Annals of Agricultural Sciences 64 (2019) 188–195

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Annals of Agricultural Sciences

journal homepage: www.elsevier.com/locate/aoas

Combining reference trials, farm surveys and mathematical models to assess carbon footprint and mitigation measures in tropical agriculture

Rodrigo A. Morales A.[a,d,*], Percy Zorogastúa C.[b], Diana Feliciano[c], Felipe de Mendiburu D.[a,b], Roberto Quiroz[a,e]

[a] International Potato Center (CIP), Crop and Systems Sciences Division, P.O. Box 1558, Lima 12, Peru
[b] Universidad Nacional Agraria La Molina, Agronomy Department, 456 Lima, Peru
[c] University of Aberdeen, Institute of Biological and Environmental Sciences, Aberdeen AB24 2TZ, UK
[d] Panamanian Agricultural Research Institute (IDIAP), 6-4391 El Dorado, Panamá 6A, Panama
[e] CATIE-Tropical Agricultural Research and Higher Education Center, Cartago Turrialba 30501, Costa Rica

ARTICLE INFO

Keywords:
Peru
Emissions
Maize
Sweet potato
Cassava
Fertilizers

ABSTRACT

This study aimed at estimating carbon footprint (CF) and assessing mitigation options for selected tropical crops using excel-based models, parameterized with data collected through closed-ended questions questionnaires, combined with a reference trial (RT). Most of the estimates using structured interviews were similar to those measured in the RT and the literature. Total average emission intensities ranged from 24 to 290 kg CO_2eq·Mg^{-1}, where the extreme values corresponded to cassava in the RT (24 kg CO_2eq·Mg^{-1}) and maize in interviewed farmers in Barranca province (290 kg CO_2eq·Mg^{-1}). Overall, fertilizer production and application contributed to 77% of total greenhouse gas (GHG). Transportation generated emissions comparable to field estimates. Farm emissions can be reduced in 17 to 27% with incorporation of mitigation practices. The methodology used in this study constitute a useful and easily applicable tool to assess *ex-ante* the impact of policies and decisions on CF under farm conditions. It can also be used by different stakeholders for different purposes; including but not limited to: label products offered in the market with GHG emission estimates, make decisions to regulate the emissions in the agricultural sector, and to enable farmers to negotiate prices and incentives for environmental preservation with quantitative information.

1. Introduction

Agricultural production accounts for around 5 Gigatons (1 Gt = 10^9 metric tons) of carbon dioxide equivalent (CO_2eq); that is about 10 to 16% of the total anthropogenic greenhouse gas (GHG) emissions (Burney et al., 2010; IPCC, 2013). Since the population will continue to grow – with a projected increment of around 35% for the world population by 2050 - and thus food demand; it is expected that without appropriate policies, the main GHG produced by agricultural activities will increase; i.e. N_2O emissions from 35% to 60%, and CH_4 by 60% by 2030 (IPCC, 2013). The challenge then is not only ensuring a sustainable use of resources, e.g. nutrients, water, energy, and others (van Wart et al., 2013), but also to ascertain how to achieve sustainability.

Currently, the sustainability of food production is a concern of the food industry (Pretty et al., 2010), policy and research (Godfray et al., 2010). Carbon footprint (CF) has been proposed as an appropriate indicator of agroecosystems sustainability (Smith et al., 2007; Haverkort et al., 2014; Ma et al., 2014). The CF is the amount of greenhouse gases (GHG) emitted into the atmosphere by human activities (e.g. productive process in agriculture). Emissions are thus estimated in terms of either total GHG in kg CO_2 eq·ha^{-1} (CF_{ha}) or GHG intensity in kg CO_2 eq Mg^{-1} (CF_i) (Lal, 2004). Considering the exponential growth of the human population, it can be assumed that GHG emissions from food production and consumption will keep rising (Searchinger et al., 2013). Gross estimations of CF in economically important crops in Latin American (LAC) countries have been used to analyze their potential contribution to climate change (CC). Moreover, Decision-makers have started to be concerned about environmental-related trade restrictions expected to be imposed in the future, which will demand CF labeling for all agricultural exports. In LAC, this is particularly important for crops that evidence a sharp increment in area planted (FAO, 2018) –e.g. cassava, maize, and sweet potato- with their contribution to GHG emissions.

Quantitative methods available are not currently used in developing

* Corresponding author at: Panamanian Agricultural Research Institute (IDIAP), 6-4391 El Dorado, Panamá 6A, Panama.
E-mail address: rodrigoamoralesa@gmail.com (R.A. Morales A.).

https://doi.org/10.1016/j.aoas.2019.12.002
Received 13 August 2018; Received in revised form 19 November 2019; Accepted 10 December 2019
Available online 19 December 2019

Table 1
Characterization of soils and average annual temperature of the localities in La Molina, Barranca and Cañete, Peru.
Source: Soil, Plant, Water and Fertilizer Analysis Laboratory of the UNALM.

Locality	Texture	Texture class	Organic carbon (%)	N (%)	OM (%)	pH	Apparent density (g·cm^{-3})	Annual average T° (°C)
La Molina	Loamy/sandy	Medium	0.50	1.06	0.86	7.60	1.50	19.30
Barranca								
La Campiña	Loamy/sandy	Coarse	0.86	0.08	1.48	7.70	1.46	19.00
Northern S. Elena	Sandy	Coarse	0.41	0.05	0.70	8.02	1.44	18.80
Southern S. Elena	Sandy	Coarse	0.23	0.04	0.47	7.85	1.49	18.51
San José Pativilca	Loamy/sandy	Coarse	0.64	0.06	1.04	7.09	1.31	18.51
Arguay	Silty	Coarse	1.05	1.00	1.81	7.00	1.42	18.51
Cañete								
Hualcará	Sandy	Coarse	0.17	0.03	0.29	7.54	1.50	24.33
Unanue	Sandy	Coarse	0.09	0.03	0.16	7.20	1.49	21.50
Herbay	Loamy	Medium	1.14	0.08	2.14	7.78	1.42	21.50

OM: Organic matter.

countries where crop specific CF estimations -needed to inform decision-makers on the environmental impact of new policy decisions for crops of economic importance (IPCC, 2013)- do not exist. In Peru, public environmental policies promote interaction with the private sector to design sustainable schemes oriented to reduce the sources or enhance the sinks of greenhouse gases and adaptation of agroecosystems (Porfir'ev, 2016). The implementation of such environmental policies demands the adaptation of quantitative tools for estimating CF and to ascertain the potential impact of proposed mitigation options.

