Assessing the sustainability performance of coffee farms in Vietnam: a social profit inefficiency approach

Supplementary material 1

The maximum social profit is obtained by solving the following linear programming model:

$$\Pi(p,w,r,f) = \max_{y,x,b} \left(\sum_{m=1}^{M} p_m y_m - \sum_{n=1}^{N} w_n x_n - \sum_{j=1}^{J} r_j b_j \right)$$

$s.t.$

$$\sum_{k=1}^{K} \alpha^k y_m^k \geq y_m, \quad m = 1,2,\dots,M$$

$$\sum_{k=1}^{K} \alpha^k x_n^k \leq x_n, \quad n = 1,2,\dots,N$$

$$\sum_{k=1}^{K} \alpha^k f_d^k \leq f_d, \quad d = 1,2,\dots,D$$

$$\sum_{k=1}^{K} \alpha^k b_j^k \leq b_j, \quad j = 1,2,\dots,J$$

$$\alpha \geq 0; \quad k = 1,2\dots,K$$

The model yields the optimum output, input and externality combinations that provide the maximum attainable social profit given the production technology, prices (shadow), and the available level of the fixed inputs.

In the model, the set α of intensity variables is restricted to be greater or equal to zero, implying a production technology that exhibits constant returns to scale (CRS).

The Overall Technical Inefficiency (*OTI*) and Pure Technical Inefficiency (*PTI*) component for DMU k' is obtained by solving the following linear programming model:

$$\overrightarrow{D_T^{k'}}(y^k, x^k, f^k, b^k; g_y, g_x, g_b | CRS) = max\beta$$

$s.t.$

$$\sum_{k=1}^{K} \alpha^k y_m^k \geq y_m^{k'} + \beta g_y, \quad m = 1,2,\dots,M$$

$$\sum_{k=1}^{K} \alpha^k x_n^k \leq x_n^{k'} - \beta g_x, \quad n = 1,2,\dots,N$$

$$\sum_{k=1}^{K} \alpha^k f_d^k \leq f_d^{k'}, \quad d = 1,2,\dots,D$$

$$\sum_{k=1}^{K} \alpha^k b_j^k \leq b_j^{k'} - \beta g_b, \quad j = 1,2,\dots,J$$

$$\alpha^k \geq 0; \quad k = 1,2\dots,K$$

The Overall Technical Inefficiency (*OTI*) is computed with this model that has a set α^k of intensity variables that is restricted to be greater or equal to zero, implying a production technology that exhibits constant returns to scale (CRS). To compute the Pure Technical Inefficiency (*PTI*) the CRS assumption is relaxed to assess the DMUs under a production technology that exhibits variable returns to scale. In this case the sum of intensity variables is constrained to be equal to one $\sum_{k=1}^{K} \alpha^k = 1$.

Supplementary material 2

Underlying assumptions, data and the related sources used for the calculation of the externalities and their respective shadow prices.

1 Nitrate pollution

A tentative Nitrogen (N) balance was calculated to estimate the nitrate pollution externality. As it is assumed that coffee farm systems are in equilibrium with respect to N in the system, the nitrate pollution externality was calculated for each coffee farm as the difference between the N that enter the system (N inputs) and the N that leaves the system (N outputs and N loss):

$$NO_3^- - N = N \text{ inputs} - (N \text{ outputs} + N \text{ loss}) * Fpol$$

Where: N inputs = amount of N in fertilizers (synthetic and organic) + N amount in residues; N outputs = amount of N in harvest material; N loss = N loss via background N_2O-N emissions (N_2O-N+NO-N) + fertilizer induced and crop residue N_2O-N emissions (N_2O-N+NO-N) + volatilization (NH_3-N and NO-N). Fpol = given that about 50% of the difference between the N that enters and leaves the system remains stored in soils and plants for several years in the permanent framework of roots, stems and branches [60], it is assumed that only the remaining 50% causes nitrate pollution problems.

N inputs:

N amount in fertilizers (NI)

N inputs from fertilizers were estimated as the quantity of each type of fertilizer (kg of synthetic and organic fertilizer) multiplied by the known (or estimated[1]) N concentration per kilogram of fertilizer.

$$NI_i = F_i * CN_i$$

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[1] N contents of organic material used as fertilizer are generally not measured and estimates are based on existing literature.

Where: F_i = amount of fertilizer type i (kg product year^{-1}); CN_i: N concentration in fertilizer i (kg N per kg product).

