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Carbon Assessment of the Everglades Agricultural Area

SUBMITTED TO:

The Everglades Foundation

SUBMITTED BY:

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Table of Contents

Acronyms and abbreviations

Acronym	Meaning
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
BMP	Best Management Practices
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
DOC	Dissolved Organic Carbon
EAA	Everglades Agricultural Area
FEB	Flow Equalization Basin
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
SOC	Soil Organic Carbon
SFWMD	South Florida Water Management District
STA	Stormwater Treatment Area
USDA	U.S. Department of Agriculture
US EPA	U.S. Environmental Protection Agency
VOC	Volatile Organic Compound

Executive Summary

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Winrock is providing The Everglades Foundation with assistance to estimate annual greenhouse gas (GHG) emissions from lands cultivated for sugarcane in the Everglades Agricultural Area (EAA), which is dominated by sugarcane cultivation. This includes emissions from land preparation, management, harvest, and transportation of sugarcane, as well as the emissions from rotational crops grown on fallow sugarcane land.

The sources of emissions considered in this assessment include those from peat oxidation, dissolved organic carbon (DOC) export, canals, combustion of fuel for agricultural equipment, fertilizer production and application, pesticide production, in-field sugarcane burning, and agricultural soil management, both for sugarcane cultivation and for crops grown in rotation with sugarcane (i.e., flooded rice and other crops). Rotational rice cultivation includes emissions from flooded rice. Emissions from CO_2, CH_4, and N_2O are accounted for as GHGs covered by the Kyoto Protocol, while indirect emissions from CO, VOCs, and NO_x are reported separately but are not reported in units of CO_2e (carbon dioxide equivalent).

This assessment suggests that annual sugarcane cultivation in the EAA emits over 7.3 million metric t CO_2e, amounting to 0.42 t CO_2e (t sugarcane produced)$^{-1}$. The greatest source of emissions in this agricultural system is from CO_2 released during the oxidation of the drained peat soils. Drainage is necessary for sugarcane cultivation and growth.

Emissions source	Annual emissions (t CO_2e)	Annual emissions per sugarcane produced (t CO_2e t sugarcane^{-1})	% of total EAA emissions
Peat oxidation, DOC export, and EAA canals: entire EAA sugarcane cultivation area	6,686,839	0.378	90.7
Sugarcane cultivation: total annual EAA area with planted cane and ratoon cane	647,817	0.037	8.8
Rotational crop cultivation: total annual EAA area planted with rice and other crops in fallow sugarcane areas	29,244	0.002	0.4
Total	**7,363,900**	**0.42**	**100**

This report is divided into two sections:

1. *Background*: provides context and history on sugarcane cultivation in the EAA.
2. *Carbon footprint of sugarcane cultivation in the EAA:* presents the outcomes of this assessment.

The main report is followed by an Appendix detailing the methodological approaches followed, assumptions made, and data sources and default factors used to estimate EAA's GHG emissions.

Report

1. Background

1.1. The development of the Everglades Agricultural Area

The Everglades Agricultural Area (EAA) was developed on the wetland plains south of Lake Okeechobee in the northern portions of the Everglades basin. Prior to anthropogenic drainage, the area was known as the Sawgrass Plains landscape because of the almost monotypic sawgrass (*Cladium jamaicense*) vegetation and its very uniform topography [1]. Over millennia, the Everglades developed as a freshwater wetland thanks to seasonal rains, overflowing water from the lake, and the presence of slightly elevated areas to the east and west [2]. The wetland conditions and the nearly flat landscape topography led to the accumulation of peat in this limestone basin [3], with the thickness of the peat layers (2.8-3.8 m) increasing with distance northward [2]. The lake's southern shoreline was partly bordered by sawgrass and partly by a pond apple (*Annona glabra*) forest (known as the Custard Apple Swamp) [1]. Some of the areas nearest Lake Okeechobee recorded historical peat deposits of up to 4.3-6 m. With an original area of 89 x 10^4 ha, the peatland portions of the Everglades became the largest contiguous body of organic soils in the continental US [4].

The thick organic soils, subtropical climate, water availability, and the flat topography of the Sawgrass Plains portion of the Everglades (27 x 10^4 ha [5]) drew the attention of farmers. Drainage for agricultural development in the Everglades started in the 1880s [4]. Early drainage (1880s to 1930s) likely affected the northern portion of the Everglades (i.e., the Sawgrass Plains) most severely, initiating microbial oxidation of the peat soils and sometimes leading to widespread peat fires [5]. Early agricultural researchers warned of the dangers of soil oxidation due to drainage and recommended maintaining water tables as high as possible [6]. The area has been referred to as the Everglades Agricultural Area (EAA; **Error! Reference source not found.**) since the late 1950s [3]. For a variety of reasons, including adjacent urbanization, dike safety, post-drainage lake ecological objectives, and maintenance of agricultural conditions in the EAA, the water level in Lake Okeechobee has been maintained well below its original elevation of about 21 feet above mean sea level [5]. Outflows have been redirected to the Atlantic and Gulf coasts instead of through the Everglades in the original southward direction. Cut off from Lake Okeechobee outflows by a dike, the EAA remains drained, with canals controlling water movement in and out of the area for optimum crop irrigation through seepage [7]. South of the EAA, thinner peat deposits less suited

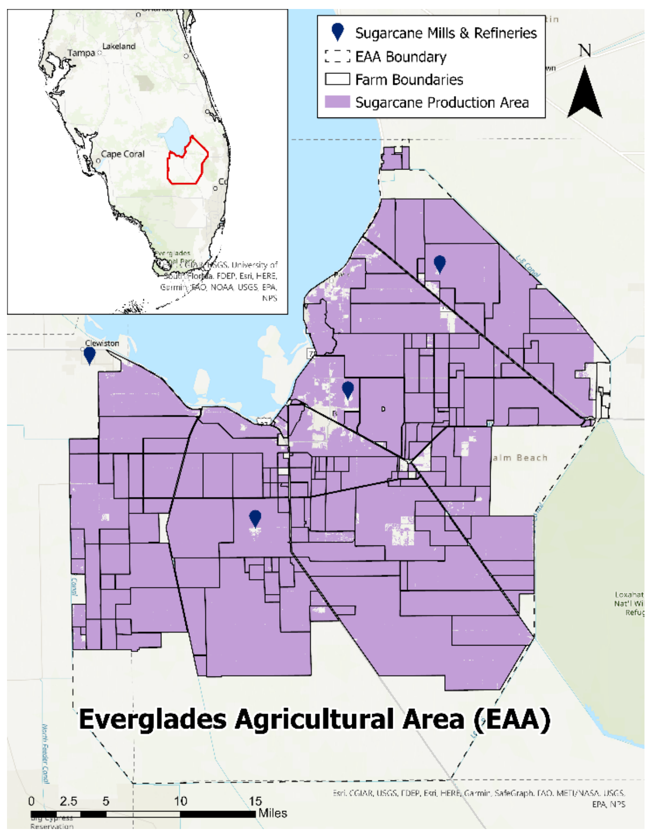

Figure 1. Map of the Everglades Agricultural Area, indicating boundaries, farms, and location of sugarcane mills and refineries.

for agriculture were designated as Water Conservation Areas (WCAs) from 1960-1963. The WCAs are maintained as hydrologically separated basins with water levels manipulated by dikes and canals for the purposes of flood control, water supply, and to support wildlife [1].

Despite the water management and the Best Management Practices (BMPs) implemented across the EAA as required by the 1995 Everglades Forever Act [8], the continued drainage of EAA's peat soils has resulted in extensive land subsidence due to peat oxidation to a lesser extent, peat compaction [3].

1.2. Land subsidence in the Everglades Agricultural Area

Drainage of the EAA's organic soils has led to ongoing decreases in peat thickness (i.e., subsidence) due to the oxidation of peat [3], [9]. Peat loss due to water erosion is considered negligible because of the extremely flat surface slope of this landscape and thus, soil carbon transport losses are virtually non-existent [4]. Wind erosion due to hurricanes and extreme weather events is also considered to be minimal in this assessment. The continued peat degradation due to this drainage has changed the soil classification of this area over time. These soils are classified as Saprists, the most decomposed peat type [4], [10]. Progressive peat degradation has also resulted in the progressive degradation of recalcitrant peat components such as lignin [11], a decrease in soil organic carbon (SOC) content through accelerated mineralization, and a corresponding increase in soil bulk density. EAA peat now has, on average, a 39.1% SOC content and a 0.38 g soil cm^{-3} bulk density in the top 40 cm of soil [12], a bulk density four times greater than that of the original pre-drainage peat [4], [7].

Under the original pre-drainage wetland conditions, the rate of peat accretion in this area was estimated to have started at 7 cm per century, reaching 12 cm per century during the last millennium [1], [13]. This process built a thick layer of peat in the area currently occupied by the EAA that decreased in thickness towards the south [2]. Currently, the peat depth above the limestone bedrock is only 0.3-1.5 m, depending on location within the EAA [4]. It is therefore estimated that the EAA subsided 1-3 m. Accordingly, the EAA is estimated to have lost 4.5-4.9 x 10^9 m^3 of its original peat volume, approximately 60-69% [2], [4].

Various studies have estimated the subsidence rates that resulted from this continued peat loss. Subsidence was reportedly highest by 1931, when drainage and thus physical consolidation and compaction of the peat was most aggressive, with a calculated subsidence rate of 9 cm y^{-1} [7]. By 1951, with managed flooding practices, subsidence was estimated to be 2.5-3 cm y^{-1} and 1.4-1.45 cm y^{-1} by 1998 [7], [14], [15]. Currently, subsidence is modeled at 0.65 cm y^{-1} [7]. Some attribute the decrease in the subsidence rate to the EAA-wide implementation of BMPs, to the limited amount of peat left on the area, or to the increased mineral character of the soil [7], [14], [16], [17].

1.3. Sugarcane production in the Everglades Agricultural Area

Sugarcane is the most extensive and most valuable commercial crop in the EAA. From 2014-2020, approximately 444,000 acres of the EAA were cultivated for sugarcane, 97% of which were on organic soils (based on the analysis presented in Appendix). These organic soils are nitrogen-rich due to peat oxidation and thus do not require inputs of nitrogen fertilizers to ensure crop productivity.

Farms growing sugarcane partition the land into subareas or quadrants of similar size [18], [19]:

- Quadrant where sugarcane is planted (*plant cane)*
- Two quadrants where different rounds of ratoon are grown (*ratoon cane)*

- Quadrant left fallow or under a non-sugarcane crop rotation

Three annual sugarcane crops are therefore harvested before the field is replanted. After harvest, the quadrant rotates to grow subsequent ratoon rounds, plant cane in the portion left fallow, and leave fallow in the oldest ratoon round. In the EAA, however, 40% of the sugarcane area is grown in succession, i.e., with no fallow quadrant rotation [18]. Rice, sod, and vegetables are also commonly grown in the fallow quadrant of the sugarcane farm [20]–[23].

