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LCA FOR AGRICULTURE

Assessing climate impacts of agroforestry system in LCA: case study in Zambia

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Abstract

Purpose Agroforestry systems have the potential to reduce the carbon footprint (CF) of food production. One of the advantages of these systems is carbon removal from the atmosphere to biogenic carbon of trees. Nevertheless, there is not a common agreement on the method to include the climatic benefits of agroforestry systems in life cycle assessment (LCA). This study aims to evaluate methods for including biogenic carbon in the LCA of agroforestry systems.
Methods We studied three different maize production systems in Zambia: Low-input, High-input, and Agroforestry scenario. In the Agroforestry scenario, we studied a maize–*Faidherbia albida* system by investigating three methodological approaches with a functional unit (FU) of 1 ha. In Methodological Approach 1, biogenic carbon in the above- and belowground biomass of trees in the agroforestry system was considered as a temporary carbon dioxide (CO_2) storage via correction flow. In Methodological Approach 2, the biomass of trees was used as an energy source. In Methodological Approach 3, the mass balance principle was employed. The system expansion method was utilized to make each production system comparable. Three sensitivity analyses with a FU of 1000 kg of dry matter maize grain were also conducted following the methodological approaches.
Results and discussion The Agroforestry scenario had the lowest CF in all methodological approaches and in all sensitivity analyses when the maize grain yield level was the same as reported in the literature. Yet, uncertainty levels were high, as an IPCC tier 1 method was used. It was found that the biogenic carbon of the trees in agroforestry systems can be included in LCA by the currently available methods. The mass balance principle was a practical method for including the biogenic carbon of the trees in LCA. System expansion was another feasible method, wherein processes are added to the compared systems until they include the provision of the same functions.
Conclusions Biogenic carbon in the biomass of trees in agroforestry systems can greatly contribute to decreasing the CF if it is considered in LCA. If the FU and allocation methods are selected accordingly, the biogenic carbon can be effectively included in LCA. Based on the results of this case study, the maize–*F. albida* agroforestry system has the potential for decreasing the CF of maize production in Zambia.

Keywords Agroforestry · LCA · Biogenic carbon · Zambia · System expansion · Temporary storage · Mass balance principle

1 Introduction

In 2020, Africa experienced a significant contribution — 51% — from its agriculture, forestry, and other land use (AFOLU) sectors to the total anthropogenic greenhouse gas (GHG) emissions (FAOSTAT 2023). Of this, agriculture alone contributed 23%. In comparison, agriculture contributed 12% to the global anthropogenic GHG emissions. In Africa in 2020, agriculture accounted for 45% of the methane (CH_4) and 76% of the nitrous oxide (N_2O) emissions

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(FAOSTAT 2023). These figures highlight the substantial impact of agriculture on Africa's GHG emissions, particularly in terms of methane and nitrous oxide, underscoring the need for targeted mitigation strategies in the agricultural sector to address climate change.

Methods like Climate-Smart Agriculture, which encompasses measures such as soil erosion prevention, organic residue recycling, and agroforestry implementation, present viable solutions for agriculture to mitigate to climate change (Anuga et al. 2020). In particular, agroforestry — a centuries-old practice in Africa — has garnered attention due to its multiple benefits over industrial agricultural systems (Nair 1993; Rosati et al. 2021).

The advantages of agroforestry are multi-faceted, including enhancing soil organic carbon (SOC) levels (Cardinael et al. 2018), increasing energy efficiency (Pérez Neira 2016), and aiding in climate change mitigation (Blaser et al. 2018; Feliciano et al. 2018; Kay et al. 2019). Because of the benefits, agroforestry systems have also been studied in industrialized countries like Finland (Heimsch et al. 2023).

Life Cycle Assessment (LCA) has been a primary methodology for studying the environmental impacts of agriculture. The advantages of LCA are that it can include all the environmental impacts of the system during the whole life cycle of the process of the product. Also, LCA can be used to compare different systems and production methods. However, its application has mainly been within the context of food production in industrialized regions. Studies in Africa have been limited, with only 199 peer-reviewed LCA studies conducted by 2020; this is considerably lower than in other continents (Karkour et al. 2021).

While LCA studies on agroforestry exist, challenges remain. Plassmann and Norton (2017) identified perennial tree-related issues in LCAs, such as (i) differentiating between carbon stocks and sequestration and the non-permanence of removals; (ii) the focus is generally only on the carbon in the studied product, but not in the biomass that can be part of the production; (iii) the allocation of removals between co-products and the main products can be difficult; and (iv) failure to include the lifespan of the entire system in the study. To address these concerns, these authors provided the following recommendations: (i) carbon sequestration cannot be included in LCA; (ii) the whole life cycle of the product should be covered; and (iii) the biogenic carbon should be included when a land use change (LUC) is increasing the total carbon stock of the system, fossil fuels are replaced by biogenic carbon, or biogenic carbon is stored for more than 100 years.

Although Plassmann and Norton (2017) recommend that biogenic carbon should be included in LCA when it is stored for over 100 years, the trees in agroforestry systems are not always standing in the field for this long. Therefore, the benefits of carbon sequestration of the trees standing in the field for a few decades cannot be realized in LCA studies. Nevertheless, if the aforementioned recommendations cannot be utilized to include the biogenic carbon in LCA, Plassmann and Norton (2017) recommend utilizing other mechanisms to encourage increasing carbon stocks. For example, JRC-IES (2010) and Leinonen (2022) provide methods for including a shorter time of carbon storage in LCA.

This study aims to explore Plassmann and Norton's (2017) recommendations and analyze JRC-IES's (2010) temporary carbon storage method and Leinonen's (2022) mass balance principle. We use a case study from the Central Province of Zambia to demonstrate the integration of biogenic carbon in agroforestry systems within LCAs. In Sub-Saharan Africa, mineral fertilizers are deemed vital for combating rural poverty and hunger (Jayne and Rashid 2013). Accordingly, Zambia has seen a rise of 427% in mineral fertilizer consumption from 2003 to 2023 (Ministry of Agriculture (MoA) and CSO 2003, 2023). However, with increasing GHG emissions and the need for cost-effective yield enhancement methods (Yengwe et al. 2018), this study aims to find ways to reduce the carbon footprint (CF) of agriculture by comparing different maize production systems in Zambia. Moreover, the findings and methodologies from this study could guide similar LCAs across various continents.

2 Methods

This study considers the biomass of the trees in agroforestry by three methods. (1) Temporary carbon storage, where the correction flow for temporary CO_2 storage is studied (JRC-IES 2010). This implies that we assume both the above- and below-ground biomass of these trees to serve as carbon storage for the duration they stand in the field. (2) Energy from the above-ground biomass of the trees in agroforestry utilized to decrease the level of the charcoal use. (3) Carbon balance of the system through the mass balance principle (Leinonen 2022). To cover the whole life cycle of the product, a maize grain production system is studied for 1 year, which considers the life cycle from the cradle to the farm gate, as well as the full 60-year harvest cycle and the life cycle of the trees in the agroforestry system. We utilize the system expansion method to account for emission reductions from the agroforestry system's trees. Additionally, we conduct sensitivity analyses focusing on the allocation of carbon removals by trees to the primary product. Through these assumptions, we analyze both the recommendations of Plassmann and Norton (2017) and the effects of carbon storage lasting less than 100 years.

2.1 Scenarios

This case study examined three maize production systems in Zambia's Central Province, located in agro-ecological zone 2a (Mtambo et al. 2007) and within the tropical montane climate zone (IPCC 2019). Given the absence of primary data from the fields, soils were assumed to be high activity clay soils, as the soils in this agro-ecological zone are mostly Lixisols, Luvisols, Alisols, Acrisols, Leptosols, and Vertisols (Sichinga 2013). According to a national survey report (IAPRI 2016), agricultural practices in the Central Province usually exclude the application of manure to fields. However, we assumed that crop residues remained in the fields after harvest.

The Low-input scenario (Fig. 1) reflects the typical practices of Zambia's smallholder farmers, who cultivate maize as a monoculture using only seeds for sowing and no other external inputs (IAPRI 2016).

In the High-input scenario (Fig. 2), monoculture maize is cultivated using both mineral fertilizers and seeds for sowing. According to 2015 data from Zambia's Central Province, farmers applied 148 kg/ha of basal fertilizer annually (10% nitrogen, 20% phosphorus, 10% potassium) and 149 kg/ha of urea-based top dressing (46% nitrogen) (IAPRI

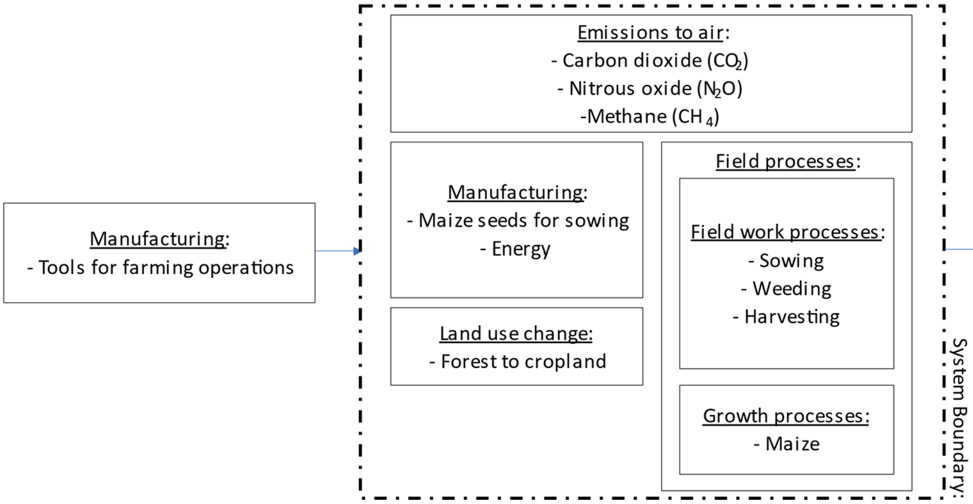


Fig. 1 Flow diagram of the Low-input scenario. Arrows represent flow into and out from the system. Dotted line represents the system boundary of the study. Boxes represent the life cycle stages