Despite having the guidelines for national greenhouse gas inventories, the methods to estimate CF for a specific type of user are inexistent and estimation initiatives lack internationally recognized standards (Colomb et al., 2013). Nonetheless, there is some progress in that direction since the literature offers a cadre of tools to calculate CF from agricultural and forestry practices - e.g. CALM, Full CAM, IFSC, ClimAgri®, ALU, C-Plan, USAID FCC, Holos, Carbon Farming Calculator, AFOLU-Calculator and EX-ACT (Ogle et al., 2005; Yan et al., 2005; IPCC, 2006; Bernoux et al., 2010; Haverkort and Hillier, 2011; Colomb et al., 2013; Feliciano et al., 2017). Notwithstanding, the accuracy of estimates are limited by the availability of context-specific reference data (Olander, 2011; Richards et al., 2016), seldom available in developing countries. Accessible and user-friendly models, requiring input data easy to collect from farmers will help particularly developing countries to generate CF estimates. There is, therefore, a clear demand for methods where in situ measurements are combined with published empirical models to increase the accuracy of CF estimates while reducing the complexity of the calculations.

The overall aim of this study was to test quantitative tools to ascertain the sources of GHG emissions associated to the production of important agricultural crops in Peru (maize, cassava, sweet potato) and to initiate discussions with farmers on how these emissions can be reduced, by using simulation estimates. The specific objectives were: 1) To evaluate the practicality of using reference trials to filter potential outliers in responses from farmers' interviews to parameterize excel-based simulation models for the comparative estimation of CF in maize, sweet potato and cassava; 2) to calculate CF generated by the implementation of agronomic practices in mechanized maize, sweet potato and cassava cropping systems; and 3) to identify and propose mitigation options in the systems studied, i.e. simulated mitigation options that farmers perceive might be implemented.

2. Materials and methods

2.1. Study sites

The contribution of agriculture to Gross Domestic Product (GDP) in Peru is 7.3%, out of which the coastal region accounts for 46%. In turn, the coastal provinces within the Department of Lima play a significant role as evidenced in 2015, contributing with 8.2% of the national agricultural GDP (Espinoza et al., 2018). The most important national market is the capital city, Lima, -located on the central coast- where about a third of the national population lives. To feed this mega city, agriculture is practiced in the outskirts of Lima (represented by La Molina in this study) and neighboring areas to the North (represented by Barranca) and South (represented by Cañete) of the capital city. The experimental station where the reference trial in La Molina (within the city limits) was conducted is located at latitude and longitude 12°04′36.4″S and 76°57′01.1″W, respectively. Latitude and longitude for Barranca province are 10° S and 77° W, whereas for Cañete, 13° S and 76° W, respectively. Annual precipitation in the coast is almost absent.

Predominant soils for the Central Coast include Fluvisols, Regosols and Leptosols. In each locality, various agricultural units were selected and their soils were analyzed in the Soil, Plant, Water and Fertilizer Laboratory of the Universidad Nacional Agraria La Molina, in Lima. Similar analyses were done for the soils in La Molina. The texture determined for La Molina was loamy/sandy; for Barranca, loamy/sandy, sandy and silty soil; and for Cañete, sandy and loamy soil (Table 1). All these variables are required as input to model GHG; therefore, the Carter and Gregorich (2007) methodology, was used to determine the number of samples and sampling strategy per farm.

2.2. Reference trial

A trial was established in the experimental field of the International Potato Center (CIP) in La Molina, Lima, Peru, to assess the use of agricultural inputs and management practices, following the recommendations given to farmers in the coast. This data was used as a reference to filter out outliers in the data obtained by interviews held with producers from different localities of Barranca and Cañete provinces, in the central coast of Peru. Agronomy activities and input were carefully recorded from soil preparation through post-harvest (when applicable) and used as model input to estimate CF for maize, sweet potato and cassava crops.

The experiment was conducted between December 2014 and September 2015 on loamy/sandy soils. Maize was harvested in April, sweet potato in June and cassava in September. Six plots of 150 m^2 (15 × 10 m) were established per crop. The maize, cassava and sweet potato varieties used were PM-213, Amarilla Criolla and Jonathan, respectively. Initial planting density in maize plots was 62,500 plants·ha^{-1} i.e. the distance among furrows was 0.80 m and among plants, 0.20 m. For sweet potato, the density was 42,000 plants·ha^{-1} (distances of 0.80 m and 0.30 m among furrows and plants, respectively) whereas for cassava 10,000 plant·ha^{-1}.

Crops were harvested manually. Average yields per plot were used to calculate the commercial yield (Mg·ha^{-1}), needed to estimate GHG emissions intensity. The dry matter content of the harvested maize grains - based on 14% grain moisture - was determined with the Burrow digital moisture computer-700 (Burrows Seedburo Equipment Co., Chicago, IL.) (Hurburgh Jr. et al., 1985).

2.3. Interviews to farmers in Barranca and Cañete

2.3.1. General description of the structured interviews and sampled area

Between November 2015 and January 2016, 100 structured interviews – with an estimated sampling error for a finite population of 9.8% (Cochran, 1977) - were held with mechanized maize, (36), sweet potato (30), and cassava (34) farmers from Barranca and Cañete. In total, 47 farmers in La Campiña de Supe, Arguay, San José de Pativilca, and Northern-Southern Santa Elena, located in the province of Barranca were interviewed; and 53 in Hualcará, Herbay and Unanue, in the province of Cañete. The location of each farm was recorded using GPS and visualized in Google Earth. Coordinates were used to determine the distance between the places where the crops were produced and the place where the crops were sold, mainly the Central Market in Lima. The interview questionnaire contained closed-ended questions to record all crop production practices including soil preparation, seed management, applications of agrochemicals in general (fertilizers and phytosanitary products), commercial yields and the final transport of crop products. The information obtained on the planted area, the total production and the average yield, was complemented with knowledge from local extension agents and verified with the official database (FAO, 2018). The cropping area per farmer -extension fixed by the 1969 Agrarian Reform- in Barranca and Cañete is 4 ha and 3 ha, respectively. They represent the production systems of the central coast of Peru, where 48%, 72% and 5% of respective country-wide total maize, sweet potato and cassava are produced.

2.4. Online calculators to estimate CF

For the CF calculation, two open access excel-based mathematical models were used: the CCAFS Mitigation Options Tool (CCAFS-MOT, https://ccafs.cgiar.org/mitigation-option-tool-agriculture#.Wp7DeU1LFeU) and Cool Farm Tool v.2 - beta 3 (CFT, https://www.coolfarmtool.org/CftExcel). Both models adopt a process of harmonization of data, calibration and validation required by international standards (Haverkort and Hillier, 2011; Feliciano et al., 2017) (Table 2). These models complement each other if the user is interested in estimating whole farm GHG emissions and for testing potential mitigation options. By combining both models, emissions associated to most farm activities could be accounted for. That is, emissions for each activity were added, regardless of the model used. Thus, estimated farm GHG values, per site, contained the mean and positional mean (Montgomery and Runger, 2003) for each emission source using input from all the interviews (measured for La Molina) for each model. Since emissions associated to fertilizer production and application were estimated by both models, for these two sources we followed the suggestion that the average of the estimates of several models may reflect reality more precisely and accurately than estimations based on individual models (Martre et al., 2015; Fleisher et al., 2016), but provided the values estimated by each model as well. The CCAFS-MOT model integrates several empirical models already validated in rainfed crops, rice, pasture and livestock farming (e.g. Bouwman et al., 2002; Yan et al., 2005; Stehfest and Bouwman, 2006; Smith et al., 2010). It estimates the GHG emissions throughout all the production stages featuring land management, the use and characteristics of agro-chemicals and the production and use of synthetic fertilizers. To estimate the emissions associated to synthetic and organic fertilizer application and production (CO_2, N_2O and NO), the multivariate empirical model was used (Stehfest and Bouwman, 2006; Zhang et al., 2013). The Nitrogen loss due to ammonia (NH_3) volatilization was estimated (Bouwman et al., 2002).