N content in residues (*NR*)

Nitrogen inputs from crop residues were estimated as the annual amount of crop residues (kg of dry matter per year), multiplied by the average estimated N concentration per kilogram of dry matter (% N per kg dry matter). As it is assumed that the amount of pruning residues proportionally increases with the number of coffee trees our estimate was corrected for each farm according to number of trees per hectare.

$$NR = R * CN_R$$

Where: R = amount of residues (kg dry matter year^{-1}); CN_R = N concentration in residues (kg N per kg dry matter).

N harvest material (NH)

Nutrient export through the coffee harvest was estimated using yield data and published values of nutrient removal in coffee beans.

$$NH = Y * CN_H$$

Where: Y = yield (kg year^{-1}); CN_H = N concentration in harvest (kg N per kg of coffee cherries).

N loss:

N loss via N$_2$O and NO background emissions

N$_2$O-N background emissions were calculated based on the emission factor proposed by [56] for tropical climates on a per-hectare basis. Based on [56] N loss as N$_2$O-N+NO-N in background emissions is of about 16 kg N$_2$O–N ha^{-1} yr^{-1}, which refers to the mineralization rates in tropical climates.

$$N_2O_{(bkg)} - N = EF_{bkg} * area$$

Where: $N_2O_{(NIR)}$–N= annual background N_2O–N emissions from tropical areas (kg N_2O–N yr^{-1}); EF_{bkg} = emission factor annual direct N_2O–N emissions from tropical areas (kg N_2O–N yr^{-1}). The default value f is 16 kg N_2O–N ha year as it is assumed to be twice the N_2O emission for temperate climates (mineralization rates are assumed to be about 2 times greater in tropical climates) [56].

Nitrogen loss via fertilizer and crop residues – N_2O emissions

Fertilizer-induced and crop-residue N emissions were estimated using the generic emission factors of [65], which reflect the percentage of the applied N that is lost via N_2O-N and NO-N emissions. The generic emission factors differ per type of fertilizer. The average emission factor of [65] is approximately 1% of total N fertilizer. This value is similar to the default value published by [56] and to the results of N_2O-N emissions found in the field by [63] and [66] in coffee plantations in Costa Rica. N loss via volatilization was estimated using Tier II [56]. N export through the coffee harvest was estimated using yield data and figures on nutrient removal from harvesting coffee beans [55].

N loss via N_2O fertilizer induced and crop residue emissions is estimated as:

$$N_2O_{(NIR)} - N = \sum_i NI_i * EF_{(NI_i)} + NR * EF_{(R)}$$

Where: $N_2O_{(NIR)}$–N = annual amount of N_2O–N produced from fertilizer use and crop residues (kg N_2O– N yr^{-1}); NI_i = N amount via fertilizer *i* (kg N yr^{-1}); NR = applied N via crop residues (kg N yr^{-1}); $EF_{(NIi)}$ = Bouwman N_2O-N (N_2O-N+NO-N) emission factor for fertilizer *i* (kg N_2O–N per kg N^{-1}) (Table S1); $EF_{(R)}$ = N_2O-N emission factor for crop residues (kg N_2O–N per kg N^{-1}). Based on [56] the emission factor for crop residues is 1%.

Table S1: Generic emission factors ($EF_{(NIi)}$) as percentage of applied N for different fertilizer types [56].

Fertilizer type	Bouwman N_2O-N (N_2O-N+NO-N)- $EF_{(NIi)}$	Volatilization (NH_3) - $Frac_{vi}$
Ammonium Bicarbonate	0.0107	
Ammonium nitrate	0.0101	0.037
Ammonium sulphate	0.0107	0.013
Ammonium sulphate nitrate	0.0105	

Anhydrous ammonia	0.0107	0.011
Calcium ammonium nitrate	0.0099	0.022
Calcium nitrate	0.0088	0.009
Compound NK	0.0088	0.037
Compound NPK	0.0094	0.037
Diammonium phosphate	0.0094	0.113
Kainit / Magnesium Sulphate	0.0000	
Lime - 52% CaO	0.0000	
Limestone - 55% $CaCO_3$ / 29%CaO	0.0000	
Lime, algal - 30% CaO	0.0000	
Monoammonium phosphate	0.0094	0.113
Muriate of potash / Potassium Chloride	0.0000	
Phosphate/Rock Phosphate	0.0000	
Potassium sulphate	0.0000	
Super phosphate	0.0000	
Triple super phosphate	0.0000	
Urea	0.0112	0.243
Urea ammonium nitrate solution	0.0057	0.125
Compost (zero emissions)	0.0037	
Manure	0.0037	

