RESEARCH ARTICLE

The cost of mitigating greenhouse gas emissions in farms in Central Andes of Ecuador

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Abstract

Aim of study: Reduction of the greenhouse gas (GHG) emissions derived from food production is imperative to meet climate change mitigation targets. Sustainable mitigation strategies also combine improvements in soil fertility and structure, nutrient recycling, and the use more efficient use of water. Many of these strategies are based on agricultural know-how, with proven benefits for farmers and the environment. This paper considers measures that could contribute to emissions reduction in subsistence farming systems and evaluation of management alternatives in the Central Andes of Ecuador. We focused on potato and milk production because they represent two primary employment and income sources in the region's rural areas and are staple foods in Latin America.

Area of study: Central Andes of Ecuador: Carchi, Chimborazo, Cañar provinces

Material and methods: Our approach to explore the cost and the effectiveness of mitigation measures combines optimisation models with participatory methods.

Main results: Results show the difference of mitigation costs between regions which should be taken into account when designing of any potential support given to farmers. They also show that there is a big mitigation potential from applying the studied measures which also lead to increased soil fertility and soil structure improvements due to the increased soil organic carbon.

Research highlights: This study shows that marginal abatement cost curves derived for different agro-climatic regions are helpful tools for the development of realistic regional mitigation options for the agricultural sector.

Additional key words: marginal abatement cost curves; cost-effectiveness; mitigation; climate change

Abbreviations used: CO2e (Carbon dioxide equivalent) CIP (International Potato Centre); GHG (Greenhouse Gases); INIAP (National Institute of Agricultural and Livestock Research); MACC (Marginal Abatement Cost Curves); MAGAP: Ministry of Agriculture of Ecuador

Introduction

Agricultural Greenhouse gas (GHG) emissions are increasing at around 1% yr-1. While substantial emissions reduction is needed in all sectors (IPCC, 2014), reducing agricultural emissions is a challenging issue, because the reductions achievable by changing agricultural practices are limited (Franks & Hadingham, 2012) and must be implemented without hampering production to respond to a rapidly increasing food demand (Alexandratos & Bruinsma, 2012). The Kyoto Protocol under the United Nations Framework Convention on Climate Change recognised the large potential to reduce atmospheric CO_2 concentration achievable

through agricultural management for soil organic carbon sequestration (UNFCCC, 2008, Smith, 2012; IPCC, 2014). Moreover, well-planned land management leads to improved soil health, reduction in degradation, soil carbon depletion and emissions reduction (Lal, 2013) and thus, changes in soil management carbon stocks do not only benefit soil but also enhance crop productivity (Sanchez *et al.*, 2016).

Significant research has been undertaken to assess mitigation options in agriculture (IPCC, 2014). In Latin America, agricultural mitigation is especially important since almost 80% of the area is dedicated to agriculture (FAOSTAT, 2017). In the coming years, agriculture in Latin America will have to evolve to produce fewer emissions and therefore agricultural policies need to be defined on the alternatives for climate-smart agriculture that link climate change mitigation measures with options that increase crop yields (UNFCC, 2016; Lal, 2013). This study contributes to the evaluation of sustainable alternative for agriculture in the Andean region of Ecuador, combining economic, social and environmental targets. The focus is on mixed production systems that include milk and potato production, analysing the marginal abatement costs of different production choices.

Latin America contributes about 10% of global emissions (4.6 million tonnes of carbon dioxide equivalent - CO_2e), which translates into a per capita emission of 7.7 tonnes CO_2e (WRI, 2014). The relationship between carbon emissions and soil degradation is an interesting choice to reduce GHG emissions, since it also improves soil quality. In this context, avoiding deforestation, reforestation, and adoption of sustainable agricultural measures are highly promoted practices in Latin American agriculture (Hansen *et al.*, 2013). Mitigation measures also add value in terms of energy security (through the control of domestic renewable feedstocks), food security (through increase food production), quality of life (through land restoration), and access to international financing given to low-carbon investments (Vergara *et al.*, 2016).

