From Soil to Factory Gate: A Cradle-to-Gate Life Cycle Assessment of Sri Lankan Tea

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S1. Calculations related to fertilizer inputs

a. Calculations of fertilizer and citronella inputs

Equation S1 was used to calculate the availability of elemental N, P, and K in fertilizer applied. Information from Table S10: was used to obtain percentage composition of nutrient levels in each fertilizers type.

$N = F \times N_P$ …… **Equation S1**

Where;

N =Nutrient input

F =Amount of fertilizer used

N_P =Percentage composition of nutrient [%]

b. Calculations of fertilizer and citronella outputs

Usage of fertilizers in tea cultivation is associated with major environmental pollutants and their impacts. This section presents the calculation methodology for those emissions that arise from application of fertilizers. The equations and definitions are derived from IPCC methodologies on N_2O Emissions from Livestock and Manure Management (IPCC, 2006b) and N2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application (IPCC, 2006c).

I) N_2O emission from fertilizer:

Use of nitrogenous fertilizer causes addition of different chemical species containing elemental N. These chemical species undergo various reactions and result in several emissions. There are a number of pathways that result in nitrous oxide emissions from agricultural fertilizer application, which can be divided as follows.

i. Direct emissions (release of N_2O directly from fertilizer)

ii. Indirect emissions (N_2O emissions through a more intricate mechanism)

iii. Other nitrous emissions from activities such as a change in organic soil management, and emissions from urine and dung inputs to grazed soils.

I. Direct emissions (release of N_2O directly from fertilizer)

A portion of elemental N from fertilizer is converted to N_2O directly after fertilizer application. These are known as direct released N_2O and represented in equation S2

$(N_2O\text{-}N \text{ direct}) = (N_2O\text{-}N \text{ inputs}) + (N_2O\text{-}N_{OS}) + (N_2O\text{-}N_{prp})$ **……..……..Equation S2**

Where,

$N_2O - N_{direct}$	= direct N_2O–N emissions produced from managed soils, [kg N_2O–N]
N_2O–N_{input}	= direct N_2O–N emissions from N inputs to managed soils, [kg N_2O–N]
N_2O–N_{OS}	= direct N_2O–N emissions from managed organic soils, [kg N_2O–N]
N_2O–N_{PRP}	= direct N_2O–N emissions from urine & dung inputs to grazed soils, [kg N_2O– N]

According to the system boundary and scope of the present study, only the N_2O emission from direct inputs are considered, including synthetic fertilizer and organic fertilizer. The latter variables were not taken into account in this crop cultivation models. N2O–NOS was excluded as it is assumed that tea is cultivated on established agricultural areas and the management of soils does not substantially change. N_2O–NPRP was disregarded as the cropland is not grazed by cattle.

The N_2O emissions from inputs are driven by four different parameters (see equation S3); the application of synthetic fertilizer, application of organic fertilizer (e.g. Citronella), and amount of crop residue left after

harvest, and annual release of N in soil organic matter due to land use change. However, within the present study it did not focus on releasing N from soil organic matter (FSOM) which is available naturally.

N_2O- N inputs= (F_{SN}+ F_{ON} + F_{CR} + F_{SOM}) x EF_1…….…… **Equation S3**

Where;

N_2O–N inputs = direct N_2O–N emissions from N inputs to managed soils, [kg N_2O–N]

F_{SN} = the amount of synthetic fertiliser N applied to soils, [kg N]

F_{ON} = the amount of animal manure, compost, sewage sludge and other organic N additions applied to soils, [kg N]

F_{CR} = the amount of N in crop residues [kg N]

F_{SOM} = the amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management, [kg N]

EF_1 = emission factor* for N_2O emissions from N inputs

Table S11 provides a list of emissions factors and constants adopted from IPCC. Note: The unit [kg N_2O-N] should be interpreted as kg nitrous oxide measured as kg nitrogen. To obtain [kg N_2O], [kg N_2O-N] needs to be multiplied by (44/28), to account for the mass of nitrogen (2xN) within the mass of a nitrous oxide molecule (2 x N+1 x O).

II. Indirect emissions (N_2O emissions through a more intricate mechanism)

In addition to direct released N_2O emissions, there are two other indirect mechanisms that also contribute to the total N_2O emissions. The two processes are atmospheric deposition and leaching. Collectively, they are termed indirect released N_2O and represented in equation S4.