Many sugarcane cultivars planted today in the EAA are tolerant to short-term flooding [17]. A water table of -60 cm was considered optimal for sustainable EAA crops, but since sugarcane became the dominant EAA crop in the late 1960s water tables have generally been maintained deeper [4]. The ongoing problem of progressive soil subsidence aggravated by deeper water tables led to the development of sugarcane varieties adapted to shallow water tables [7].

2. Carbon footprint of sugarcane cultivation in the Everglades Agricultural Area

2.1. Objective and scope of this assessment

This analysis aims to estimate GHG emissions from sugarcane production in the EAA, including land preparation, land management, harvest, and processing. The scope of this assessment is:

- ***Geographic***: This assessment focuses on the area that is cultivated for sugarcane in the EAA, including the area of rotational crops (rice and other crops, predominantly vegetables) that is grown on fallow sugarcane land. It does not include all small areas within the EAA that are cultivated only for non-sugarcane crops, water treatment and management, and wildlife management areas.
- ***Temporal***: Annual emissions are estimated based on current practices. This is not an analysis of historical emissions since agriculture began in the EAA.
- ***Greenhouse gases***: Emissions from CO_2, CH_4, and N_2O, when relevant, are included. These are transformed to CO_2equivalents (CO_2e) using Global Warming Potentials (GWPs) from the 2021 IPCC's Sixth Assessment Report (AR6) [24]. Emissions from CO, VOCs, and NO_x are reported separately and not in CO_2e, as they are not included as greenhouse gases within the Kyoto Protocol.
- ***Emissions sources***: The analysis estimates emissions from the following sources:

    1. Peat oxidation and DOC export
    2. Methane emissions from EAA canals
    3. Equipment for agricultural production
    4. Pesticides
    5. Fertilizers applied to crops in inorganic soils
    6. Pre-harvest fire sugarcane crop management
    7. Crop residues
    8. Rotational crops
    9. Transportation of harvested sugarcane to local mills

Emissions from sugarcane processing are excluded from this assessment, as sugar mills and refineries near the EAA produce enough energy through the combustion of sugarcane by-products (i.e., bagasse) to meet all their energy demands. Furthermore, this analysis does not account for indirect consequences of sugarcane farming that may influence net carbon impact outside the EAA (e.g., downstream changes in Everglades' plant growth), nor any emissions from byproducts of sugar production, such as molasses, ashes, or solid waste.

This assessment relied on data and defaults provided by the Intergovernmental Panel on Climate Change (IPCC), US Environmental Protection Agency (US EPA), University of Florida Institute of Food and Agricultural Sciences Extension, South Florida Water Management District (SFWMD) Environmental Monitoring database, and peer-reviewed data and literature published on the EAA.

2.2. Assessment results

We estimate that sugarcane production in the EAA emits over 7.3 million metric tons of CO_2e per year. This amounts to approximately 0.42 metric t CO_2e per metric ton of sugarcane produced, or 16.6 metric t CO_2e $acre^{-1}$ (41.0 t CO_2e ha^{-1}). The biggest source of emissions is peat loss via oxidation, resulting in peat subsidence and accounting for 84% of emissions from the EAA (Figure 2). Emissions from peat oxidation, dissolved organic carbon (DOC) export, and CH_4 from drainage canals generated across the entire EAA, amount to 90.7% of the total EAA annual emissions. Rotational crops refer *only* to crops and flooded rice cultivated annually in the "fallow" quadrant area of EAA's sugarcane farms.

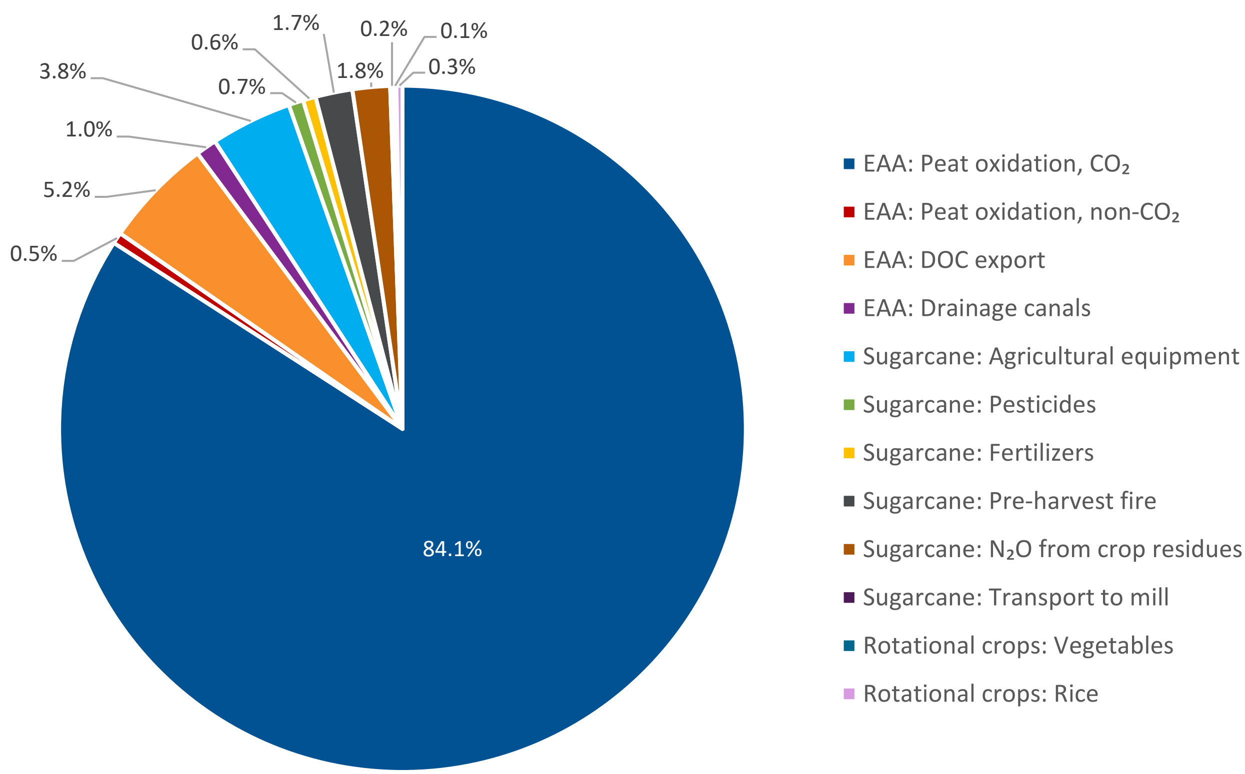

Figure 2. Annual emissions in the EAA, by source (%). Rotational crops refer only to crops and flooded rice cultivated annually in the fallow quadrant area of EAA's sugarcane farms.

Nitrous oxide (N_2O) emissions from these managed soils under sugarcane cultivation account for 34% of the emissions not due to peat oxidation, followed by fossil fuel use by agricultural equipment (21%) and fertilizer application and production (15%; Figure 3).

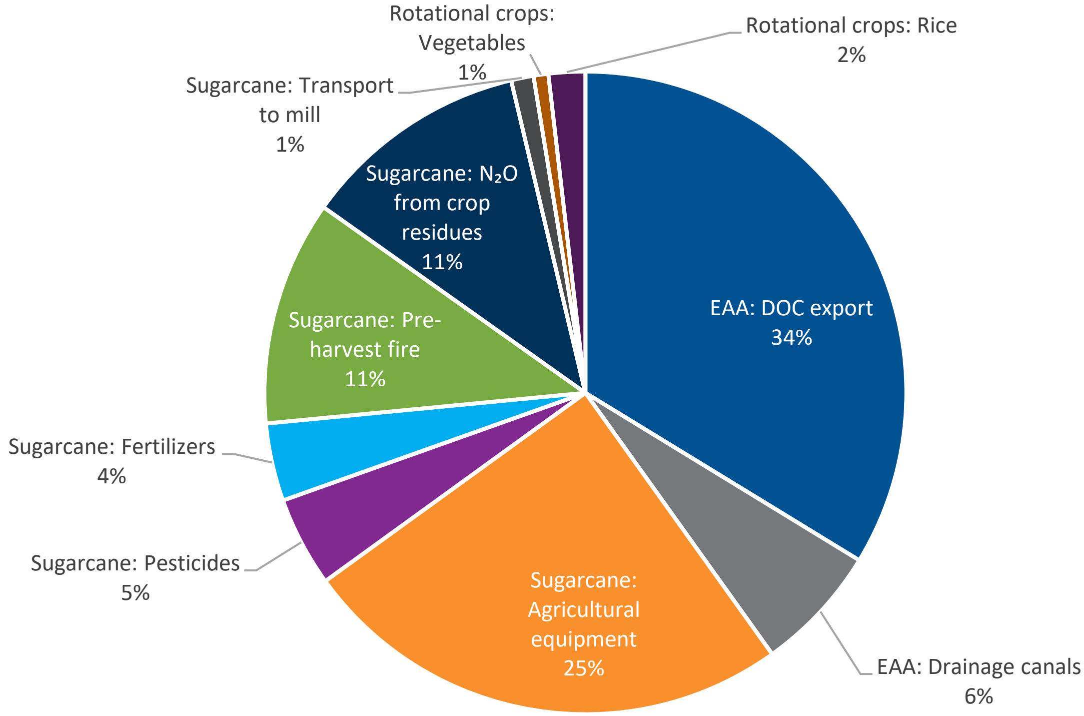

Figure 3. Annual emissions other than those from peat oxidation in the EAA, by source (%). Rotational crops refer only to crops and flooded rice cultivated annually in the fallow quadrant area of EAA's sugarcane farms.

The total annual emissions included in this GHG footprint assessment are reported in Table 1, indicating rates in metric tons CO_2e per year, per annual area, and per metric ton of sugarcane produced in the EAA. CO, NO_x, and VOC emissions, which are not reported in t CO_2e, were estimated to be 319 tons, 2,353 tons, and 17 tons, respectively.

Table 1. Annual emissions in the EAA (t CO_2e) by emissions source, per annual area, and per ton of sugarcane produced annually in the EAA. Emissions from rotational crops include the same sources as those listed out for sugarcane. Rice cultivation includes methane emissions from flooding.