The Andean region includes the Northern Andes (Venezuela and Colombia), the Central Andes (Peru, Bolivia and Ecuador), and the Southern Andes (in Chile and Argentina). The Andes represent a very distinctive agro-climatic and cultural region of Latin America (Veeger *et al*., 2019) and the main economic activity in this area is agriculture. The main mixed system in the Andean region is based on the production of potatoes and milk, which represents from 25% to 40% of the economic production in high altitude areas of South America (Parra *et al*., 2019). The potato production is located in the central Andes.

In 2017, the entire region of the Andes produced about 30 million tonnes, equivalent to 89% of South America´s potato production (*i.e*. 34 million tonnes) and about 26 million tonnes of milk equivalent to 41% of milk production in South America (*i.e*. 62 million tonnes) (FAOSTAT, 2019). Milk and potato production is one of the main employment and income sources for the farmers and those commodities are staple foods of the local diet (Devaux *et al.*, 2010). The potato per capita consumption in the word is almost 40 kg person^{-1} yr^{-1} (FAOSTAT, 2016) and in the Andean region it is in general much larger, averaging 70 kg person^{-1} yr^{-1} (Deveaux *et al*., 2011). Consumption trends reflect income, available sources of food and consumption calorie choices (Deveaux *et al*., 2011). In Ecuador, the average consumption is lower than in other areas of the Andean region due to lack of empowerment of small farmers to reach the markets, and there are many initiatives that promote an increase in the sustainable potato cultivation (*e.g*., the LISFAME project, Cavatassi *et al*., 2008). Regarding the consumption of milk according to FAO-FEPALE (2012), in 2011 the average milk consumption of the region was 141 L of milk person^{-1} yr^{-1}, while the global average was 119 L. The relative higher consumption of milk in the region may be linked to the concept of "food sovereignty", interaction with other food groups, consumption patterns or eating habits of the population (FAO-FEPALE, 2012).

The mixed potato-milk systems in the Andean region sustain a population of 120 million people that have few food alternatives. The typical diet includes at least 400 g of potatoes day^{-1}. Potatoes were first cultivated 8,000 years ago in Latin America and the area of production has expanded greatly over the years (Devaux *et al*., 2010). Over time, Andean farmers have continuously adapted their agricultural practices to new circumstances, in particular producing more milk when the mark*et al*lows it to increase revenue and calorie intake.

The Andean zone of Ecuador is characterised by mixed systems of milk and potato production. Approximately 12,000 ha in the province of Carchi in northern Ecuador are destined for the cultivation of potato associated with pastures (INEC, 2019), which has been studied by Parra *et al*. (2019) as a system can effectively contribute to the reduction of GHG in Latin America. In the last 12 years, the National Institute of Agricultural Research (INIAP) and the International Potato Centre (CIP) have conducted research in Ecuador to characterize mixed systems (*i.e*. crop-livestock), increase productivity and improve profitability for farmers (Barrera *et al*., 2004). However, environmental issues have barely been addressed, except the most recent research carried out by Parra *et al*. (2019) in pastures associated with potato crop in Colombia.

The choices for mitigation are limited due to the challenges of the Andean orography. As in most mountain areas, steep slopes (more than 20% slope) impede the use of agricultural machinery, instead manual tillage and animal traction is used (Devaux *et al.*, 2010), which increases production costs because more person-hours are required. However, manual techniques benefit the environment because replacement of capital by labour avoids the emissions related to fossil fuel use by machinery (Cayambe *et al.*, 2015). Research to define sustainable mitigation measures is extensive (Moran *et al.*, 2011; Lal, 2013), including more efficient use of resources and integrated nutrient addition using organic manure and compost collected from the farm's own livestock, reduced tillage, crop rotation, legumes/ improved species mix, growing cover crops during the off seasons, plant waste management, and land use change (conversion of grass/trees). However, knowledge about the application and the cost of the measures as well as specific farming mitigation technologies is limited and fragmented (Smith, 2012; MacLeod *et al.*, 2010).

The marginal abatement cost curves (MACC) have been developed as a methodology to analyse the efficiency of GHG reduction measures. This methodology is commonly used to support policymakers in understanding the opportunities for reducing GHG emissions and their costs. MACC illustrate the costs of specific crop, soil, and livestock abatement measures against a business as usual scenario. Costs per unit can differ among the measures adopted and in some cases, farmers can implement measures that could help reduce emissions at negative cost (Moran *et al.*, 2011).