Table 2
Sources of greenhouse gas emissions using the CCAFS-MOT and CFT models for the estimation of CF in the maize, sweet potato and cassava crops.

Emission source	CCAFS-MOT	CFT
Fertilizer production (kg CO_2eq·ha^{-1})	+	+
Fertilizer application kg CO_2eq·ha^{-1} N_2O (kg CO_2eq·ha^{-1})	+	+
Soil mining (kg CO_2eq·ha^{-1})	+	–
CH_4 manure management CH_4 (kg CO_2eq·ha^{-1})	+	–
Waste burning CH_4 (CO_2eq·ha^{-1}) N_2O (kg CO_2eq·ha^{-1})	+	–
Use of pesticides (kg CO_2eq·ha^{-1})	–	+
Use of energy in the field (kg CO_2eq·ha^{-1})	–	+
Crop transport (kg CO_2eq·ha^{-1})	–	+

In the reference trial (La Molina) as well as in farms in Barranca and Cañete, the emissions associated to fertilizer production (kg CO_2eq·ha^{-1}) and application [N_2O (kg CO_2eq·ha^{-1}) and kg CO_2eq·ha^{-1}], were estimated by both models (CCAFS-MOT and CFT). Estimates were compared through the non-parametric Wilcoxon test (also known as Mann-Whitney test). This test assesses the hierarchical order of pairwise comparisons of different crops/sites conditions and assumes no specific distribution (Öztürk and Wolfe, 2000; McKnight and Najab, 2010). Nine pairs of data were formed, corresponding to the measurements by source of emissions by crop and sites. For the pair two-sample cases, the wilcox.test() in the R program statistical package was used (de Mendiburu, 2016). Emissions by sites and crops were compared with an analysis of variance followed by the post hoc Duncan test. The CFT model, in turn, is made up of sub models that estimate -e.g. maximum restricted likelihood- of GHG emissions (CO_2, N_2O and NO); by production systems, including as emission sources agricultural practices, crop protection, soil and climate characteristics, direct energy use for agricultural work, and transportation of crop products and livestock (Bouwman et al., 2002; Ogle et al., 2005; Audsley et al., 2009; IPCC, 2013). The control factors, for the N_2O and NO emissions of agricultural fields, by production systems, were the application rate of N, pH of the soil, soil texture, climate and type of crop (Bouwman et al., 2002). We used the following worksheets: 1. General information (country, locality, year, product, yield per area, climate, and average annual temperature); 2. Crop management (crop, soil, product, nutrients, quantity and method of fertilizer applications, number of pesticide applications, such as herbicides, insecticides, fungicides and crop residue management). Integrates the emission factors for the production of fertilizers in Europe and the world average for the production of fertilizers. Each dose of active ingredient per pesticide is counted as one application, whether it is applied alone or in mixtures; 5. Use of energy in the field·ha^{-1} (electricity, gasoline, diesel per equipment or machinery from soil preparation to harvesting); and 7. Transportation of crops. This model was used to estimate emissions associated to machinery use as well as produce transportation (Zhang et al., 2013).

The CCAFS-MOT, also provides the GHG emission reduction potential of 16 mitigation options for crop production (e.g. optimal N application, straw addition/residue return, no tillage/reduced tillage, cover crops, etc.). The IPCC (2013), defines mitigation as an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (any process, activity or mechanism that removes GHG from the atmosphere). For the farmers that apply fertilizer in excess (mainly synthetic and organic N), the CCAFS-MOT model estimates the risk of high N losses because the applied N rate exceeds the total crops demand. For its calculation, Brentrup et al. (2004), adapted the nitrogen use efficiency (NUE), which considers the optimal synthetic N application rate for a crop and average N content per crop (default in the tool). Soil mining, un turn, occurs when N removals exceed N inputs. The contribution of manure application to the N input (Moran et al., 2008), were also considered. The addition of animal manure contributes to increasing soil carbon stocks (Smith et al., 1997), and to estimate the amount of residue produced by crop using equations from IPCC (2006). To estimate the potential soil C sequestration in crops, the model used tillage factors to estimate annual soil organic carbon (SOC) storage due to changing from conventional tillage to no-till or reduced (Ogle et al., 2005). The model also considers mitigation options for production systems without affecting production capacity per crop, with energy reduction from fossil fuels and consequently reducing the environmental impact and preserving non-renewable energy resources. The 16 mitigation options were discussed with farmers and those perceived as of feasible implementation in their farms, used for estimating potential mitigation for the three crops.

3. Results

3.1. Agronomic data for model input

3.1.1. From the reference trial

The seven mechanical soil tillage operations recorded for maize included plough (1) and harrow passes (2), furrow for seeding, and hilling (3) for the incorporation of fertilizers. Machinery requirements for land preparation and incorporation of fertilizers in cassava were similar to those for maize. Only mechanized soil tillage operations were carried out in sweet potato. Soil analyses revealed low amounts of N (1.06%) and P (6.9 ppm), and high amounts of K (102 ppm). According to local soil experts it is low. Low-level thresholds for N, P and K were added: (< 2.0%, < 7.0 ppm and 100 to 240 ppm; respectively: source UNALM Soil Laboratory, based on Carter and Gregorich, 2007). Therefore, fertilizers were applied accordingly, urea plus P and K sources in 20-20-20 and 40-60-20 formulations (see Table 3). In addition, Potassium Chloride (KCl) was used as a Potassium Oxide (K_2O) source. In maize, high N (> 200 kg ha^{-1}), medium P (40 to 80 kg P_2O_5·ha^{-1}) and low K (≤ 40 kg K_2O·ha^{-1}) applications were made. In sweet potato and cassava, medium doses of N, P and K (in sweet potato; 60 to 80 kg N·ha^{-1}, 40 to 60 kg P_2O_5·ha^{-1} and 100 to 120 kg K_2O·ha^{-1}; cassava 40 to 80 kg N·ha^{-1}, 40 to 100 kg P_2O_5·ha^{-1} and 60 to 100 kg K_2O·ha^{-1}), were applied. Pest management was based on the diagnosis made in situ following the respective population thresholds per phenological stages for each crop (De Souza et al., 2017). For the chemical control of *Spodoptera frugiperda* (J. E. Smith) and *Heliothis zea* (Boddie) pests in maize, five applications of insecticides were made. As for the control of foliar pests *Prodenia* (=*Spodoptera*) *eridania* (Cramer) and aphids in sweet potato, 10 insecticides applications were made. In cassava, *Erinnyis ello* (L), *Tetranychus* sp. and *Trialeurodes* spp. pests were found. Six insecticides and acaricides applications were made for control. Gravity irrigation was applied, where water was pumped from a well using a 30 HP electric pump (conversion factor of 1 HP = 0.73 kWh). Therefore, irrigation water supply during the whole crop cycle of maize (6500 m^3), sweet potato (2000 m^3) and cassava (7000 m^3) caused an energy expenditure of 166, 66 and 185 kWh, respectively. It was also estimated that the direct energy used in cultivation (machinery use) was 1395, 901 and 1465 MJ per crop cycle·ha^{-1}; respectively.