Emission factors for N_2O-N fertilizer induced emissions from soils (kg N_2O-N kg N year^{-1}) [56]; Emission factors for total NH_3 emissions from soils due to N fertilizer volatilization and foliar emissions (kg NH_3 kg N year^{-1}) [61]

N loss via NH$_3$ volatilization

Nitrogen loss via NH_3 volatilization is estimated using Tier II [56] as:

$$N_2O_{(V)} - N = \left[\sum_i NI_i * Frac_{V_i} + \left(NR * Frac_{(R)} \right) \right] * EF_{(V)}$$

Where: $N_2O_{(V)}$–N = annual amount of N_2O–N produced from atmospheric deposition of N volatilized (kg N_2O–N yr^{-1}); NI_i = amount of N applied via fertilizer i (kg N year^{-1}); NR = applied N via crop residues (kg N yr^{-1}); $Frac_{V_i}$ = fraction of fertilizer i that volatilizes as NH_3 (kg N applied year^{-1}) (Table S1); $Frac_{(R)}$ = fraction of N in crop residues that volatilizes as NH_3 (kg N year^{-1}); $EF_{(V)}$ = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg N-N_2O per kg NH_3–N volatilized year^{-1}).

2 Global Warming Potential

The Global Warming Potential (GWP) of the greenhouse gases (GHGs) emitted in a coffee farm is the result of the sum of the emission of GHG i (kg CO_2, CH_4 and N_2O) times its global warming potential over a time frame of 100 years (Table S2).

Table S2: Global Warming Potential of greenhouse gases (GWP_s)

Carbon dioxide	CO_2-eq./kg CO_2	1.00
Methane	CO_2-eq./kg CO_2	25.00
Nitrous Oxide	CO_2-eq./kg CO_2	298.00

Source: [56]

We estimated the emission of GHGs in coffee production as:

$$\text{Total GWP} = \text{GHG(embodied)} + \text{GWP}(N_2O)$$

Where: GWP come from the emission of GHGs from two different sources: 1) emission of GHGs embodied in fertilizers and pesticides, GHG(embodied) and 2) N_2O emissions from managed soils, GWP(N_2O).

Greenhouse Gas Emissions embodied in fertilizer and pesticide production:

GHGs emitted in the production of the fertilizers and inputs that are used in coffee production. The GHGs embodied in inputs (CO_2-eq. year^{-1}) are estimated as:

$$\text{GHG(embodied)} = \sum_i F_i * EF_{F_i} + \sum_j P_j * EF_{P_j}$$

Where: F_i = amount of fertilizer type i (kg product year^{-1}); P_j = amount of active pesticide ingredient j (kg active pesticide ingredient year^{-1}); EF_{F_i} = CO_2-eq. emission factor for fertilizer type i (kg CO_2-eq. per kg of product year^{-1}) (Table S3); EF_{P_j} = CO_2-eq. emission factor for pesticide type j (kg of CO_2-eq. per kg of active pesticide ingredient year^{-1}) (Table S4).

Table S3: Emission Factors of production of fertilizers (CO_2-eq. per kg N; kg P_2O_5 , kg K_2O or product).

Fertilizers	Emission Factor per kg	Unit
Ammonium nitrate - 35% N	11.80 (10.18-16.71)	per kg N
Ammonium sulphate - 21% N	5.20 (1.69-8.17)	per kg N
Ammonium sulphate nitrate - 26%N [a]	1.14	per kg product
Anhydrous ammonia - 82% N	6.36 (5.16-7.98)	per kg N
Calcium ammonium nitrate -27% N	11.86 (10.24-16.77)	per kg N
Calcium nitrate - 15% N [a]	1.49	per kg product
Compound NK - 14% N; 44% K_2O [a]	2.67	per kg product
Compound NPK 15%N 15% K_2O 15% P_2O_5	8.98 (8.11-9.67)	per kg N
Diammonium phosphate - 18% N; 46% P_2O_5	6.76 (3.97-8.38)	per kg N
Kainit / Magnesium Sulphate - 11% K_2O; 5% MgO [a]	0.00	per kg product
Lime - 52% CaO	0.074 (0.054-0.089)	per kg lime
Monoammonium phosphate - 11% N; 52% P_2O_5	7.06 (2.42-9.37)	per kg N
Muriate of potash / Potassium Chloride - 60% K_2O	0.91 (0.62-1.12)	per kg K_2O
Phosphate/Rock Phosphate - 25% P_2O_5	0.31 (0.03-0.34)	per kg P_2O_5
Potassium sulphate - 50% K_2O; 45% SO_3	0.31 (0.08-0.37)	per kg K_2O
Single Super phosphate - 21% P_2O_5	0.21 (-1.10-0.74)	per kg P_2O_5
Triple super phosphate - 48% P_2O_5	0.59 (-0.07-0.83)	per kg P_2O_5
Urea - 46.4% N	7.41 (6.64-8.34)	per kg N
Urea ammonium nitrate solution - 32% N (UAN)	9.65 (5.23-17.12)	per kg N
Compost (zero emissions) - 1% N [a]	0.00	per kg product
Compost (fully aerated production) - 1% N [a]	0.24	per kg product
Compost (non-fully aerated production) - 1% N [a]	0.36	per kg product