The main objective of this research focused on assessing possible agricultural options and policies for climate change mitigation on potato and milk production by quantifying GHG emissions and analyzing the mitigation potential of specific agricultural practices for each region with minimal barriers to implementation.

Material and methods

Framework

Our approach to explore the cost effectiveness of mitigation measures combines models and participatory methods as summarised in Fig. 1. The methodology includes five sequential steps: first, surveys to 120 farmers detailing farming systems were used to characterize the baseline scenario. Second, focus groups that include experts in agricultural, environmental and economic sciences were used to define the possible choices of mitigation measures adapted to the reality of the farming systems. These two steps represent the
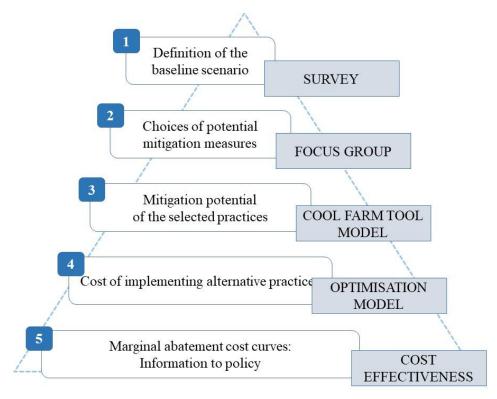

Figure 1. Methodological framework to define the cost and effectiveness of greenhouse gases mitigation measures.

methodology`s participatory approach. Third, the Cool Farm Tool model was used to define the mitigation potential of the selected measures (Haverkort & Hillier, 2011). Fourth, an optimisation model was used to estimate changes in the farmers´ net margin as a proxy for the cost of implementing the measures. Last, MACC were used to calculate the cost-effectiveness of the mitigation measures in order to guide policy choices.

Definition of the baseline scenario: Farming systems in the case study and data

The study was carried out in 2013 in three sites in Ecuador that exemplify subsistence farming systems in the Central Andes. These farming systems are located between 2,200 and 3,800 meters above the sea level; the temperature ranges from 4 to 21°C and precipitation ranges from 500 to 2000 mm yr^{-1}. These characteristics produce particular agro-ecological environments. The potato-milk system is the key farming system in this region, with 96% of land dedicated to potato cultivation and 4% of land dedicated to livestock pasture (INIAP, 2013). This system consists of growing potatoes during 2-3 cycles on soils previously occupied by pastures for approximately 2 years, completing a cycle of 4-5 years (Proaño & Paladines, 1998; Paladines & Jacome, 1999; Barrera *et al.*, 2004). Pasture is used for livestock feeding and therefore milk production. After potato production, other crops can be planted for one cycle only to take advantage of residual fertilizers; this third crop is not considered in the study. About 75% of the cultivated area is non-irrigated (INEC, 2016). Soils in this region are Andosols which are primarily characterized by having a high content of organic matter (IUSS Working Group WRB, 2014).

The Andes is topographically variable and has high agro-ecological heterogeneity, with different production zones that exemplify the production range in high altitude zones. Location selection was done according to a bio-socio-economic characterisation which distinguishes three different zones (Table 1).

We selected three zones and representative locations of the mixed production systems (potato and milk) located in the central Andes of Ecuador (Table 1 and Fig. 2). This selection was established based on the following criteria: a) potato and milk production in the area is important for family income and nutrition, b) technology is essential for production sustainability, and c) selected locations are representative for the region.

As such, each of the three locations represents a different producer and production systems: Carchi represents large producers and intensive systems. Chimborazo represents medium producers of mixed systems,

Table 1. Selected locations in the Central Andes of Ecuador and representative locations included in the study

Characteristics	Andean region		
	North zone	Centre zone	South zone
Total potato area (ha)	12,398	30,191	6,622
Representative location for the model	Carchi	Chimborazo	Cañar
Maximum temperature (°C) (1990-2010)	21	18	18
Minimum temperature (°C) (1990-2010)	4	6	6
Average temperature (°C) (1990-2010)	11.8	13.5	11.9
Total annual precipitation (mm) (1990-2010)	1013	1100	467

Source of data: INAMHI (2015), INEC (2016).

and Cañar represents small producers, with extensive systems and family farming.