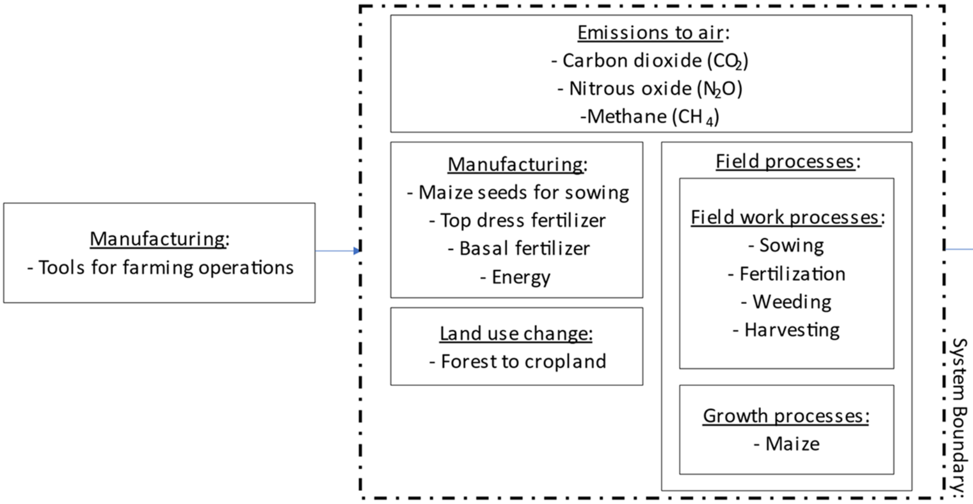


Fig. 2 Flow diagram of the high-input scenario. Arrows represent flow into and out from the system. Dotted line represents the system boundary of the study. Boxes represent the life cycle stages

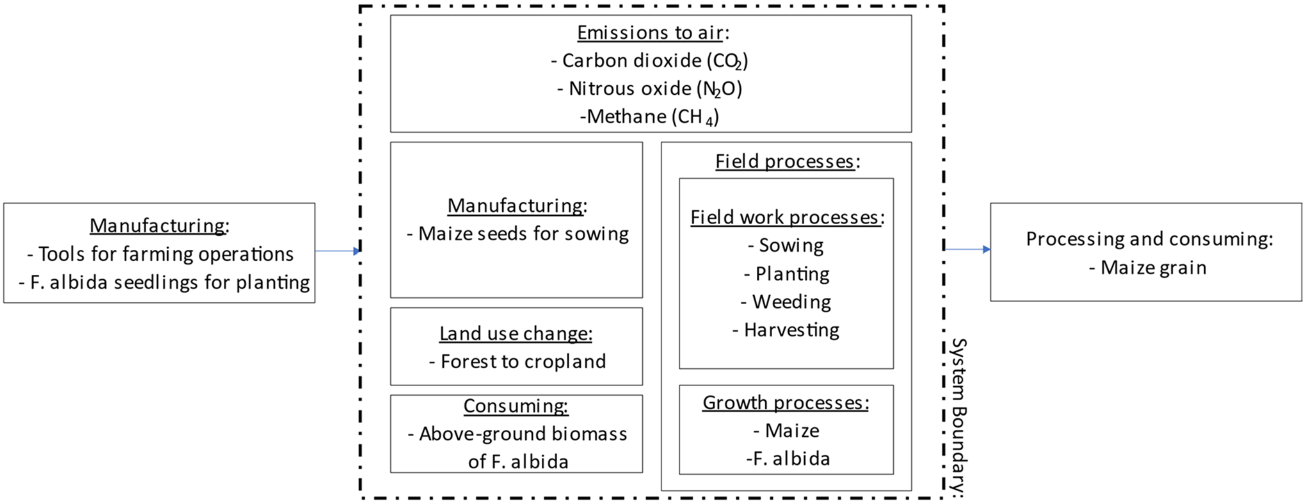


Fig. 3 Flow diagram of the agroforestry scenario. Arrows represent flow into and out from the system. Dotted line represents the system boundary of the study. Boxes represent the life cycle stages

2016, p. 55), totaling 83 kg N/ha per year. We calculated the emissions from producing and transporting these fertilizers using the ecoinvent database (Wernet et al. 2016).

The Agroforestry scenario (Fig. 3) involves a maize–*Faidherbia albida* agroforestry system. The only external inputs are maize seeds for sowing, similar to the Low-input scenario. Though, in this scenario, *F. albida* trees add approximately 49.13 (± 0.57) kg N/ha annually to the field through dead organic matter (Yengwe et al. 2018).

In all three scenarios, field operations are conducted without machinery or animals, relying exclusively on human labor. Also, the harvesting of the trees is assumed to be done by human labor. The system boundary of the study was set from the cradle-to-farm gate, excluding any processes beyond the farm gate, like maize grain processing or consumption.

2.2 Scenario data

2.2.1 Yields

The national survey report (IAPRI 2016, p. 31) recorded yield levels of 1470 kg dry matter per ha (kg DM/ha) for the Low-input scenario and 2200 kg DM/ha for the High-input scenario, assuming a moisture content of 13%.

In the Agroforestry scenario, Yengwe et al. (2018) estimated yields of 2720 kg DM/ha. This was calculated by averaging yields near and under the canopies of 8- and 15-year-old *F. albida* trees. Yields were higher (2900 kg DM/ha) under the canopy compared to outside the canopy (300 kg DM/ha). Calculating the area under (0.93 ha) and outside (0.07 ha) the canopy for 1 ha and considering the tree boles' area (0.0011 ha) from 100 trees, the overall yield for the Agroforestry scenario was established to be 2720 kg DM/ha.

2.2.2 Above- and below-ground biomass of Agroforestry scenario

In the Agroforestry scenario, *F. albida* trees were planted in a 10 m × 10 m grid and thinned over time for 25 trees per hectare, as described by Garrity et al. (2010). Assumptions based on this practice included tree thinning at ages 20, 30, 40, and a complete harvest at age 60 years, with 25 trees thinned at each interval. The total harvest cycle of *F. albida* in the Agroforestry scenario was assumed to be 60 years, as *F. albida* provides nitrogen-rich leaf litter for over 60 years (Coulibaly et al. 2017).

In studying the bole diameter at breast height (DBH) of *F. albida*, Depommier and Detienne (1996, cited in Barnes and Fagg 2003) found an annual growth rate of 3 cm. Commonly, *F. albida* achieves a DBH of 1 m (Wood 1992); Umar et al. (2013) observed an average DBH of 0.99 m in 25–100-year-old *F. albida* trees in Zambia. For this study's model, we assumed an annual DBH growth of 3 cm for *F. albida* for the first 33 years, with no significant growth afterward. Thus, we assumed DBH values of 0.60 m, 0.90 m, 0.99 m, and 0.99 m at harvest ages of 20, 30, 40, and 60 years, respectively, with the DBH remaining constant after 33 years.

To determine the above-ground biomass of *F. albida*, the equation from Beedy et al. (2016) was followed:

$$Ln(TAGB) = -2.68 + 2.5 \times Ln(DBH) \tag{1}$$

where:

Ln	natural logarithm
TAGB	total above-ground biomass, kg DM/tree

To estimate the below-ground biomass of the *F. albida* trees, the method proposed by the UNFCCC (2006) was used:

$$\begin{aligned}\text{Below} - \text{ground biomass}(td.m.\text{per ha}) \\ = exp(-1.085 + 0.9256 \times Ln(E))\end{aligned} \tag{2}$$

where:

E Estimate of above-ground biomass (t DM per ha)

The fraction of carbon in the above- and below-ground biomass of *F. albida* was assumed to be 0.5 as recommended by UNFCCC (2006).

2.3 Methodological approaches and sensitivity analyses

Three different methodological approaches were studied. In all approaches, different scenarios were made comparable by using the system expansion method, where processes are added to the compared systems until they include the provision of the same functions (ISO/TR 14049:2012 (2012); Heijungs et al. 2021). The system expansion was used by adding functions into the systems and comparing the impacts of the whole system. As the maize grain yield levels were lower in the Low- and High-input scenarios compared with the Agroforestry scenario, there were maize imports from other sources to the Low- and High-input scenarios to meet the same maize grain level in all scenarios in Methodological Approaches 1, 2, and 3.

Methodological Approach 1 This approach investigates the Agroforestry scenario, focusing on the CF effects of temporary CO_2 storage due to the biogenic carbon in the above- and below-ground biomass of *F. albida* trees. The biomass of these trees was not utilized post-harvest, as the trees are assumed to be used in a manner that the carbon is released to the atmosphere within a short time after harvest. Therefore, the temporary CO_2 storage by standing trees was factored into the CF as explained in Section 2.4. The functional unit (FU) was set as a 1 ha primary maize field.

Methodological Approach 2 In this approach, system expansion was necessary since the above-ground biomass of *F. albida* was used as an energy substitute. This involved adding an energy equivalent (derived from charcoal) to the Low- and High-input scenarios, matching the energy from the *F. albida* trees in the Agroforestry scenario. Again, the FU was a 1 ha primary maize field.

Methodological Approach 3 This approach studies mass balance principle for the Agroforestry scenario (Leinonen 2022). In mass balance principle "… (1) all reductions in biogenic carbon stock should be counted as carbon emissions, (2) all increases in carbon stock should be counted as removals of carbon from the atmosphere (negative emissions) and (3) all these changes should be counted only once (thus avoiding double counting)." (Leinonen 2022). The FU was a 1 ha primary maize field as in previously presented Methodological Approaches.

Three sensitivity analyses were also undertaken to explore variations in the FU (changing from the 1 ha primary maize field to 1000 kg of DM maize grain) and maize grain yield levels in the Agroforestry scenario to match those in the Low- and High-input scenarios.

To assess the carbon footprint (global warming potential for 100 years), the ReCiPe midpoint (H) LCIA method (Huijbregts et al. 2017) was employed. The metric used for this was carbon dioxide equivalents (CO_2 eq.), with calculations executed in MS Excel and OpenLCA. Data was carefully selected from peer-reviewed literature, a national survey report, and the ecoinvent database (Wernet et al. 2016) as explained in Sections 2.3–2.7.

