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

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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 CO2eq·Mg−1, where the extreme values corresponded to cassava in the RT (24 kg CO2eq·Mg−1) and maize in interviewed farmers in Barranca province (290 kg CO2eq·Mg−1). Overall, fertilizer production and application contributed to 77% of total greenhouse gas (GHG) emissions. 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 = 109 metric tons) of carbon dioxide equivalent (CO2eq); 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. N2O emissions from 35% to 60%, and CH4 by 60% by 2030 (IPCC, 2013). The challenge then is not only ensuring a sustainable food industry (Pretty et al., 2010), policy and research (Godfray 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 CO2 eq·ha−1 (GFha), or GHG intensity in kg CO2 eq Mg−1 (CF) (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...
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 (Porfiriev, 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 certain 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 Analysis 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.

### 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.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Texture</th>
<th>Texture class</th>
<th>Organic carbon (%)</th>
<th>N (%)</th>
<th>OM (%)</th>
<th>pH</th>
<th>Apparent density (g cm⁻³)</th>
<th>Annual average T° (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Molina</td>
<td>Loamy/sandy</td>
<td>Medium</td>
<td>0.50</td>
<td>1.06</td>
<td>0.86</td>
<td>7.60</td>
<td>1.50</td>
<td>19.30</td>
</tr>
<tr>
<td>Barranca</td>
<td>Loamy/sandy</td>
<td>Coarse</td>
<td>0.86</td>
<td>0.08</td>
<td>1.48</td>
<td>7.70</td>
<td>1.46</td>
<td>19.00</td>
</tr>
<tr>
<td>La Campana</td>
<td>Sandy</td>
<td>Coarse</td>
<td>0.41</td>
<td>0.05</td>
<td>0.70</td>
<td>8.02</td>
<td>1.44</td>
<td>18.80</td>
</tr>
<tr>
<td>Northern S. Elena</td>
<td>Sandy</td>
<td>Coarse</td>
<td>0.23</td>
<td>0.04</td>
<td>0.47</td>
<td>7.85</td>
<td>1.49</td>
<td>18.51</td>
</tr>
<tr>
<td>Southern S. Elena</td>
<td>Sandy</td>
<td>Coarse</td>
<td>0.64</td>
<td>0.06</td>
<td>1.04</td>
<td>7.09</td>
<td>1.31</td>
<td>18.51</td>
</tr>
<tr>
<td>San José Pativilca</td>
<td>Loamy/sandy</td>
<td>Coarse</td>
<td>1.05</td>
<td>1.00</td>
<td>1.81</td>
<td>7.00</td>
<td>1.42</td>
<td>18.51</td>
</tr>
<tr>
<td>Aragua</td>
<td>Silty</td>
<td>Coarse</td>
<td>0.17</td>
<td>0.03</td>
<td>0.29</td>
<td>7.54</td>
<td>1.50</td>
<td>24.33</td>
</tr>
<tr>
<td>Cañete</td>
<td>Sandy</td>
<td>Coarse</td>
<td>0.09</td>
<td>0.03</td>
<td>0.16</td>
<td>7.20</td>
<td>1.49</td>
<td>21.50</td>
</tr>
<tr>
<td>Huancarí</td>
<td>Sandy</td>
<td>Loamy/sandy</td>
<td>1.14</td>
<td>0.08</td>
<td>2.14</td>
<td>7.78</td>
<td>1.42</td>
<td>21.50</td>
</tr>
</tbody>
</table>

OM: Organic matter.

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.

### 2.2. 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 m² (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#.) 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 (CO2, N2O and NO), the multivariate empirical model was used (Stehfest and Bouwman, 2006; Zhang et al., 2013). The Nitrogen loss due to ammonia (NH3) volatilization was estimated (Bouwman et al., 2002).

In the reference trial (La Molina) as well as in farms in Barranca and Cañete, the emissions associated to fertilizer production (kg CO2eq·ha−1) and application (N2O (kg CO2eq·ha−1) and kg CO2eq·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 (CO2, N2O 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 N2O 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

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.