Source: Values for China and India in [57]. [a.] Not available values for China-India were taken from [58].

Table S4: Emission Factors of production of pesticides (CO_2-eq. per kg a.i.)

Herbicides	CO_2-eq. per kg a.i.	Fungicides	CO_2-eq. per kg a.i.
2, 4-D	6.23	Ferbam	4.40
Alachlor	20.53	Maneb	7.33
Atrazine	13.93	Captam	8.43
Diquat	29.33	Benomyl	29.33
Glyphosate	33.37	**Insecticides**	
Metolachlor	20.17	Methyl Parathion	11.73
Paraquat	33.73	Phorate	15.40
Propachlor	21.27	Carbofuran	33.37
Diuron	19.80	Carbaryl	11.37
Dicamba	21.63	Cypermethrin	42.90
Linuron	21.27	Chlorodimeform	18.33
		Methoxychlor	5.13
		Malathion	16.87

Source: Values according to [59]. Values were converted from C to CO_2-eq using the factor 44/12.

GHG emission resulting from direct and indirect N_2O-N emissions:

$$\text{Total } N_2O = \left(N_2O_{(bkg)} - N + N_2O_{(NIR)} - N + N_2O_{(V)}\right) * \frac{44}{28}$$

Where N_2O-N emissions estimated in the sub-section Nitrate pollution, are converted to N_2O emissions using the factor 44/28.

$$\text{GWP}(N_2O) = \text{Total } N_2O * \text{GWP}_{N_2O}$$

N_2O emissions are afterwards converted to CO_2-eq. by using the Nitrous Oxide Global Warming Potential (GWP_{N2O}) (Table S2).

Table S5: Description of variables, emission factors and sources

Variable name	Variable	Unit	Value	Source	Description
N harvest (N outputs)					
N concentration in harvest	CN_H	kg N per 100 kg of coffee cherries	0.55	Vietnam data	
N inputs					
Crop residues	*R*	kg dry matter ha^{-1} year^{-1}	5,764	[62] [63]	
N concentration crop residues	CN_R	kg N per kg dry matter	0.02	[62] [63] [64]	Average concentration of N in litterfall and pruning (leaves and branches).
N loss					
Emission Factor background	EF_{bkg}	kg N_2O–N ha^{-1} yr^{-1}	16	[56]	Mineralization rates are assumed to be about 2 times greater in tropical climates than in temperate climates.
Emission Factor crop residues	$EF_{(R)}$	kg N_2O–N per kg N year^{-1}	0.01	[56]	N losses from crop residues are comparable with application of N in fertilizers and manure.
N_2O emission factor from N volatilized	$EF_{(V)}$	kg N_2O-N per kg NH_3–N volatilized year^{-1}	0.01	[56]	
Fraction of N in fertilizers and crop residues that volatilizes	$Frac_{(R)}$	kg NH_3-N per kg of N additions year^{-1}	0.10	[56]	

3. **Shadow price Pesticide toxicity**

Shadow price for the environmental, farmworker and consumer toxicity of pesticide use:

A proxy shadow price for *pesticide toxicity* was estimated using the pesticide environmental accounting (PEA) tool developed by [71], combined with the approach of [21].

First step: External costs associated with the application of one kg of pesticide active ingredient reported by [72], were redistributed over the three components of the EIQ model, i.e. environmental, farmworker, and consumer components (derived from [71]) (Table S6).