2.4 LCI of Methodological Approach 1

As *F. albida* trees undergo thinning or harvesting—25 trees each at 20, 30, 40, and 60 years—the CO_2 emissions were stored for the number of years that the tree is standing in the field. The method used draws upon guidelines set by the JRC-IES (2010, p. 227). The temporary CO_2 storage can be included in LCA by calculating the correction flow for the delayed emission of biogenic CO_2 within 100 years as emissions to air. The CO_2 from the air is considered an input to the system, and the CO_2 emissions at the end-of-life phase of the wood product are considered an output.

Another output of the system is the correction flow for the delayed emission of biogenic CO_2 within 100 years as emissions to the air. This is calculated by multiplying the

Table 1 Values for calculating the temporary CO_2 storage by the above- and below-ground biomass of F. albida in the Agroforestry scenario using Methodological Approach 1 and the Sensitivity Analysis 1. Assumed time of temporary carbon storage, CO_2 in the tree biomass, the actual number of emissions, correction flow, GWP 100 benefit for the temporary CO_2 storage and GWP 100 benefit per year

Assumed time of temporary carbon storage (years)	CO_2 in the tree biomass (t CO_2/ha)[a]	Actual emissions (t CO_2/ha)[b]	Correction flow (t*a)[c]	GWP 100 benefit for the temporary CO_2 storage (t CO_2 eq.)	GWP 100 benefit per year (t CO_2 eq./year)
20	110	110	2,197	−22	−1
30	298	298	8,947	−90	−3
40	377	377	15,088	−151	−4
60	377	377	22,632	−226	−4
Total	1,163	1,163	48,864	−489	−11

[a] Kg CO_2 as resources from the air to the biomass of trees in the Agroforestry scenario (input)

[b] The actual number of emissions at the end-of-life of the wood products in a unit of kg CO_2 (biogenic) as emissions to the air (output)

[c] Correction flow for the temporary carbon storage of biogenic CO_2 (within first 100 years) as emissions to the air from the biomass of the trees in the Agroforestry scenario (output)

Assumed time of temporary carbon storage, CO_2 in the tree biomass, the actual number of emissions, correction flow, GWP 100 benefit for the temporary CO_2 storage and GWP 100 benefit per year

biogenic CO_2 emissions to the air by the number of years that the temporary CO_2 storage lasts before the CO_2 is released back to the air. To calculate the benefit of temporary CO_2 storage, the CO_2 as resources from the air and CO_2 emissions (biogenic) as emissions to the air cancel each other out. After this, the correction flow for the delayed emission of biogenic CO_2 within 100 years is multiplied by − 0.01 kg CO_2 eq./(kg*a) (JRC-IES 2010, p. 227; Table 1).

The Agroforestry scenario records the highest maize grain yield. Hence, both Low- and High-input scenarios needed maize grain supplementation to fulfill the same yield: 1249 kg for the former and 518 kg for the latter. Emission data for this grain input comes from Ecoinvent 3.7.1 cut-off regionalized (Wernet et al. 2016). Each scenario required 25 kg of maize seed for sowing.

Emission calculations followed recognized protocols: N_2O emissions (direct and indirect) were based on the Tier 1 method by IPCC (2019); CO_2 emissions resulting from urea application came from the IPCC (2006) Tier 1 method; and emission data for fertilizer production was sourced from Ecoinvent 3.7.1 (Wernet et al. 2016). Allocation for maize straw was not necessary, as it remained on the field post-harvest (Boone et al. 2016).

Carbon emissions due to LUC were addressed by assuming the conversion of primary forests to maize fields in each scenario, noting that a significant portion of 2016's cropland originated from primary forest conversions between 1972–2016 (Phiri et al. 2019). The assumption was that the primary forest was cleared by burning, hence the above- and below-ground carbon were emitted into the atmosphere. When assessing CO_2 emissions, factors like above- and below-ground biomass, dead organic matter (DOM), and SOC were taken into account based on recommendations from IPCC (2019). The calculation for LUC CO_2 emissions was steered by the Tier 1 method of IPCC (2019). The emissions were divided by 20 years as recommended by IPCC (2019).

From a geographical perspective, Zambia lies in the tropical dry forest zone (FAO 2015a, p. 19). Here, the primary forests' above-ground biomass averages roughly 69,600 kg of DM/ha and the below-ground biomass at about 23,100 kg of DM/ha, as per data from IPCC (2019, vol. 4, p. 4.12, Table 4.4). The carbon composition of the biomass is assumed to be 0.48 (Martin et al. 2018). The spread of CO_2 emissions from LUC was evenly distributed over two decades, in line with suggestions from IPCC (2006, vol. 4, p. 5.29).

2.5 LCI of Methodological Approach 2

In Methodological Approach 2, energy derived from the above-ground biomass of *F. albida* was considered as a replacement for charcoal in the Low- and High-input scenarios. Charcoal's calorific value was set at 31 MJ/kg (FAO 1985, p. 129), while the *F. albida* biomass was set at 20 MJ/

Table 2 The amount of harvested above-ground biomass in *F. albida* (kg DM/ha) and the energy in harvested biomass (MJ/ha) per thinning or harvest time

Thinning or harvest year	Harvested biomass (t DM/ha)	Energy in harvested biomass (GJ/ha)
20	48	1,000
30	132	2,600
40	167	3,300
60	167	3,300
Total	514	10,300

kg (Orwa et al. 2009). Production-related emissions for charcoal were sourced from Ecoinvent 3.7.1 (Wernet et al. 2016). The biomass estimation of *F. albida* was determined using the methodologies outlined in Section 2.2.2 (Table 2).

To compute the energy obtained from the *F. albida* biomass, both the quantity and its calorific value were accounted for. By dividing the cumulative calorific value from all four harvests by 60 years, the yearly average calorific production was deduced to be 170,000 MJ/ha per year.

Emission estimates, such as direct and indirect N_2O, CO_2 emissions from urea application, and emissions tied to fertilizer production followed the same methodology as in Methodological Approach 1. The FU remained consistent at 1 ha primary maize field for both methodological approaches, as did the maize grain for sowing and the substituted maize grain amounts. LUC was similarly approached as in Methodological Approach 1. Lastly, there was no need for maize straw allocation in Methodological Approach 2, mirroring Methodological Approach 1, since the straw was retained in the field (Boone et al. 2016).

Table 3 The amount of carbon in *F. albida* (kg C/ha) during different stages of the rotation cycle

Time	Amount of *F. albida* trees	Carbon in *F. albida* (t C/ha)
Year 0	0	0
Year 20 before harvest	100	120
Year 20 after harvest	75	90
Year 30 before harvest	75	244
Year 30 after harvest	50	163
Year 40 before harvest	50	206
Year 40 after harvest	25	103
Year 60 before harvest	25	103
Year 60 after harvest	0	0

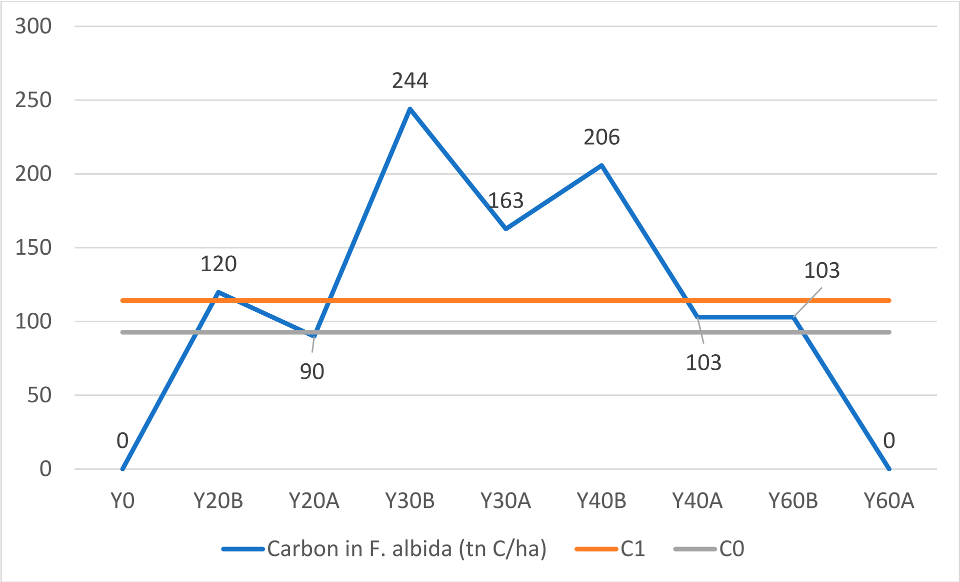
2.6 LCI of Methodological Approach 3

In Methodological Approach 3 the amount of biogenic carbon in the system was calculated in the same manner as in Methodological Approach 1. The difference is that the biogenic carbon was considered in LUC emissions, whereas, in Methodological Approach 1, the temporary carbon storage was considered separately. The mean amount of biogenic carbon in Agroforestry scenario during the rotation cycle was calculated. The rotation cycle was 60 years, and the harvesting was done in the same manner as in Methodological Approach 1.

The emissions from LUC were divided by one rotation cycle of *F. albida*, as recommended by Leinonen (2022). One rotation cycle of *F. albida* was assumed to be 60 years. The mean amount of carbon in Agroforestry scenario was 114 t C/ha during the rotation cycle of *F. albida* (Table 3 and Fig. 4). The amount of carbon stock in primary forest was 93 t C/ha as calculated in Methodological Approach 1. The difference of carbon in Agroforestry scenario and primary forest was calculated and divided by the number of years during one rotation cycle of *F. albida*. This value was considered in the LUC.

Emission calculations, including N_2O and CO_2 emissions from urea use and related to fertilizer production, were based on the same methods as in Methodological Approach 1. The FU used was consistently 1 ha of primary maize field across all methods, and the amounts of maize grain for planting and displaced grain remained the same. Like Methodological Approach 1, allocation for maize straw was

Fig. 4 Amount of carbon in primary forest (C0) and mean amount of carbon during one rotation cycle of *F. albida* (C1). Amount of the carbon in the biomass of *F. albida* in the field at the harvest years 20, 30, 40, and 60 before (B) and after (A) the harvest



not required in this approach since it was left in the field, as Boone et al. (2016) indicated.

