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ORIGINAL ARTICLE

Implication of soil carbon changes on the greenhouse gas emissions of pickled ginger: a case study of crop rotation cultivation in Northern Thailand

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Abstract As the global demand for ginger products continues to increase due to its medicinal and culinary properties, concerns arise regarding the loss of soil carbon (C) caused by agricultural management practices. It is crucial to understand the impact of these practices on soil C changes, especially in ginger rotation cropping systems. The goal of this study was to estimate the soil C changes resulting from management practices of ginger rotation cropping systems, and understand their influence on greenhouse gas (GHG) emissions of pickled ginger. The Intergovernmental Panel on Climate Change (IPCC) Tier 1 method with modification was used to predict the soil C changes of two different 4-year rotation cycles, one of maize-ginger rotation relative to the reference of maize-pumpkin rotation, and the other of upland rice-ginger rotation relative to the reference of upland rice-vegetable rotation for 20 years of cultivation. From the results, ginger rotation cropping systems could lead to soil C changes, ranging from − 0.02 to 0.31 Mg C ha^{-1} yr^{-1}, compared to − 2.02 Mg C ha^{-1} yr^{-1} when converting forests to ginger plantations. Consequently, the net GHG emissions of pickled ginger varied from − 6.71% to 0.00% for ginger rotations and 46.33% for converting forest to cultivate ginger. The waste disposal was the primary source of GHG emissions of pickled ginger. Sustainable waste management practices could potentially reduce GHG emissions by over 60%. Implementing certain practices, such as reduced tillage, keeping all crop residue on the field, and avoiding deforestation to ginger plantations, could increase soil C sequestration.

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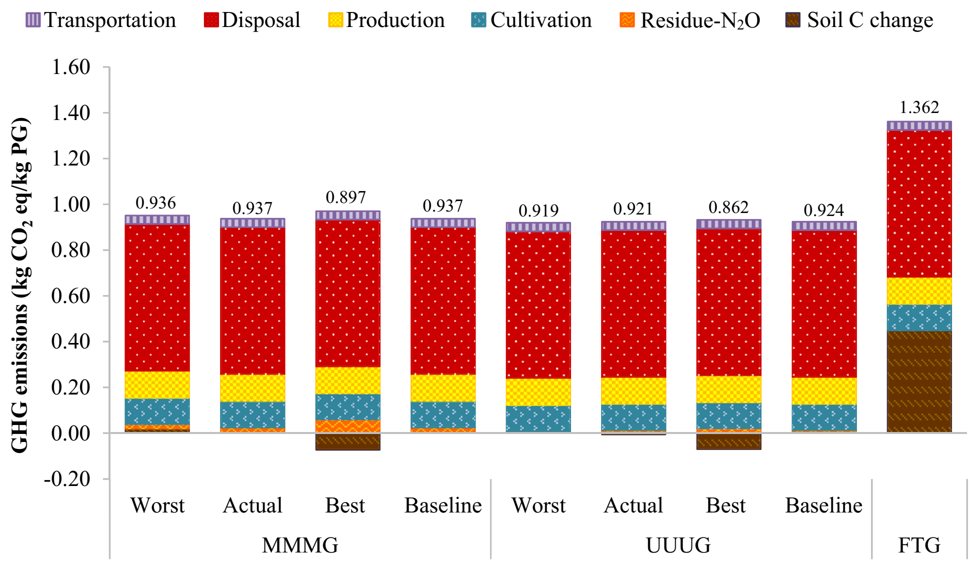
Graphical abstract



Keywords Soil carbon change · Greenhouse gas emissions · Pickled ginger · Crop rotation · Life cycle assessment

Abbreviations

C	Carbon
CF	Carbon footprint
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide
N	Nitrogen
LMC	Land management change
LUC	Land use change
dLUC	Direct land use change
iLUC	Indirect land use change
MMMP	Maize-maize-maize-pumpkin rotation
MMMG	Maize-maize-maize-ginger rotation
UUUV	Upland rice-upland rice-upland rice-vegetable rotation
UUUG	Upland rice-upland rice-upland rice-ginger rotation
FTG	Forest to ginger cultivation
FT	Full tillage
RT	Reduced tillage
NT	No tillage
L	Low level of crop residue input
M	Medium level of crop residue input
H	High level of crop residue input
F_{LU}	The relative carbon stock change factors for land use
F_{MG}	The relative carbon stock change factors for tillage practice
F_I	The relative carbon stock change factors for residue input
% SOC	The percentage of soil organic carbon
SOC_{REF}	The reference carbon stock (Mg C ha^{-1})
Mg C ha^{-1}	Megagram carbon per hectare
PG	Pickled ginger
NaCl	Sodium chloride
SI	Supplementary information

1 Introduction

Agriculture activities constitute a significant source of GHG emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Agriculture contributes a large portion of total global emissions, which accounts for approximately 20% of global GHG emissions (Ahmed et al. 2020). However, agriculture soils also have a significant potential to mitigate GHG emissions as soils are the second largest carbon sink after oceans (European Commission, 2011). Globally, the soil carbon (C) pool is estimated at 2,500 gigatons of carbon, a change in the soil C pool through soil C sequestration is considered as one of the most promising GHG mitigation strategies for agriculture (Goglio et al. 2015; Lal 2004). Lal (2004) estimated that soil C sequestration had the potential to offset GHG emissions from fossil fuel by 0.4 to 1.2 gigatons of C per year, which is equivalent to 5% to 15% of global fossil fuel emissions.

The management of C storage in soil has been recognized as a crucial factor in addressing the global issue of climate change (Srivastava et al. 2016). However, soil C stocks vary widely, depending on land management change (LMC) and land use change (LUC). LMC refers to a change in the type of management practices applied to existing land coverage of agricultural crops (Goglio et al. 2015). The LUC refers to the process of converting or removing existing vegetation for the purpose of different utilizations, which can result in a change in land cover (Goglio et al. 2015; Sharma et al., 2019). Management practices that can affect agricultural soil C stocks include tillage practices, crop residue, crop rotations, and fertilizer management (Aalde et al. 2006; Lasco et al. 2006). Tillage practices such as conventional tillage or full tillage involve the use of the moldboard plow to break up and invert the soil. This process exposes of organic matter to oxygen, which can increase the decomposition rate of organic materials and cause soil C oxidation (Kumar et al. 2017), directly creating CO_2 emissions. Crop residues provide sources of C for agricultural soil (Fu et al. 2021), in which leaving crop residues in fields after harvesting can help to sequester C in soil (Kumar et al. 2017). Crop rotation is the practice of planting a sequence of different crops in the same area over time (Deen et al. 2016). The types of crops grown for rotation can vary from a simple two-species rotation to involving numerous species (Deen et al. 2016). King and Blesh (2017) investigated the soil C sequestration from 169 rotation cropping systems. They reported that changes in soil C levels could either increase or decrease and increasing the diversity of crop rotations tended to increase soil C if accompanied by an increase in C input (King and Blesh 2017). Nutrient management is essential to achieving optimal plant growth and increasing plant residue for soil C. Application of both chemical fertilizer and organic manure is more advantageous, rather than applying them separately, as this leads to higher organic C in the soil (Chahal and Singh 2021). While changes in land use play a vital role in affecting the rate of soil C stocks. Guo and Gifford (2002) conducted a meta-analysis on soil C stock for land use change and reported that soil C stocks decrease when land use shifts from pasture to plantation, native forest to plantation, native forest to cropland, and pasture to cropland. However, reversing these changes usually resulted in an increase of soil C (Guo and Gifford 2002). These changes in land management and land use have a significant impact on soil C stocks (Goglio et al. 2015). Accordingly, several countries also have implemented policies that encourage soil C sequestration, such as the USA (Mulligan et al. 2020), Australia (Australian Government 2021), France (Kon Kam King et al. 2018), Canada (Agriculture and Agri-Food Canada, 2022), and Brazil (Carauta et al. 2021; Galford et al. 2013). These policies offer incentives to farmers while encouraging them to implement practices that help store C in the soil and reduce GHG emissions from their fields.