<table>
<thead>
<tr>
<th>Emission source</th>
<th>CCAFS-MOT</th>
<th>CFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer production (kg CO2eq·ha−1)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Fertilizer application (kg CO2eq·ha−1)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>N2O (kg CO2eq·ha−1)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Soil mining (kg CO2eq·ha−1)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>CH4 (kg CO2eq·ha−1)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Waste burning (kg CO2eq·ha−1)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>CH4 (kg CO2eq·ha−1)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>CH4 (kg CO2eq·ha−1)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Use of pesticides (kg CO2eq·ha−1)</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Use of energy in the field (kg CO2eq·ha−1)</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Crop transport (kg CO2eq·ha−1)</td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>
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, on 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 (< 2.0%, < 7.0 ppm and 100 to 240 ppm; respectively: source to local soil experts it is low. Low-level thresholds for N, P and K were (1.06%) and P (6.9 ppm), and high amounts of K (102 ppm). According carried out in sweet potato. Soil analyses revealed low amounts of N when grains have 14% moisture (veri fi ed 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.

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 hillings). 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 NH₄NO₃, (NH₄)₂HPO₄ and the formulation 20-20-20. Sweet potato farmers in Barranca fertilized with NH₂NO₃, (NH₄)₂HPO₄ and KCl and K₂SO₄ as K₂O sources. Whereas in Cañete, farmers also added NH₄NO₃, Ca(H₂PO₄)₂ and 0-46-0. For cassava, farmers in Barranca complemented urea with Ca(H₂PO₄)₂ and 0-46-0; but in Cañete,

<table>
<thead>
<tr>
<th>Table 3</th>
<th>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.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locality</td>
<td>Maize</td>
</tr>
<tr>
<td></td>
<td>N (kg·ha⁻¹)</td>
</tr>
<tr>
<td>La Molina</td>
<td>210</td>
</tr>
<tr>
<td>Barranca</td>
<td>119 to 345</td>
</tr>
<tr>
<td>Cañete</td>
<td>105 to 200</td>
</tr>
</tbody>
</table>

* Actual application.
  * From interviews to farmers.
cassava was also top dressed with (NH₄)₂HPO₄, 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 Conionthyrum 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 m³ (maize) and 7000 m³ 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 CO₂eq 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 N₂O emissions (176, 211, 403, 475 and 179 kg CO₂eq 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 CH₄ and N₂O 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 CH₄ and N₂O 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 CH₄ 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, for maize was 306 kg CO₂eq Mg⁻¹. For sweet potato and cassava: 221 and 258 kg CO₂eq Mg⁻¹, respectively. In Cañete, the resulting emission intensities in these crops were 187 and 167 kg CO₂eq Mg⁻¹. We then added the GHG emitted by the transportation of produce 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 (CO₂eq 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·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.

<table>
<thead>
<tr>
<th>Component/model</th>
<th>La Molina</th>
<th>Barranca</th>
<th>Cañete</th>
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<td>...</td>
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</table>

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

Table 6

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\(_2\)eq·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\(_2\)O, NO and NH\(_3\), through nitrification, denitrification and volatilization, which occur naturally in soils (Nyakatwa 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 CO₂ eq·ha⁻¹ as N₂O) 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, in maize for Barranca (Table 4) was comparable to values reported for La Pampa, Argentina; 300 kg CO₂eq·Mg⁻¹ (Woerishofer, 2011). For sweet potato, GHG intensities were similar across sites (range of 81 to 98 kg CO₂eq·Mg⁻¹). Similar intensities were reported for the Philippines (Flores et al., 2016 who reported up to 95 kg CO₂eq·Mg⁻¹). Cassava, in turn, ranged from 24 to 126 kg CO₂eq·Mg⁻¹. These values are comparable to those published in the literature for smallholder farmers in Nigeria (Cervigni et al., 2013; reporting 105 kg CO₂eq·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 NH₄ from being transformed into NO₂ and finally into NO₃ (Akiyama et al., 2010). The CCAFS-MOT estimated a low emission reduction potential (a maximum average of CF reduction in cassava, of 104 kg CO₂eq·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 CO₂eq·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 CO₂eq·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 of 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 N₂O 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.

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