Emissions source	t CO_2e	t CO_2e $acre^{-1}$	t CO_2e (t $sugarcane)^{-1}$
Total peat oxidation, DOC export, and methane emissions from canals from sugarcane farm areas	6,614,631	14.90	0.374
CO_2 emissions	6,194,096	13.95	0.350
Non-CO_2 emissions (CH_4 and N_2O)	39,256	0.09	0.002
DOC export	381,279	0.86	0.022
Methane emissions from EAA canals	72,208	0.16	0.004

Total sugarcane cultivation: planted and ratoon cane	647,817	1.46	0.037
Agricultural equipment	281,794	0.63	0.016
Pesticide production	51,196	0.12	0.003
Fertilizer production and application	44,238	0.10	0.003
Pre-harvest fire	128,118	0.29	0.007
N_2O from crop residues	129,678	0.29	0.007
Transport to mill	12,792	0.03	0.001
Total non-sugarcane crops in fallow sugarcane areas	29,244	0.07	0.002
Flooded rice	8,402	0.02	0.000
Other crops	20,843	0.05	0.001
Total	**7,363,900**	**16.59**	**0.417**

Our estimate of 0.42 t CO_2e per metric ton of sugar produced is in line with that from Izursa et al. [25] for sugarcane grown in organic soils in the Everglades (0.46 t CO_2e (t sugar)$^{-1}$ yr^{-1}), a study that included very similar emissions sources to this analysis. Murphy et al. [18] estimate sugarcane grown across the United States has a GHG footprint of 17.6 t CO_2e yr^{-1} ha^{-1} (compared to our estimate of 41.0 t CO_2e yr^{-1} ha^{-1}). The approximately 50% lower estimate by Murphy et al. is driven by their assumption that only 35% of sugar in the United States is grown on organic soils, including more non-organic soils in their area-weighed estimate than our EAA assessment. Using their estimates, if Murphy et al. had assumed that 97% of sugarcane emissions were grown on organic soils as in the EAA, their estimate would be 39.0 t CO_2e yr^{-1} ha^{-1}, a result comparable to the estimate presented in this report.

When comparing our estimates solely for emissions from peat oxidation, which comprise the bulk of emissions, our estimate of 34.5 t CO_2e per ha falls between the IPCC default emissions from cropland on drained peatland in tropical (51.3 t CO_2e per ha) and temperate (28.97 t CO_2e per ha) areas [26]. Our EAA results therefore align well with IPCC default emission factors, given the Everglades are in a subtropical climate.

Appendix: Greenhouse Gas Footprint Assessment Methodology

1. Introduction

This methodological Appendix is divided into different sections, corresponding to each source of emissions described:

- Peat oxidation
- Dissolved organic carbon (DOC) export
- Methane emissions from EAA canals
- Equipment for agricultural production
- Pesticides
- Fertilizers
- Pre-harvest fire sugarcane crop management
- Crop residues
- Rotational crops
- Transportation of harvested sugarcane to local mills

All emissions are calculated on a per-year basis. Within each of these GHG sources, we detail the scope, activity data, emission factors, and emissions estimate approaches followed. Activity data and assumptions made in this analysis are presented in green tables, while emission factors are presented in purple tables. Formulas used to estimate emissions are highlighted throughout the sections of this Appendix.

Note that all tons (t) reported in this assessment refer to metric tons.

2. Key assumptions

Global Warming Potentials

GWPs are applied across the GHG assessments to convert non-CO_2 emissions to CO_2 equivalents (CO_2e). GWP used are from the updated GWPs in the 2021 IPCC's Sixth Assessment Report (AR6) [24].

Table 1. Global warming potentials applied in this analysis. Source: [24]

GHG	100-year GWP	Source
CO_2	1	IPCC AR6
CH_4	27.9	IPCC AR6
N_2O	273.0	IPCC AR6

Area

Sugarcane cultivation is partitioned into subareas of similar size: one fallow or planted with a non-sugar crop, one where sugarcane is planted, and two where different rounds of ratoons are grown [18]. Three annual crops are therefore harvested before the field is replanted. In some cases, after three annual cycles have passed, the sugarcane directly starts a new cycle without a fallow period or period where another crop is grown (it is grown "in succession"). During a one-year fallow period, these areas are often planted with other crops such as rice, vegetables, or sod, rather than being left bare (with the sugarcane being grown "in rotation").

Total area estimates of sugarcane and other crops are derived from a spatial analysis using the USDA CropScape dataset [27]. All areas that had been classified at least once as cultivated sugarcane land from 2014-2020 contributed to the total sugarcane area considered in this analysis. Any areas classified as sugarcane that were also classified as developed, barren, forest, native vegetation, shrubland, or open water during the same period (i.e., 2,117 acres) were excluded as they were likely due to errors in the classification dataset or could mean that the areas transitioned out of sugarcane production. The area of sugarcane grown on organic and mineral soils is estimated using the SSURGO database [28] and by grouping soil classifications into either the "organic"[1] or "mineral"[2] category (Figure 4). Estimates of the areas of sugarcane in different conditions are presented in Table 2. The areas estimated to be rice, other crops, or fallow each year are an average of the annual area in each of those categories from 2014-2020.

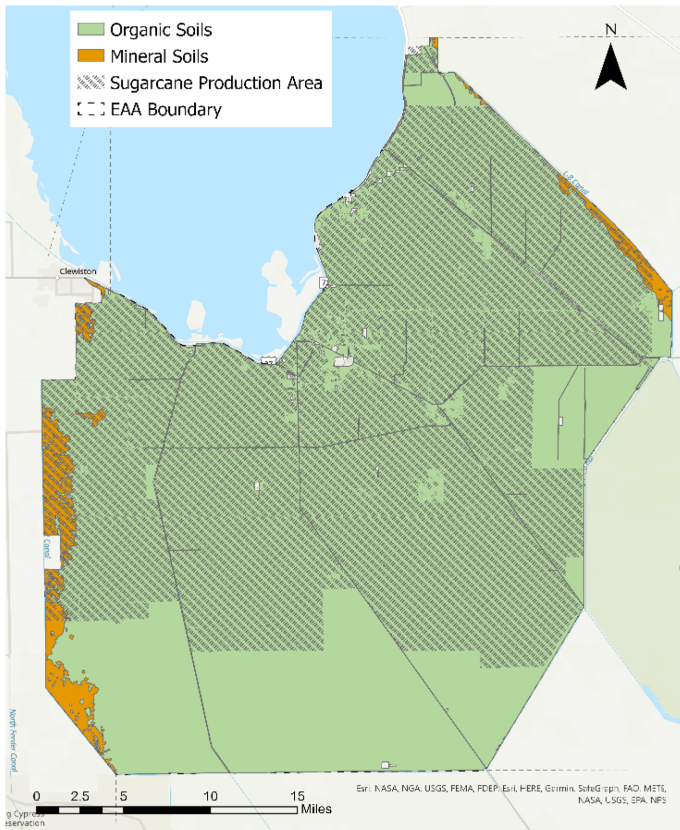

Figure 4. Organic and mineral soils in the EAA sugarcane production area.

[1] ***Organic Soils:*** *Aquents, organic substratum; Clewiston muck, drained, frequently ponded, 0 to 1 percent slopes; Dania muck, drained, frequently ponded, 0 to 1 percent slopes; Denaud muck; Gator muck, frequently ponded, 0 to 1 percent slopes; Lauderhill muck, drained, frequently ponded, 0 to 1 percent slopes; Okeechobee muck; Okeelanta muck; Okeelanta muck, drained, frequently ponded, 0 to 1 percent slopes; Pahokee muck, drained, 0 to 1 percent slopes; Pahokee muck, drained, frequently ponded, 0 to 1 percent slopes; Sanibel muck; Tequesta muck, frequently ponded, 0 to 1 percent slopes; Terra Ceia muck, drained, frequently ponded, 0 to 1 percent slopes; Terra Ceia muck, frequently ponded, 0 to 1 percent slopes; Torry muck.*

[2] ***Mineral Soils:*** *Basinger and Myakka sands, depressional; Basinger fine sand, 0 to 2 percent slopes; Basinger sand, 0 to 2 percent slopes; Brynwood sand, frequently ponded, 0 to 1 percent slopes; Brynwood sand, wet, 0 to 2 percent slopes; Cypress Lake fine sand, 0 to 2 percent slopes; Cypress Lake sand, 0 to 2 percent slopes; Cypress Lake sand, frequently ponded, 0 to 1 percent slopes; Delray sand, depressional; Floridana fine sand, frequently ponded, 0 to 1 percent slopes; Gentry fine sand, depressional; Holopaw fine sand, 0 to 2 percent slopes; Holopaw sand, 0 to 2 percent slopes; Holopaw sand, limestone substratum; Immokalee fine sand, 0 to 2 percent slopes; Immokalee sand, 0 to 2 percent slopes; Jenada fine sand, 0 to 2 percent slopes; Jupiter fine sand, 0 to 2 percent slopes; Myakka fine sand, 0 to 2 percent slopes; Myakka sand, 0 to 2 percent slopes; Oldsmar sand, 0 to 2 percent slopes; Oldsmar sand, limestone substratum; Pineda sand, limestone substratum; Riviera fine sand, 0 to 2 percent slopes; Riviera fine sand, frequently ponded, 0 to 1 percent slopes; Riviera sand, frequently ponded, 0 to 1 percent slopes.*

Table 2. Estimated area of various land uses in the EAA.[3]

Area	Acres	Hectares
Total EAA	441,760	178,774
Organic soils	428,471	173,396
Inorganic soils	13,289	5,378
Annual area in ratoon cane	257,770	104,316
Organic soils	232,773	94,200
Inorganic soils	7,219	2,922
Annual area in plant cane	128,885	52,158
Organic soils	116,386	47,100
Inorganic soils	3,610	1,461
Annual area in fallow or planted without sugarcane	81,772	33,092
Fallow (bare)	63,855	25,841
Rice in rotation	8,125	3,288
Other crops in rotation	9,792	3,963

Yield

The yield of the crops covered by this analysis, converted to metric tons per acre, is detailed in Table 3 following [29]–[31].

Table 3. Yield of crops in the EAA included in this analysis.

Commodity	Yield (metric tons/acre)	Source
Sugarcane	39.8	USDA, 2021
Rice	6.1	Bhadha et al., 2019
Vegetables (representative of the "other crops" category)	9.6	USDA, 2016

The yield estimated for vegetables, which is applied here as the yield of other crops, is based on average yields for snap beans, cabbage, sweet corn, cucumbers, bell peppers, squash, and tomatoes grown in Florida in 2015. The exact area of each of these crops within the EAA is beyond the scope of this analysis.

3. Peat oxidation

Scope

This component refers to the emissions generated by peat oxidation due to drainage of EAA organic soils to sustain crop productivity. Oxidation of peat generates CO_2 and N_2O emissions from the drained soil. DOC export due to peat drainage and subsequent oxidation is also an important source of emissions; the approach to estimate this is described in Appendix Section 4 below. Similarly, the network of canals that manage the hydrology of these peats is an important source of CH_4 emissions, described in Appendix Section 5.