N_2O –N indirect = N_2O–$N_{(ATD)}$ + N_2O-$N_{(L)}$……. **Equation S4**

Where,

$N_2O_{(ATD)}$–N = amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, [kg N_2O–N]

$N_2O_{(L)}$–N = amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, [kg N_2O–N]

<u>N_2O from atmospheric deposition:</u>

$N_2O_{(ATD)}$–N depends on the fraction of applied N that volatizes as NH_3 and NO_x, and the amount of volatized N that is converted to N_2O, shown in equation S5.

$$N_2O\text{-}N_{(ATD)} = (F_{SN} \times Frac_{GASF}) + [(F_{ON} + F_{prp}) \times Frac_{GASM})] \times EF_4 \text{.....} \textbf{Equation S5}$$

Where,

F_{SN} = Amount of synthetic fertiliser N applied to soils, [kg N]

F_{ON} =Amount of animal manure, compost, sewage sludge and other organic N additions applied, [kg N]

$Frac_{GASF}$ = Fraction of synthetic fertiliser N that volatilizes as NH_3 and NO_x

$Frac_{GASM}$ = Fraction of applied organic N fertiliser materials (FON) that volatilizes as NH_3 and NO_x

F_{PRP} = Amount of urine and dung N deposited by grazing animals on pasture, range and paddock, [kg N]

EF_4 = Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces

In the present study area, no mixed enterprise farming systems are practiced. Therefore, in the crop cultivation models, F_{PRP} was set to 0 as there is no deposition of urine and dung from grazing animals.

<u>N_2O from leaching:</u>

The second intricate pathway of indirect released N_2O is leaching. In order to determine the N_2O emission from leaching of applied N from fertiliser (N_2O-N_L) the following equation was used. Here also, F_{CR}+ F_{prp} +F_{SOM} were set to zero as mentioned before (see equation S6).

N_2O-N_L = [(F_{SN}+F_{ON}+F_{CR}+F_{prp}+F_{SOM}) x Frac $_{LEACH}$] x EF_5 **……. Equation S6**

Where,

$Frac_{LEACH}$-(N) = Fraction of all N added to mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff

EF_5 = Emission factor for N_2O emissions from N leaching and runoff

(b) Ammonia (NH_3) and Nitrate (NO_3^-) emissions from fertilizer application:

NH_3 and NO_3^- are inherently emitted by all nitrogenous fertilizers, through volatilization and leaching, respectively (see equation S7 and S8). It is assumed that all nitrogen that volatizes converts to ammonia (NH_3), and that all nitrogen that leaches is emitted as nitrate (NO_3^-). Once more, the IPCC calculation rules were applied to determine the ammonia and nitrate emissions.

<u>Ammonia (NH_3) emissions to atmosphere:</u>

NH_3-N = (F_{SN} x Frac $_{GASF}$) + (F_{ON} +F_{prp}) x Frac $_{GASM}$ **…….Equation S7**

Where,

NH_3-N = Ammonia produced from atmospheric deposition of N volatilized from managed soils, [kg NH_3–N]

Note: The unit [kg NH_3–N] should be interpreted as kg ammonia measured as kg nitrogen. To obtain [kg NH_3], [kg NH_3-N] needs to be multiplied by (17/14), to account for the mass of nitrogen (1xN) within the mass of an ammonia molecule (1 x N+3 x H).

<u>Nitrate (NO_3^-) emissions to soil:</u>

NO_3^-—N = (F_{SN}+F_{ON}+F_{CR}+F_{prp}+F_{SOM}) Frac $_{LEACH}$ **……. Equation S8**

Where,

NO_3^-—N = Nitrate produced from leaching of N from managed soils, [kg NO_3^-N]

Note: The unit [kg NO_3^-N] should be interpreted as kg nitrate measured as kg nitrogen. To obtain [kg NO_3^-], [kg NO_3^-N] needs to be multiplied by (62/14), to account for the mass of nitrogen (1xN) within the mass of a nitrate molecule (1 x N+3 x O).

(c)Phosphorous emissions from application of fertilizer:

A portion of the phosphorous in fertilizers and manure is emitted to the soil and subsequently has an impact on freshwater eutrophication. The phosphate emissions to water were calculated using the phosphorus content of the fertilizer and manure that is applied. The fraction of phosphate emission that reaches freshwater is approximately 0.05 for phosphorus from fertilizer and manure, as stated in equation S9.

$Q = (F_{SN}+F_{ON}) \times P_{frac}$ **…….. Equation S9**

Where,

Q = Amount of phosphate emissions to water [kg]

P_{frac} = Fraction of phosphate emission that actually reaches freshwater = 0.05

(d) Carbon dioxide emission from urea in chemical fertilizers:

The fertiliser mix (U709) used by farmers contains urea as the source of nitrogen. Decomposition of urea releases CO_2. Carbon dioxide emissions from fertiliser application can be calculated using equation S10.