2.7 LCI of Sensitivity Analysis 1

In Sensitivity Analysis 1, the FU for Methodological Approach 1 was shifted from a focus on a 1 ha primary maize field to emphasizing 1000 kg of DM maize grain. The CO_2 emissions, which were presumed to be temporarily stored by the biomass of *F. albida*, were allocated towards maize grain production, as the trees were cultivated specifically to enhance the nutrient supply for maize cultivation. The land area essential for the production of 1000 kg of DM maize grain is dependent on the respective maize grain yield of each scenario.

The maize grain yield levels for both the Low- and High-input scenarios were sourced from IAPRI (2016), whereas the yield level for the Agroforestry scenario A was based on Yengwe et al. (2018). Moreover, within Sensitivity Analysis 1, various yield levels for the Agroforestry scenario were examined. These incorporated yield levels matching those of the Low- and High-input scenarios (Table 4).

Emission estimations, including CO_2 emissions from LUC, direct and indirect N_2O emissions, CO_2 emissions from urea applications, emissions associated with seed production, and those resulting from fertilizer production adhered to the methodologies employed in Methodological Approach 1.

2.8 LCI of Sensitivity Analysis 2

In Sensitivity Analysis 2, we shifted our focus from a 1 ha field in Methodological Approach 2 to 1000 kg of DM maize grain yield. Similar to Methodological Approach 2, the above-ground biomass of *F. albida* was harnessed as an energy source. Additionally, this analysis mirrored Sensitivity Analysis 1 by examining diverse maize grain yield levels within the Agroforestry scenario (Table 4).

Emission calculations retained the methodologies from Methodological Approach 1. These calculations encompassed CO_2 emissions from LUC, direct and indirect N_2O emissions, CO_2 emissions tied to urea application, emissions derived from seed production, and those linked to fertilizer production, and the amount of above-ground biomass of the trees in the Agroforestry scenario. Finally, the emissions related to the production and transportation of charcoal were consistently derived from the approach in Methodological Approach 2.

2.9 LCI of Sensitivity Analysis 3

In Sensitivity Analysis 3, our perspective shifted from analyzing of 1 ha maize field as in Methodological Approach 3 to considering 1000 kg of DM maize grain yield. Like in Methodological Approach 3, we factored in the biogenic carbon from *F. albida* in LUC calculations. This analysis also paralleled Sensitivity Analysis 1 by evaluating different maize grain yield levels under the Agroforestry scenario (Table 4).

The emission estimates kept the methods from Methodological Approach 1, covering direct and indirect N_2O emissions, CO_2 from urea use, emissions from seed and fertilizer production, and above- and below-ground biomass in Agroforestry. The LUC emissions were calculated as in Methodological Approach 3.

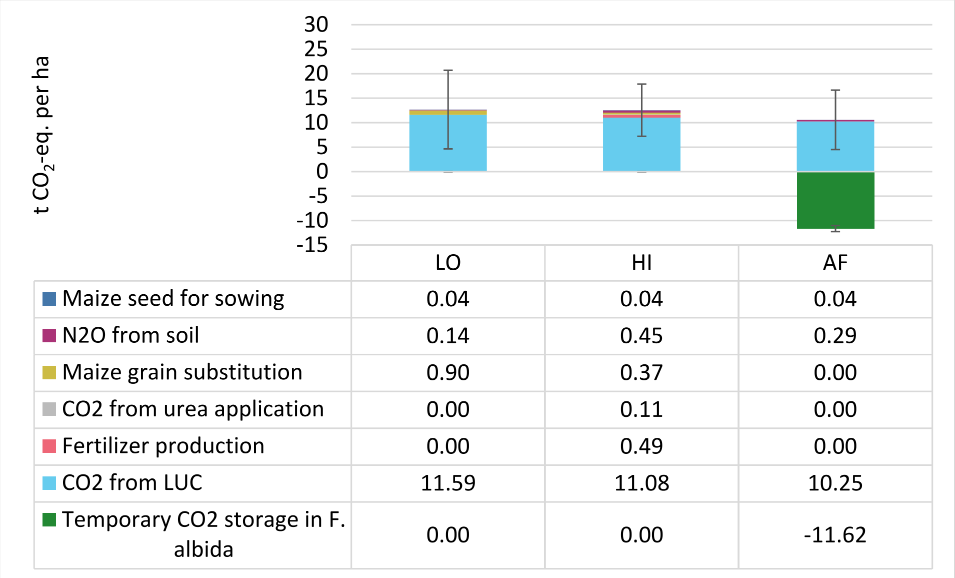
2.10 Monte Carlo analysis

We employed the Monte Carlo analysis using MS Excel. Uncertainty evaluations, especially for N_2O emissions originating from the soil, CO_2 emissions related to LUC, and CO_2 emissions tied to urea application, were grounded in guidelines from IPCC (2006, 2019). Due to the absence of official uncertainty figures, we made a broad assumption: the uncertainties for factors like fertilizer production, the biomass of *F. albida*, and the production processes for charcoal, maize seeds (for sowing), and maize grain (for substitution in all Methodological Approaches) were all pegged at 10% normal distribution. Opting for precision, while 1000 or 10,000 runs are typically advised, we limited our Monte Carlo simulation to 100 runs, following Heijungs' (2019) recommendation.

Table 4 Yield levels, field area, the number of trees planted, and the amount of maize seed for sowing in each scenario of Sensitivity Analysis 1 and Sensitivity Analysis 2

Scenario	Maize grain yield level (t DM/ha)	Area needed to produce 1000 kg of DM maize grain yield (ha)	Number of trees planted in the field	Maize seed for sowing (kg)
Low-input	1.47	0.68	0	17
High-input	2.20	0.45	0	11
Agroforestry A	2.72	0.37	37	9
Agroforestry B	2.20	0.45	45	11
Agroforestry C	1.47	0.68	68	17

Fig. 5 Methodological Approach 1 (FU = 1 ha primary maize field). CF (kg CO_2 eq./ha) of the Low-input scenario (LO), High-input scenario (HI), and Agroforestry scenario (AF). The biomass of *F. albida* was included as temporary CO_2 storage, as the whole system was studied. Uncertainty range presents the lowest and highest values of the Monte Carlo analysis. More detailed results of the Monte Carlo analysis are presented in Appendix



	LO	HI	AF
🟦 Maize seed for sowing	0.04	0.04	0.04
🟪 N2O from soil	0.14	0.45	0.29
🟨 Maize grain substitution	0.90	0.37	0.00
⬜ CO2 from urea application	0.00	0.11	0.00
🟥 Fertilizer production	0.00	0.49	0.00
🟦 CO2 from LUC	11.59	11.08	10.25
🟩 Temporary CO2 storage in F. albida	0.00	0.00	-11.62

3 Results

3.1 Methodological Approach 1

Three scenarios were evaluated using this approach: Low-input, High-input, and Agroforestry. Emissions varied across these scenarios, with soil N_2O emissions being the highest in the High-input scenario, as well as the emissions from CO_2 from urea application and emissions from fertilizer production. The Low-input scenario had elevated emissions attributed to maize grain substitution and CO_2 emissions from LUC. Higher CO_2 emissions from LUC in Low-input scenario were due to low input level of organic matter. The medium input level was used in High-input and Agroforestry scenarios. The factors for different input levels are based on IPCC (2019) Table 5.5. The Agroforestry scenario demonstrated higher soil N_2O emissions compared with the Low-input scenario, but these were still lower than those in the High-input scenario. Most notably, the Agroforestry scenario achieved a negative CF, setting it apart from the other scenarios. Across all scenarios, CO_2 emissions from LUC were the most dominant, contributing between 88 and 97% of the total emissions (Fig. 5).

3.2 Methodological Approach 2

In this approach, the Low-input and Agroforestry scenarios once again demonstrated the highest and lowest CFs, respectively. Charcoal production was responsible for 34% of the total CF in both the Low- and High-input scenarios. Of particular importance, the CO_2 emissions from LUC remained the largest contributor, accounting for 58% of the total emissions (Fig. 6).

3.3 Methodological Approach 3

In Methodological Approach 3, Agroforestry scenario had the lowest CF followed by Low-input scenario and finally the High-input scenario (Fig. 7). LUC accounted for the highest impact on the CF. In Low- and High-input scenarios, the LUC accounted for 72–78% of the emissions. In Agroforestry scenario, the LUC removals exceeded the emissions of the scenario.

3.4 Sensitivity Analysis 1

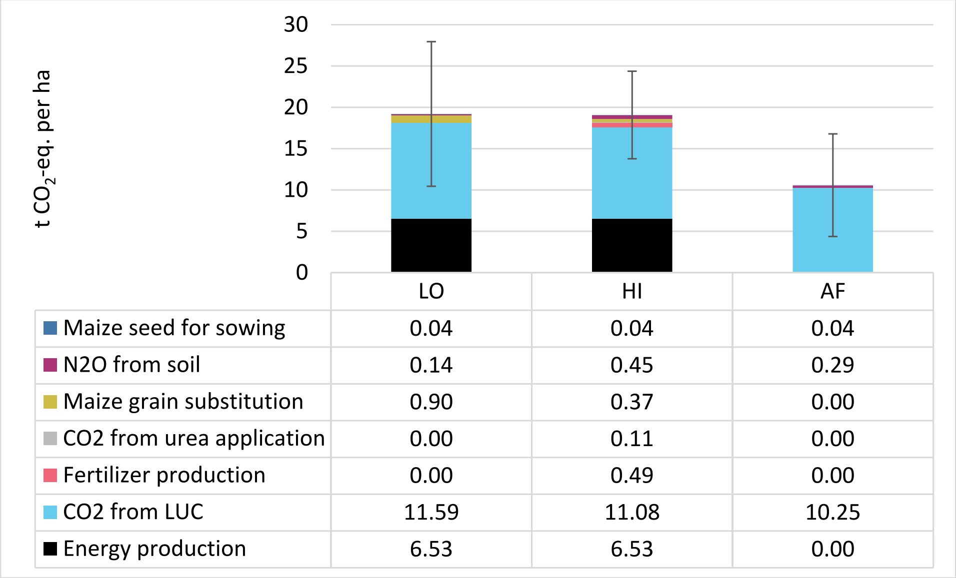
When the biomass of *F. albida* was considered as temporary CO_2 storage, the findings remained consistent: the Agroforestry scenario sustained the lowest CF, while the Low-input scenario yielded the highest CF. This pattern held true regardless of the maize grain yield level in the Agroforestry scenario. The CO_2 emissions from LUC were dominating, contributing a substantial 91–99% to the total CF (Fig. 8).