[3] Note that although the total area and areas in organic and mineral soils are estimated using geospatial analysis, the other areas are based on assumptions.

Activity data

This assessment assumes that EAA's peat oxidation and associated subsidence applies, on average, to the top 30 cm of peat across the entire organic soil EAA area included in this assessment (Table 2). While the depth of the peat column affected by this phenomenon can be expected to vary across the EAA given the peat thickness differences and heterogeneous water table management, limited information on water table dynamics across EAA's sugarcane farms led us to make the conservative assumption that only the top 30 cm of peat would be, on average, subsiding due to peat oxidation.

Emission factors

a. Peat loss (CO_2 emissions)

To determine the rate of subsidence, the modeled estimate for current EAA subsidence rates of 0.65 cm per year from Rodriguez et al. [7] was assumed. Note that the implication of using a subsidence rate to estimate peat CO_2 emissions is that subsidence is due to peat oxidation and is thus a source of CO_2, and that physical compaction is not contributing to that subsidence rate. With the information available for this assessment, it is not possible to differentiate between the proportion of subsidence due to oxidation and the proportion due to compaction. It was also assumed that the portion of the peat soil profile that is subsiding (i.e., the portion above the water table, usually the upper 30 to 60 cm) all has on average, a peat SOC content of 39.1% and a bulk density of 0.38 g soil cm^{-3} which, according to [12], represent EAA's undrained peat conditions. Couwenberg and Hooijer [32] and references therein recommend that estimates of peat subsidence emissions based on subsidence rates should use the bulk density of the peat layers below the water table (i.e., layers not actively oxidizing). However, assessing the dynamic water table depths across the EAA to follow such an approach would require detailed data to conduct a spatially-explicit assessment of how hydrology changes across the EAA and what the differences of peat thickness and characteristics across farms are. We were not able to integrate these in this assessment and thus proxy data was used instead. The bulk density used, however, was measured in [12] under undrained conditions, and it can be considered a proxy of the bulk density of the EAA peat below the water table, assuming a homogeneous peat profile.

b. CH_4 and N_2O emissions produced by peat drainage

Hu et al. [12] report EAA peat emissions due to drainage, which are used in this assessment (Table 4). The cited study indicates that CH_4 emissions were highly variable, showing non-significant differences between drained and undrained conditions, whereas N_2O emissions were higher under drainage. Note that these N_2O emissions do not represent emissions due to fertilization (see Appendix Section 8 for fertilizer emissions).

While these peat data and emission factors are generated by a laboratory experiment that might not fully reflect natural conditions [12], this assessment uses these estimates because they are based on EAA sugarcane peat samples and hydrological conditions, considered more representative of EAA peat oxidation emissions than regional IPCC Tier 1 or 2 factors. These values, however, should be considered a proxy of actual emissions generated by peat drainage in the EAA. To assess the actual peat emissions, a field study that investigates in-depth EAA peat conditions and resulting emissions would be necessary.

Table 4. Emission factors for peat drainage. Source: [12].

Gas	Emission factor	Unit
CH_4	110.5	µg CH_4-C m^{-2} d^{-1}
N_2O	135	µg N_2O-N m^{-2} d^{-1}

CH_4 emissions from ditches and canals are estimated in Appendix Section 5 below and are not included in the CH_4 estimate in Table 4.

Emissions estimate

a. Peat loss (CO_2 emissions)

The annual subsidence rate is converted to the mass of soil carbon lost per year using the equation below and default values presented above. This results in a current annual soil organic carbon loss of 12.26 t C ha^{-1} yr^{-1}.

$$\begin{aligned} &Mass\ of\ lost\ soil\ carbon\ (t\ C\ ha^{-1} yr^{-1}) \\ &\qquad = Annual\ subsidence\ rate\ (cm\ yr^{-1}) \times Average\ peat\ SOC\ content\ (\%) \\ &\qquad \times Bulk\ density\ (g\ soil\ cm^{-3}) \times 100 \end{aligned}$$

Soil carbon losses can then be converted to CO_2e:

$$Emissions\ (t\ CO_2e\ yr^{-1}) = Mass\ of\ lost\ soil\ carbon\ (t\ C\ ha^{-1}\ yr^{-1}) \times EAA\ peat\ area\ (ha) \times \frac{44}{12}$$

b. CH_4 and N_2O emissions produced by peat drainage

The emission factors in Table 4 are converted to t CH_4 and N_2O, respectively, per ha per year, using the mass ratios of 16/12 (CH_4-C) and 44/28 (N_2O-N) and resulting in 0.000538 t CH_4 ha^{-1} yr^{-1} and 0.000774 t N_2O ha^{-1} yr^{-1}. These factors are converted to t CO_2e using the corresponding GWPs (Table 1) and multiplied by the EAA peat area to obtain t CO_2e yr^{-1}.

$$\begin{aligned} &Emissions\ (t\ CO_2e\ yr^{-1}) \\ &\qquad = Emission\ factor_{gas}\ (\mu g\ \ m^{-2}\ d^{-1}) \times 365 \times Mass\ ratio_{gas} \\ &\qquad \div 10^8 \times EAA\ peat\ area\ (ha) \times GWP_{gas} \end{aligned}$$

where *Mass ratio$_{gas}$* is either CH_4-C or N_2O-N and *gas* is either CH_4 or N_2O.

4. Dissolved organic carbon export

Activity data

This phenomenon applies to the entire organic soil EAA area included in this assessment (Table 2).

Emission factors

The change in DOC in the EAA (i.e., the difference between DOC inflow and outflow) was determined using DOC data from the South Florida Water Management District (SFWMD) DBHYDRO Database [33], provided by the Everglades Foundation. The change was converted to a percent DOC change, following IPCC guidelines in the "2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands" (referred to here as the IPCC Wetlands Supplement) [26]. This percent DOC change is therefore assumed to be 36% or 8.73 mg L^{-1} (Table 5). This DOC change factor cannot guarantee that the DOC inflow has not already been accounted for as DOC in the outflow, due to the lack of information on carbon cycling inside the EAA and the water recirculation in and out of the EAA. The Winrock-Everglades Foundation team prioritized using local data over general IPCC Tier 1 defaults when possible (i.e., only for DOC change with drainage, as indicated in Table 6).

Table 5. DOC concentrations measured in EAA's inflow and outflow waters. Source: [33].

Site	Average DOC concentration (mg L^{-1})
Inflow	24.26
Outflow	33.00
DOC change	8.73

The IPCC Wetlands Supplement provides a series of coefficients (Table 6) to estimate the emission factor for DOC export in drained peat soils.

Table 6. Emission factors for peat drainage.

Variable	Value	Unit	Source
DOC flux natural (tropical)	0.49	t C ha^{-1} yr^{-1}	IPCC
DOC change with drainage	0.36	Unitless (factor from % change)	SFWMD data
$Frac_{DOC\text{-}CO2}$	0.9	Unitless	IPCC

The IPCC Wetlands Supplement provides these default factors for permanently drained peatlands in which exported DOC is completely lost. It is unclear if that is consistently the case for the EAA, given the water recirculation in and out of the EAA and the simplified view of the process that having only inflow and outflow DOC data without a full hydrological budget provides. Furthermore, the EAA peats are managed without a representative natural undrained peat site nearby that could be used to compare drained vs. undrained conditions. It should be noted, however, that the IPCC [34] recommends that assessments in managed lands should account for all emissions and must not make subtractions for what the emissions in the unmanaged situation would have been. In this case, the lower bound of the tropical default value was applied for conservative purposes, given the EAA's location at the border between the tropical and temperate zones.

Following the IPCC Wetlands Supplement, the emission factor for DOC export in drained organic soils (t CO_2 ha^{-1} yr^{-1}) is calculated using the following equation:

$$Emission\ factor\ (t\ CO_2e\ ha^{-1}yr^{-1}) = DOC\ flux\ natural\ (t\ C\ ha^{-1}yr^{-1}) \times (1 + DOC\ Change) \times Frac_{DOC-CO2} \times \frac{44}{12}$$

Emissions estimate

$$Emissions\ (t\ CO_2e\ yr^{-1}) = Emission\ factor\ (t\ CO_2e\ ha^{-1}yr^{-1}) \times EAA\ peat\ area\ (ha)$$

5. Methane emissions from EAA canals

Scope

Peat drainage and management of peat water tables require the use of canals and ditches. The EAA is crisscrossed with numerous canals that bring water in and out of the farm fields and in and out of the EAA, managed by the SFWMD. These canals and ditches maintain standing water that generates CH_4 emissions that, according to the IPCC Wetlands Supplement, can be significantly higher than the CH_4 generated by peat drainage itself.

Activity data

The EAA has primary, secondary, and local canals (Figure 5). Primary canals are 300 ft wide, secondary canals are 100 ft wide, and local canals are 50 ft wide. High-resolution satellite images show that there are additional ditches within the farms, but there is no publicly available information about their dimensions and thus they cannot be included in the activity data calculations. Secondary canals are also excluded from this assessment because they are not part of the EAA farm area, as they are Stormwater Treatment Areas (STAs) and Flow Equalization Basin (FEBs) canals.

The total canal area was calculated assessing canal length and width. The canal areas used as activity data in this assessment are provided in Table 7, estimated by The Everglades Foundation. This assessment assumes that local and primary canals are always flooded, even though local canals are known to be occasionally dry.

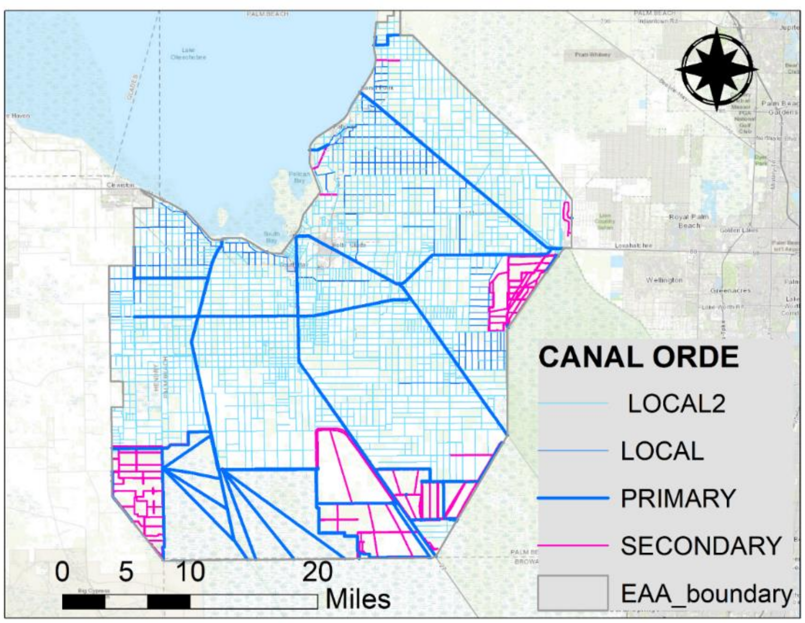

Figure 5. Map of EAA canals and canal orders. Source: The Everglades Foundation.