The recent publication of a technical standard for estimates of GHG emissions and carbon footprint (CF) of products (ISO 14067:2018) states that the emissions and removals due to soil C changes resulting from LUC and LMC should be included in the study. Recently, several researchers included soil C changes in the production systems. According to Joensuu et al. (2021), the changes in soil C had an impact on the GHG emissions of wheat production, which varied from − 4% to 5% in Southwest Finland and from 5 to 21% in Northern Savonia. Similarly, Knudsen et al. (2019) found that including soil C changes in the calculation decreased emissions from milk production by 5% to 18%. Röös et al. (2011) also reported a similar discrepancy in pasta production in Sweden, where GHGs were underestimated by 10% due to the exclusion of soil C changes. Ukaew et al. (2015) found that changes in soil C from growing rapeseed in rotation with wheat in the USA varied widely, from − 92% to 77% of emissions. They concluded that changes in soil C affected the GHG emissions throughout the entire life cycle of the products. Additionally, there is a growing interest in reducing the GHG emissions of agricultural products, in which several certifications are available globally, including carbon labeling in Europe, the United States, and Asia (Gheewala and Mungkung 2013; Wu et al. 2014).

As a commercial product of agriculture, ginger is produced in approximately 40 countries worldwide with a total harvested area of 393,762 hectare (ha) and with a production yield of 4,080,927 tonnes in 2018 (FAOSTAT 2020b). Thailand was the sixth largest producer of ginger in 2018 with a volume of 166,196 tonnes, which accounted for 6% of the total world production (FAOSTAT 2018). It was also the third largest exporter of non-crushed and non-ground ginger in the world with a value of 54.8 million US dollars in 2019 (Workman 2020). As ginger production and its byproducts increase globally (FAOSTAT 2020a), the available land for growing ginger has becomes increasingly constrained. Ginger cultivations has created a circumstance whereby the plants are not sustainable for long continuous periods of time because of soil/plant diseases, which forces farmers to cultivate the crop in new areas every year to protect ginger from disease (Lhakchaiyagul 2013). This creates the direct land use change (dLUC) challenge, the clearing of natural forest areas that are replaced with land, which is used to cultivate ginger (Choenkwan 2017; Thairath News 2016).

One possible strategy that has arisen related to the production of increased volumes of ginger, while reducing the destruction of forest land, is to cultivate ginger in rotation with other crops to reduce the need for a fallow period. For example, maize and upland rice crops were grown in the northern part of Thailand, in which 38% of approximately 215,667 ha and 44% of 69,593 ha, respectively, was not rotated (LDD 2016). Ginger has been cultivated along with other crops such as maize, rice, chilies, and other commercially grown vegetables (Choenkwan 2017; Goudar et al. 2017; Smith et al. 2012). In Fiji, ginger is generally grown with cassava or taro plants because both are poor hosts for pathogens, which helps to reduce disease severity in the soil (Smith et al. 2012). In addition, Choenkwan (2017) reported that crop yields of maize and rice increased when rotated with ginger due to the nutrients available in soil after growing ginger. Stirling et al. (2012) conducted field experiments by growing ginger with other crops for 4 years in Australia, whereby different management practices were applied. They reported that the soil C accumulation levels from continuously leaving all crop residue on the field and adding soil amendment under no tillage practice was higher than the bare fallow without soil amendment under tillage practice (Stirling et al. 2012). Therefore, cultivation ginger in rotation with other crops and improving management practices may be able to sequester C in soil.

Several carbon-based models such as Introductory Carbon Balance Model (ICBM), Rothamsted Carbon (RothC), Daily Century (DAYCENT), DeNitrification-DeComposition (DNDC), and Environmental Policy Integrated Climate (EPIC) are used to predict soil C and N dynamics for several crops (i.e., soybean, wheat, corn, barley, rice, sugar beet, and short rotation coppice willow) (Goglio et al. 2015). Furthermore, these process-based models involve substantial expertise to operate and validate, and it also requires more data inputs to support these models (Goglio et al. 2015). However, there are limited studies available on the management practices involved in growing ginger and its impact on soil C changes in crop rotation. For this reason, the Intergovernmental Panel on Climate Change (IPCC) Tier 1 method with modification (Ukaew et al. 2015) was used to predict the soil C changes of two different 4-year rotation cycles, one of maize-maize-maize-ginger (MMMG) relative to the reference practice of maize-maize-maize-pumpkin (MMMP) and the other of upland rice-upland rice-upland rice-ginger (UUUG) rotation relative to the reference practice of upland rice-upland rice-upland rice-vegetable (UUUV) rotation for 20 years of cultivation. The predicted changes in soil C involving ginger rotation were compared to the results of soil C change obtained from land use change associated with the conversion of forest to ginger plantation. The estimation of soil C changes will be made based on data collected from ten ginger farms located in Phayao province in the northern part of Thailand, where significant young ginger production as a raw material for pickled ginger occurs. The objectives of this study were to estimate the soil C changes of maize-ginger rotation or upland rice-ginger rotation as affected by changes in management practices; to evaluate the life cycle GHG emissions of pickled ginger induced by soil C changes through a cradle-to-gate approach; and to determine the impact of soil C changes on the GHG emissions of pickled ginger.

2 Materials and methods

2.1 Estimation of soil C changes from ginger cultivation

2.1.1 *The change in management practices: assumptions of crop rotations*

In this study, farmers cultivated ginger as a crop rotation with maize or upland rice in two different 4-year rotation cycles, one of maize-maize-maize-ginger (MMMG) and the other of upland rice-upland rice-upland rice-ginger (UUUG) for long-term production over an assumed period of 20 years. Full tillage practice was commonly used to cultivate farmlands for maize, upland rice, and ginger; whereby, farmers typically removed maize and rice residues before planting; however, ginger residue was always left on the field. According to the 2006 IPCC guidelines, field residue levels were low for the removal process (burning, collecting, or yielding low residue production), medium for all crop residues left on the field, and high for yielding high residue production (Lasco et al. 2006). Consequently, the residue input levels of both maize and rice were assumed to be low and the level of ginger residue was assumed to be medium.

The prediction of soil C changes from the two rotation cropping systems of MMMG and UUUG were compared to the reference practice system, which was based on the actual practices used by farmers who grew pumpkin in rotation with maize (MMMP), and vegetables (i.e., cabbage and garlic) in rotation with upland rice (UUUV) over a 4-year rotation cycle, which has been the standard for many years. Full tillage was applied to all crops, and the residue input level of the main crops (maize or upland rice) were low due to the typical practice of removal of the residue from the fields. The residue input levels of pumpkin and vegetables were assumed to be medium due to leaving all crop residue on the field, and low due to yielding low residue production, respectively. Although full tillage typically applies to all crops and the main crop residues

Table 1 The change in management practices from the reference practice of MMMP rotation to the post-conversion practice of MMMG rotation

Reference practice	Three-year maize (MMM)			One-year pumpkin (P)		
	Land-use (F_{LU})	Tillage (F_{MG})	Residue input (F_I)	Land-use (F_{LU})	Tillage (F_{MG})	Residue input (F_I)
	Long-term cultivated (0.48)	Full (1)	Low (0.92)	Long-term cultivated (0.48)	Full (1)	Medium (1)
Post-conversion practice	**Three-year maize (MMM)**			**One-year ginger (G)**		
	Long-term cultivated (0.48)	Full (1)	Low (0.92)	Long-term cultivated (0.48)	Full (1)	Low (0.92)
		Reduced (1.15)	Medium (1)		Reduced (1.15)	Medium (1)
		No (1.22)	High (1.11)		No (1.22)	High (1.11)

Table 2 The change in management practices from the reference practice of UUUV rotation to the post-conversion practice of UUUG rotation