3.5 Sensitivity Analysis 2

The above-ground biomass of *F. albida* was treated as an energy source. Here, the impact varied based on the maize grain yield level in the Agroforestry scenario (Fig. 9). The Agroforestry scenario consistently exhibited the lowest CF.

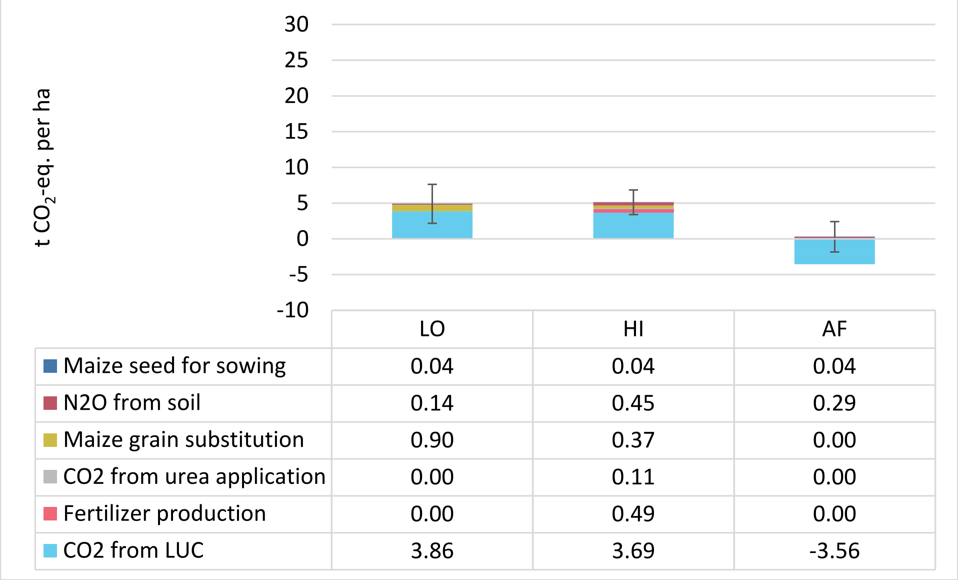
3.6 Sensitivity Analysis 3

In Sensitivity Analysis 3, the Agroforestry scenario had the lowest CF (Fig. 10). The CF got lower when the maize grain yield level got lower. As in previous Methodological



	LO	HI	AF
🟦 Maize seed for sowing	0.04	0.04	0.04
🟪 N2O from soil	0.14	0.45	0.29
🟨 Maize grain substitution	0.90	0.37	0.00
⬜ CO2 from urea application	0.00	0.11	0.00
🟥 Fertilizer production	0.00	0.49	0.00
🟦 CO2 from LUC	11.59	11.08	10.25
⬛ Energy production	6.53	6.53	0.00

Fig. 6 Methodological Approach 2 with charcoal (FU = 1 ha primary maize field). CF (kg CO_2 eq./ha) of the Low-input scenario (LO), High-input scenario (HI), and Agroforestry scenario (AF). The above-ground biomass of *F. albida* in the Agroforestry scenario was utilized as an energy source. The same amount of energy was produced by charcoal in the Low- and High-input scenarios. Uncertainty range presents the lowest and highest values of the Monte Carlo analysis. More detailed results of the Monte Carlo analysis are presented in Appendix



	LO	HI	AF
🟦 Maize seed for sowing	0.04	0.04	0.04
🟥 N2O from soil	0.14	0.45	0.29
🟨 Maize grain substitution	0.90	0.37	0.00
⬜ CO2 from urea application	0.00	0.11	0.00
🟥 Fertilizer production	0.00	0.49	0.00
🟦 CO2 from LUC	3.86	3.69	-3.56

Fig. 7 Methodological Approach 3 (FU = 1 ha primary maize field). CF (kg CO_2 eq./ha) of the Low-input scenario (LO), High-input scenario (HI), and Agroforestry scenario (AF). The biogenic carbon of *F. albida* was considered in LUC. Uncertainty range presents the lowest and highest values of the Monte Carlo analysis. More detailed results of the Monte Carlo analysis are presented in Appendix

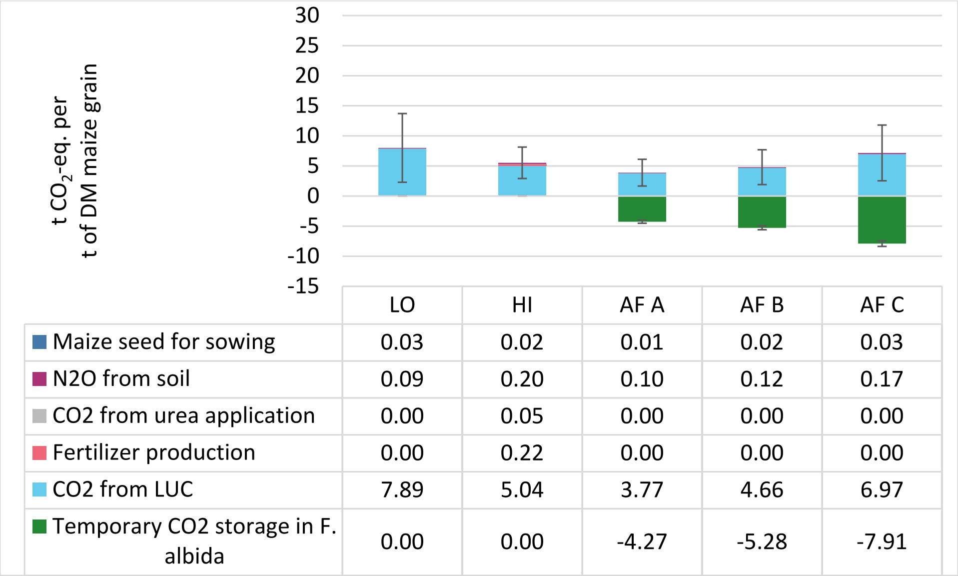
Approaches and Sensitivity analyses, the LUC is the largest contributor to CF.

4 Discussion

By 2023, there was a total of 15 agroforestry LCA studies that had included inventory data on carbon sequestration (Quevedo-Cascante et al. 2023). Based on Quevedo-Cascante et al. (2023), only “a handful of studies include both, carbon sequestration in soils and the woody biomass.” In this study, carbon sequestration in soils were considered through LUC, and in woody biomass by three different methods while addressing the concerns raised by Plassmann and Norton (2017). This study drew distinctions among carbon stocks, carbon sequestration, and non-permanence of carbon removals.

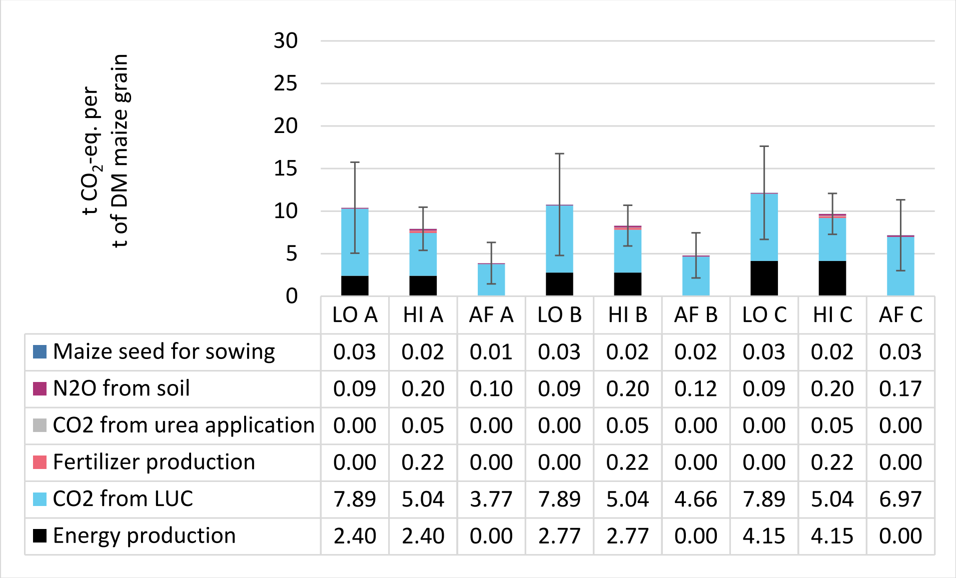
4.1 Life cycle interpretation of the case study

In Methodological Approach 1, where the FU was a 1 ha primary maize field, the Agroforestry scenario demonstrated the lowest CF, regardless of whether temporary CO_2 storage was considered. The biomass of *F. albida*, followed by CO_2 emissions from LUC, was the main factor affecting this reduced CF. Conversely, the highest CF was attributed to the



	LO	HI	AF A	AF B	AF C
🟦 Maize seed for sowing	0.03	0.02	0.01	0.02	0.03
🟪 N2O from soil	0.09	0.20	0.10	0.12	0.17
⬜ CO2 from urea application	0.00	0.05	0.00	0.00	0.00
🟥 Fertilizer production	0.00	0.22	0.00	0.00	0.00
🟦 CO2 from LUC	7.89	5.04	3.77	4.66	6.97
🟩 Temporary CO2 storage in F. albida	0.00	0.00	-4.27	-5.28	-7.91