Table 7. Total area of local and primary EAA canals, in sq ft and ha. Source: The Everglades Foundation.

EAA canal	Sum of Canal Top Area (sq ft)	Sum of Canal Top Area (ha)
LOCAL	62,679,953	582
LOCAL 2	694,622,452	6,453
PRIMARY	475,946,623	4,422
Grand Total	1,233,249,028	11,457

Emission factors

The IPCC Wetlands Supplement provides Tier 1 default factors to estimate CH_4 emissions from canals and ditches (Table 2.4, Chapter 2). This assessment uses the tropical emission factor (2,259 kg CH_4 ha^{-1} yr^{-1}). This table provides a default estimate for the fraction of the total area of drained organic soil occupied by canals and ditches. Because the canal area can be estimated for the EAA thanks to currently available EAA data, this assessment uses the canal area reported in Table 7 rather than a regional IPCC Tier 1 default.

Emissions estimate

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = Emission\ factor\ (kg\ CH_4\ ha^{-1}yr^{-1}) \times Canal\ area\ (ha) \div 10000 \times GWP$$

6. Agricultural equipment

6.1 Ground equipment

Scope

This component includes the equipment (e.g., tractors) for preparing the land, tilling, applying fertilizers and pesticides, planting, and harvesting. This analysis assumes that all equipment uses diesel, and accounts for CO_2, CH_4, and N_2O emissions from diesel combustion. NO_x and CO are estimated but are not reported in CO_2e units given the uncertainty regarding their GWP and their exclusion as a greenhouse gas from the Kyoto Protocol.

Activity data

Ground equipment used in EAA is assumed to follow standard practices for growing sugarcane as described in Louisiana in 2021 [35]. Activity data are reported in the total amount of diesel fuel costs per acre that every piece of equipment requires for each different stage of the sugarcane cultivation process (e.g., land preparation, planting, management, and harvesting). For each piece of equipment, the fuel cost per acre was divided by the average price of diesel in 2021 ($1.73) to determine the total volume of diesel needed per acre per year [35].

Billet harvesting is assumed not to apply in this analysis, as whole stalks are typically hand planted in Florida [36]. Therefore, the equipment required for billet seedcane harvest and mechanical planting of billet that is reported for Louisiana is excluded. Reported equipment for wholestalk harvesting is also excluded, as sugarcane in Florida typically relies on combine harvesters [18]. We assume that 95% of the area with planted cane is hand planted and 5% is planted mechanically [19].

Emission factors

The emission factors for CO_2, CH_4, and N_2O from diesel used in non-road agricultural equipment are sourced from the US EPA GHG Inventory Guidance [37]. Emission factors are converted to kg gallon^{-1} where necessary. For CO and NO_x, equipment is assumed to be the most recent year listed for the emission factors provided [38].

Table 8. Emission factors for mobile combustion by non-road agricultural equipment, from [37] *and* [38].

Gas	Emission factor	Unit
CO_2	10.21	kg gallon^{-1}
CH_4	0.28	g gallon^{-1}
N_2O	0.49	g gallon^{-1}
CO (all horsepower)	1	g (hp-hr)$^{-1}$
NO_x (50-100 horsepower)	3.3	g (hp-hr)$^{-1}$
NO_x (100-300 horsepower)	2.8	g (hp-hr)$^{-1}$

Emissions estimate

For CO_2, CH_4, and N_2O:

$$\begin{aligned} &Emissions\ (t\ CO_2e\ \ yr^{-1}) \\ &\quad = Emission\ factor\ (kg\ gallon^{-1}) \times Diesel\ (gallons\ \ yr^{-1}) \div 1000 \times GWP \end{aligned}$$

The number of horsepower hours ("hp-hr") (required for CO and NO_x estimates) was determined by multiplying the horsepower reported for each piece of equipment by the hours required per acre [35].

For CO and NO_x:

$$\begin{aligned} &Emissions\ (t\ CO\ or\ NO_x\ \ yr^{-1}) \\ &\quad = Emission\ factor\ (g\ (hp-hr)^{-1}) \times Horsepower\ hours\ (hp-hr\ \ yr^{-1}) \\ &\quad \div 1{,}000{,}000 \end{aligned}$$

6.2 Airplanes

Scope

Airplanes (or "air tractors" in the context of this assessment) are used to apply certain chemicals to sugarcane crops [35]. Emissions are estimated for CO_2, CH_4, and N_2O.

Activity data

The number and frequency of air tractors' passes over the EAA sugarcane crops are based on the use of air tractors in Louisiana's sugarcane cultivation [35]. Air tractors are only assumed to be used for plant cane and ratoon cane, not for fallow land.

Emission factors

Emission factors are derived from the US EPA factors for aviation gasoline [37], which is assumed to be the most relevant fuel for agricultural planes [39]. Emission factors are converted to kg gallon^{-1} where necessary.

Table 9. Emission factors for aviation gasoline. Source: [37].

Gas	Emission factor	Unit
CO_2	8.31	kg gallon^{-1}
CH_4	7.06	g gallon^{-1}
N_2O	0.11	g gallon^{-1}

Emissions estimate

To determine the amount of fuel used, the average capacity of an air tractor is assumed to be 1.8 hectares per minute [40] and the rate of fuel use is assumed to be 200 liters per hour [39]. The gallons of fuel used are then calculated based on the number of hectares that air tractors cover. Emissions are then calculated using the total gallons of fuel used:

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = Emission\ factor\ (kg\ gallon^{-1}) \times Total\ aviation\ gasoline\ (gallons\ \ yr^{-1}) \div 1{,}000 \times GWP$$

6.3 Drainage equipment

Scope

Emissions in this category refer to the use of field pumps for draining water out of agricultural fields to control farm water levels. Irrigation is typically controlled by gravity flow from rain or Lake Okeechobee in the EAA [41], and therefore it is not relevant in this assessment. Emissions are estimated for CO_2, CH_4, and N_2O.

Activity data

The average annual amount of water pumped from each EAA farm during 2000-2019 was sourced from the South Florida Water Management District (SFWMD) DBHYDRO Database[4], provided by the Everglades Foundation.

Emission factors

Emission factors are derived from the EPA factors for stationary combustion of diesel [37]. Emission factors are converted to kg gallon^{-1} where necessary.

Table 10. Emission factors for stationary combustion of diesel. Source: [37].

Gas	Emission factor	Unit
CO_2	10.21	kg gallon^{-1}
CH_4	0.41	g gallon^{-1}
N_2O	0.08	g gallon^{-1}

Emissions estimate

The total amount of water pumped annually is used to determine the amount of diesel required, under the assumption that every 10^6 liters of water would require 10.16 liters of diesel [18].

[4] *SFWMD Environmental Monitoring web map available here:* https://apps.sfwmd.gov/WAB/EnvironmentalMonitoring/index.html

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = Emission\ factor\ (kg\ gallon^{-1}) \times Diesel\ (gallons\ \ yr^{-1}) \div 1{,}000 \times GWP$$

7. Pesticides

Scope

The production of pesticides requires energy, which is accounted for in this assessment. Emissions in CO_2e are estimated for CO_2, CH_4, and N_2O. Emission factors for CO, NO_x, VOC, and other gases were available for Atrazine 4L but not for any other pesticides and therefore are not reported in this subsection.

Activity data

Farms are assumed to apply the pesticides in Table 11, based on farmer surveys of agricultural management practices on both mineral [42] and organic [43] soils in the EAA.

For pesticides where units are provided in terms of the liquid application required per acre (i.e., gallons and quarts for Roundup, Prowl 3.3 EC, 2,4-D Amine 4, and Asulox LA), these volumes were converted into grams of pesticide applied per acre to be able to apply emission factors. This required information regarding the density of the pesticide, for which we used:

- **Roundup:** 4 lbs. per gallon [44]
- **Prowl 3.3 EC:** 3.3 lbs. per gallon (the name of the product is based on its density)
- **2,4-D Amine 4**: 3.8 lbs. per gallon [45]
- **Asulox LA**: 3.34 lbs. per gallon [46]

The last ripener application for ratoon cane is assumed to only be applied to the final crop cycle, rather than to all sugarcane in ratoon.

Table 11. Pesticide application rate in EAA used in this assessment from [42], [43].

Pesticide name and sugarcane quadrant application	Pesticide type	Amount applied on Organic soil	Amount applied on Mineral soil	Unit
Fallow land				
Roundup	herbicide	4	4	quarts acre^{-1}
Plant cane				
Thimet	insecticide	11.25	11.25	lbs. acre^{-1}
Atrazine 4L	herbicide	4	4	lbs. acre^{-1}
Prowl 3.3 EC	herbicide	0	1	gallons acre^{-1}
Evik	herbicide	0.5	0	lbs. acre^{-1}
2,4-D Amine 4	herbicide	2	2	quarts acre^{-1}
Asulox LA	herbicide	0.5	0.25	gallons acre^{-1}
Ratoon cane				
Atrazine 4L	herbicide	4	4	lbs. acre^{-1}
Prowl 3.3 EC	herbicide	0	1	gallons acre^{-1}
Evik	herbicide	0.5	0	lbs. acre^{-1}
2,4-D Amine 4	herbicide	2	2	quarts acre^{-1}

Asulox LA	herbicide	0.5	0.5	gallons acre^{-1}
Ripener (assumed to be glyphosate)	herbicide	1.5	1.5	oz acre^{-1}

Emission factors

The emission factor for Atrazine is from the GREET1 2020 model [47]. For all others, general herbicides and insecticides defaults were applied, sourced from the GREET "Feedstock Carbon Intensity Calculator (FD-CIC)." For herbicides and insecticides, unlike for Atrazine, emission factors were not provided broken down by gas but rather as a total t CO_2e (Table 12). The "total" estimate of CO_2e from the table below is used as the emission factor.

Table 12. Emission factors for pesticides. Source: [47].

Gas	Emission factor g gas (g-pesticide)$^{-1}$		
	Atrazine	Herbicide	Insecticide
CO_2	14.223	-	-
CH_4	0.0003	-	-
N_2O	0.0203	-	-
Total (CO_2e)	14.97	19.05	21.89

Emissions estimate

To use the "herbicide" emission factor in Table 12, the total amount of herbicide applied per acre was calculated by adding all herbicides other than Atrazine in each land stage category (either fallow, plant cane, or ratoon cane). The total grams of each pesticide applied is then calculated by multiplying the grams per acre by the total number of acres in each of the land stages above (fallow, plant cane, or ratoon cane).

Emissions in t CO_2e were then estimated using the "total" emission factor from Table 12.