$CO_2\text{-}C_{em} = (M_{urea} \times EF_{urea})+(M_{limestone} \times EF_{limestone}) +(M_{dolomite} \times EF_{dolomite})$ **… Equation S10**

Where,

CO_2–C_{em} = C emissions from lime, dolomite and urea application, [kg CO_2]

M_{urea} = Amount of urea in [kg]

EF_{urea} = Emission factor for urea

$M_{limestone}$ = Amount of limestone in [kg]

$EF_{limestone}$ = Emission factor for limestone

$M_{dolomite}$ = Amount of dolomite in [kg]

$EF_{dolomite}$ = Emission factor of dolomite

However, in the study sample, usage of dolomite and limestone were not recorded therefore $M_{limestone}$ and $M_{dolomite}$ were set to zero.

Note: The unit [kg CO_2–C] should be interpreted as kg carbon dioxide measured as kg carbon. To obtain [kg CO_2], [kg CO_2–C] needs to be multiplied by (44/12), to account for the mass of carbon (1xC) within the mass of a carbon dioxide molecule (1 x C+2 x O).

S2. Calculation of pesticide and Zinc sulphate inputs

Tea farmers in the study area apply agrochemicals to control the pests, in particular weeds. Initially, plantation owners were inquired of which types of agrochemicals are used by them frequently for their cultivation process. However, the plantation owners were only able to mention the agrochemicals by their brand names and commercial trade names. Then information on chemical compound names and active ingredients of those brands were gathered by observing the actual containers during the farmer interviews. The information was further verified by literature review. Using the raw data on pesticide usage, the rate of application of Active Ingredient (AI) was calculated.

S3. Calculation of pesticide and Zinc sulphate emissions / outputs

Finally, the effective physical input was calculated with proper impact allocation. Effective physical inputs for agrochemicals refer to the portion of pesticides that directly impacts on environment compartment (see equation S11).

$I_{EFF} = A_R \times P_A$ …… **Equation S11**

I_{EFF} = Rate of application of AI [g per ha]

P_A = Impact allocation percentage (For pesticides: 100%, for $ZnSO_4$: 100%.)

A_R = Effective physical input per 4650 kg of fresh tea leaves (1 tonne of processed tea) [g]

S4. Representative processes and Inventories

Table S1: Representative processes in eco invent v3.11

Process in tea manufacturing	Representative intermediate process in eco invent v3.11
Polythene sleeves production	Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U
Fertilizer (T-65) production	NPK (15-15-15) fertiliser {RoW}| market for NPK (15-15-15) fertiliser | Cut-off, U
Zinc Sulphate production	Zinc monosulfate {RoW}| market for zinc monosulfate | Cut-off, U
Fertilizer (T-200) production	NPK (15-15-15) fertiliser {RoW}| market for NPK (15-15-15) fertiliser | Cut-off, U
Fertilizer (U-709) production	Urea {RoW}| market for urea | Cut-off, U
Glyphosate 36g/L production	Glyphosate {GLO}| market for glyphosate | Cut-off, U
Copper hydroxide 57.6% w/w production	Copper sulfate {GLO}| market for copper sulfate | Cut-off, U
Fertilizer (T-750) production	NPK (15-15-15) fertiliser {RoW}| market for NPK (15-15-15) fertiliser | Cut-off, U
Fuelwood	Cleft timber, measured as dry mass {RoW}| hardwood forestry, eucalyptus ssp., planted forest management | Cut-off, U
Electricity generation	Electricity, medium voltage {LK}| market for electricity, medium voltage | Cut-off, U
Packaging production	Paper sack {RoW}| market for paper sack | Cut-off, U
Transportation-Tipper	Transport, freight, lorry, diesel, unspecified {RoW}| market for transport, freight, lorry, unspecified | Cut-off, U
Transportation-Truck	Transport, freight, tractor and trailer, diesel, agricultural {RoW}| market for transport, freight, tractor and trailer, diesel, agricultural | Cut-off, U
Transportation-Tractor	Transport, freight, tractor and trailer, diesel, agricultural {RoW}| market for transport, freight, tractor and trailer, diesel, agricultural | Cut-off, U
Transportation-Three-wheeler	Transport, freight, light commercial vehicle, fleet average {RoW}| market for transport, freight, light commercial vehicle, fleet average | Cut-off, U

Transportation-Maxi truck	Transport, freight, light commercial vehicle, fleet average {RoW}| market for transport, freight, light commercial vehicle, fleet average | Cut-off, U