Fig. 8 Sensitivity Analysis 1 (FU = 1000 kg of DM maize grain yield). CF (kg CO_2 eq./kg of DM maize grain) of the Low-input scenario (LO), High-input scenario (HI), Agroforestry scenario with the maize grain yield level of 2719 kg of DM (AF A), Agroforestry scenario with the maize grain yield level of 2201 kg of DM (AF B), and Agroforestry scenario with the maize grain yield level of 1470 kg of DM (AF C). The temporary CO_2 storage by the biomass of *F. albida* was allocated for the maize grain. Uncertainty range presents the lowest and highest values of the Monte Carlo analysis. More detailed results of the Monte Carlo analysis are presented in Appendix



	LO A	HI A	AF A	LO B	HI B	AF B	LO C	HI C	AF C
🟦 Maize seed for sowing	0.03	0.02	0.01	0.03	0.02	0.02	0.03	0.02	0.03
🟪 N2O from soil	0.09	0.20	0.10	0.09	0.20	0.12	0.09	0.20	0.17
⬜ CO2 from urea application	0.00	0.05	0.00	0.00	0.05	0.00	0.00	0.05	0.00
🟥 Fertilizer production	0.00	0.22	0.00	0.00	0.22	0.00	0.00	0.22	0.00
🟦 CO2 from LUC	7.89	5.04	3.77	7.89	5.04	4.66	7.89	5.04	6.97
■ Energy production	2.40	2.40	0.00	2.77	2.77	0.00	4.15	4.15	0.00

Fig. 9 Sensitivity Analysis 2 with charcoal (FU = 1000 kg of DM maize grain yield). CF (kg CO_2 eq./kg of DM maize grain) of the Low-input scenario (LO), High-input scenario (HI), Agroforestry scenario (AF). Different maize grain yield levels of Agroforestry were analyzed: the maize grain yield level of 2719 kg of DM (A), maize grain yield level of 2201 kg of DM (B) and maize grain yield level of 1470 kg of DM (C). The above-ground biomass of *F. albida* in the Agroforestry scenario was utilized as an energy source. The same amount of energy was produced by charcoal in the Low- and High-input scenarios. Uncertainty range presents the lowest and the highest values of Monte Carlo analysis. More detailed results of Monte Carlo analysis are presented in Appendix

Low-input scenario due to high emissions stemming from LUC and maize grain substitution, caused mainly by its low maize grain yield level.

Similarly, in Methodological Approach 2 with the same FU, both the Low-input and Agroforestry scenarios replicated the highest and lowest CFs, respectively. The reason

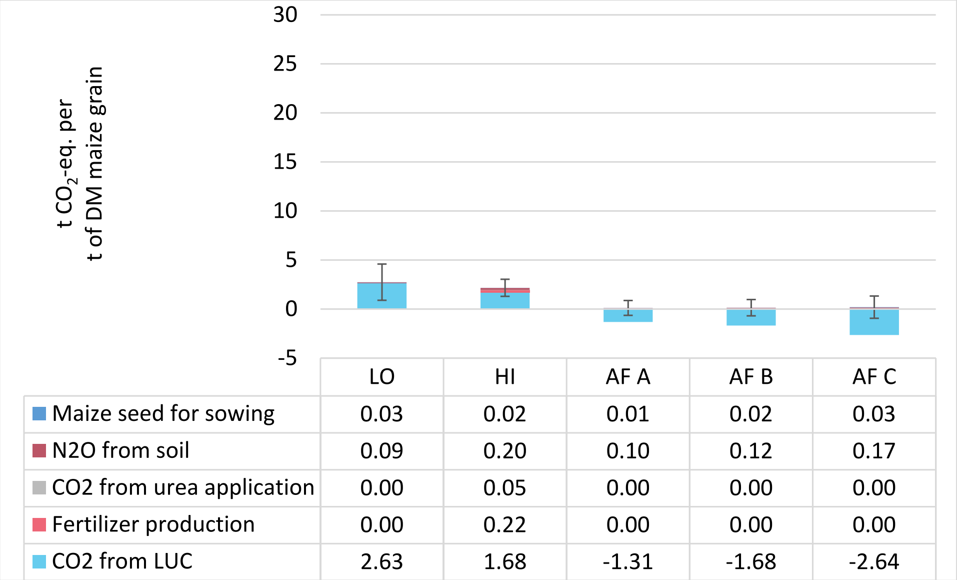


Fig. 10 Methodological Approach 3 (FU = 1000 kg of DM maize grain yield). CF (kg CO_2 eq./ha) of the Low-input scenario (LO), High-input scenario (HI), and Agroforestry scenario (AF). The biogenic carbon of *F. albida* was considered in LUC. Uncertainty range presents the lowest and highest values of the Monte Carlo analysis. More detailed results of the Monte Carlo analysis are presented in Appendix

	LO	HI	AF A	AF B	AF C
🟦 Maize seed for sowing	0.03	0.02	0.01	0.02	0.03
🟥 N2O from soil	0.09	0.20	0.10	0.12	0.17
⬜ CO2 from urea application	0.00	0.05	0.00	0.00	0.00
🟥 Fertilizer production	0.00	0.22	0.00	0.00	0.00
🟦 CO2 from LUC	2.63	1.68	-1.31	-1.68	-2.64

remained consistent with Methodological Approach 1, primarily driven by lower LUC-based CO_2 emissions attributed to the perennial trees in the Agroforestry scenario.

In Methodological Approach 3 the Agroforestry scenario had the lowest CF as the biogenic carbon in *F. albida* was considered through the mass balance principle. Whereas in Methodological Approach 1, the Low-input scenario had a higher CF than High-input scenario, the results were different in Methodological Approach 3. Low-input scenario had lower total emissions due to relatively lower emissions compared to Methodological Approach 1. In Methodological Approach 1, the LUC was divided by 20 years. In Methodological Approach 3, the LUC emissions were divided by full rotation cycle of *F. albida*, which was 60 years.

In Sensitivity Analysis 1, where the FU was set at 1000 kg of DM maize grain, the Agroforestry scenario consistently exhibited the lowest CF across all assumed maize grain yield levels. Notably, even without accounting for temporary CO_2 storage by *F. albida*, the Agroforestry scenario still had the lowest CF when the maize grain yield level was assumed to match that of the High-input scenario. Conversely, when the maize grain yield level in the Agroforestry scenario was assumed to be equivalent to the Low-input scenario and temporary CO_2 storage was excluded, the CF of the Agroforestry scenario surpassed that of the High-input scenario yet remained lower than the Low-input scenario.

This observed variability in the CF of the Agroforestry scenario in Sensitivity Analysis 1, with the yield level equal to the Low-input scenario, can be explained by differences in LUC emissions. Specifically, the Agroforestry scenario required a larger field area to produce 1000 kg of DM maize grain, leading to higher emissions from LUC compared with the High-input scenario. In contrast, despite having the same assumed field area, the Agroforestry scenario had lower LUC emissions than the Low-input scenario. This was due to the perennial nature of the Agroforestry system, which, in accordance with IPCC guidelines, did not assume emissions released from SOC after the initial clearing of the primary forest.

In Sensitivity Analysis 2, where the FU was designated as 1000 kg of DM maize grain and the above-ground biomass of *F. albida* was utilized as an energy source, the energy source employed in the Low- and High-input scenarios did have an impact on the outcomes. Without the substitution of energy, and assuming that the maize grain yield level in the Agroforestry scenario was equivalent to that in the Low-input scenario, the High-input scenario would have been the one with the lowest CF. On the other hand, if the yield level in the Agroforestry scenario was matched with that of the High-input scenario, the Agroforestry scenario would have maintained the lowest CF, even without considering any energy production considerations. The energy source used in both the Low- and High-input scenarios played a significant role in determining the CF of each scenario. Depending on assumptions about maize grain yield levels, as well as whether energy production was considered, either the High-input or the Agroforestry scenario emerged as having the lowest CF.

The results of Sensitivity Analysis 1 and Sensitivity Analysis 3 seem contradictory. Lower maize yield level in Agroforestry scenario did lead to lower CF of the maize. This is because the mean amount of carbon in *F. albida* trees in the Agroforestry system was higher than the amount of carbon in primary forest based on the IPCC Tier 1 methodology. There is a high uncertainty in these results, due to the IPCC Tier 1 methodology. The IPCC Tier 1 was used due to the lack of primary data. Because of this, these results shall not be used as a justification for converting the forest into the fields.

In this study, the allometric equation by Beedy et al. (2016) was used. There was also an allometric equation for the above-ground biomass of *F. albida* by Moussa and Mahamane (2018). Yet, this model was created for the *F. albida* in Niger whereas the equation by Beedy et al. (2016) was created for *F. albida* in Malawi which is geographically closer to Zambia. There are also more generic methods provided by, for example, UNFCCC (2006). Yet, these more generic methods were not used as the method by Beedy et al. (2016) was developed exactly for *F. albida*. Finally, the below-ground biomass was estimated by utilizing the method provided by UNFCCC (2006) as there were no specified methods for *F. albida* available.

The SOC of each scenario was considered in LUC calculations by utilizing the method provided by IPCC (2019) Tier 1. Based on this method, Low-input scenario did reduce 0.12 t C ha^{-1}, High-input scenario 0.08 t C ha^{-1}, and Agroforestry scenario 0 t C ha^{-1}. These results are valid because the agroforestry scenario included perennial trees that can store SOC, while the other scenarios involved only annual crops that do not store SOC and instead release it into the atmosphere.

The CFs from maize production in this study are notably higher compared to previous studies. For instance, Tongwane et al. (2016) reported GHG emissions of 0.57 t CO2 eq. per ha from maize in South Africa, while Mwambo et al. (2021) found emissions ranging from 0.27 to 2.02 t CO2 eq. per ha in Ghana. These studies, however, did not account for land use change (LUC), leading to lower reported emissions. Excluding LUC, the GHG emissions in our study ranged from 0.17 to 1.1 t CO_2 eq. per ha. Furthermore, the FAO (2015b) indicates that Zambia's annual average GHG emissions from maize production vary between 0.1 and 0.6 t CO2 eq. per ha, influenced by nitrogen fertilizer usage. It is unclear which emissions FAO (2015b) included in their assessment; if LUC was omitted, this might explain the significantly lower emissions compared to this study.