Sample size was estimated based on the number of potato and milk farmers registered in the Ministry of Agriculture and Livestock: 112 in Carchi, 98 in Chimborazo, and 85 in Cañar. Therefore, 40 surveys in each study area were done for this research.

The surveys gathered information related to crop management such as yield, area, and amount of fertilizer, labour and fuel used. Additional information related to the representativeness of the statistical data for the local realities was obtained from face-to-face interviews with a group of experts from the INIAP and CIP-Ecuador. Socioeconomic information of the population and agro-meteorological characteristics (soil-water-plant-animal) from the selected locations were obtained from the Ministry of Agriculture of Ecuador (MAGAP), the National Institute of Meteorology and Hydrology (INAMHI), and the Military Geographical Institute (IGM).

Based on INIAP (2013) the study areas can be characterized from a sociodemographic perspective. The inhabitants are 48% male and 52% female. An illiteracy rate of approximately 20% is observed. Household average size is 5. The level of education of 70% of heads of household reaches primary education and 18% reaches secondary education. Both men and women have access to secondary education, but usually, neither of them shows interest in continuing education because young people are used to managing their own money and they know that the opportunity for higher education is not possible because it is very expensive. Instead, they decide to invest their capital in the livestock business, selling coal, buying and selling food, making handicrafts or simply growing potatoes. They are aware that education is important, but they prefer not to study
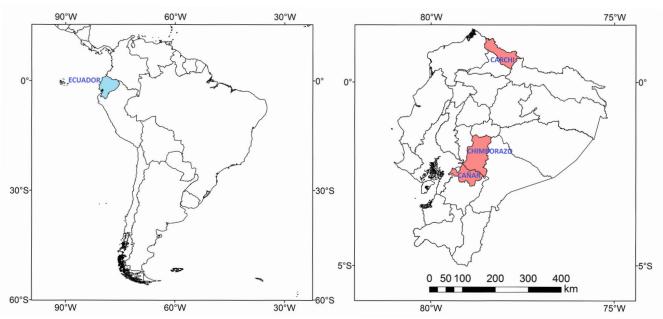
Figure 2. Schematic image of the scenarios evaluated. Left: Location of Ecuador in Latin America. Right: Scenarios evaluated in Ecuador.

in universities. It should be noted that in recent years, the creation of extensions of several universities, as well as the availability of distance university studies, has increased the number of people who have access to university. About 79% of producers have their own land with a property title and 6% of producers without a title. Moreover, 13% of producers use loaned land, and 2% of producers produce on leased land. Finally, 80% of the producers own their own home, while the rest have their homes leased and/or mortgaged. The majority of agricultural activities are under the responsibility of the heads of household or of the male children, although women also participate in these as well as taking care of housework-related activities and the production of handicrafts, mainly textiles. Everyone in the household works; the children are in charge of collecting grass to the guinea pigs and feeding the chickens. After fulfilling their school tasks; the younger children accompany their parents to milk the cows and change the cattle from one paddock to another.

Selection of the potential mitigation measures

We made an initial list of GHG mitigation measures in agricultural soils based on a published literature review and the datasets available at INIAP. The potential list of measures and their feasibility was discussed and evaluated by scientists on pastures, crops and soil science in the above-mentioned focus groups. Focus groups participants were selected based on the following criteria: i) prior involvement in research; ii) experience related to agricultural GHG mitigation for at least five years; iii) regular contact with farmers; and iv) crop specific knowledge of pastures and potatoes. The measures which showed less implementation barriers were selected, resulting in a list of measures with a higher abatement potential rate chosen for this region and specific crop system.

Definition of the mitigation potential of the selected measures

Using the data obtained in the farmer survey GHG emissions in the baseline scenario and mitigation scenarios were calculated using the open-source software Cool Farm Tool (Haverkort & Hillier, 2011). This site-specific software has been tested in potato farm systems in various countries: The Netherlands (Haverkort & Hillier, 2011), United Kingdom (Hillier *et al.*, 2011), Spain and Peru (Cayambe *et al.*, 2015). Estimates emissions from potato and livestock were analysed separately. Recognising that the mitigation potential varies greatly in different agro-climatic regions and agricultural practices; Cool Farm Tool software defines the mitigation potential for all study sites. In order to calculate the mitigation potential of the measures, emissions data in baseline scenarios were required.