Reference practice	Three-year upland rice (UUU)			One-year vegetable (V)		
	Land-use (F_{LU})	Tillage (F_{MG})	Residue input (F_I)	Land-use (F_{LU})	Tillage (F_{MG})	Residue input (F_I)
	Long-term cultivated (0.48)	Full (1)	Low (0.92)	Long-term cultivated (0.48)	Full (1)	Low (0.92)
Post-conversion practice	**Three-year upland rice (UUU)**			**One-year ginger (G)**		
	Long-term cultivated (0.48)	Full (1)	Low (0.92)	Long-term cultivated (0.48)	Full (1)	Low (0.92)
		Reduced (1.15)	Medium (1)		Reduced (1.15)	Medium (1)
		No (1.22)	High (1.11)		No (1.22)	High (1.11)

commonly remove from the field, this study focused on the range of tillage practices and residue inputs. Ploughing management practices included: full tillage (FT), reduced tillage (RT), and no tillage (NT); whereby, residue inputs produce included low (L), medium (M), and high (H) levels. To simplify the analysis, the same tillage practices were assumed to be applied to the production of maize and ginger as well as upland rice and ginger. Therefore, the 27 cases were conducted to achieve an understanding of how tillage practices and residue inputs would impact soil C changes. The management practices of MMMG and UUUG rotations relative to the reference practices of MMMP and UUUV are shown in Tables 1 and 2. According to the classification scheme for default climate regions in Fig. 3A.5.2 in the 2006 IPCC, Phayao province was classified as "Tropical moist" region, see detail in Supplementary Information (SI), Section B, and was the focus of this study. The default value of the relative C stock change factors for land use (F_{LU}), tillage practice (F_{MG}), and residue input (F_I) are illustrated as the numbers in parentheses, in Tables 1 and 2. The research flow chart of the study is shown in Fig. 1.

2.1.2 The change in land use: assumption of land conversion

The conversion of forest into ginger cultivation still exists in many areas (Choenkwan 2017; Thairath News 2016). The study also estimated the soil C change from converting forest to ginger plantation and its effect on the GHG intensity of pickled ginger. It was assumed that once the tropical forest lands were converted to ginger plantation, the land was continuously used to grow other crops thereafter. For ginger cultivation, full tillage practice was assumed to be adopted, and the level of its residue was medium, see detail in SI, section C2.

2.1.3 Estimation of the reference C stock

Soil samples were collected from 10 farms prior to planting the ginger rhizome, in which all farms were in the Mae Na Ruea district of Phayao province. There were seven farms, which grew ginger in rotation with maize, while the other three farms, which grew ginger in rotation with upland rice.

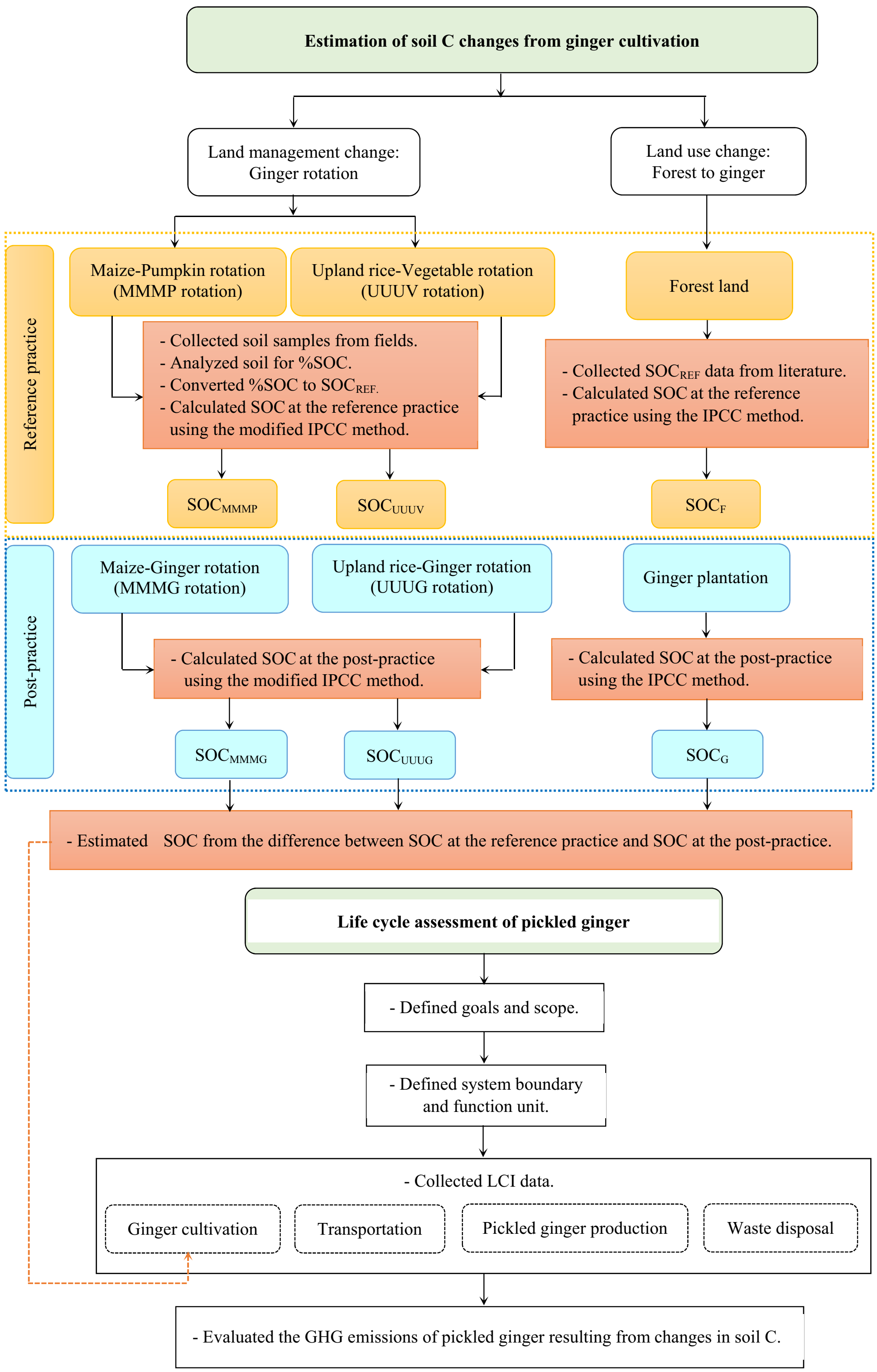


Fig. 1 The flow chart of research methodology

The location map of the soil sampling sites was recorded by Google map (Suksamran 2023), as illustrated in Fig. 2.

Soil from a depth of 0–30 cm was collected randomly throughout the plot for 8–10 subsamples in each field plot (one plot per farm). The samples collected were air-dried in shade and ground passed through a 2 mm sieve. The percentage of soil organic carbon (% SOC) was determined based on the Walkley–Black chromic acid wet oxidation method (NSW, n.d.-b). The carbon present in the soil organic matter (SOM) was oxidized by 1 N $K_2Cr_2O_7$ solution, with the reaction assisted by the heat generated when two volumes of H_2SO_4 were mixed with

Fig. 2 The location map of the soil sampling sites for rice and maize fields in the Mae Na Ruea, Phayao province (Red filled circle for rice fields and Yellow filled circle for maize fields)

one volume of the dichromate. The remaining dichromate was titrated with ferrous sulphate. These procedures were repeated three times. The amount of $FeSO_4$ used in sample titration was then used to calculate the %SOC using Eq. 1 (NSW, n.d.-b). The soil bulk density was measured at three random locations within each field plot, at a soil depth of 0–15 cm using stainless steel cylinder. The soil cores were then dried in an oven at 105 °C for 48 h until constant weight. The soil bulk density was calculated by dividing the dry weight of the soil core by the internal volume of the stainless steel cylinder (NSW, n.d.-a). The % SOC was converted to the reference C stock (SOC_{REF}) using the soil bulk density and soil depth (Lasco et al. 2006), as seen in Eq. 2.

$$\%SOC = \frac{3(1 - T/S)}{ODW} \quad (1)$$

$$SOC_{REF} = \frac{(B \times \%SOC \times D)}{100} \quad (2)$$

where T is volume of $FeSO_4$ used in sample titration (ml), S is volume of $FeSO_4$ used in blank titration (ml), ODW is oven-dried sample weight (g), SOC_{REF} is the reference C stock (Mg C ha^{-1}), B is the soil bulk density (Mg m^{-3}), and D is soil depth of 0–30 cm (0.3 m). The values of %SOC, soil bulk density, and soil depth are illustrated in SI, Table A2.

