.54 a	−16.3 bAB	−13.9 aA
>60–80	0.44 bC	1.07 aBC	13.79 b	32.20 a	−16.6 bAB	−13.8 aA
>80–100	0.40 bC	0.88 aC	13.55 b	27.81 a	−17.3 bB	−13.6 aA
0–100			94.20 b	168.57a		

Averages in the row followed by the same small letter and in the column by the same capital letter are not significantly different by the Tukey test at the 0.05 probability level.

Mg C ha^{-1}, assuming the C concentrations of the roots (39.4%) and culms (40.0%), measured in the fields (Table 3). Most of this underground biomass, including the underground stem, is concentrated in the top 30 cm layer (Ball-Coelho et al. 1992; Jackson et al. 2017; Otto et al. 2009; Sampaio, Salcedo, and Cavalcanti 1987; Silva-Olaya et al. 2017). Comparing the estimated C input and the increase in soil C stocks, approximately 20% of the biomass C was lost, most likely as CO_2.

The N stocks, as the C ones, also increased after the 10 years of cultivation, from 8.5 to 12.3 Mg ha^{-1} from the 10th to the 30th year (Table 4). Significant increases occurred in the three upper soil layers, matching the increases in C so that their C/N ratios varied between 15 and 24, while the ratios in the deeper layers increased to more than 32. A proper interpretation of these changes is not possible because they are complex, being influenced not only by the input and decomposition of organic matter, but also by the input of fertilizer and N losses due to leaching, volatilization and denitrification (Amorim et al. 2022; He et al. 2023; Spohn and Stendahl 2024), plus the possible input of symbiotic fixation of N_2 by the sugarcane (Taulé et al. 2012). The data of $\delta^{15}N$ in the soil, similar in all layers and only marginally and non-significantly lower in the 30th year compared to the 10th year (Table 4),

Table 3. Carbon concentrations and isotopic signals in irrigated sugarcane and native vegetation plant parts in Juazeiro municipality, Bahia state, Brazil.

	C (%)	$\delta^{13}C$ (‰)	N (%)	$\delta^{15}N$ (‰)
Sugarcane				
Aboveground	40.01 A	−13.14 A	0.67 A	7.06 A
Root	39.39 A	−12.75 A	0.67 A	6.56 A
Native vegetation				
Aboveground	40.07 A	−27.96 B	1.06 A	5.59 A
Root	39.09 A	−27.00 B	1.17 A	5.62 A
Litter	38.02 A	−27.48 B	1.30 A	3.70 B

Averages in the column followed by the same capital letter are not significantly different by the Tukey test at the 0.05 probability level.

Table 4. Soil nitrogen concentration, stock, and isotopic signal, and C/N relation in a vertisol cultivated with irrigated sugarcane for 10 and 30 years, in Juazeiro municipality, Bahia state, Brazil.

	N concentration (%)		N stock (Mg ha^{-1})		$\delta^{15}N$ (‰)		C/N	
Layer depth (cm)	10 years	30 years	10 years	30 years	10 years	30 years	10 years	30 years
0–10	0.07 bA	0.09 aA	947 b	1364 a	10.43 aA	9.45 aA	15.06 aB	15.78 aC
>10–20	0.06 bA	0.08 aA	835 b	1148 a	10.17 aA	9.71 aA	15.68 aB	16.71 aC
>20–40	0.03 bB	0.06 aB	1945 b	3801 a	10.86 aA	10.03 aA	23.71 aA	19.46 bBC
>40–60	0.03 aB	0.04 aC	1678 b	2549 a	10.64 aA	9.85 aA	23.55 aA	22.80 aB
>60–80	0.02 aB	0.03 aC	1582 a	1777 a	10.79 aA	9.97 aA	17.98 bB	36.36 aA
>80–100	0.02 aB	0.03 aC	1545 a	1670 a	10.26 aA	9.91 aA	17.43 bB	32.60 aA
0–100			8532 b	12309 a				

Averages in the row followed by the same small letter and in the column by the same capital letter are not significantly different by the Tukey test at the 0.05 probability level.

indicate that if fixation occurred it had a very small contribution, but the application of fertilizer, with its unknown ^{15}N signal, adds to the complication of the issue. The ^{15}N signals in the sugarcanes, similar to those in the forest species, also point to an absence of symbiotic N fixation. On the other hand, the lower signal in the litter than in the aboveground and root samples taken to represent the vegetation in the native forest (Table 4) indicates a higher contribution to the litter of leguminous than non-leguminous plants.

After the additional 20 years of cultivation, the ^{13}C isotopic signal increased in all soil layers (Table 3), reflecting the incorporation of C from the C4 sugarcane biomass, which had an average $\delta^{13}C$ of −12.75 ‰ ± 0.38, and the simultaneous loss of C from the original organic matter, derived from the C3 native vegetation with its average $\delta^{13}C$ of −27.48 ‰ ± 0.82. Considering these signals and that all soil organic matter under the native vegetation maintained the C3 signal, 21.6% of the soil organic C was still derived from the previous native vegetation after the first decade of sugarcane cultivation, while after 30 years, this proportion decreased to only 5.1% (Table 5). Since the total amount of organic matter also increased from 10 to 30 years of cultivation, the loss of the original C was proportionally lower, from 20.3 to 8.7 Mg ha^{-1}, corresponding to an average loss of 57% for the whole soil profile. This total loss is equivalent to an annual loss of 2.85%, assuming a constant rate along the 20 years of additional cultivation. Considering the soil layers separately, the C remaining from the native vegetation increased with depth, from 18% to 30%, at 10 years and from 2.6% to 4.1% at 30 years. However, the increases in the remaining C were not consistent throughout the soil profile.