The input information required by the software was: general information (location, year, product, production area, and weather), crop management (agricultural operations, crop protection, fertilizer use, and management of crop residues), carbon sequestration (soil use and soil management, plant biomass), livestock (feed options, enteric fermentation, nitrogen excretion, and

manure management), and energy use (irrigation, agricultural machinery). All these data were obtained from the surveys, except weather data which was obtained from weather stations (INAMHI, 2015).

The output information generated by the program consisted of CO_2e emissions from the time of sowing to harvest and can be represented - for each agricultural management choice - per unit area, or per tonne of product produced, of nitrous oxide in the soil, emissions generated in the field by applied fertilizers, emissions generated for pesticide use, energy use, and crop residue management (Haverkort & Hillier, 2011).

The Cool Farm Tool program calculates GHG emissions from different sources using conversion rates that are internationally agreed and used by the IPCC. Table 2 summarises the conversion rates and the sources of data.

Cost of implementing alternative measures. Changes in the net margin for farmers

Production costs in the baseline scenario are derived from data published in the National Information System of the MAGAP (2016a,b), in which the yearly input and output prices are recorded. The costs of implementing alternative measures were estimated through an optimisation model (*i.e.* net margin maximization). This method consists of maximizing the net margin of producers when a GHG mitigation practice is implemented in the system. For this calculation we relied on a linear programming model valid for potato-milk systems in Ecuador; which considers different production alternatives imposing restrictions related to the practices and

available resources (Annexes A and B). The model defines the production plan that optimizes the use of resources to achieve the maximization of net margin. Net margin was obtained from the difference between the profit and the input cost (fertilizer, seed, crop protection, labour costs, and domestic consumption).

Baseline and mitigation scenarios were optimized under the assumption of maximizing net margin using the linear programming software LINDO (LINDO Systems, 2003).

MACC to guide policy choices

The cost-effectiveness of a mitigation measure (CEp) is the ratio between the change in the net margin related to practice (ΔNMp) and the change in GHG emissions associated with practice ($\Delta GHG\ p$) (Eq. 1) (Cayambe *et al.,* 2015; Dequiedt & Moran, 2015). '$\Delta GHGp$' was calculated as the difference between emissions generated in the baseline scenario less emissions from mitigation scenarios.

'ΔNMp' was calculated as the difference between the net margin in mitigation scenarios (Eq. 2).

$$CEp = \frac{\Delta NMp}{\Delta GHGp} \qquad [1]$$

$$\Delta NM_p = (USD\ ha^{-1}\ yr^{-1})_{BAU} - (USD\ ha^{-1}\ yr^{-1})_M \quad [2]$$

where CEp is the marginal abatement cost for each practice or measure "p", and represents the cost-effectiveness of each measure; ΔNM_p is the net margin in dollars ha^{-1} yr^{-1} in baseline (*BAU*) and in the mitigation

Table 2. The Cool Farm Tool program: sources of data and conversion rates

Type of operation that affects GHG emissions	Conversion to GHG emissions	Source of information
Production and distribution of fertilizer	Ecoinvent base data	Ecoinvent Centre, 2007
Fertilizer application, type of fertilizer, application frequency	NO_x calculated with an empirical model that takes into account the characteristics of the soil	FAO/IFIA, 2001
Application of nitric oxide (NO) and ammonia (NH$_3$)	NO_x calculated with an empirical model that takes into account the characteristics of the soil	IPCC, 2006
Application of urea and lime	NO_x calculated with an empirical model that takes into account the characteristics of the soil	IPCC, 2006
Organic matter addition	Climate data, soil characteristics, farming practices, and crop residue management	Smith, 2012
Use of energy (gasoline, diesel, electricity) for field operations and primary processing have	Technical standards of American Society of Agricultural and Biological Engineers-ASABE	ASABE, 2007
Emissions from soil are calculated by introducing climate data, soil characteristics, farming practices, and crop residue management		Smith, 2012

option (M), respectively. The result is the cost of the mitigation measure.

Finally, we represented a MACC showing the relationship between the cost-effectiveness of abatement options selected and the total amount of GHG reduction. The x-axis represents the amount of abatement potential from the measure (in tonnes of CO_2e). The y-axis represents the cost per tonne of CO_2e saved.