The reasons for including or omitting LUC in LCA need clarification. Firstly, a significant portion of Zambia's fields has been converted from primary forests as highlighted in Section 2.4. Secondly, when LUC is incorporated into LCA, SOC differences among production systems can be evaluated following the IPCC (2006) guidelines, as Bessou et al. (2020) recommend. Lastly, incorporating LUC allows for the consideration of varying field areas required for production. Excluding LUC might lead to underestimating emissions in systems with lower yields, as it fails to account for the larger field areas they occupy.

Due to the use of IPCC Tier 1 methodology, the results of this study, outlined in Appendix, carry high uncertainty levels. Nevertheless, there were also some results that were clearer than others. In Methodological Approach 1, the Agroforestry scenario's third quartile was lower than the first quartile of the High-input scenario. Also, in Sensitivity Analysis 1, where the maize grain yield level of the Agroforestry scenario was on the baseline or equal to the High-input scenario, the third quartile of the Agroforestry scenario was lower than the first quartile of the High-input scenario.

The highest uncertainty in the Low-input scenario during sensitivity analyses was attributed to the "Input" factor for management activities on cropland, as per IPCC (2019, Table 5.5, p. 5.28) guidelines. While these guidelines provided a 50% uncertainty level for low input, no such level was specified for medium input level.

Studies report varied amounts of *F. albida*'s above- and below-ground biomass. Reported values include 2 t C/ha (Dilla et al. 2019), 3 t C/ha (Beedy et al. 2016), and 54 t C/ha (Takimoto et al. 2008) for above-ground biomass. In our study, *F. albida*'s above-ground biomass contained approximately 7 t C/ha over a 60-year rotation. Dilla et al. (2019) suggest that such variations could result from differences in tree stocking. Furthermore, the age and DBH of *F. albida* significantly influences the biomass amount, directly impacting the carbon content per tree.

In this study, it was found that different assumptions can have a great effect on the results. In Methodological Approach 2, the energy from the tree biomass was substituted by charcoal which is a commonly used energy source in Zambia. Yet, using some other energy sources could lead to different results. Also, in Methodological Approach 2, it is important to know what the trees are used for after the harvest as it affects the results.

4.2 Agroforestry in LCA

The lifespan of the entire system was partly considered in this study, whereas Plassmann and Norton (2017) recommended including the whole life cycle of the product. The maize production was considered from maize seed production to the farm gate, but the processing of the maize was outside of the system boundaries. This was because the different maize production systems in the field were studied; thus, there was no need to consider the emissions after harvest in the field.

On the other hand, the lifespan of the one rotation of *F. albida* trees in the Agroforestry scenario was considered from planting to the end-of-life of the wood products. This was done because without considering the whole life cycle of the trees, it would not have been possible to calculate the total temporary CO_2 storage, energy provided by the trees or the mass balance in the Agroforestry scenario. Therefore, the assumption in the thinning and harvesting times had to be made.

Carbon stocks cannot be included in LCA (Plassmann and Norton 2017) whereas carbon sequestration might be considered (Plassmann and Norton 2017; Quevedo-Cascante et al. 2023). In Methodological Approach 1, the carbon sequestration was included, yet it was acknowledged that carbon removals from the air are not permanent. Therefore, the temporary CO_2 storage of the agroforestry system was considered in Methodological Approach 1. The suitable method to consider temporary CO_2 storage of the agroforestry system appeared to be the method provided by JRC-IES (2010, p. 227). The correction flow for the delayed emission of biogenic carbon dioxide (within the first 100 years) is calculated based on the amount of biogenic carbon in the product and time that the biogenic carbon will be stored before it is released back into the atmosphere. Such an approach had far-reaching implications: viewing the biomass as a carbon stock would have indicated a lower CF than accounting for temporary CO_2 storage. Also, without considering the carbon in the trees in the agroforestry system, the comparison between the monocultural system would not have identified the important benefit of the agroforestry system.

The mass balance principle by Leinonen (2022) was also found to be a valid method for including the non-permanent carbon storage into LCA. In Methodological Approach 1, the carbon storage was persistent only for 60 years, and land use type after this period was not considered. In Methodological Approach 3, it was assumed that the land use change from primary forest to agroforestry system is permanent. This means that it is assumed that after 60 years of rotation cycle of the trees in agroforestry system, the trees are planted again. Therefore, the new carbon balance in the system is permanent until it is changed to a new land use type.

There are also other methods for including the biogenic carbon into LCA. Yet, these methods are not always suitable for comparing agroforestry to other crop production systems. For example, JRC (2021) recommends the use of the method presented by JRC (2014). In JRC (2014) method, the difference between the carbon stock in harvested forest and forest without harvesting was calculated. The difference between these is considered an emission of the system, i.e., harvesting the system is penalized as the carbon stock would be higher without the harvest. At the same time, the emission reductions from substituting fossil energy were considered, i.e., the bioenergy system is rewarded for reducing the use of fossil energy. Using this approach, bioenergy becomes carbon neutral when the emission savings from replacing fossil fuels equal the emissions from additional harvesting.

The method recommended by JRC (2021) is suitable for studying if fossil fuel should be substituted by forest bioenergy. Yet, it is not suitable when comparing agroforestry to field crop monoculture. This is because the primary function of agroforestry is to provide food, not to produce energy. Also, the comparison is made between area without biogenic carbon and with biogenic carbon. Therefore, the method recommended by JRC (2021) is lacking, as it would penalize the agroforestry system for harvesting the woods whereas there would not be the penalize in monocultural systems.

Other more complex methods are also provided for including biogenic carbon in an LCA. For example, IPCC (2019) provides the methodology for including the carbon emissions and removals of harvested wood products. Both the IPCC methods and Leinonen's (2022) mass-balance approach share the principle of mass balance, ensuring accurate accounting of carbon stock changes. They both emphasize the importance of consistency across different scales and sectors to avoid partial or double counting. However, the IPCC methods do not use a time-dependent approach, focusing instead on annual carbon stock changes, whereas Leinonen argues that a time-dependent approach is unnecessary if mass balance is consistently applied. Leinonen's method simplifies the treatment of product carbon stocks by applying the same principles as for biomass and soil carbon, avoiding arbitrary choices like a 100-year storage period. The IPCC methods provide detailed guidelines and are widely accepted for national greenhouse gas inventories, while Leinonen offers a more straightforward approach that is easier to apply in practical assessments. Both methods are crucial for evaluating the climate impacts of biogenic carbon, with their application depending on the context and objectives of the assessment. Leinonen's approach is particularly noted for its simplicity and consistency with other bio-based sectors. In contrast, the IPCC methods offer a more comprehensive and detailed framework.

Plassmann and Norton (2017) recommend that the biogenic carbon in the biomass that is part of the production should be included in LCA, even if the biogenic carbon is not in the studied product. This is recommended if LUC is increasing the total carbon stock of the system, if the fossil fuels are replaced by biogenic carbon or biogenic carbon is stored for long timescales. Also, they recommend that the emission removals should be allocated for the main product.

In Methodological Approaches 1, 2, and 3, the FU was a 1 ha primary maize field; therefore, it can be argued that the trees should be considered, as they are part of the 1 ha field in the Agroforestry scenario. On the other hand, there are different products produced in each scenario (trees in the Agroforestry scenario, and a different amount of maize), so it could also be argued that the production systems cannot be compared. Therefore, system expansion was found to be a suitable method to solve these issues. While the FU was the unit of a product rather than the unit of an area in Sensitivity Analysis 2, and the trees functioned as products, as they provided energy, the system expansion made it possible to consider the energy delivered by trees in LCA.

In Sensitivity Analysis 1, it was more difficult to justify why the carbon of the trees should be included in LCA and allocated for the main product. The argument was tackled by utilizing the *F. albida* trees only as a nutrient provider, so trees are not functioning as individual products. As the trees were functioning as a nutrient supplier to the maize, the environmental aspects — positive or negative — should be considered in the same manner as the mineral fertilizer production was considered in the High-input scenario.

The mass balance principle was found to be the best method for including the carbon in tree biomass into LCA. Especially two main reasons for this were found. (1) There is a rather small risk for double counting regardless of the usage of the trees after the rotation cycle. As the mass balance of the carbon is calculated during the time that the trees are standing on the field, it does not matter what is done to the trees after harvest. By using the mass balance principle, the tree biomass could be used to substitute energy sources while the biogenic carbon could also be considered in LUC. (2) biogenic carbon can be considered in LUC as it should. As the emissions from previous land use are compared to current land use, the emissions and removals can be presented in LUC.

Whereas three different methods for including the biogenic carbon into LCA were presented in this study, other methods should be studied as well. For example, the Sensitivity Analyses 1 and 2 would have very different results if economic or mass allocation would have been utilized. Also, different FUs should be studied. For example, the nutritional FU. Overall, possibly the best available FU for food systems seems to be the amount of the product. This is because reduced yield levels could result in an increased demand for land conversion.

Finally, in this case study, the primary data was not used. Therefore, it cannot be concluded that primary forest shall be transformed into agroforestry systems to increase the carbon stocks. The goal of this case study was to present different methods for including the climatic benefits of agroforestry in LCA, especially when comparing to systems without the agroforestry. When considering the transformation of primary forest into agricultural purposes, all the aspects of sustainability shall be considered and calculated.

5 Conclusions

Based on this case study, the agroforestry system has the potential to decrease the CF of the maize production systems in Zambia. The potential is dependent on the yield level of the system, and LCA allocation methods, FU and other decisions made in the study, for example, the decisions considering the system expansion.

The issues found in previous agroforestry LCA studies can be solved with the available methods, whereas the allocation issues are harder to solve in more complex agroforestry systems. However, these issues can be solved by utilizing system expansion, where processes are added to compared systems until they include the provision of the same functions. By this method, the comparison of the agroforestry system to other production systems can be done.

It was found that the best method for including the biogenic carbon of the trees in agroforestry systems into LCA was the mass balance principle. By the mass balance principle, the emission reductions of shorter time than 100 years can be considered.