Table S6: Redistributed base values for an average active pesticide ingredient

US $ per kg pesticide active ingredient	Categories [63]						
	Sources of water	Pollution incidents	Biodiversity	Cultural, landscape, tourism	Bee losses	Humans	Total
EIQ categories							
Applicator effects	0.64	–	–	–	–	0.34	0.98
Picker effects	0.64	–	–	–	–	0.06	0.70
Subtotal Farmworker component							**1.68**
Consumer effects	3.87	–	–	0.80	–	0.02	4.69
Ground water	0.64	0.44	–	–	–	–	1.08
Subtotal consumer component							**5.77**
Aquatic effects	0.64	0.44	0.20	0.32	–	–	1.60
Bird effects	–	–	0.20	0.16	–	–	0.36
Bee effects	–	–	0.07	0.32	0.17	–	0.56
Beneficial insect effects	–	–	0.20	–	–	–	0.20
Subtotal Environmental component							**2.72**
Total	**6.45**	**0.87**	**0.65**	**1.59**	**0.17**	**0.43**	**10.17**

External costs estimated by [72] and redistributed to the EIQ categories. Values expressed in 2011 US $.

Second step: The average EIQ score of an average pesticide active ingredient on each of the three components was estimated. It was done by listing the pesticide active ingredients that were used in the USA in 2001 and collecting their respective EIQ scores for each component (Table S7).

Table S7: Average EIQ score for the three components for an average pesticide active ingredient

Product [a]	EIQ farmer per kg a.i. [b]	EIQ farmer per kg a.i. [b]	EIQ environment per kg a.i. [b]
Glyphosate	8	3	35
Atrazine	8	7	53.55
Metam sodium	24.15	8.08	47.55
2,4-D	8	5	33
Acetochor	10.65	5.33	43.59
Malathion	9	4.5	58
Methyl Bromide	74	10.4	76.3
Dichloropropene	41.4	7.9	33.95
Metolachlor-s	12	9	45
Metolachlor	12	9	45
Pendimethalin	12	5.5	73
Trifluralin	9	5.5	42
Chlorothalonil	20	11	81.25
Copper Hydroxide	24.3	9.05	66.25
Cholorpyrifos	6	2	72.55
Alachlor	10.65	5.33	37.59
Propanil	10.65	5.33	37.59
Chloropicrin	34.5	7.45	85.36
Dimethenamid	9	4.5	22.55
Mancozeb	20.25	8.13	48.79
Ethephon	21.3	5.65	47.45
EPTC	6	4	18.3
Simazine	10.65	14.48	39.42
Dicamba	12	8	59
Sulfosate	8	6	66
Diazinon	6.9	2.45	122.75
MCPP	8	7	31
Carbaryl	15	5.5	47.7
Copper sulfate	24.3	13.15	148.25
Chlorothalanil	20	11	81.25
Chlorpyrifos	6	2	72.55
Diuron	20	8.5	50.9
MSMA	8	5	41
DCPA	9	4	33.3
Benefin	9	4	39
TOTAL	**15.65**	**6.68**	**55.31**

a. Derived from: Kiely, Donaldson & Grube (2004).
b. EIQ scores were obtained from the Integrated Pest Management Program, Cornell University [67]).

Third step: The redistributed base values for external costs on each component (Table S6) were divided by their respective average EIQ scores (total values in Table S7) to obtain an external cost per unit of EIQ.

Table S8 External cost per unit of EIQ on each component.

	2011 US \$/EIQ
EIQ Environment	0.05
EIQ Farm worker	0.86
EIQ Consumer	0.11

Fourth step: To estimate the shadow price for pesticide toxicity the estimated external costs per unit of EIQ on each component were adjusted to reflect the differences in socio-economic conditions in Vietnam. Hence, the external cost per unit of EIQ on each component was multiplied by the factor 0.12, which represents the ratio of the GDP per capita of Vietnam to the average GDP per capita of the USA, Germany and the UK (derived from statistics from The World Bank). In addition, the external cost unit for the farm worker component was adjusted by the factor 28.8, which represents the difference between the share of agricultural employment in Vietnam and the average share of agricultural employment in the USA, Germany, and the UK (derived from statistics from The World Bank).

Table S9 Adjusted external cost unit estimates for the Vietnamese context and shadow price for the externality pesticide toxicity.

	2009 US \$/EIQ
EIQ Environment	0.01
EIQ Farm worker	0.10
EIQ Consumer	0.35
Shadow price pesticide toxicity	0.15