The soil C stock samples were averaged and used as the SOC_{REF}, with the values of 32.80 Mg C ha^{-1} for maize field (averaged from 7 farms) and 30.06 Mg C ha^{-1} for upland rice field (averaged from 3 farms), as seen in SI, Table A2. However, the average value of soil C stock at 77.56 Mg C ha^{-1} was used as the SOC_{REF} for the forests in Phayao province (Chumpookul 2012; Intanil et al. 2016).

2.1.4 *Estimation of annual soil C change*

The changes in soil C of both rotation cycles were estimated by applying the modified IPCC (Tier 1) method, which was based on the fraction of ginger in the rotation, as described in the study by Ukaew et al. (2015). While the soil C change from the conversion of forest to ginger planting was determined using the IPCC Tier1 method, Eq. 2.25 in the IPCC guidelines (Aalde et al. 2006).

The annual soil C change for ginger rotation was calculated from the difference between total soil C (SOC) at the reference practice of MMMP and at the post-conversion practice of MMMG, and dividing by time, as shown in Eq. 3. The SOC associated with change in management practices for the reference MMMP and the post-practice MMMG were calculated from the sum of three years of maize and 1 year of pumpkin in the rotation, as well as 1 year of ginger with the adjustment factor of 1/4 to account for the fraction of pumpkin and ginger in the rotation, as shown in Eqs. 4–5, which were modified from Ukaew et al. (2015) study. These equations were applied to ginger in rotation with upland rice scheme as well.

$$\Delta SOC = \frac{(SOC_{MMMG} - SOC_{MMMP})}{T} \quad (3)$$

where

$$SOC_{MMMG} = [3 \cdot (SOC_{REF} \cdot F_{LU} \cdot F_{MG} \cdot F_I \cdot A)_{MMM} + (SOC_{REF} \cdot F_{LU} \cdot F_{MG} \cdot F_I \cdot A)_G] \cdot \frac{1}{4} \quad (4)$$

and

$$SOC_{MMMP} = [3 \cdot (SOC_{REF} \cdot F_{LU} \cdot F_{MG} \cdot F_I \cdot A)_{MMM} + (SOC_{REF} \cdot F_{LU} \cdot F_{MG} \cdot F_I \cdot A)_P] \cdot \frac{1}{4} \quad (5)$$

where ΔSOC is the annual soil C change (Mg C yr^{-1}), SOC_{MMMG} is the total soil C of MMMG rotation at the post-conversion practice (Mg C), SOC_{MMMP} is the total soil C of MMMP rotation at the reference practice (Mg C), the subscript MMM is 3-years of maize, G is 1-year of ginger, P is 1-year of pumpkin, 3 is the multiplier for 3-years of maize, T is time (default value, 20 years), while 1/4 is the adjustment factor for a 4-year ginger rotation, as well as for a 4-year pumpkin rotation, SOC_{REF} is the reference C stock (Mg C ha^{-1}), A is the land area (1 ha), F_{LU}, F_{MG}, and F_I are the stock change factor for land-use, management regime, and the input of organic matter (dimensionless), respectively.

2.2 Life cycle assessment of pickled ginger

2.2.1 *Goals and scope*

One goal of this study was to estimate the soil C changes affected by change in management practices when replacing pumpkin with ginger in rotation with maize or replacing vegetables with ginger in rotation with upland rice. The second goal was to evaluate the GHG emissions of pickled ginger induced through growing ginger as a crop rotation, including identifying the processes associated with the most significant impacts within the pathway. Phayao province was chosen as the prime location for young ginger production as a raw material for pickled ginger occurs.

2.2.2 *System boundary and functional unit*

The system boundary was "cradle to gate", stated above as the logistics of the production cycle, which starts from the cultivation and harvesting of young ginger (the soil C changes and residue-N_2O emissions were included in this stage) through the production of pickled ginger, including the transportation of all the inputs of material into the pathway and the disposal of waste from the pickling process, as shown in Fig. 3. It should be noted that the pickled ginger produced at the factory gate was not the final product as it needed to be exported to other countries for further processing and packaging. The functional unit was one kilogram of pickled ginger (kg PG). The indirect land use changes (iLUC) were excluded from this study since we assumed that both crop yields of maize and upland rice will be unaffected by the rotation with ginger, according to the study by Choenkwan (2017).

2.2.3 *Life cycle inventory analysis and assumptions*

The life cycle inventory data for the upstream processes of materials, chemicals, and energy were obtained from the Thai national life cycle inventory database (TGO 2020; Thai National LCI, 2021) and the ecoinvent database (Frischknecht et al. 2005; Wernet et al. 2016). The main GHGs considered were carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), of which 100-year global warming potential (GWP) values were 1, 28, and 265, respectively (Myhre et al. 2013). The emission factors of material inputs are provided in SI in Table E1. The details of each stage and the assumptions are described below.

2.2.3.1 Ginger cultivation Young ginger as the raw material of pickled ginger is widely cultivated in Phayao province, where it is grown as a crop in rotation with maize or upland rice, once every 4 years. Ginger, which usually matures after 1 year of growth, is normally cultivated at the beginning of the wet season during the month of May. Young ginger, however, is harvested after 4–6 months from September to October. Ginger cultivation begins with tillage of the land before the planting of the rhizome, followed by the application of fertilizer, and once planted

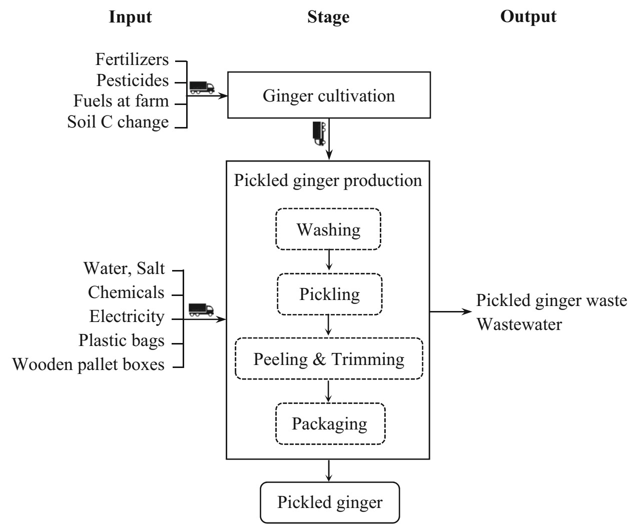


Fig. 3 The system boundary of pickled ginger life cycle

maturity has been achieved the harvesting stage, it is collected by hand, leaving the ginger residue on the land. The average application of nitrogen (N) fertilizer rate was 150 kg N ha^{-1}. The amount of phosphorus (P_2O_5), and potassium (K_2O) were applied at an average rate of 128 kg P_2O_5 ha^{-1} and 192 kg K_2O ha^{-1}, respectively. Urea was commonly used as form of N fertilizers in Thailand (Chitibut et al. 2014). Fuel consumption was assumed to be different depending on types of tillage practices. The amount of fuel used for full tillage in this study was 18.49 kg ha^{-1} (obtained from interview), while fuel consumption for reduced tillage, and no tillage were assumed to be 12.39, and 9.21 kg ha^{-1} (López-Vázquez et al. 2019), respectively. The young ginger yield was 21.41 t ha^{-1} (an average of 10 farms in this study). The CO_2 emission resulting from soil C changes and residue-N_2O emissions were included in the cultivation stage. The N_2O emissions from crop residue associated with MMMG and UUUG were calculated from sum of the total of 3-year maize residue and 1-year ginger residue with an adjustment factor of 1/4 to account for ginger rotation, as shown in Eqs. 6–8 (modified from Ukaew et al. (2015) study). These equations were adjusted to determine the N_2O emissions of UUUG due to a different quantity of N contained in the upland rice residue, see calculation details in SI, Section D. The default value of 0.01325, and 0.01425 from the 2006 IPCC guidelines was used to estimate the total N_2O emissions from N fertilizer and organic N applied to soil (Klein et al. 2006). The average data input of the cultivation stage obtained from ginger farming are illustrated in Table 3.