Table S2: Inputs and Outputs in the Nursery Phase for Smallholder and Estate-Owned Plantations per 1 Tonne of Processed Tea

Parameter	**Smallholder**	**Estate-owned**	**Unit**
Inputs			
Soil	0.323	0.281	m^3
Tea cuttings	323	281	pieces
Polythene sleeves	323	281	pieces
Water	1,940	1,693	L
Fertilizer (T65)	2.18	1.90	kg
Zinc sulphate	0.00504	0.00437	kg
Outputs			
Direct N_2O	0.00379	0.00329	kg N_2O
Indirect N_2O (ATD)	0.00042	0.00036	kg N_2O
Indirect N_2O (leaching)	0.00100	0.00087	kg N_2O
Total N_2O	0.00518	0.00450	kg N_2O
NH_3 volatilized	0.03210	0.02787	kg NH_3
NO_3^- leached	0.255	0.222	kg NO_3^-
PO_4^{3-} to water	0.00524	0.00456	kg PO_4^{3-}
$ZnSO_4$ (22% Zn)	0.00111	0.00096	kg

Table S3: Inputs and Outputs in the Land Preparation Phase for Smallholder Plantations per 1 Tonne of Processed Tea

Parameter	**Smallholder**	**Unit**
Citronella grass - Dry Matter	104.4	kg
Direct N_2O	0.0312	kg N_2O
Indirect N_2O (ATD)	0.0066	kg N_2O

Indirect N_2O (leaching)	0.0083	kg N_2O
Total N_2O	0.0459	kg N_2O
NH_3 volatilized	0.508	kg NH_3
NO_3^- leached	2.107	kg NO_3^-
PO_4^{3-} to water	0.00683	kg PO_4^{3-}

Table S4: Inputs and Outputs in the Unproductive Phase for Smallholder and Estate-Owned Plantations per 1 Tonne of Processed Tea

Parameter	**Smallholder**	**Estate-owned**	**Unit**
T-200 applied	74.36	65.99	kg
Direct N_2O	0.121	0.106	kg N_2O
Indirect N_2O (ATD)	0.013	0.011	kg N_2O
Indirect N_2O (leaching)	0.032	0.028	kg N_2O
Total N_2O	0.165	0.147	kg N_2O
NH_3 volatilized	1.024	0.909	kg NH_3
NO_3^- leached	8.14	7.224	kg NO_3^-
PO_4^{3-} to water	0.112	0.099	kg PO_4^{3-}

Table S5: Inputs in the Productive Phase for Smallholder and Estate-Owned Plantations per 1 Tonne of Processed Tea

Parameter	**Smallholder**	**Estate-owned**	**Unit**
Land occupation	0.029	0.0205	ha
T-200 fertilizer	55.68	—	kg
U-709 fertilizer	560.28	486.36	kg
T-750 fertilizer	—	57.09	kg
Glyphosate (active)	—	0.057	kg
Copper hydroxide	—	0.0803	kg

Table S6: Outputs in the Productive Phase for Smallholder Plantations per 1 Tonne of Processed Tea

Parameter	U-709	T-200	Total	Unit
Direct N_2O	2.50	0.097	2.597	kg N_2O
Indirect N_2O (ATD)	0.276	0.010	0.286	kg N_2O
Indirect N_2O (leach)	0.660	0.025	0.685	kg N_2O
Total N_2O	3.44	0.132	3.572	kg N_2O
NH_3 volatilized	21.26	0.759	22.019	kg NH_3
NO_3^- leached	168.66	6.079	174.739	kg NO_3^-
PO_4^{3-} to water	0.439	0.084	0.523	kg PO_4^{3-}

Table S7: Outputs in the Productive Phase for Estate-Owned Plantations per 1 Tonne of Processed Tea

Parameter	U-709	T-750	Total	Unit
Direct N_2O	2.18	0.123	2.303	kg N_2O
Indirect N_2O (ATD)	0.240	0.013	0.254	kg N_2O
Indirect N_2O (leach)	0.576	0.032	0.608	kg N_2O
Total N_2O	2.99	0.168	3.158	kg N_2O
NH_3 volatilized	18.56	1.049	19.609	kg NH_3
NO_3^- leached	147.19	8.327	155.517	kg NO_3^-
PO_4^{3-} to water	0.368	0.046	0.414	kg PO_4^{3-}
CO_2 from urea	217.41	—	217.41	kg CO_2
Glyphosate (active)	—	—	0.057	kg
Copper (elemental)	—	—	0.052	kg