To estimate GHG intensity, yield estimates were recorded. The average commercial yield obtained per crop was 11.35 Mg·ha^{-1} for maize; 3.5 Mg·ha^{-1} (equivalent to 14.56 Mg·ha^{-1} fresh) for sweet potato storage roots and 11.8 Mg·ha^{-1} of dry foliage (equivalent to 39.1 Mg·ha^{-1} biomass); and 11.34 Mg·ha^{-1} (fresh weight: 38.86 Mg·ha^{-1}) for cassava storage roots. In the reference trial, fresh and dry weights were recorded, following the units used for commercial yields. Commercial maize yields are reported by farmers as dry weight for maize, whereas for sweet potato and cassava, as fresh weight. Additionally, the latter two crops are also marketed as fresh weight.

3.1.2. From farmers' interviews

Maize farmers in both provinces performed, on average, eight soil tillage operations (two plough passes, two harrow passes, the furrow and three hilling). In Barranca, 50% of maize farmers carried out mechanized planting and harvesting whereas in Cañete, maize was harvested by hand when the plants were completely senescent. Whole cobs were sun dried in the fields. In this province shelling was performed when grains have 14% moisture (verified by agribusiness buyers). This moisture in the grains allows good preservation and tolerance to storage pests and diseases. When harvesting was mechanized with a drying system, moisture was periodically checked. Ten conventional tillage operations were performed for sweet potato in Barranca and five in Cañete. In turn, eight conventional tillage operations were reported for cassava in Barranca and Cañete.

All farmers interviewed applied urea to the three crops (Table 3). Other sources varied with the crop and site. Maize farmers in both sites reported using NH_4NO_3 $(NH_4)_2HPO_4$ and the formulation 20-20-20. Sweet potato farmers in Barranca fertilized with NH_4NO_3, $(NH_4)_2HPO_4$, and KCl and K_2SO_4 as K_2O sources. Whereas in Cañete, farmers also added NH_4NO_3, $Ca(H_2PO_4)_2$, and 0-46-0. For cassava, farmers in Barranca complemented urea with $Ca(H_2PO_4)_2$ and 0-46-0; but in Cañete,

Table 3
N, P and K Levels (kg·ha^{-1}) and fertilizers applied on maize, sweet potato and cassava in La Molina and in agricultural units in Barranca and Cañete, Peru.

Locality	Maize				Sweet potato				Cassava			
	N	P	K	Fertilizers	N	P	K	Fertilizers	N	P	K	Fertilizers
La Molina[a]	210	60	40	Urea 20-20-20	105.2	50	87	Urea 20-20-20 KCl	80	120	125	40-60-20 KCl
Barranca[b]	119 to 345	69 to 92	33 to 75	Urea NH_4NO_3 0-46-0 $(NH_4)_2HPO_4$ KCl	80 to 128	60 to 92	33 to 50	Urea NH_4NO_3 $(NH_4)_2HPO_4$ KCl K_2SO_4	174 to 300	81 to 92	50 to 68	Urea $(NH_4)_2HPO_4$ 0-46-0 KCl
Cañete[b]	105 to 200	40 to 120	100 to 140	Urea 0-46-0 20-20-20 KCl	92 to 112	92	50 to 100	Urea NH_4NO_3 0-46-0 $(NH_4)_2HPO_4$ KCl $Ca(H_2PO_4)_2$	92 to 132	40 to 92	50 to 140	Urea 20-20-20 0-46-0 $(NH_4)_2HPO_4$ KCl

[a] Actual application.
[b] From interviews to farmers.

cassava was also top dressed with $(NH_4)_2HPO_4$, 20-20-20, and 0-46-0. On average, > 120 kg·ha^{-1} of N were applied to maize in both sites; whereas for sweet potato and cassava, > 80 kg·ha^{-1} and > 100 kg·ha^{-1}, respectively. Low (< 40 kg·ha^{-1}) to high (> 80 kg·ha^{-1}) doses of P and K were reported for maize, and medium for sweet potato and cassava, in both sites.

Farmers in both provinces indicated that *Agrotis* spp., *S. frugiperda*, *H. zea*, aphid, and tar spot complex (caused by the interaction between *Phyllachora maydis*, *Monographella maydis* and *Coniothyrium phyllachorae*) pests are found in the biological cycle of maize. For the chemical control of pests and diseases in Barranca farmers reported making 14 applications contrasting with the ten pesticides applications reported in Cañete. The main pests reported for sweet potato in Barranca and Cañete were *Agrotis* spp., *P. eridania*, aphids and bacterial diseases. Chemical control was performed with 15 pesticides applications in Barranca and 10 in Cañete. In both provinces cassava farmers reported 10 applications of fungicides and insecticides to control *E. ello*, *Tetranychus* sp., *Trialeurodes* spp. and *Oidium* spp.

The energy used (per ha), in cultivation for maize in Barranca and Cañete estimates were 1461 and 838 MJ, respectively. For sweet potato; 918 and 705 MJ and cassava, 779 MJ and 838 MJ, respectively. Irrigation modules – 2500 (sweet potato), 5000 m^3 (maize) and 7000 m^3·ha^{-1} in cassava (users are grouped in irrigation sub-districts)- supplied irrigation water and gravity drainage for the maize, sweet potato and cassava. Irrigation managers of the local boards were consulted and the estimated energy costs for maize, sweet potato and cassava (both provinces) were 142, 75 and 200 kWh, respectively.

With regards to commercial yields, the average reported for maize in Barranca was 11.5 Mg·ha^{-1}, whereas for Cañete, 10.75 Mg·ha^{-1}. Commercial sweet potato and cassava roots yields were recorded in fresh weight and estimated in conjunction with buyers, by means of senescent plant samples. Farmers did not weight fresh foliage used as fodder, so no data was elicited. In Barranca and Cañete, average sweet potato fresh storage root yields reported were around 25 Mg·ha^{-1}. The respective cassava storage roots fresh yields in Barranca and Cañete were 18 Mg·ha^{-1} and 26 Mg·ha^{-1}. It is worth indicating that as to maize varieties, growers preferred Pioneer 30F35, Dekalb 8008, Dekalb 5005, Dekalb 7088, BG-9621 and XB-8010 hybrids. For sweet potato, preferred varieties were Jonathan, INIA Huambachero and Jewel (orange varieties) as well as the Milagroso and Limeño Morado (purple varieties). For cassava, preferred varieties were Amarilla Criolla and Señorita.