Table 3 Inventory data input and output of ginger cultivation (per kg of young ginger)

Detail	Unit	Amount
Input		
Ginger rhizome	g	170.17
Synthetic N fertilizer	g	6.97
Organic N fertilizer	g	0.26
Phosphorus (P) fertilizer	g	6.19
Potassium (K) fertilizer	g	9.21
Pesticides	g	0.50
Fuel use at farm	g	1.23
Fuel use for tillage	g	0.86
Full tillage	g	0.58
Reduced tillage	g	0.43
No tillage		
Output		
Young ginger	kg	1.00
N_2O from crop residue inputs	g	Vary[a]
CO_2 from soil C change	g	Vary[a]

[a] Variations depending on management practices

$$N_2O_{MMMG} = \left[(N_{MMM} + N_G) \cdot \frac{1}{4}\right] \cdot 0.01425 \cdot \frac{44}{28} \cdot 1000 \tag{6}$$

where

$$N_{MMM} = 3 \cdot Maize_{residue} \cdot 0.0165 \tag{7}$$

and

$$N_G = Ginger_{residue} \cdot 0.0281 \tag{8}$$

where N_2O_{MMMG} is the total N_2O emissions from crop residue (kg N_2O ha^{-1}), N_{MMM} is the total N contained in crop residue for MMMG rotation (t N ha^{-1}), The subscript MMM is 3-year maize and G is 1-year ginger, 0.01425 is the emission factor for organic N applied to soil (kg N_2O–N (kg N input)$^{-1}$) (Klein et al. 2006), 44/28 is the conversion of N_2O–N emissions to N_2O emissions, $Maize_{residue}$ is the amount of maize residue input (t ha^{-1}), $Ginger_{residue}$ is the amount of ginger residue input (t ha^{-1}), 3 is multiplier for 3-year maize, 0.0165 (Luanmanee and Paisancharoen 2013) and 0.0281 (Singh et al. 2016) are the N content of maize and ginger residue, 1/4 is the adjustment factor for a 4-year ginger in rotation.

2.2.3.2 Pickled ginger production After harvesting, young ginger from the different farms is transported to a pickling factory, located in Phitsanulok province. First, ginger is washed to remove the soil particles, then transported to the fermentation tank that contains a solution of salt, citric acid, and calcium chloride, where the ginger is soaked for two months. The pickled ginger is then transferred to the primary peeling equipment, trimmed, washed, and finally packed in large industrial grade plastic bags with the pickling solution, and stacked in wooden pallet boxes prepared for shipping. The remaining pickling solution and the water from the washing process is collected and treated in a constructed wetland system. About 1.3 kg of young ginger was needed to produce one kg of pickled ginger, with a weight loss of 23%. The data input and output of pickled ginger production that were obtained from the manufactory, are shown in Table 4.

Table 4 Inventory data input and output of the pickled ginger production (per kg of pickled ginger)

Detail	Unit	Amount
Input		
Ginger	kg	1.30
Water	L	4.99
Electricity	kWh	33.24
Salt	g	571.14
Citric acid	g	8.39
Calcium chloride	g	5.35
Plastic bags	g	5.56
Wooden pallet boxes	g	244.44
Output		
Pickled ginger	kg	1.00
Pickled ginger waste	g	249.38
Wastewater	L	4.65

2.2.3.3 Transportation The transportation consists of three stages: (1) transportation of inputs from local stores to the farms, (2) transportation of the young ginger from the farms to the manufactory, and (3) transportation of material inputs from stores to the manufactory. The details of the transportation stage are illustrated in Table 5.

2.2.3.4 Waste disposal The pickled ginger waste is usually disposed of in a landfill site near the manufactory. The industrial wastewater from the pickling process is treated through a constructed wetland system for which the CH_4 and N_2O emissions were calculated based on the 2006 IPCC guidelines (Doorn et al. 2006). The amounts of waste are shown in Table 6.

3 Results and discussion

3.1 The annual soil C change

Figure 4 shows the annual changes of soil C for the MMMG and UUUG rotations compared to the conversion

Table 5 The details of transportation of materials (per kg of pickled ginger)

Detail	Vehicle type	Distance (km)
N P K fertilizers	Pickup truck (4 wheel), 7 ton	10.10
Organic N fertilizer	Pickup truck (4 wheel), 7 ton	6.63
Pesticides	Pickup truck (4 wheel), 7 ton	10.01
Young ginger	Truck (6 wheel), 8.5-ton	304.20
Salt	Truck (10 wheel), 16-ton	405.00
Citric acid	Truck (6 wheel), 8.5-ton	393.00
Calcium chloride	Truck (6 wheel), 8.5-ton	393.00
Plastic bags	Truck (6 wheel), 8.5-ton	382.00
Wooden pallet boxes	Truck (10 wheel), 16-ton	107.00

of forest to ginger cultivation (FTG). For rotation cropping systems, only 9 of 27 management practices were selected to provide an understanding of the related soil C change as affected by changes in management practices. The selected practices were based on the similar levels of residue input of the main crops (maize or upland rice) and ginger under full tillage, reduced tillage, and no tillage. Results and calculation details of the soil C changes for each of MMMG, UUUG, and FTG are provided in SI, Tables C1–C3.

The results showed that changes in land management from replacing pumpkin with ginger in rotation with maize or replacing vegetables with ginger in rotation with upland rice affected changes in soil C. The changes in soil C could either increase (positive value), decrease (negative value), or remain unchanged depending on tillage and residue input. The conversion of land use from forest to ginger cultivation caused the most significant loss of soil C change compared to growing ginger as a crop rotation. The predicted results of soil C changes from MMMG and UUUG rotations varied from − 0.02 to 0.33 and 0.00 to 0.31 Mg C ha^{-1} yr^{-1}, respectively. In contrast, FTG showed the largest loss of soil C change at − 2.02 Mg C ha^{-1} yr^{-1}.

Table 6 The waste of the disposal stage (per kg of pickled ginger)

Waste	Unit	Amount
Pickled ginger waste	g	249.38
Wastewater	L	4.65

Soil C change was greatly affected by tillage practices and crop residue input. Increasing residue input of the main crops (maize or upland rice) and ginger combined with decreased tillage led to an increase in soil C changes for both MMMG and UUUG rotations. Crop residues provided a source of C, and increasing the levels of residue input were directly related to the amount of biomass produced during cultivation. As organic matter gradually decomposed, it released C into the soil (Kumar et al. 2017; Srivastava et al. 2016). The impacts of the main crop residues

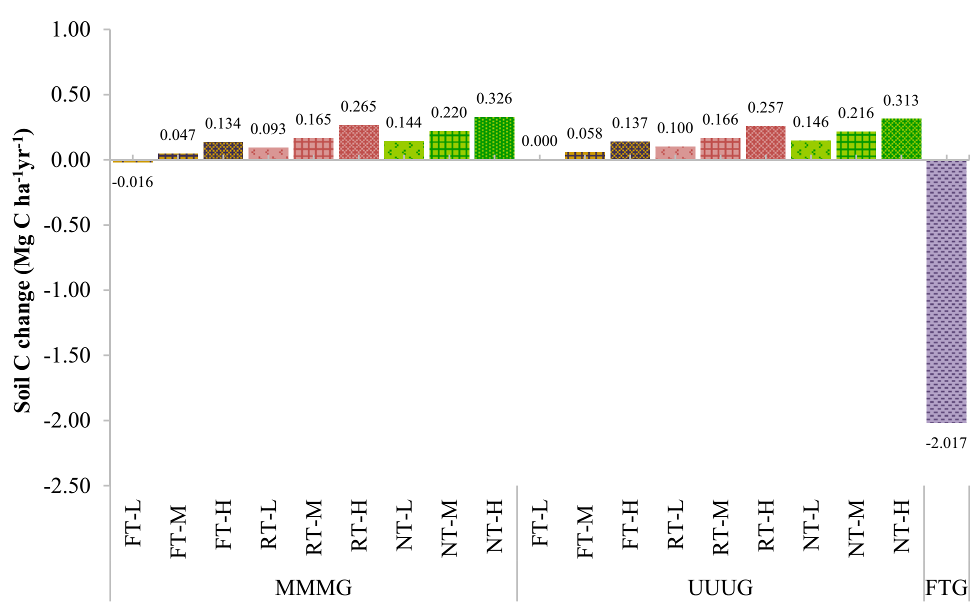


Fig. 4 The changes in soil C resulting from MMMG and UUUG rotations compared to the FTG