Some measures may be able to reduce emissions and save money (negative costs) being the more efficient options that pay for themselves; these measures are showed below the x-axis in the MACC. Other measures may mitigate more emissions but incur substantial costs, and therefore are less efficient options. These expensive options are represented above the x-axis in the MAAC. The final step is to define the best policy options for the case study based on the cost-effectiveness analysis.

Results

Defining the baseline in potato-milk Andean farming systems

The characterisation of current potato-milk farming systems is defined by the baseline. This is characterised with the information obtained from surveys (Table 3). The results showed that productivity and production costs vary greatly among the three locations. According to the surveys, farmers employ mostly household labour but sometimes hired labour as well. Soil tillage is mostly done manually with 38 people ha^{-1} for the production of potatoes in Cañar to 103 people ha^{-1} in Carchi. In some cases, the tillage of the soil is done with agricultural machinery using 60 L of fuel ha^{-1}. High rates of fertilization and frequent use of pesticides are common in the potato-milk system. In general, potato production in Carchi is more mechanized, uses more inputs, and also attains higher productivity. The baseline productions in Chimborazo and Cañar were very similar. In all cases the year to year variability is very high (from 80% to 110% of average production). Milk production varied among the three locations and was also more mechanized in Carchi, especially with high labour inputs. This results in higher milk productivity. Cañar is the location that favours milk production over potato production in terms of pasture area occupied.

Measures selected with high abatement potential

Seven potential mitigation measures were selected by scientists at the focus group (Table 4). The selection also included a qualitative analysis of the barriers (climate, agronomic and social constraints) and incentives for implementing the measures. Some of the measures identified are already implemented by some farmers in

Table 3. Characterisation of farming systems in the selected sites based on data from 40 representative farms in each province to define the baseline.

Representative farming systems in each area	Carchi		Chimborazo		Cañar	
	Mean	SD	Mean	SD	Mean	SD
Total area (ha)	11.33	8.32	4.69	5.29	7.03	6.31
Potato area (ha)	2.41	1.83	0.61	0.44	0.66	0.46
Pasture area (ha)	7.66	5.99	2.45	2.81	4.67	5.54
Subsistence crop area (ha)	1.26	0.75	1.63	0.68	1.7	0.84
Potato yield (kg ha^{-1})	14,449	12,761	13,590	11,170	10,865	9,754
Potato seed farm^{-1} (kg)	2,214	1,989	698	627	604	410
N (kg ha^{-1})	198	57	129	27	83	69
P_2O_5 (kg ha^{-1})	417	158	222	42	122	77
K_2O (kg ha^{-1})	182	88	81	25	34	21
Crop protection (no. controls ha^{-1})	8	2	4	2	4	2
Milk cattle (no. animals farm^{-1})	18	9	10	6	14	11
Milk production (L day^{-1})	12	8	10	11	10	9
Fuel used in labour (L ha^{-1})	60	0	60	0	60	0
Hired labour for potato production (no. people ha^{-1})	103	80	76	25	36	38
Household labour for potato production (no. people ha^{-1})	25	27	59	25	63	42
Hired labour for milk production (no. people ha^{-1})	3	8	0	0	0	0
Household labour for milk production (no. people ha^{-1})	345	269	242	119	240	252

Table 4. Mitigation measures for mixed farming systems selected by the focus group.

Mitigation measures defined by the focus group	Reference of similar measures in other filed studies
M1. Management of organic soils Organic soils contain high C densities. Emissions in these soils may be reduced by avoiding row crops, avoiding deep ploughing and keeping the groundwater table close to the surface	Quintero & Comerford, 2013
M2. Multipurpose fodder trees Tree species contribute to soil organic carbon through biomass and create shade for cattle. Legumes can increase the nitrogen content in soils.	Naranjo *et al.,* 2012; Smith*,* 2012; Montagnini, *et al.,* 2013
M3. Manure management N_2O emissions will be reduced if the manure is applied at the exact moment that the crop is going to use it. Previous investigations suggest covering compost piles to reduce N_2O emissions.	Chadwick *et al.,* 2011; Smith*,* 2012
M4. Grazing management. Pasture improvement and fertilization Grazing intensity affects carbon storage in soils. Pasture productivity will increase by proper fertilization. Using biological fixation to provide nitrogen inputs (clover).	MacLeod *et al.*, 2010; Smith, 2012
M5. Reduced tillage + Use of crop residues Reduced tillage allows management of crop residues which promotes carbon sequestration in soil by less decomposition and erosion. In Ecuador a type of reduced tillage called "Huacho rozado" is practiced.	Smith, 2012; Jahan *et al.*, 2016
M6. Cropland management agronomy Adopt new varieties that provide equal or greater yield, but need less fertilizer (*i.e.*, in Ecuador: Natividad and Libertad varieties) Early varieties can reduce the use of inputs (*i.e.*, Victoria and Libertad varieties)	Smith, 2012
M7. Nutrient management Practices that improve nitrogen use efficiency (*i.e.*, slow release fertilizer or nitrification inhibitors), avoid excessive nitrogen applications, or remove applications where possible.	Moran *et al*, 2011; Xia *et al.*, 2016