3.2. Estimation of GHG emissions in farms

Average emissions associated to fertilizer production and application contributed to 77% of the total GHG (Table 4), across sites and crops, and using the mean of both models. Fertilizer application (39% in average) was the main emission source. Total GHG emission estimates in sampled provinces (kg CO_2eq·ha^{-1}) were higher than the reference trial in La Molina ($p < 0.01$). This was particularly high (3 times higher in Cañete and 5 times in Barranca) for cassava. La Molina also presented higher estimated yield (38.86 Mg·ha^{-1}), but yield for the other two crops were statistically similar. That is, reported yields for maize and sweet potato, and the estimated GHG intensity among the provinces were similar. In the maize crops in La Molina, Barranca and Cañete, and sweet potato (Barranca and Cañete), due to the high amounts of N applied, the estimate surplus was associated with N_2O emissions (176, 211, 403, 475 and 179 kg CO_2eq·ha^{-1}; respectively). All the cassava producers in Barranca and Cañete indicated that 10% of the stems are reserved as vegetative material (seed stakes) and the rest was burned and thus a source of CH_4 and N_2O emissions by combustion. This practice was performed after the harvest, as a field cleaning method. The rationale is that there is direct control of pests and diseases present in plant foliage. This contributes to GHG emissions, and the emission factors for CH_4 and N_2O from the burning of agricultural residues were taken from the IPCC (2006) and Johnson et al. (2007). Feliciano et al. (2017), indicated that straw from crop residues is estimated with the equations provided by the IPCC (2006) guidelines. In addition, 20% of sweet potato and cassava producers interviewed in Cañete indicated that they incorporated 7 Mg·ha^{-1} of poultry manure, causing CH_4 emissions, which is transformed by direct oxidation into anaerobic digestion after the aerobic phase, as poultry manure is managed before its incorporation to the soil. It was highlighted that the fertilization component, -within the production structure of sweet potato and cassava in Cañete- represented an average of 25.70% and 17.10%; respectively of the relative economic value of the total cost. Our modeling results indicate that by implementing this mitigation options costs might reduce while maintaining similar yields. Nonetheless, these emissions combined (Table 4) were < 0.5% of the total estimated farm emissions.

Emissions due to produce transportation were an issue for the sites outside Lima. Most of the maize, in both sampled provinces were transported up to 63 km. In Barranca and Cañete, 90% of sweet potato and cassava harvests are transported to the large wholesale market in Lima, i.e. 182 to 216 km from Barranca and 155 to 177 km from Cañete. The rest of the produce is consumed in local restaurants. Considering transport emissions for Barranca, the resulting intensity or CF_i for maize was 306 kg CO_2eq·Mg^{-1}. For sweet potato and cassava; 221 and 258 kg CO_2eq·Mg^{-1}, respectively. In Cañete, the resulting emission intensities in these crops were 187 and 167 kg CO_2eq·Mg^{-1}. We then added the GHG emitted by the transportation of produces to either the local market or to Lima. Maize is mainly sold in local markets so the transportation contribution to the total GHG emission was up to 17%, in the case of Cañete. For sweet potato and cassava, in Barranca and Cañete, emission estimates for transportation were as high as those estimated for agricultural practices.

3.3. Impact of mitigation practices

Table 5 shows the results of the scenarios for mitigation practices, estimated with the CCAFS-MOT model (CO_2eq ha^{-1} kg year^{-1}). The use of organic fertilizer was consistently the main mitigation practice deemed as easy to implement by farmers across crops and sites. This was followed by reduced tillage, which might also constitute an important mitigation practice for the three crops. Incorporation of waste, on the other hand, was significant for maize in La Molina.

4. Discussion

4.1. Estimation of GHG emissions in maize, sweet potato and cassava

The reliability of CF estimates depends on the quality of input introduced into the models. To establish a metric against which data elicited through interviews could be compared, we conducted a reference trial in conditions as similar as feasible to the farms in the Peruvian coast where the data were collected from farmers through structured interviews. Reported range of most inorganic fertilizers (N, P, K) applied to maize either contained or were closed to the levels applied to the reference trial (La Molina). The exception was the reported range for K in Cañete, where farmers reported applying up to three times the level used in La Molina. Farmers in both sampled provinces reported applying more P to sweet potato, but similar levels of N and K. Applications of N, P and K reported by farmers to cassava, in turn, differed more from the applications to the reference trials than for the other two crops. Farmers in Barranca reported applying two to four times more N than in La Molina; whereas for Cañete, reported values are just over the applied levels in La Molina. Nonetheless, reported levels for P, in both sampled provinces, were below the levels used in La Molina. Farmers in Barranca also reported applying less K (in sweet potato and cassava) than those applied in the reference trial. But, farmers in Cañete reported applying up to four times more K than in La

Table 4
Average yield ($t \cdot ha^{-1}$) and GHG emissions per production component on maize, sweet potato and cassava farms, and the respective CF, estimated with the CCAFS-MOT and CFT models. La Molina, Barranca and Cañete, Peru.

Component/model	La Molina			Barranca			Cañete		
	Maize	Sweet potato	Cassava	Maize	Sweet potato	Cassava	Maize	Sweet potato	Cassava
Fertilizer production									
($kg\ CO_2eq \cdot ha^{-1}$)[a]	693	515	323	1087	347	663	441	633	393
($kg\ CO_2eq \cdot ha^{-1}$)[b]	620	559	727	1097	670	659	560	1208	656
($kg\ CO_2eq \cdot ha^{-1}$)[c]	657	537	525	1092	508	661	501	921	525
Fertilizer application									
($kg\ CO_2eq \cdot ha^{-1}$)[a]	147	88	0	1097	99	265	138	85	107
($kg\ CO_2eq \cdot ha^{-1}$)[b]	931	541	94	1750	825	1118	986	938	713
($kg\ CO_2eq \cdot ha^{-1}$)[c]	539	315	47	1424	462	692	562	512	410
N_2O ($kg\ CO_2eq \cdot ha^{-1}$)[a]	184	169	53	484	295	673	196	449	390
N_2O ($kg\ CO_2eq \cdot ha^{-1}$)[b]	205	205	205	328	271	303	152	174	133
N_2O ($kg\ CO_2eq \cdot ha^{-1}$)[c]	195	187	129	406	283	488	174	312	262
Nitrate surplus[a]									
N_2O ($kg\ CO_2eq \cdot ha^{-1}$)	176	0	0	211	403	0	475	179	0
CH_4 manure management[a]									
CH_4 ($kg\ CO_2eq \cdot ha^{-1}$)								383	383
Waste burning[a]									
CH_4 ($CO_2eq \cdot ha^{-1}$)						134			149
N_2O ($kg\ CO_2eq \cdot ha^{-1}$)						30			34
Use of pesticides[b]									
($kg\ CO_2eq \cdot ha^{-1}$)	103	205	123	205	294	205	205	205	205
Use of energy in the field[b]									
($kg\ CO_2eq \cdot ha^{-1}$)	95	62	100	103	65	55	59	50	59
Subtotal ($kg\ CO_2eq \cdot Mg^{-1}$)	155	90	24	299	81	126	184	98	79
Subtotal ($kg\ CO_2eq \cdot ha^{-1}$)[e]	1764	1306	924	3438	2015	2264	1975	2560	2026
Average yield ($t \cdot ha^{-1}$)	11.35	14.56	38.86	11.5	25.0	18.0	10.75	26.0	26.0
Crop transport[b]									
($kg\ CO_2eq$)[d]	0	0	0	185	3503	2374	334	2348	2287
Total ($kg\ CO_2eq \cdot Mg^{-1}$)	155	90	24	315	221	258	215	187	167
Total ($kg\ CO_2eq \cdot ha^{-1}$)[f]	1764	1306	924	3623	5518	4638	2309	4908	4313