The loss of 78.4% of the original soil C after 10 years of land-use change (100–21.6% remaining; Table 4) can be considered a plausible one, considering that in the following 20 years, 57% of the C remaining after 10 years was lost. Higher initial losses are expected due to the mineralization of the more labile organic matter while the more recalcitrant matter accumulates (Ukalska-Jaruga, Klimkowicz-Pawlas, and Smreczak 2019). The loss of 94.86% of the original soil C after 30 years of cultivation (100–5.14% remaining; Table 4) seems relatively high and deserves further consideration.

A small part of the organic matter under the native vegetation could have derived from C4 grasses or Crassulacean Acid Metabolism (CAM) plants (*Cactaceae*), both with $\delta^{13}C$ signals similar to that of sugarcane (Mendonça et al. 2010). Currently, only a few sparse *Cactaceae* plants, all belonging to permanent species, occur in the areas under native vegetation surrounding the cane fields. If they represent the previous vegetation of the sugarcane fields, the contribution of these *Cactaceae* to biomass incorporation into the soil would certainly be small. Grasses in the surrounding area also comprised a small amount of the herb biomass, developed only during the short rainy season, and their contribution would also be small. However, there are no records of the previous vegetation in the sugarcane fields apart from oral information from local people that the vegetation was similar to the one in the present native vegetation. However, the vegetation, mainly the herbaceous one, which varies from year

Table 5. Soil carbon proportions and stocks originated from the previous native vegetation in irrigated sugarcane fields cultivated for 10 and 30 years and percentage of the native vegetation soil stock lost from 10 to 30 years of cultivation in Juazeiro municipality, Bahia state, Brazil.

	Carbon from the previous native vegetation				
Layer depth	10 years	30 years	10 years	30 years	Loss
cm	%		Mg ha^{-1}		%
0–10	18.10 aC	4.21 bA	2.63 a	0.92b	65.0 A
>10–20	15.86 aC	3.12 bB	2.06 a	0.60 b	70.6 A
>20–40	17.66 aC	3.51 bA	3.71 a	1.29 b	65.2 A
>40–60	23.50 aB	7.41 bA	4.31 a	2.26 b	47.4 B
>60–80	25.84 aB	6.65 bA	3.56 a	2.14 b	39.9 C
>80–100	30.09 aA	5.17 bA	4.08 a	1.44 b	64.8 A
0–100	21.60 a	5.14 b	20.35 a	8.66 b	57.4

Averages in the row followed by the same small letter and in the column by the same capital letter are not significantly different by the Tukey test at the 0.05 probability level.

to year, could be different. In case more biomasses had been incorporated from the *Cactaceae* and C4 grasses before the sugarcane fields were established, the soil C would have higher $\delta^{13}C$ signals and the calculations of the losses of the original C until 10 years of cultivation would be overestimated. However, the calculations from 10 to 30 years of cultivation would not be affected.

Therefore, we can estimate a minimum loss over the 30 years, based on the assumption that the proportional losses in the initial 10 years were at least equal to those in the following 20 years. This is a conservative assumption since initial losses tend to be higher than subsequent ones (Umrit et al. 2014). The loss in the 10- to 30-year period was 57% and assuming that the annual rates of loss were equal in the two periods, the loss in the first decade would be half of that (28.5%). Thus, along the 30 years, the total loss would have been about 85% (57 + 28%) of the C stock that had accumulated under the native vegetation.

Therefore, the real loss of the original C stock probably lies in the interval of 85 to 95%, most likely closer to 90%. Although high, this loss is not far from those reported by Tiessen, Salcedo, and Sampaio (1992, 2001), and certainly much higher than under temperate conditions (Tiessen, Cuevas, and Salcedo 1998). High losses in this irrigated area of the Brazilian semiarid region can be explained by the high and almost constant temperature and soil humidity throughout the year. However, the losses of the original C stock were more than compensated by the large inputs of biomass, most of it likely coming from the underground parts, attained by the high cane productivities with adequate temperature, solar radiation, water, and nutrient availability. The soil C stock in the 30-year sugarcane fields was much higher than the stocks reported for all soils in the same region, all of which lost C when cultivated under rain-fed conditions (Gava et al. 2021; Menezes et al. 2021; Santana et al. 2019) and also when cultivated with irrigated crops with lower biomass productivity than sugarcane (Santana et al. 2022, 2024).

The potential of irrigated sugarcane to sequester atmospheric CO_2 is even higher than that reported in this work. The productivities along the 30 years (88–95 Mg ha^{-1}), although higher than the regional and national averages, are far below the potential for the crop. With ample light, adequate temperature and enough water and mineral nutrients, sugarcane can produce up to 200 Mg ha^{-1} of culms. Certainly, the production of belowground would also be higher than that obtained in the area and the amount incorporated into the soil could be further increased if the harvest would be done without previous burning of the fields. Mechanical harvesting without burning has been recommended for some years and it is mandatory in other Brazilian regions, due to sanitary reasons. Without burning, all the leaves, corresponding to 10–20% of the culm biomass (Carvalho, Veiga, and Bizzo 2017), remain in the soil surface and part of their biomass would eventually turn into soil organic matter. The possibility of increasing productivities and improvement management of the fields certainly deserve further studies.

Conclusions

The substitution of deciduous tropical dry forest (Caatinga) by irrigated sugarcane resulted in a considerable loss of the original forest-accumulated soil organic C, at least 85% and up to 95%, after 30 years of cultivation in the Vertisol studied. However, this loss was more than compensated by the high inputs of biomass of the irrigated canes. Therefore, irrigated sugarcane is a C sink under the semiarid conditions of Northeast Brazil.

Disclosure statement

No potential conflict of interest was reported by the authors.

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