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = Emission\ factor\ (g\ CO_2e\ (g - nutrient)^{-1}) \times total\ nutrients\ (g\ \ yr^{-1}) \div 1{,}000{,}000$$

8. Fertilizers

Scope

The production of fertilizers requires energy, which is accounted for here. The analysis also accounts for CO_2 from dolomite application and N_2O emissions (direct as well as indirect emissions from volatilization and leaching/runoff) from N-based fertilizer application. Emissions in CO_2e are estimated for CO_2, CH_4, and N_2O and are reported separately for VOCs, CO, and NO_x.

Activity data

Farms are assumed to apply the synthetic fertilizers listed in Table 13, based on farmer surveys of agricultural management practices on both mineral [42] and organic [43] soils in the EAA. No manure, compost, urine, or dung is assumed to be applied in EAA's sugarcane farms.

Table 13. Assumed fertilizer application in EAA, from [42], [43].

Fertilizer type	Amount applied on		Unit
	Organic soil	Mineral soil	
Land prep			
Slag	3	1.5	U.S. tons acre^{-1}
Dolomite	0	1	U.S. tons acre^{-1}
Plant cane			
N	0	200	lbs. acre^{-1}
P_2O_5/K_2O Mix	50	0	lbs. acre^{-1}
P_2O_5	0	60	lbs. acre^{-1}
K_2O	0	160	lbs. acre^{-1}
Micronutrients	15	20	lbs. acre^{-1}
Ratoon cane			
N	0	200	lbs. acre^{-1}
P_2O5/ K_2O Mix	50	0	lbs. acre^{-1}
P_2O_5	0	60	lbs. acre^{-1}
K_2O	0	160	lbs. acre^{-1}
Micronutrients	30	0	lbs. acre^{-1}

Although micronutrients are applied in sugarcane cultivation in the EAA, emissions from the production of micronutrients are not estimated in this assessment because of the lack of an emission factor available, likely due to the wide range of micronutrient mixes that this fertilizer type may involve. Emissions from slag are also excluded in this assessment because it is a metallurgical solid waste byproduct, and therefore its production emissions are likely not additional. Furthermore, this assessment assumes that dolomite is applied only once per sugarcane cycle, i.e., just on fallow land [48].

It is also recommended that farmers apply 250–500 pounds of elemental sulfur per acre for sugarcane grown on organic soils with a pH higher than 7.5 [49]. This application resulted in sulfate contamination of Everglades waters, including altered native plant communities, increased sulfate reduction, and higher levels of methylmercury [50]. However, this is not accounted for in this analysis given the unknown confirmed levels of what quantities farmers apply and the lack of an emission factor for its production.

Emission factors

a. Production

Emission factors for N, P_2O_5, and K_2O are derived from the GREET1 2020 model [47]. No emission factors for dolomite were provided in the GREET1 2020 model. However, as dolomite is a type of lime (i.e., dolomitic lime), the emission factor for lime from the GREET “Feedstock Carbon Intensity Calculator (FD-CIC)” was used. To estimate the emission factor of the P_2O_5/K_2O fertilizer mix, we used the average of P_2O_5 and K_2O emission factors.

Table 14. Emission factors for fertilizers, derived from the GREET1 2020 model. Dolomite's emission factor is that of lime.

Gas	Emission factor				Unit
	Dolomite	N	P_2O_5	K_2O	
CO_2	-	3.0393	1.8819	0.5165	g gas (g fertilizer)$^{-1}$
CH_4	-	0.0075	0.0034	0.0008	g gas (g fertilizer)$^{-1}$
N_2O	-	0.0020	0	0	g gas (g fertilizer)$^{-1}$
Total (t CO_2e)	9.31	3.79	1.98	0.54	g CO_2e (g fertilizer)$^{-1}$

b. Application

Default factors for the variables listed in the equations below are sourced from the IPCC 2019 refinement to the 2016 Guidelines [51], except for $EF_{Dolomite}$, which is based on Tier 2 factors provided by the United States Annual GHG Inventory [52]. The value for EF1 in Table 15 is the default for "synthetic fertilizer in wet climates."

Table 15. Emission factors and default factors used for synthetic fertilizer application, volatilization, leaching, and runoff [51], [52].

Variable	Default factor	Unit
$EF_{Dolomite}$	0.064	t C (t dolomite)$^{-1}$
EF1	0.016	kg N_2O–N (kg N)$^{-1}$
$Frac_{GASF}$	0.11	kg NH_3–N + NO_x–N volatilized (kg of N applied)$^{-1}$
EF_4	0.010	kg N_2O–N (kg NH_3–N + NO_x–N volatilized)$^{-1}$
$Frac_{LEACH}$	0.24	kg N (kg of N additions)$^{-1}$
EF_5	0.011	kg N_2O–N (kg N leached and runoff)$^{-1}$

Emissions estimate

All emissions from the following calculations are summed to obtain a total estimate of emissions from fertilizer. The approach follows that outlined by the IPCC Guidelines [51].

a. Production

The total kg of fertilizer applied per ha is estimated by multiplying the application rate of each fertilizer by the total area in each planting stage. This weight is then used to calculate the emissions.

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = Emission\ factor\ (g\ CO_2e\ (g - fertilizer)^{-1}) \times total\ fertilizer\ (g\ \ yr^{-1}) \div 1{,}000{,}000$$

b. Application of synthetic fertilizers

1. *Direct emissions – CO_2 emissions from dolomite*

$$Emissions\ (t\ CO_2e\ yr^{-1}) = M_{Dolomite}\ (t\ dolomite\ applied\ \ yr^{-1}) \times EF_{Dolomite}\ (t\ C\ (t\ dolomite)^{-1}) \times \frac{44}{12}$$

2. *N_2O from N-based fertilizers inputs in managed soils*

These emissions are only from N-based fertilizers (i.e., not from P_2O_5 or K_2O), and in this assessment are only relevant for mineral soils since no N-based fertilizers are applied to crops growing on peat soil (Table 13)[18], [53].

Direct emissions:

$$Emissions\ (t\ CO_2e\ yr^{-1}) = F_{SN}(kg\ N\ applied\ \ yr^{-1}) \times EF_1(kg\ N - N_2O\ (kg\ N\ applied)^{-1}) \times \frac{44}{28} \times GWP \div 1000$$

Indirect emissions – Volatilization:

$$Emissions\ (t\ CO_2e\ yr^{-1}) = F_{SN}(kg\ N\ applied\ \ yr^{-1}) \times Frac_{GASF}(kg\ N\ volatilized\ (kg\ N\ applied\ \ yr^{-1})^{-1}) \times EF_4(kg\ N - N_2O\ (kg\ NH_3 - N + NO_x - N\ volatilized)^{-1}) \times \frac{44}{28} \times GWP \div 1000$$

Indirect emissions – Leaching/Runoff:

$$Emissions\ (t\ CO_2e\ yr^{-1}) = F_{SN}(kg\ N\ applied\ \ yr^{-1}) \times Frac_{LEACH}(kg\ N\ lost\ (kg\ N\ applied)^{-1}) \times EF_5(kg\ N - N_2O\ (kg\ N\ lost)^{-1}) \times \frac{44}{28} \times GWP \div 1000$$

Combining the above equations from indirect and direct emissions (with units listed above) following IPCC Guidelines leads to:

$$Emissions\ (t\ CO_2e\ yr^{-1}) = F_{SN} \times \frac{44}{28} \times GWP \div 1000 \times (EF_1\ + (Frac_{GASF} \times EF_4) + (Frac_{LEACH} \times EF_5))$$

9. Pre-harvest fire sugarcane crop management

Scope

Sugarcane is burned pre-harvest to facilitate and increase the efficiency of the harvesting process [19], [25], [36], [54]. Emissions are estimated in CO_2e for CH_4 and N_2O and are reported separately for NO_x. Emissions from CO_2 are assumed to be zero, following IPCC guidance, as carbon is re-sequestered during the next growth cycle [55]. Emissions from VOCs and CO are estimated to be rapidly converted to CO_2 and therefore their emissions are also assumed to be zero [25].

Activity data

In the 2018-2019 season, 3% of burn permits for sugarcane in Florida were denied [56]. For conservative accounting purposes we therefore assume that 3% of the EAA's sugarcane area is not burned before harvest and that 97% of the area in planted cane and ratoon cane (Table 2. Estimated area of various land uses in the EAA.) is assumed to be burned. Organic certified sugarcane is not burned, yet this assessment assumes no organic sugarcane is grown in the area based on state surveys [57].

Emission factors

The defaults provided in Table 16 are sugarcane values from the US EPA's State Inventory Projection Tool [58], the US EPA's GHG Inventory Agriculture Methods [52], and Mugica-Álvarez et al. [59].

Table 16. Emission factors used to estimate emissions from sugarcane pre-harvest crop residue burning [52], [58], [59].

Variable	Description	Default factor	Source
RCR	t residue (t crop production)$^{-1}$	0.2	State Inventory Projection Tool
FB	proportion of residue biomass consumed, unitless	1	State Inventory Projection Tool
DMF	t residue dry matter (t residue biomass)$^{-1}$	0.62	State Inventory Projection Tool
BE	proportion of dry biomass exposed to burning that burns	0.93	State Inventory Projection Tool
CE	proportion of C or N released with respect to the total amount of C or N in burned material, unitless	0.88	State Inventory Projection Tool
F_C	t C (t residue dry matter)$^{-1}$	0.424	State Inventory Projection Tool
F_N	t N (t residue dry matter)$^{-1}$	0.004	State Inventory Projection Tool
CH_4-C emission ratio	t CH_4-C released (t C released)$^{-1}$	0.005	GHG Inventory: Agriculture Methods
CH_4-C mass ratio	t CH_4 (t CH_4-C)$^{-1}$	1.33	GHG Inventory: Agriculture Methods
N_2O-N emission ratio	t N_2O-N released (t N released)$^{-1}$	0.007	GHG Inventory: Agriculture Methods
N_2O-N mass ratio	t N_2O (t N_2O-N)$^{-1}$	1.57	GHG Inventory: Agriculture Methods

Emissions estimate

The approach used follows that outlined in the US EPA's State Inventory Projection Tool and GHG Inventory methods for agriculture [52], [58]. Units for variables are listed in the table above.

$$Emissions_i\ (t_i\ \ yr^{-1}) =\ Crop\ production\ (t\ \ yr^{-1}) \times RCR \times FB \times DMF \times BE \times CE \times F_i$$

where *i* is either C or N. Emissions for each gas are then calculated:

$$Emissions_g(t\ CO_2e\ \ yr^{-1}) =\ Emissions_i\ \times emission\ ratio_g \times mass\ ratio_g \times GWP_g$$

where *g* is either CH_4-C, CO-C, N_2O-N, or NO_x-N, matched with either the relevant C or N value for $Emissions_i$.