[a] Emission per source and estimated amount by CCAFS-MOT model.
[b] Emission per source and estimated amount by CFT model.
[c] Average emission estimates from both models.
[d] This is total production per crop cycle from the area farmed.
[e] Subtotal ($kg\ CO_2eq \cdot ha^{-1}$) = $\sum$average emission estimates to fertilizer production and application from both models + emission estimates from other sources.
[f] Total ($kg\ CO_2eq \cdot ha^{-1}$) = $\sum$average emission estimates to fertilizer production and application from both models + emission estimates from other sources + crop transport emissions.

Table 5
Options for CF mitigation strategies in mechanized production of maize, sweet potato and cassava. Estimated with the CCAFS-MOT. Peru.

Crop	Mitigation practices (reduced weight: $CO_2eq\ ha^{-1}\ kg\ year^{-1}$)				
	CF reference ($kg\ CO_2eq\ ha^{-1}$)	Nitrification inhibitor	Reduced tillage	Organic fertilizer	Incorporation of waste
Maize					
La Molina	1669	11	107	200	504
Provinces[a]	2264	43	138	258	181
Sweet potato					
La Molina	1244	16	107	200	
Provinces	2284	48	198	370	
Cassava					
La Molina	824	4	107	200	
Provinces	2326	104	150	255	

[a] Average values Barranca and Cañete.

Molina. Overall, the values reported by farmers, in spite of the high variability typical of data collected through interviews, were similar to those applied in the reference trial in La Molina, with some exceptions.

Although we followed the recommendation that the average of the estimates of several models may reflect reality more precisely and accurately than estimations based on individual models (Martre et al., 2015; Fleisher et al., 2016), it was noteworthy that CFT consistently estimated higher emissions for fertilizer applications ($p < 0.01$, in $kg\ CO_2eq \cdot ha^{-1}$). It is thus advisable to design future studies to compare model outputs with actual emissions. Albeit our discussion is based on the mean of both models -for fertilizer production and application, as originally planned- results for individual models are also provided (Table 4).

The highest average emissions estimated for maize farms in Barranca was attributed to the type of fertilizers used. The production of applied fertilizers requires the use of significant amounts of fossil fuels, which depends on the production technologies and the country where the fertilizer is manufactured (Brentrup et al., 2004), and statistics indicate that 98% of nitrogen fertilizer imports come from the United States.

The application of these fertilizers increases the emissions of N_2O, NO and NH_3, through nitrification, denitrification and volatilization, which occur naturally in soils (Nyakatawa et al., 2011; IPCC, 2013). Both models estimated GHG emissions magnitudes with similar efficiency ($p > 0.05$). The CCAFS-MOT model, estimated that the NUE was too low (< 69%) with a risk of high N losses and GHG emissions (represented 25% and 20% of the total CF of corn in Cañete and Barranca, respectively), because the applied N fertilizer exceeded the total crop demand. On the other hand, when N fertilization met total crop demand - i.e. balanced input/output N- there was no GHG emissions. Maize farms in Barranca, were characterized by applications of high N levels, of up to 345 kg (1.6 times more urea and other nitrogen fertilizers, than in La Molina), along with the highest yields, thus influencing the calculation of total CF. These results are consistent with those obtained in fields planted with maize in Canada for 19 consecutive years (Ma et al., 2014). Moreover, cassava production systems in Barranca are also based on applications of high N levels, up to 300 kg (3.75 times higher than in La Molina) and thus high (488 kg CO_2 eq·ha^{-1} as N_2O) emissions were estimated.

Fertilizer applications for maize in La Molina, Barranca and Cañete, contributed to 44%, 39% and 34%, of the total emissions, respectively. The CF calculated in the conventional maize production system in all sites, reflects the intensity of agronomic practices based on high and continuous use of agrochemicals, especially nitrogen fertilization. As far as GHG intensity is concerned, even the highest resulting CF_i in maize for Barranca (Table 4) was comparable to values reported for La Pampa, Argentina; 300 kg CO_2eq·Mg^{-1} (Woerishofer, 2011). For sweet potato, GHG intensities were similar across sites (range of 81 to 98 kg CO_2eq·Mg^{-1}). Similar intensities were reported for the Philippines (Flores et al., 2016 who reported up to 95 kg CO_2eq·Mg^{-1}). Cassava, in turn, ranged from 24 to 126 kg CO_2eq·Mg^{-1}. These values are comparable to those published in the literature for smallholder farmers in Nigeria (Cervigni et al., 2013; reporting 105 kg CO_2eq·Mg^{-1}).

4.2. Assessing the potential impact of mitigation practices

The calculation of CF per cropping system is a valuable input for efficient policy and sustainability management to address climate change. The mitigation scenarios run for maize, sweet potato and cassava – that farmers indicated could be easily implemented - were: (i) incorporation of agricultural waste to improve soil fertility; (ii) application of organic manure subject to previous processing, to be used as an improver or to provide soil nutrients and improve water retention (sweet potato and cassava crops in Cañete). Its implementation is based on the fact that the reduction of fossil fuels needed for the production of synthetic fertilizers was the largest GHG source (Adler et al., 2007); (iii) minimum tillage consisting of a single semi-heavy harrow pass for soil preparation; and (iv) use of nitrification inhibitors -available in Peru at a low cost- whose chemical compounds prevent NH_4 from being transformed into NO_2 and finally into NO_3 (Akiyama et al., 2010). The CCAFS-MOT estimated a low emission reduction potential (a maximum average of CF reduction in cassava, of 104 kg CO_2eq·ha^{-1} kg year^{-1}). Estimated potential emission reductions for those practices are presented in Table 5.