Table S8: Inputs and Outputs per 1 tonne of processed tea, CTC processing method

Stage	Inputs	Amount	Output	Amount
1.Withering	Fresh tea leaves (kg)	4650	Withered tea leaves (kg)	3255
	Electricity (kWh)	444.6633	Wood Ash (kg)	4.64
	Fuelwood (kg)	400	CO2, Biogenic (kg CO2)	716.8
			Methane	0.192

			N2O (kg N2O)	0.025
2. CTC	Withered tea leaves (kg)	3255	Rolled tea leaves (kg)	2440
	Electricity (kWh)	85.21		
3. Fermentation	Rolled tea leaves	2440	Fermented tea leaves (kg)	2440
	Electricity (kWh)	21.19		
4. Drying	Fermented tea leaves (kg)	2440	Dried tea leaves (kg)	1025
	Electricity (kWh)	75.46	Wood Ash (kg)	12.76
	Fuelwood (kg)	1100	CO2, Biogenic (kg CO2)	1971.2
			Methane (kg CH4)	0.528
			N2O (kg N2O)	0.0704
5.Sorthing and Grading	Dried tea leaves (kg)	1025	Graded tea (kg)	1000
	Electricity (kWh)	9.68	Refused tea (kg)	25
7. Packaging	Graded tea (kg)	1000	Packed tea (kg)	1000
	Electricity (kWh)	0.133		
	Packaging	80		

Table S9: Inputs and outputs per 1 tonne of processed tea, Orthodox processing method Orthodox

Stage	**Inputs**	**Amount**	**Output**	**Amount**
1.Withering	Fresh tea leaves (kg)	4650	Withered tea leaves (kg)	2700
	Electricity (kWh)	444.6633	Wood Ash (kg)	5.8
	Fuelwood (kg)	500	CO2, Biogenic (kg CO_2)	896
			Methane (kg CH_4)	0.24
			N_2O (kg N_2O)	0.032
2. Rolling	Withered tea leaves (kg)	2700	Rolled tea leaves (kg)	2650
	Electricity (kWh)	110.307		
3. Fermentation	Rolled tea leaves (kg)	2650	Fermented tea leaves (kg)	2600
	Electricity (kWh)	45.196		
4. Drying	Fermented tea leaves (kg)	2600	Dried tea leaves (kg)	1111
	Electricity (kWh)	78.11	Wood Ash	12.76
	Fuelwood (kg)	1100	CO2, Biogenic (kg CO2)	1971.2

			N2O (kg N_2O)	0.0704
			Methane (kg CH4)	0.528
5.Sorthing and Grading	Dried tea leaves (kg)	1111	Graded tea (kg)	1000
	Electricity (kWh)	25.5	Refused tea (kg)	111
7. Packaging	Graded tea (kg)	1000	Packed tea (kg)	1000
	Electricity (kWh)	0.133		
	Packaging	80		

Table S10: The percentage availability of N, P_2O_5 and K_2O in each type of fertilizer

	Citronella	T-200	U-709	T-65	T-750
N	1.9%	10.3%	28.4%	11%	13.7%
P_2O_5	0.13%	6.9%	3.6%	11%	3.7%
K_2O	0.075%	7.5%	14.2%	11%	8.0%

Table S11: Emission factors and constants

Emission Type	Parameter	Default Value	Description	Unit	Source
Direct N_2O from soil	EF1	0.010	Direct N_2O-N emissions per kg of N applied (synthetic or organic)	kg N_2O-N / kg N applied	IPCC 2019 Refinement, Table 11.1
$NH_3 + NO_x$ volatilization	Frac_GASF	0.11 (Urea – 0.15) Ammonium based – 0.	Fraction of synthetic N that volatilizes as $NH_3 + NO_x$	kg NH_3-N + NO_x-N / kg N applied	IPCC 2019 Refinement, Table 11.3
	Frac_GASM	0.21	Fraction of organic N (e.g., citronella) that volatilizes as $NH_3 + NO_x$	kg NH_3-N + NO_x-N / kg N applied	IPCC 2019 Refinement, Table 11.3
	EF4	0.010	Indirect N_2O-N emissions per kg $NH_3 + NO_x$ volatilized	kg N_2O-N / kg N volatilized	IPCC 2019 Refinement, Table 11.3
NO_3^- leaching/runoff	Frac_LEACH	0.24	Fraction of N lost via nitrate leaching or runoff	kg NO_3^--N / kg N applied	IPCC 2019 Refinement, Table 11.3
	EF5	0.011	Indirect N_2O-N emissions per kg NO_3^- leached	kg N_2O-N / kg N leached	IPCC 2019 Refinement, Table 11.3