10. N_2O emissions from crop residues

Scope

The majority of sugarcane biomass is expected to be burned before harvest, yet the burning efficiency of aboveground biomass is not 100%, leaving behind crop residues that contribute to N_2O emissions.

Additionally, a portion of crop residues is belowground biomass that generally does not burn but may still release substantial amounts of N_2O. Emissions estimated in this category include direct N_2O emissions as well as indirect emissions from volatilization and leaching/runoff from both above and belowground biomass left behind as crop residues.

The IPCC describes other sources of N_2O from soils other than crop residue inputs (or N-based fertilizers, described above). However, those are excluded from this component because:

- N_2O from managed peat is already captured in the peat oxidation emissions estimate described above, which relies on a published EAA study. Including them here would incur in double counting of emissions.
- Emissions from N in mineral soils because of the soil C loss due to changes to land use or management are also excluded, changes in land use management do not apply to this EAA assessment.

The default factors to estimate crop residues from rotational crops (i.e., flooded rice and other crops) are the same factors included in this section and are not repeated in Section 3.8.

Activity data

The amount of crop residue is estimated using default factors from the IPCC and EPA in the tables Table 17 and Table 18, based on the yields presented in section 3.1 of this Appendix.

a. Estimating crop residues and F_{CR}

F_{CR} is the final estimate of crop residues, calculated using the equations below with variables listed in the table below. $AGR_{(T)}$, $BGR_{(T)}$, $AG_{DM(T)}$, and $Crop_{(T)}$ in the table below are also calculated using these equations. These equations are adapted from Equation 11.6 in the updated IPCC 2019 Guidelines [51].

1. $Crop_{(T)} = Yield\ fresh_{(T)} \times DRY$
2. $AG_{DM(T)} = Crop_{(T)} \times R_{AG(T)}$
3. $AGR_T = AG_{DM(T)} \times Area_{(T)} \times Frac_{Renew(T)}$
4. $BGR_T = \left(Crop_{(T)} + AG_{DM(T)}\right) \times RS_{(T)} \times Area_{(T)} \times Frac_{Renew(T)}$
5. $F_{CR} = \sum_T \{[AGR_{(T)} \times N_{AG(T)} \times (1 - Frac_{Remove(T)} - Frac_{Burnt(T)} \times C_f)] + [BGR_{(T)} \times N_{BG(T)}]\}$

Default values are sourced from the IPCC 2019 guidelines, the EPA State Inventory Projection Tool, and the EPA GHG Inventory [51], [52], [58].

Table 17. Default factors for estimating crop residues (CR) for any given crop (assigned variable T) and calculated activity data from [51], [52], [58]. For transparency, the numbers in this table show the calculated values including all significant figures. Note that for reporting purposes beyond this report, these figures should be rounded to two or three significant figures to avoid giving a false sense of accuracy in the assessment.

Variable	Description	Value, sugar	Value, rice	Value, other crops	Source and Notes
Yield Fresh$_{(T)}$	Harvested fresh yield for crop T, kg fresh weight ha^{-1}	98,411	14,952	23,788	Table 3, converted into kg ha^{-1}

DRY	Dry matter fraction of harvested crop T, kg d.m. (kg fresh weight)$^{-1}$	0.62	0.91	0.08	State Inventory Projection Tool (sugar and rice) or EPA GHG Inventory (“vegetables” value for other crops)
$Crop_{(T)}$	Harvested annual dry matter yield for crop T, kg d.m. ha^{-1}	61,015	13,606	1,903	*calculated from equations and values above*
$R_{AG(T)}$	Ratio of aboveground residue dry matter to harvested yield	0.2	1.4	0.708	State Inventory Projection Tool (sugar and rice) or EPA GHG Inventory (“vegetables” value for other crops)
$AG_{DM(T)}$	Above-ground residue dry matter for crop T, kg d.m. ha^{-1}	12,203	19,048	1,347	*calculated from equations and values above*
$Area_{(T)}$	Total annual area harvested of crop T, ha yr^{-1}	145,682	3,288	3,963	Areas from Section 3.1 and 3.8 converted to ha
$Frac_{Renew\ (T)}$	Fraction of total area under crop T that is renewed annually, dimensionless. For countries where pastures are renewed on average every X years, FracRenew = 1/X. For annual crops FracRenew = 1	1	1	1	IPCC 2019
$AGR_{(T)}$	Annual total amount of above-ground crop residue in dry matter (d.m.) for crop T, kg d.m. yr^{-1}	1,777,747,556	62,632,205	5,339,078	*calculated from equations and values above*
$RS_{(T)}$	Ratio of below-ground root biomass to above-ground shoot biomass for crop T, kg d.m. ha^{-1} (kg d.m. ha^{-1})$^{-1}$	0.8	0.16	0.22	IPCC 2019, Perennial grasses, rice, or generic crop

$BGR_{(T)}$	Annual total amount of belowground crop residue for crop T, kg d.m. yr^{-1}	8,533,188,267	17,179,119	2,833,633	*calculated from equations and values above*
$N_{AG(T)}$	N content of above-ground residues for crop T, kg N (kg d.m.)$^{-1}$	0.004	0.0072	0.01	State Inventory Projection Tool (sugar and rice) or EPA GHG Inventory ("vegetables" value for other crops)
$Frac_{Remove(T)}$	Fraction of above-ground residues of crop T removed annually for purposes such as feed, bedding and construction, dimensionless.	0	0	0	IPCC 2019, assumed to be zero - survey of experts in-country is required to obtain data
$Frac_{Burnt(T)}$	Fraction of annual harvested area of crop T burnt, dimensionless	1	0	0	Assumed 100% of sugarcane area burnt and 0% of rice and other crops
C_f	Combustion factor, dimensionless	0.88	0.88	0.85	State Inventory Projection Tool (sugar and rice) IPCC 2019 (other crops)
$N_{BG(T)}$	N content of below-ground residues, %	0.004	0.0072	0.01	Assumed to be same as $N_{AG(T)}$ following EPA
F_{CR}	Annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually, kg N yr^{-1}	34,986,072	574,642	81,727	*calculated from equations and values above*

Emission factors

Emission factors from direct emissions (Table 18) and indirect emissions (Table 19) from leaching and runoff are provided below. For $EF_{1(FR)}$, the value for continuous flooding is applied.

Table 18. Emission factors to estimate direct N_2O emissions from crop residues. Source: [51].

Variable	Description	Default factor
EF_1	EF_1 for N additions from synthetic fertilizers, organic amendments and crop residues, and N mineralized from mineral soil as a result of loss of soil carbon [kg N_2O–N (kg N)$^{-1}$]	0.01
EF_1	synthetic fertilizer inputs in wet climates, kg N_2O–N (kg N input)$^{-1}$	0.016
EF_1	inputs other than synthetic fertilizer in wet climates, kg N_2O–N (kg N input)$^{-1}$	0.006
$EF_{1(FR)}$	emission factor for N2O emissions from N inputs to flooded rice, kg N_2O–N (kg N input)$^{-1}$ (flooded rice)	0.003

Table 19. Emission factors to estimate indirect N_2O emissions from leaching/runoff from crop residues, from [51].

Variable	Description	Default factor, sugar	Default factor, rice	Default factor, other crops
$Frac_{LEACH-(H)}$	Fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$	0.24	0.24	0.24
EF_5	Emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$	0.011	0.011	0.011

Emissions estimate

a. Direct emissions from F_{CR}

These equations are adapted from Equation 11.1 in the updated IPCC 2019 Guidelines.

$$Emissions\ of\ N_2O\ (t\ CO_2e\ \ yr^{-1}) = F_{CR} \times EF_1 \times \frac{44}{28} \div 1{,}000$$

Or, in the case of rice:

$$Rice\ emissions\ of\ N_2O\ (t\ CO_2e\ \ yr^{-1}) = (F_{CR})_{FR} \times EF_{1FR} \times \frac{44}{28} \div 1{,}000$$

b. Indirect emissions from leaching/runoff

This equation is adapted from Equation 11.10 in the updated IPCC 2019 Guidelines.

$$Emissions\ of\ N_2O\ (t\ CO_2e\ \ yr^{-1}) = F_{CR} \times Frac_{LEACH-(H)} \times EF_5 \times \frac{44}{28} \div 1{,}000$$

11. Rotational crops

Scope

Although the EAA has a wide variety of crops that are grown in rotation with sugarcane, two categories are accounted for in this analysis – flooded rice and other cropland. Emissions from equipment, fertilizer application and production, pesticide production, and crop residues are estimated for both rice and other crops (assumed to be predominantly vegetables) that are grown in rotation with sugarcane. For flooded rice, we also account for CH_4 emissions from flooding and N_2O emissions from flooded peat. Therefore, estimates of CO_2, CH_4, and N_2O (in addition to VOCs, CO, and NO_x reported separately) are included depending on the emissions category. Generally, estimating emissions from each of these sources follows the approaches outlined above and therefore only the differences in activity data and approach are presented in this section.

Activity data

a. Area

The average annual area under flooded rice is estimated to be 8,125 acres based on the spatial analysis described above. All rice is assumed to be cultivated in organic soils. The average annual area planted with other crops (including fruit, vegetables, nuts, beans, hay, cotton, grain, and sod) is 9,792 acres (Table 2), covering organic and inorganic soils (Table 2).

Some rice and other crops are grown in rotation together in the fallow year for sugar, i.e., vegetables could be grown in the winter and rice in the summer on the same area of land [8], [60]. As a result, the estimate of land dedicated to other crops may be underestimated. However, given the lack of specific information on where this happens, it is an approach that ensures double-counting emissions is avoided. Furthermore, there are minor areas within the EAA that are not cultivated for sugarcane and exclusively grow either rice or other crops every year; these are not included here as the scope of this analysis is the EAA farmland used for sugarcane cultivation, and only non-sugarcane crops grown on sugarcane farms as rotational crops in the fallow quadrant are part of this assessment.

b. Equipment

Due to the lack of detailed data on equipment used for rice and other crop harvesting in the EAA, the same equipment that is used on fallow land to prepare the land for sugarcane is assumed to be used for rice and other crops, in addition to the equipment needed for fertilizer/pesticide application and harvest and excluding equipment that is clearly specific to sugarcane harvest (e.g., a cane wagon). A conservative approach is adopted to only include equipment that would be essential, although this may exclude some steps where equipment is used in land preparation, maintenance, and harvest. Therefore, it is assumed that there is no aerial application of fertilizers or pesticides.

c. Fertilizers

EAA's flooded rice is assumed to go through the same fertilizer application process as sugarcane grown in organic soils. For other crops, fertilizer inputs in organic soils are derived from median values of best management practices recommended for celery, sweet corn, endive, escarole, lettuce, and radish grown in Florida [61]. In other crops grown in mineral soils, median values of recommended inputs for a range of vegetables are taken based on recommended nutrient management [62]. It is assumed that there is no tractor spreading of slag or dolomite.