In La Molina, for each selected option, the ability to reduce total emissions per crop varies, e.g. in maize, the average CF is reduced from 1669 to 1562 kg CO_2eq·ha^{-1} kg year^{-1} due to the reduced tillage or partial removal of weeds present in the land. With this practice, there have been reductions of up to 19% in land preparation costs, degree of soil compaction, erosion risk and energy expenditure (Marquina et al., 2015). If the incorporation of maize plant waste per mechanized harvest is generalized, CF reduction would be up to 1165 kg CO_2eq·ha^{-1} kg year^{-1}; however, when using nitrification-inhibiting fertilizers, reduced tillage, organic fertilizers and agricultural waste, CF might be reduced by 49%. The average relative economic value of the total cost for the use of organic fertilizers in sweet potato and cassava (costs and labor for the application), was 13.50% and 8.60%, respectively (on average 2× less compared to applications of synthetic and organic fertilizers). A practical scenario (agreed with producers), arises in sweet potato and cassava crops when implementing reduced tillage, using nitrification-inhibiting fertilizers and organic fertilizers. Average estimated reductions were 26% and 38%, respectively. Similarly, for maize, sweet potato and cassava farms in both sampled provinces estimated reductions were 27%, 17% and 22%, respectively.

Now, why is this type of information important for a country? Let us use the case of maize in Peru as an example. The over 1.5 million Mg of dry grain produced does not meet the 4 million Mg·y^{-1} demanded by the poultry sector, the largest consumer. So, the official plan is to increase planting area and farmers plan to apply high N levels, since maize is seen as a great extractor of soil nutrients, and it is periodically restored with nitrogen fertilizers in its productive process. In the near future, the use of nitrogen fertilizers and manure production will increase, especially in developing countries (FAO, 2018). The potential impact of those decisions can be evaluated ex-ante. The models used in this study constitute a useful and easily applicable tool for CF estimation under farm conditions, which can be used by different stakeholders for different purposes; including but not limited to: label products offered in the market with GHG emission estimates, make decisions to regulate the emissions in the agricultural sector, and to enable farmers to negotiate prices and incentives for environmental preservation with quantitative information.

5. Conclusions

The structured interviews conducted in situ showed that the mechanized production systems, dependent on synthetic fertilizers and pesticides, prevail in the Peruvian coast. The methodology described in this study using open excel-based models, the farmers´ interviews and a reference trial to screen out potential outliers from elicited data – found to be < 5% of the data- generated results comparable with literature findings. Most of the estimates using structured interviews were similar to those measured in the reference trials. When differences were statistically significant -e.g. cassava in Barranca, where estimated emission intensity was up to 5.2 higher than the reference trial- input data should be validated with a more precise model input estimation, to increase accuracy of estimates.

Estimates confirmed that fertilizers used in the coast of Peru can be considered as the most important anthropogenic source of N_2O emission. If modeling results for mitigation measures approximate reality, these emissions can be reduced with technological interventions in agreement with producers. These scenarios should be evaluated in the field, integrating climate, soil and crops. Transportation of produce, to long-distance markets, doubled both total emission as well as emission intensity. The only way to reduce transportation emissions is to produce as close to the final market as feasible. The example in Peru was described in enough details to motivate researchers from developing countries to generate comparable estimates – using similar methodologies - that can be incorporated in discussions about agricultural CF and to provide input for policy debate and formulation.

Declaration of competing interest

The authors declare that they have no conflicting interests.

Acknowledgements

We would like to thank the CGIAR Research Program on Roots, Tubers and Bananas (RTB) and Climate Change, Agriculture and Food Security (CCAFS) and the CGIAR Fund donors for funding this research. For a list of CGIAR Fund donors please see: http://www.cgiar.org/whowe-are/cgiar-fund/fund-donors-2/. The senior author also acknowledges the support from the National Secretariat of Science and Technology of Panama (SENACYT, Professional Excellence subprogram) and the Agricultural Research Institute of Panama (IDIAP).

References

Adler, P.R., Del Grosso, S.J., Parton, W.J., 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol. Appl. 17, 675–691.

Akiyama, H., Xiaoyuan, Y., Yagi, Y., 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: meta-analysis. Glob. Chang. Biol. 16, 1837–1846.

Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the Greenhouse Gas Emissions From Agricultural Pesticide Manufacture and Use. Cranfield University, United Kingdom URI: http://dspace.lib.cranfield.ac.uk/handle/1826/3913.