Finally, when utilizing LCA method to study the CF of agroforestry systems, and especially when comparing it with different systems, transparency must be as high as possible to make the modelling decisions visible. Also, it is recommended that different FUs and allocation methods would be used in the studies to comprehend the effect of these decisions on the results.

Appendix

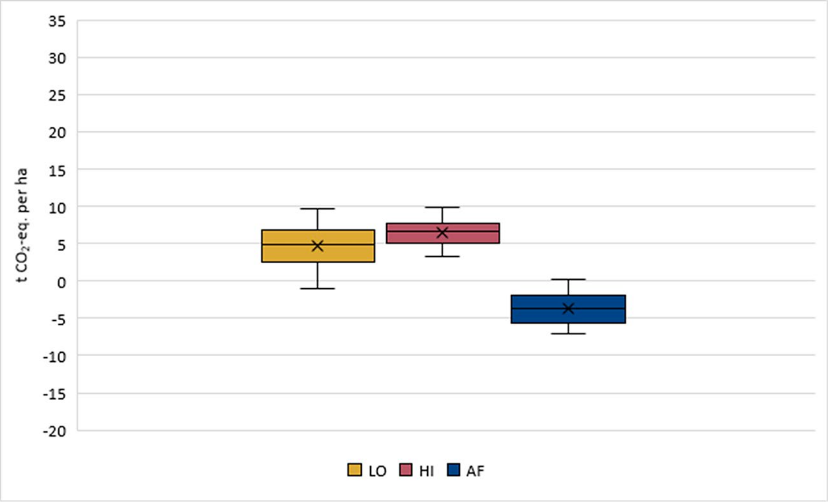


Fig. 11 Results of the Monte Carlo analysis of Methodological Approach 1 (FU = 1 ha field). The maximum and minimum numbers are presented on top of the lines; the upper and lower lines of the colored box represent the third and first quartile of the dataset, respectively; the cross represents the mean, and the line the median

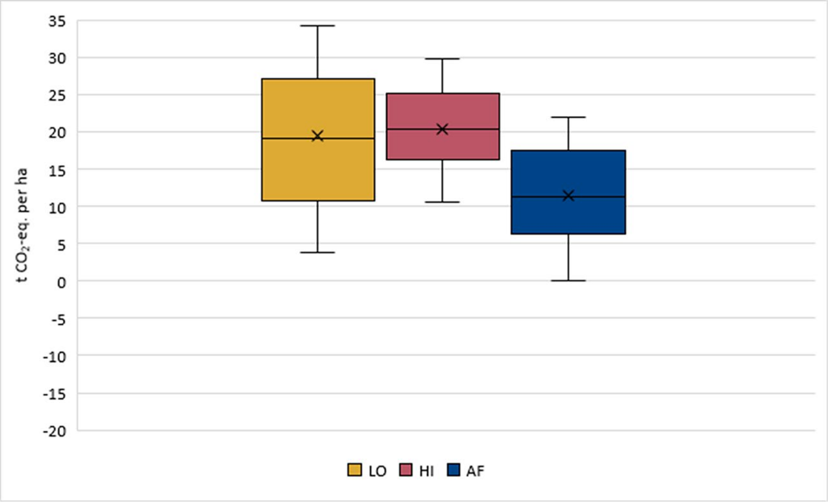


Fig. 12 Results of the Monte Carlo analysis of Methodological Approach 2 with charcoal (FU = 1 ha field). The maximum and minimum numbers are presented on top of the lines; the upper and lower lines of the colored box represent the third and first quartile of the dataset, respectively; the cross represents the mean, and the line the median

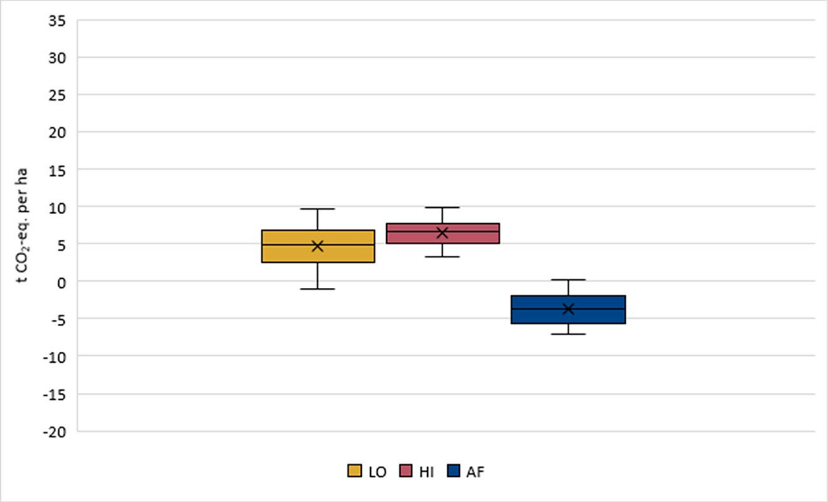


Fig. 13 Results of the Monte Carlo analysis of Methodological Approach 3 (FU = 1 ha field). The maximum and minimum numbers are presented on top of the lines; the upper and lower lines of the colored box represent the third and first quartile of the dataset, respectively; the cross represents the mean, and the line the median

Fig. 14 Results of the Monte Carlo analysis of Sensitivity Analysis 1 (FU = 1000 kg d.m. maize grain). The maximum and minimum numbers are presented on top of the lines; the upper and lower lines of the colored box represent the third and first quartile of the dataset, respectively; the cross represents the mean, and the line the median

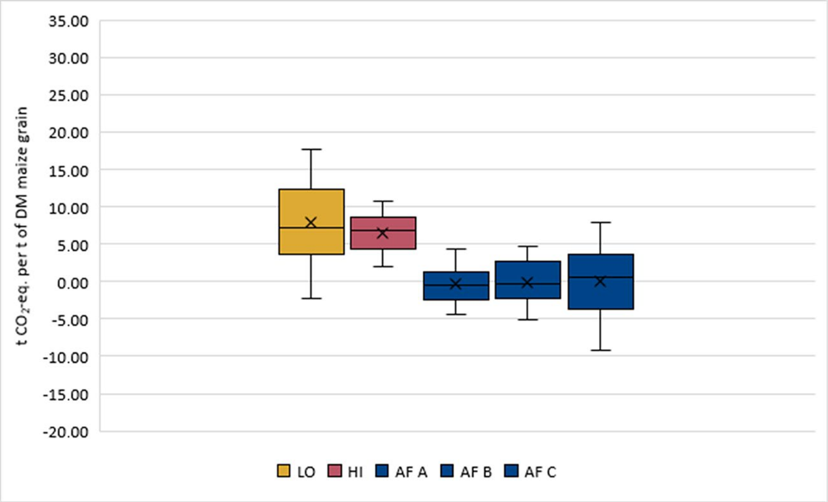


Fig. 15 Results of the Monte Carlo analysis of Sensitivity Analysis 2 with charcoal (FU = 1000 kg d.m. maize grain). The maximum and minimum numbers are presented on top of the lines; the upper and lower lines of the colored box represent the third and first quartile of the dataset, respectively; the cross represents the mean, and the line the median

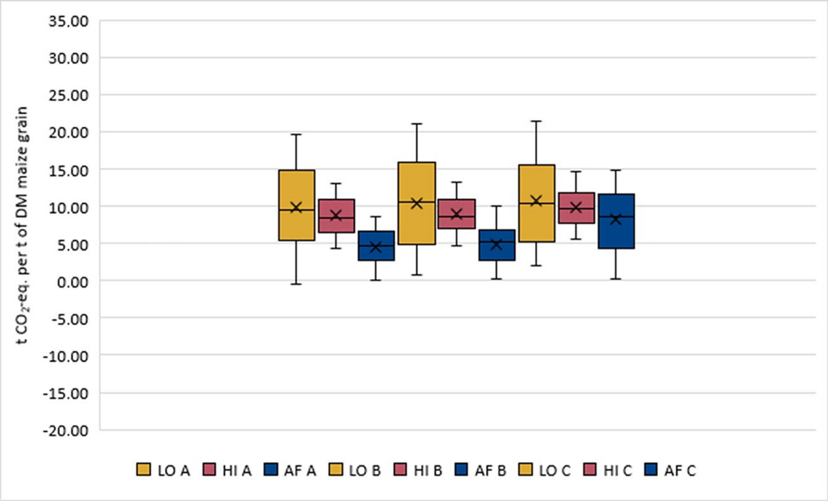
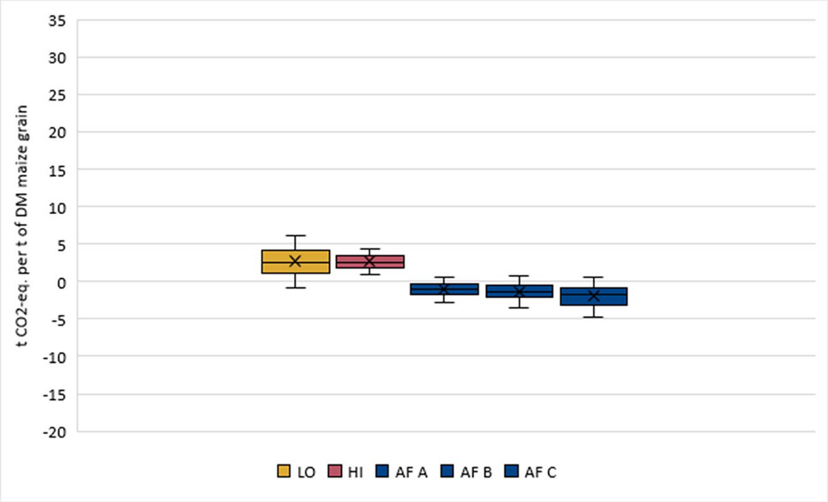


Fig. 16 Results of the Monte Carlo analysis of Sensitivity Analysis 3 (FU = 1000 kg d.m. maize grain). The maximum and minimum numbers are presented on top of the lines; the upper and lower lines of the colored box represent the third and first quartile of the dataset, respectively; the cross represents the mean, and the line the median



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Declarations

Competing interests The authors declare no competing interests.

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