were greater than those of ginger residue due to the continuously increasing amount of soil C accumulation from a 3-year of the main crops than a 1-year of ginger rotation. Increasing the main crop residues from low to high levels raised soil C by 6.37% or 15.13% for both rotation cycles. Tillage practices disturbed soil structure and exposed organic matter to oxygen, which increased the decomposition rate of soil microbes. When reducing tillage, soil microbes had less access to organic matter, so the decomposition rate was slow down, resulting in increased C storage in soil. (Kumar et al. 2017). The changes from full tillage to reduced or no tillage increased soil C by 15% or 22% for both rotation cycles. The highest gain of soil C, referred to as the best practice, was achieved by producing a high level of residue input of the main crops and ginger with no tillage, with values of 0.33 and 0.31 Mg C ha^{-1} yr^{-1} for MMMG and UUUG, respectively, as seen in SI, Tables C4 and C5, the 27th scenario.

The soil C changes were also provided for the actual practice used by farmers, in which full tillage was commonly used for cultivating the main crops and ginger; whereby maize and rice residues typically being removed before planting; while ginger residue was always left on the field (i.e., low residue input for the main crops, medium residue input for ginger, full tillage). When this practice was adopted, soil C increased for the UUUG rotation due to the difference in crop residue levels, with ginger producing more residue than vegetables. Nevertheless, no change was observed in soil C for the actual practice of MMMG rotation as there was no change in management practices. This resulted in the same soil C value before and after the practices, as seen in SI, Table C4, the 2nd scenario.

However, a higher level of soil C loss occurred when there was a decrease in crop residue coupled with increased tillage. This happened because crop residue contained organic matter, which helped store C in the soil. When crop residue decreased, the organic matter available for decomposition also decreased, leading to a reduction in the amount of C stored in the soil. Additionally, tillage practices disturbed soil structure and enhanced the availability of oxygen in the soil, which increased the decomposition rate of organic matter by microbial activity, leading to increased CO_2 emissions (Kumar et al. 2017). Thus, decreasing crop residue and increasing tillage both resulted in a reduction of soil organic matter, leading to a loss in soil C. The highest loss of soil C, referred to as the worst practice, was found concerning the MMMG rotation, because of lower level of ginger residue than pumpkin residue, under full tillage, at values of $-$ 0.02 Mg C ha^{-1} yr^{-1}, as seen in SI, Table C4, the 1st scenario.

Overall, based on these predictions, the research findings recommend enhancing soil C storage through a combined approach of no tillage and leaving all crop residues on the field for ginger crop rotation. Additionally, it was also crucial to avoid converting forests into ginger plantations to minimize soil C loss. The study identified that current farming practices for cultivating maize-ginger rotation and upland rice-ginger rotation were intensive, which could result in long-term soil C loss and degradation (Campbell et al. 1996; Chivenge et al. 2007).

Cultivating ginger in rotation with maize or upland rice could enhance soil C change by adopting decreased tillage and increased residue input. These findings agreed with several studies on rotation cropping systems. Stirling et al. (2012) conducted field experiments on growing ginger in continuous cropping systems, including maize, grass pastures, and bare fallow over 4 years under different management practices. They reported that leaving all crop residue on the field and adding soil amendment as a source of C under no tillage led to higher levels of soil C accumulation compared to bare fallow under tillage practice without soil amendment (Stirling et al. 2012). Jie et al. (2022) also found that that the ginger-rice rotation significantly increased the C content more than the ginger-vegetable rotation because more crop residue from ginger-rice rotation was left on the soil compared to ginger-vegetable. The predicted values of soil C changes from our study, $-$ 0.02 to 0.33 Mg C ha^{-1} yr^{-1}, corresponded with 0.2 $\pm$ 0.12 to 0.57 $\pm$ 0.14 Mg C ha^{-1} $year^{-1}$ for average global of soil C changes from rotation cropping systems (O. and West, 2002), $-$ 0.17 to 0.41 Mg C ha^{-1} $year^{-1}$ for Chinese cabbage-maize rotation (Xie et al. (2022), and $-$ 0.16 to 2.68 Mg C ha^{-1} $year^{-1}$ for the field observations of flooded rice rotation with other crops (i.e., maize, sweet sorghum, rice, barley, and wheat) in the tropical region (Cha-un et al. 2015; Kukal et al. 2009; Saree et al. 2012; Wang et al. 2015). However, due to variations in cropping systems, assessment methods, and assumptions among studies, direct comparison of values was not possible (Joensuu et al. 2021). Nonetheless, the soil C change values from our study were lower compared to the flooded rice rotation cropping systems. The reason for this lower value could be attributed to the fact that upland rice and maize in our study were typically grown in cultivated land (dry land). Thus, the long-term cultivated land (F_{LU} was 0.4) was chosen, rather than selecting wet paddy fields (F_{LU} was 1.10), which resulted in a lower value of soil C changes. In contrast, cultivation of flooded rice in rotation with other crops, the decomposition rate of crop residues was slower under anaerobic conditions in flooded rice soil (Cha-un et al. 2015); this was due to the limited oxygen, which was necessary for microorganisms responsible for decomposing organic matter to grow (Sahrawat 2003). This also resulted in a slower decomposition of crop residues compared to aerobic conditions, leading to higher C accumulation in flooded rice soil. In addition, our study found that the values of soil C change in maize-ginger (MMMG) rotations were higher than upland rice-ginger (UUUG) rotations in all cases. This could be explained that the soil C change, using the modified IPCC method, was directly proportional to the SOC_{REF} (Ukaew et al. 2015), in which the maize filed had a highest SOC_{REF} than rice field, resulting in the highest gain and loss of soil C for MMMG compared to UUUG rotations. The most significant loss of soil C change occurred when forest land was converted to ginger plantations, resulting in a 46% decrease in soil C, or − 2.02 Mg C ha^{-1} yr^{-1}, compared to growing ginger as a crop rotation. Forests could sequester C by absorbing it from the atmosphere and storing it in plant biomass, including roots and shoots, through photosynthesis. However, when forests were cleared for agriculture, the C that was previously stored in plant biomass was released into the atmosphere as CO_2 emissions, resulting in a significant loss of soil C (Ontl and Schulte 2012). These findings coincided with several studies, they found that changes in land use, especially converting natural forest to cropland resulted in soil C losses by 25%–52% (Scharlemann et al. 2014; Wei et al. 2014). Guo and Gifford (2002) also estimated a meta-analysis on soil C stock for land use change and reported that significant losses of soil C were caused by the conversion of native forest to cropland (-42%), plantation (-13%) and pasture to cropland (-59%).

3.2 The GHG emissions of pickled ginger

The soil C changes resulting from ginger cultivation in Sect. 3.1 were included in the life cycle pickled ginger pathway. Only three cases related to the management practices from MMMG and UUUG rotations were presented: (1) the worst practice, applying low residue input of the main crops and ginger under full tillage, (2) the actual practice, applying low residue input of the main crops while leaving ginger residue on the field under full tillage, and (3) the best practice, applying high residue input of the main crops and ginger with no tillage. The baseline case referred to excluding the soil C change in the calculation. The details of the GHG emissions for each stage are provided in SI, Table E2.