Bernoux, M., Branca, G., Carro, A., Lipper, L., Smith, G., Bockel, L., 2010. Ex-ante greenhouse gas balance of agriculture and forestry development programs. Sci. Agric. 67, 31–40.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Modeling global annual N_2O and NO emissions from fertilized fields. Global Biogeochem. Cycles 16, 28-1–28-9. https://doi.org/10.1029/2001GB001812.
Brentrup, F., Küsters, J., Lammel, J., Barraclough, P., Kuhlmann, H., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer uses in winter wheat production systems. Eur. J. Agron. 20, 265–279.
Burney, J.A., Davis, S.J., Lobella, D.B., 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Natl. Acad. Sci. U. S. A. 107, 12052–12057.
Carter, M.R., Gregorich, E.G., 2007. Soil Sampling and Methods of Análisis, second edition. Canadian Society of Soil Science. CRC Press.
Cervigni, R., Valentini, R., Santini, M., 2013. Toward Climate-Resilient Development in Nigeria. The World Bankhttps://doi.org/10.1596/978-0-8213-9923-1.
Cochran, W.G., 1977. Sampling Techniques, fifth ed. John Wiley & Sons, Inc., New Jersey, USA.
Colomb, V., Touchemoulin, O., Bockel, L., Chotte, J.L., Martin, S., Tinlot, M., Bernoux, M., 2013. Selection of appropriate calculators for landscape-scale greenhouse gas assessment for agriculture and forestry. Environ. Res. Lett. 8, 015029.
de Mendiburu, F., 2016. Agricolae: statistical procedures for agricultural research. r-package version 3.6.1. https://CRAN.R-project.org/package=agricolae, Accessed date: 15 November 2019.
De Souza, A.P., Massenburg, L.N., Jaiswal, D., Cheng, S., Shekar, R., Long, S.P., 2017. Rooting for cassava: insights into photosynthesis and associated physiology as a route to improve yield potential. New Phytol. 213, 50–65.
Espinoza, M., Fort, R., Morris, M., Sebastian, A., Villazon, L., 2018. Understanding heterogeneity in Peruvian agriculture: a meta-frontier approach for analyzing technical efficiency. https://doi.org/10.22004/ag.econ.277134.
FAO, Food and Agriculture Organization, 2018. FAOSTAT (FAO Statistics Division). http://www.fao.org/faostat/es/#data/QC, Accessed date: 16 February 2018.
Feliciano, D., Nayak, D.R., Vetter, S.H., Hillier, J., 2017. CCAFS-MOT - a tool for farmers, extension services and policy-advisors to identify mitigation options for agriculture'. Agric. Syst. 154, 100–111.
Fleisher, D.H., Condori, B., Quiroz, R., Alva, A., Asseng, S., Barreda, C., Bindi, M., Boote, K.J., Ferrise, R., Franke, A.C., Govindakrishnan, P.M., Harahagazwe, D., Hoogenboom, G., Naresh, K.S., Merante, P., Nendel, C., Olesen, J.E., Parker, P.S., Raes, D., Raymundo, R., Ruane, A.C., Stockle, C., Supit, I., Vanuytrecht, E., Wolf, J., Woli, P., 2016. A potato model intercomparison across varying climates and productivity levels. Glob. Chang. Biol. 23, 1258–1281.
Flores, E.D., Dela Cruz, R.S.M., Antolin, M.C., 2016. Energy use and greenhouse gas emissions of farmer-level sweet potato production systems in the Philippines. Asian J. Appl. Sci. 4, 110–119.
Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science. 327, 812–818.
Haverkort, A.J., Hillier, J.G., 2011. Cool farm tool – potato: model description and performance of four production systems. Potato Res. 54, 355–369.
Haverkort, A.J., Sandaña, P., Kalazich, J., 2014. Yield gaps and ecological footprints of potato production systems in Chile. Potato Res. 57, 13–31.
Hurburgh Jr., C.R., Hazen, T.E., Bern, C.J., 1985. Corn moisture measurement accuracy. Agric. Biosyst. Eng. 28, 634–640.
IPCC, Intergovernmental Panel on Climate Change, 2006. Guidelines for national greenhouse gas inventories. In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Volume 4: Agriculture, Forestry and Other Land Use. OECD Press, Paris Available from. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm, Accessed date: 9 September 2019.
IPCC, Intergovernmental Panel on Climate Change, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Johnson, J.M., Franzluebbers, A.J., Weyers, S.L., Reicosky, D.C., 2007. Agricultural opportunities to mitigate greenhouse gas emissions. Environ. Pollut. 150, 107–124.
Lal, R., 2004. Carbon emissions from farm operations. Environ. Int. 30, 981–990.
Ma, B.L., Liang, B.C., Biswas, D.K., Morrison, M.J., McLaughlin, N.B., 2014. The carbon footprint of maize production as affected by nitrogen fertilizer and maize-legume rotations. Nutr. Cycl. Agroecosyst. 94, 15–31.
Marquina, S., Pérez, T., Donoso, L., Giulante, A., Rasse, R., Herrera, F., 2015. NO, N2O and CO2 soil emissions from Venezuelan corn fields under tillage and no-tillage agriculture. Nutr. Cycl. Agroecosyst. 101, 123–137.
Martre, P., Wallach, D., Asseng, S., Ewert, F., Jones, J.W., Rötter, R.P., Boote, K.J., Ruane, A.C., Thorburn, P.J., Cammarano, D., Hatfield, J.L., Rosenzweig, C., Aggarwal, P.K., Angulo, C., Basso, B., Bertuzzi, P., Biernath, C., Brisson, N., Challinor, A.J., 2015. Multimodel ensembles of wheat growth: many models are better than one. Glob. Chang. Biol. 21, 911–925.
McKnight, PE., Najab, J., 2010. Mann-Whitney U Test. The Corsini Encyclopedia of Psychology. pp. 1. https://doi.org/10.1002/9780470479216.corpsy0524.
Montgomery, D.C., Runger, G.C., 2003. Applied Statistics and Probability for Engineers, third ed. John Wiley & Sons, Inc., USA.
Moran, D., MacLeod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, B., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2008. Developing carbon budgets for UK agriculture, land-use, land-use change and forestry out to 2022. Climate Change 105, 529–553.
Nyakatawa, E.Z., Mays, D.A., Way, T.R., Watts, D.B., Torbert, H.A., Smith, D.R., 2011. Tillage and fertilizer management effects on soil-atmospheric exchanges of methane and nitrous oxide in a corn production system. Appl. Environ. Soil Sci., 475370. https://doi.org/10.1155/2011/475370.
Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperature and tropical regions. Biogeochemistry. 72, 87–121.
Olander, L.P., 2011. Using Biogeochemical Process Models to Quantify Greenhouse Gas Mitigation From Agricultural Management Projects. Nicholas Institute for Environmental Policy Solutions.
Öztürk, O., Wolfe, D.A., 2000. An improved ranked set two-sample Mann-Whitney-Wilcoxon test. Can. J. Stat. 28, 123–135.
Porfir'ev, B., 2016. Green trends in the global financial system. Mirovaya ekonomika i mezhdunarodnye otnosheniya 60, 5–16.
Pretty, J., Sutherland, W.J., Ashby, J., Auburn, J., Baulcombe, D., Bell, M., Bentley, J., Bickersteth, S., Brown, K., Burke, J., et al., 2010. The top 100 questions of importance to the future of global agriculture. Int. J. Agric. Sustain. 8, 219–236.
Richards, M., Metzel, R., Chirinda, N., Ly, P., Nyamadzawo, G., Duong, Q., de Neergaard, A., Oelofse, M., Wollenberg, E., Keller, E., Malin, D., Olesen, E., Hillier, J., Rosenstock, T.S., 2016. Limits of agricultural greenhouse gas calculators to predict soil N_2O and CH_4 fluxes in tropical agriculture. Sci. Rep. 6, 1–8. https://doi.org/10.1038/srep26279.
Searchinger, T., Hanson, C., Ranganathan, J., Lipinski, B., Waite, R., Winterbottom, R., Dinshaw, A., Heimlich, R., 2013. Creating a Sustainable Food Future: Interim Findings. A Menu of Solutions to Sustainably Feed More Than 9 Billion People by 2050. World Resources Institute (WRI), Washington, DC.
Smith, P., Powlson, D., Glendining, M., Smith, J., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Glob. Chang. Biol. 3, 67–79.
Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Humar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneide, U., Towprayoon, S., 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agric. Ecosyst. Environ. 118, 6–28.
Smith, P., Bhogal, A., Edgington, P., Black, H., Lilly, A., Barraclough, D., Worrall, F., Hillier, J., Merrington, G., 2010. Consequences of feasible future agricultural land-use change on soil organic carbon stocks and greenhouse gas emissions in Great Britain. Soil Use Manag. 26, 381–398.
Stehfest, E., Bouwman, L., 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutr. Cycl. Agroecosyst. 74, 207–228.
van Wart, J., Kersebaum, K.C., Peng, S., Milner, M., Cassman, K.G., 2013. Estimating crop yield potential at regional to national scales. Field Crop Res. 143, 34–43.
Woerishofer, M., 2011. Carbon Footprint of Local Produced Fruits and Vegetables Compared to Imported Goods From Overseas in the Caribbean and Latin America. Soil & More International, The Netherlands.
Yan, X., Yagi, K., Akiyama, H., Akimoto, H., 2005. Statistical analysis of the major variables controlling methane emission from rice fields. Glob. Chang. Biol. 11, 1131–1141.
Zhang, W., Dou, Z., He, P., Ju, X.-T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.-L., Zhang, Y., Wu, L., Chen, X.-P., Cassman, K.G., Zhang, F.-S., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc. Natl. Acad. Sci. 110, 8375–8380.