Table 20. Fertilizer applied to vegetables in organic soils in Florida, representative of the "other crops" category [61].

Organic soils	N (lb. acre^{-1})	P_2O_5 (lb. acre^{-1})	K_2O (lb. acre^{-1})
Celery	two applications of either 40, 60, or 30 depending on harvest time	260	300
Sweet corn	40	160	80
Endive	60	200	200
Escarole	60	200	200
Lettuce	60	200	200
Radish	0	100	100
Median	**60**	**200**	**200**

Table 21. Fertilizer applied to vegetables in mineral soils in Florida, representative of the "other crops" category [62].

Mineral soils	N (lb. acre^{-1})	P_2O_5 (lb. acre^{-1})	K_2O (lb. acre^{-1})
Tomato, pepper, potato, celery, sweet corn, crisphead lettuce, endive, escarole, romaine lettuce, and eggplant	200	0-150	0-150
Broccoli, cauliflower, Brussels sprouts, cabbage, collards, Chinese cabbage, and carrots	175	0-150	0-150
Radish and spinach	90	0-120	0-120
Median	**175**	**75**	**75**

d. Pesticides

Due to limited information, pesticide application for both rice and other crops is assumed to require the same inputs as sugarcane. The final application of Roundup, which is used as a ripener before sugarcane harvest, is excluded from the assessment.

e. Crop residues

See section 3.7 for all default values used to estimate F_{CR}.

f. Flooded rice fields

Rice is assumed to be cultivated for 7 months (March to September), which is the equivalent of 214 days [30].

Emission factors

Emission factors for each emissions source are already included in the sections above, except those related to flooding rice fields.

a. CH_4 emissions from flooded rice fields

Defaults are derived from the IPCC 2019 Guidelines [55], included in Table 22.

Table 22. Emission factors for flooded rice fields [55].

Variable	Description	Default factor
SF_w, continuous flooded	Scaling factor to account for the differences in water regime during the cultivation period	0.6
SF_p, aggregated	Scaling factor to account for the differences in water regime in the pre-season before the cultivation period	1.22
EF_c, North America	Baseline emission factor for continuously flooded fields without organic amendments (kg CH_4 ha^{-1} d^{-1})	0.65
ROA	Application rate of organic amendment in dry weight, tonne ha^{-1}, assumed to be 0 given no organic amendments applied	0
C_{FOA}	Conversion factor for organic amendment, not applicable given no organic amendments applied	N/A

b. N_2O emissions from flooded rice fields

The default value for N_2O emissions from flooded peat is 48 g N_2O-N m^{-2} day^{-1} [12]. This value is converted to a per hectare value.

Emissions estimate

For both rice and other crops, emissions from each category other than flooded rice are estimated using the methods and assumptions described in the above sections. CH_4 and N_2O emissions from rice are estimated using the equations below.

a. CH_4 emissions from flooded rice fields

These equations are adapted from Equations 5.1, 5.2. and 5.3 in the updated IPCC 2019 Guidelines. Definitions for the variables are included in the table above. The emission factor is first estimated as follows:

$$EF(\text{kg}\ CH_4\ ha^{-1}d^{-1}) = EF_c \times SF_w \times SF_p \times SF_o$$

where SF_o is a scaling factor, varying by both type and amount of organic amendment applied, equal to $(1 + \sum_i ROA_i \times CFOA_i)^{0.59}$ and in this case equal to 1 given no organic amendments are assumed to be applied.

Emissions from CH_4 are then estimated as:

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = \sum EF \times time\ (days\ of\ cultivation\ period\ \ yr^{-1}) \times\ Area\ of\ harvested\ rice\ (ha) \times 10^{-3}) \times GWP_{CH_4}$$

b. N_2O emissions from flooded peat

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = Area\ of\ harvested\ rice\ (\ m^2) \times time\ (days\ of\ cultivation\ period\ \ yr^{-1}) \times\ Emission\ factor\ (g\ N_2O - N\ m^{-2}d^{-1}) \times \frac{44}{28} \times GWP_{N_2O}$$

12. Transport of harvested sugarcane to the mill

Scope

The transportation of sugarcane to the mill for processing is assumed to require diesel. Emissions from mobile combustion are estimated for CO_2, CH_4, and N_2O.

Activity data

The average distance between farms and sugarcane mills in the EAA was estimated using data on EAA Permit Application Boundaries from the SFWMD [63] and GPS points of mill locations retrieved from Google Maps. The four mills considered were the Okeelanta Sugar Mill, the Osceola Farms Co. Mill, the U.S. Sugar Mill, and the Sugar Cane Growers Cooperative of Florida Mill. The Okeelanta and Osceola mills are both run and operated by the same parent company, Florida Crystals.

From the EAA Permit Boundaries dataset, only areas that fell under the “Agriculture” or “Sugarcane” land use categories were considered, and points were generated for each of these farms (representing the central location within the farm) using GIS software. If the farm was owned by one of the milling companies mentioned above, the average distance between that farm and its respective mill was used. For all other farms, the distance between the farm and the closest mill was used for conservative purposes. An average distance of 9.45 miles was then obtained from all farm-to-mill distance estimates.

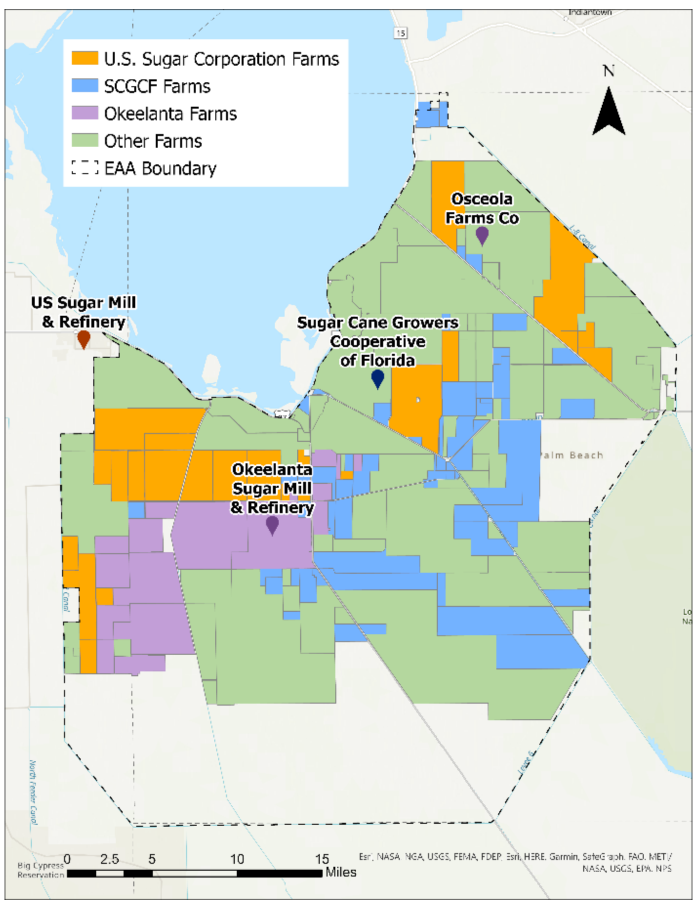

Figure 6. Map of EAA farms boundaries, mills, and refineries [63].

Based on the average yield in Table 3, the tons of sugarcane transported per truck [36], and the average gas mileage of a Class 8 truck [64], the average amount of diesel consumed is estimated. Values for Class 8 trucks were used because sugarcane is transported to mills in highway trailers [36], which is assumed to be a large truck that can have a trailer attached (therefore, a Class 8 truck) capable of transporting 20 tons per load.

Table 23. Default values to estimate emissions from transportation to mill. Source: [36], [64].

Default	Value	Unit
Tons of sugarcane transported per truck	20	US tons/load
Average miles per gallon of Class 8 truck	6	miles/gallon diesel

Emission factors

Emission factors are derived from the US EPA defaults for heavy-duty vehicles, assuming diesel fuel consumption [37].

Table 24. Emission factors for diesel for heavy-duty vehicles. Source: [37].

Gas	Emission factor	Unit
CO_2	10.21	kg gallon^{-1}
CH_4	0.0095	g mile^{-1}
N_2O	0.0431	g mile^{-1}

Emissions estimate

a. CO_2 emissions

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = \ Emission\ factor\ (kg\ gallon^{-1}) \times Diesel\ (gallons\ \ yr^{-1}) \div 1{,}000$$

b. N_2O and CH_4 emissions

$$Emissions\ (t\ CO_2e\ \ yr^{-1}) = \ Emission\ factor\ (g\ mile^{-1}) \times Distance\ (mile\ yr^{-1}) \div 1{,}000{,}000 \times GWP$$

13. Processing

There are three main sources of GHG emissions from sugarcane processing, namely raw cane processing, transportation to the refinery, and refined sugar processing. Emissions from these steps have been excluded from the estimates of overall GHG emissions from sugarcane in the EAA due to (1) the fact that mills and refineries located in Florida are powered by the renewable (i.e., carbon-neutral) energy generated from bagasse combustion, and (2) a lack of sufficient data on the refinery locations and the proportion of unrefined sugar being exported to refineries outside the EAA.

Raw and refined sugar processing

Sugar mills burn bagasse (the woody, fibrous by-product from sugarcane milling) and use it to generate the heat and electricity required for milling and refining (e.g., for mill grinding to separate sugar juice from the stalk, boiling to extract crystals, cooling, etc.). In the EAA, the available bagasse allows the mills/refineries to be self-sufficient and electricity that is not used during sugar processing is sold to the public grid. For example, the Sugarcane Growers Cooperative of Florida notes they produce enough additional energy to power 79,000 homes each year [65], while U.S. Sugar and the Florida Crystals

Corporation both highlight that they produce enough energy to power all their sugar operations [66], [67]. It is also estimated that over 100 kWh/tonne cane is exported to power plants in modern sugarcane mills [68], [69], indicating a surplus of energy production once all needs of the mills and refineries have been met. Packaging also typically happens within refineries and therefore it is assumed that all energy demand for packaging is also met through bagasse combustion. Therefore, emissions from processing are negligible as biomass burning is considered renewable (carbon-neutral) energy.

Transport to refinery

In some cases, sugar is milled and refined at the same (or adjacent) location in Florida. For example, the Florida Crystals and U.S. Sugar mills also operate refineries directly adjacent to the mills. In other cases, such as with the ASR Group (owned by Florida Crystals and Sugarcane Growers Cooperative in Florida), raw sugar is exported to be refined in either one of six different locations in North America or Europe. However, the ASR group also sources and mills sugarcane from Belize and Mexico and the proportion of sugar being exported long distances from the EAA specifically is unknown.

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