3.2.1 The main contributors to the GHG emissions of pickled ginger

Figure 5 represents the GHG emissions of pickled ginger as a result of cultivating ginger as a crop rotation for MMMG and UUUG that are associated with the worst, the actual, the best, and the baseline cases (excluding the soil C changes) compared to the conversion of forest to ginger (FTG). The GHG intensity of pickled ginger from different scenarios varied from 0.86 to 1.36 kg CO_2 eq/kg PG. However, when excluding the soil C changes (as seen in the baseline cases), the GHG emissions of pickled ginger from MMMG, UUUG, and FTG were in a narrow range of 0.93–0.97, 0.92–0.93, and 0.91 kg CO_2 eq/kg PG, respectively, which did not differ greatly among different growing ginger methods. The small differences in values for MMMG and UUUG rotations resulted from residue-N_2O emissions and fuel usage related to management practices.

When considering the baseline cases, the orders of GHG intensity of each stage averaged from high to low were as follows: disposal (69.02%) > farming (14.35%, including cultivation and residue-N_2O) > production (12.67%) > transportation (3.95%). It was obviously seen that the largest contribution to the net GHG emissions from the pickled ginger was the disposal stage at 69.02% of the

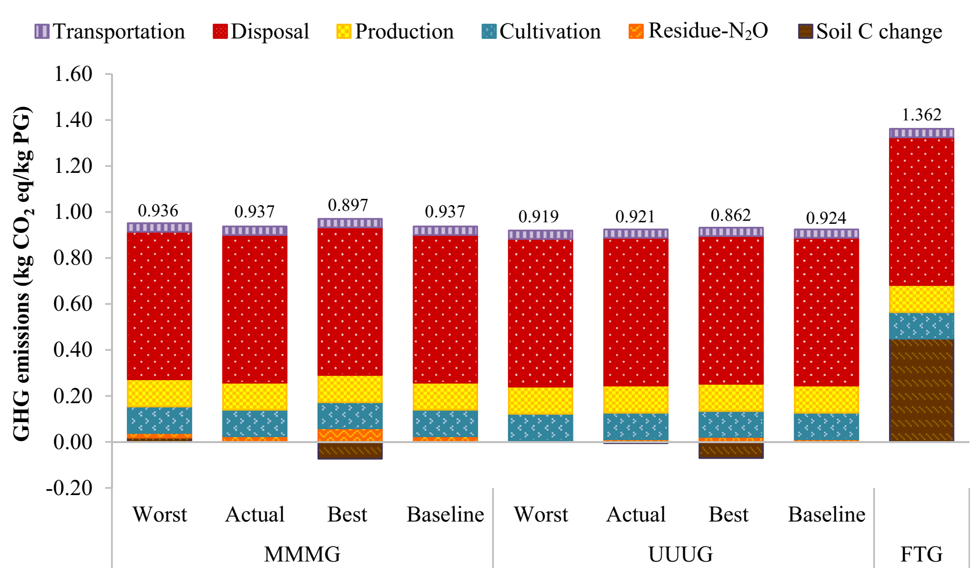


Fig. 5 The GHG emissions of pickled ginger induced through MMMG and UUUG rotations compared to the FTG

total emissions. Nevertheless, 67.81% of the total emissions were mostly from CH_4 releases that were generated in the landfill associated with the decomposition of the pickled ginger waste. The farming stage, which included the cultivation and residue-N_2O was 14.35%, whereby 5.56% of it was attributed to the N_2O emissions resulting from the application of N fertilizer, while 3.22% and 1.96% of it were from urea production and residue-N_2O emissions, respectively. In this study, we observed that the amount of N fertilizer rate applied to young ginger (150 kg N ha^{-1}) was similar to that of matured ginger cultivation as recommended noted in various studies (Pradeepkumar et al. 2001; Sathapornvorasak 2001); even though, young ginger was harvested about 6 months earlier and it generated lower yields than matured ginger. The excessive application of N fertilizer beyond ginger's harvesting requirement led to a negative impact on the N_2O emissions, which caused leaching and runoff of N into the water bodies. In addition, the residue-N_2O emissions increased as crop residue intensified. Although crop residues provided sources of C and N to the soils, increased crop residue also caused an upsurge of N_2O emissions due to N-related emissions from soil. As a result, changing the management practices from the worst practice to the actual practice, and the best practice delivered an average increase in the total GHG emissions, approximately 0.50% and 2.92%, respectively. Furthermore, changes in farming operations through adoption of decrease tillage can reduce the GHG emissions. Conversion of full tillage to reduced tillage, or no tillage helped decrease total GHG averaged by 0.14% and 0.22%, respectively, due to the reduction of fuel consumption associated with fewer trips across the field. The GHG intensity from the pickled ginger production stage was 12.67% of the total emissions, where the most dominant sources of GHG emissions were from citric acid (6.43%), wooden pallet boxes (2.44%), and electricity (2.14%). Although the amount of citric acid usage was relatively low compared to salt or the other inputs, the emission factor of citric acid production was quite high (7.13 kg CO_2 eq/kg), resulting in a leading source of GHG contributor at this stage. The transportation stage showed the lowest GHG emissions due to the use of diesel fuel for transporting ginger from multiple farms to the principal pickled ginger manufacturing facility.

As pickled ginger waste was identified as the primary contributor to GHG emissions of pickled ginger. To investigate the impact of waste management on the final GHG emissions, three scenarios were conducted, assuming all other inputs were constant. The disposal of pickled ginger waste was assumed to be reduced through incineration, composting (Karakurt et al. 2012), or using it as a sodium chloride (NaCl) feed additive for animal (Thongwittaya et al. 2011). The findings revealed that there was a significant reduction of GHG emissions by 65.21%, 63.10% or 68.80%, respectively, over the baseline result (see detail in SI, Figure F1). In addition, the N_2O emissions resulting from the application of N fertilizer were the main contributors of GHG emissions for the cultivation stage. The sensitivity analysis of the reduction of the synthesis N fertilizer rates was conducted to investigate how these factors would affect the cultivation stage and the final GHG results. The decrease in N fertilizer rates at 25%, 50%, and 75% reduced the GHG emissions from the cultivation stage by 17.34%, 34.68%, and 54.97%, respectively. This factor had a small effect on the net GHG emissions of pickled ginger, in which the GHG intensity decreased by 2.15%, 4.30%, and 6.44%, respectively.

The GHG values for pickled ginger from the baseline cases, excluding soil C changes, ranged from 0.91 to 0.97 kg CO_2 eq/kg PG. However, due to limited studies on the LCA analysis of pickled ginger, pickled vegetables in a one kg glass jar (gross weight) consumed by households were chosen for comparison. The GHG values in this study were relatively low compared to 2.37–4.20 kg CO_2 eq/kg jar for pickled vegetables (i.e., beetroots, cabbages, cucumbers, onions, bell peppers) produced in the UK (Frankowska et al. 2019), and 0.92–2.15 kg CO_2 eq/kg jar for pickled cucumbers and roasted pepper produced in Turkey (Gül et al. 2021). This can be explained by considering the system boundary used in our study, which was limited to a cradle-to-gate approach. The product produced at the factory gate was not the final product as it needed to be exported to other countries for further processing and packaging. In contrast, Frankowska et al. (2019) and Gül et al. (2021) conducted LCA analyses of pickled vegetables using a cradle-to-grave approach. They found that the production of packaging and the cultivation of the vegetables were the primary contributors to GHG emissions. This was due to energy consumption required to produce packaging as well as N_2O emissions resulting from N application. Due to the limited scope of our study, the GHG values reported were relatively small. However, when considering the cultivation stage, the study found that the GHG intensity of young ginger was 0.089 kg CO_2 eq/kg ginger, which was comparable to previous study (Audsley et al. 2009) but slightly different from data reported by Thai National LCI (2021), 0.125 kg CO_2 eq/kg ginger. The discrepancy in these figures could be attributed to differences in farming practices, such as variations in fertilizer rates, pesticide usage, and fuel consumption at the farm level, as well as crop yields. It was observed that the amount of N fertilizer applied to young ginger was similar to that of mature ginger, even though young ginger yielded less than mature ginger. Moreover, the existing nutrients in the soil from previous crops such as maize or upland would be available for the ginger crop (Adekiya Aruna et al.

2020). Therefore, excess application of N fertilizer beyond ginger's requirements could have negative consequences such as increased N_2O emissions and N runoff/leaching into water bodies.

3.2.2 *The influence of soil C changes on the GHG emissions of pickled ginger*

When the soil C changes were included, the GHG intensity of pickled ginger was shown as either a benefit or disadvantage that depended on management practices or land use, as seen in Fig. 4. Growing ginger as a crop rotation had modest differences in the value of soil C changes, which ranged from − 0.073 to 0.004 kg CO_2 eq/kg PG for MMMG and − 0.070 to 0 kg CO_2 eq/kg PG for UUUG rotations. On the other hand, FTG exhibited the largest emissions from soil C change, at 0.449 kg CO_2 eq/kg PG. However, increased soil C sequestration had an influence on N_2O emissions associated with crop residue. This effect could offset the benefit of soil C sequestration due to the higher residue-N_2O emissions, which resulted in an overall increase of GHG emissions from the pickled ginger. As a result, the net GHG intensity of pickled ginger varied from 0.00% to − 4.22% for MMMG and − 0.35% to − 6.71% for UUUG rotations compared to the baseline cases. However, when the conversion of land use from forest to ginger cultivation was included in the life cycle, the soil C change increased the overall GHG emissions of pickled ginger by 46.33%.

The changes in soil C had a significant impact on the final GHG emissions of pickled ginger. This excluded soil C changes that resulted in a narrow range of GHG emissions from 0.91 to 0.93 kg CO_2 eq/kg PG, which did not differ greatly among different growing ginger methods. However, incorporating soil C changes revealed the GHG intensity of pickled ginger as a benefit or disadvantage. The estimated GHG emissions of pickled ginger varied greatly from − 0.073 to 0.049 kg CO_2 eq/kg PG, corresponding to − 6.71% to 0.00% for ginger rotation cropping systems and 46.33% for conversion of forest to cultivate ginger. The impact of soil C changes from ginger rotation on the net GHG emissions in this study was relatively small. The results were similar to Joensuu et al. (2021), who studied on wheat production in different regions of Finland. They found that the impact on GHG emissions varied from − 4% to 5% in Southwest Finland and from 5% to 21% in Northern Savonia. Knudsen et al. (2019) also reported that considering soil C changes reduced GHG emissions of milk production by 5% to 18%. Additionally, Röös et al. (2011) also reported that the GHG emissions of pasta production in Sweden were underestimated by 10% due to the exclusion of soil C change. For advanced biofuels, Ukaew et al. (2015) found that the estimated changes in soil C from cultivating rapeseed in rotation with wheat in the U.S. varied greatly, ranging from − 92% to 77% of the emissions. Although the soil C values obtained from our study were similar to their study, there were key differences in the approach used. Ukaew et al. (2015) employed a cradle-to-grave approach, with the rapeseed yield of 2050 kg ha^{-1} and the production processes requiring a high amount of rapeseed for conversion into renewable jet fuel, which greatly influenced the results. Conversely, our study used a cradle-to-gate approach, with the ginger yield of 21,4100 kg ha^{-1} and pickling process requiring a similar amount of ginger for product production. However, the values cannot be directly compared due to differences in crop types, yields, produced products, production processes, and system boundaries between the studies.

3.3 Limitations of the study

Researchers observed several factors that limited the estimation of soil C changes for rotation cropping systems. The modified IPCC (Tier 1) method can be employed to identify general trends of soil C change in some cases during crop rotations (Ukaew et al. 2015). However, it does not account for the effects of various factors such as crop varieties, crop residue, soil composition, nutrient inputs, climate conditions, microbial activity, or the rate of decomposition, all of which significantly impact soil C and N dynamics (USDA 2001). The results of changes in soil C from the modified IPCC method were influenced by five factors: reference C stock (SOC_{REF}), land use (F_{LU}), tillage practice (F_{MG}), crop residue input (F_I), and year of cultivation. Despite variations in crop types, rotations, and residue yields, the same default values of relative stock change factors were applied for F_{LU}, F_{MG}, and F_I. As such, the SOC_{REF} was found to be the primary factor affecting soil C changes, with the highest SOC_{REF} values contributing to the greatest positive and negative value of soil C changes. Moreover, the emissions of N_2O caused by crop residue and N fertilizer application were limited because they were estimated using the same default factor for both direct and indirect N2O emissions, according to the 2006 IPCC method. Due to time constraints and the need to gather sufficient agricultural data for the LCA analysis, subcontracted ginger farms were chosen to represent the entire province. Furthermore, the data inputs for the farming stage were constrained, since the yield, fertilizer rate, pesticides, and fuels obtained from ten ginger farmers, which were considered average and assumed to be identical for both the MMMG and UUUG cropping rotation systems. This was done in order to focus on the differences in soil C changes and residue-N_2O emissions as affected by changes in management practices. As these factors are constrained, the high uncertainties of input data as a result of using the default values when calculating soil C changes and N_2O emissions are considerable, so the analysis of GHG emissions for pickled ginger were limited and contained a high uncertainty of the outcomes, accordingly.

4 Conclusions

This study aimed to determine the impact of soil C changes resulting from replacing pumpkin with ginger in rotation with maize or replacing vegetables with ginger in rotation, and the effects this would have on GHG emissions of pickled ginger. The study estimated the soil C changes of both rotation cycles using the modified IPCC Tier 1 method. It can be concluded that changes in management practices for cultivating maize-ginger or upland rice-ginger rotation cropping systems could potentially increase soil C changes. The findings of this study suggest that promoting the sequestration of C in soil while minimizing land use changes requires a combination of practices. These practices include replacing low residue crops with ginger, rotating ginger with high residue yielding crops, leaving all crop residue on the field, reducing or eliminating tillage, and avoiding the conversion of forests into ginger plantations. The LCA analysis has highlighted pickled ginger waste as the GHG hot spot of the pathways. The key to lowering overall GHG emissions is to dispose of it through incineration, composting, or using it as a feed additive, while minimizing waste disposal and the use of landfill areas. The impact of soil C changes on the GHG emissions of pickled ginger varied from -6.71% to 46.33%, depending on land management and land use changes. Other possible ways to mitigate GHG emissions during cultivation and production processes include reducing N fertilizer, replacing synthetic N fertilizer with organic fertilizer, and switching citric acid to food-grade organic acids with a lower emission factor.

The findings of this study could be useful for farmers in making decisions about crop rotation and management practices to improve soil health and reduce GHG emissions during cultivation. Farmers could consider incorporating ginger in rotation with other crops or adopting these cropping systems in their rotations to improve soil quality. They could also implement certain practices, such as reduced tillage, leaving all crop residue on the field, and avoiding deforestation to cultivate ginger. These conservation practices would not only increase soil C sequestration and contribute to sustainable agriculture, but would also reduce the cost of operation. Policymakers could also use this information to develop strategies for sustainable agriculture and reducing the environmental impact of food production. This information can furthermore assist manufacturers in making informed decisions about selecting ginger obtained from sources that employ sustainable agricultural practices, thereby leading to reduced GHG emissions during cultivation. Implementing sustainable waste management practices could serve as a guide for the ginger pickling industry to minimize their environmental impact on the product. The results from this preliminary study should be used as a baseline to support the decision-making policies related to agricultural practices used for cultivating ginger in an environmentally sustainable manner, while focusing on the reduction of the GHG emissions profiles from food production industries and their waste management practices, moving towards more sustainable patterns of production and consumption. In future studies, there is a need to improve the methods used to address the limitations and uncertainties of research. To achieve this, the soil biogeochemical-based model should be incorporated, along with field experiments, to facilitate a better interpretation of soil C changes for ginger rotation cropping systems. The areas that require further study include investigating the relationship between soil C, N input, yield, and the amount of residue returning to the field for ginger rotation cropping systems using a soil process-based model. Additionally, the LCA analysis of pickled ginger from a cradle to grave approach is necessary to gain a more comprehensive understanding and identify areas of improvement that can be made to reduce overall GHG emissions.

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Data availability The datasets generated during the current study are available in the "Supplementary Information".

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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