the region. Additionally, some references for the mitigation measures implementation in countries with similar agricultural and climatic conditions were included in Table 4. The mitigation measures were: M1, management of organic soils; M2, multipurpose fodder trees; M3, manure management; M4, grazing management, pasture improvement and fertilization; M5, reduced tillage + use of crop residues; M6, cropland management agronomy; and M7, nutrient management.

These measures have been selected based on the results obtained in other investigations. Organic soils in the Andes contain high carbon densities. Emissions in these soils can be reduced by avoiding row crops and deep ploughing and keeping the water table close to the surface.

The measure M2 was included as tree species contribute to the soil`s organic carbon through biomass and create shade for livestock. There are species of trees in the legume family that can increase the nitrogen content in soils by fixing them through nitrifying bacteria.

The "huacho rozado" practice is a pre-Columbian system of reduced tillage and cover that is applied in potato cultivation. It is practiced mainly by farmers in the province of Carchi. This system is applied to convert an old pasture into a potato crop, with yields greater than or equal to those of conventional tillage. Being a manual system prevents soil erosion and compacting. In addition, rotting of the plant cover (commonly called chamba) allows microbial activity, creating an antagonistic environment for the development of the white worm (*Premnotrypes vorax*) and the potato blight (*Phytophthora infestans*). The requirements to establish a plot with grazed huacho are: pasture with Kikuyo (*Pennisetum clandestinum*) of more than 3 years, soil slope between 15% and 45% and precipitation of at least 1000 mm yr^{-1}.

Most of these measures have been the most promising of this analysis, since some of these measures have already been implemented by farmers in the region with similar agricultural and climatic conditions, except those options very difficult to adopt because of the high implementation costs. In addition, the opinion of farmers regarding the barriers to implementation was considered to ensure the adoption of mitigation options raised in consensus with farmers and promote equity and social justice.

This research also showed that there are implications in terms of well-being. That is, if low-input farms are also those managed/owned by poorer households, the costs would be higher for the most economically disadvantaged.

The barriers to the implementation of measures can be directly related to the socioeconomic data of the farmers.

Emissions in the baseline scenario

Using the Cool Farm Tool model, we estimated the emissions in the baseline scenario. Potato and milk production account for an average of 10 ton CO_2e ha^{-1} yr^{-1}. This value includes emissions from potato and milk in the three locations (Fig. 3). Milk production emissions were calculated as the sum of dairy livestock and pasture emissions. In relative terms, crop residue management on the pasture generates the greatest contribution to the total, 40-50% of emissions generated by the mixed systems of the three zones. Emissions from livestock enteric fermentation account for an average of 2 ton CO_2e ha^{-1} yr^{-1}, which are equivalent to 18% of

emissions generated in these systems. Emissions attributed to fertilizer use in pastures were not significant, accounting for an average of 0.4 ton CO_2e ha^{-1} yr^{-1}; however, direct and indirect N_2O from excessive fertilizer application in the potato crop reached 20% of emissions generated by the mixed systems of the three zones.

Costs, benefits, and changes in farmers' net margin of implementing the selected mitigation measures

The costs and benefits for the farm (effects on yield, input costs, labour costs and machinery) are used to calculate the impact of each measure in farmers´ net margins when they apply GHG mitigation measures.

The estimation of the costs and benefits of the small measures has been published based on the assumptions of costs and benefits detailed in the published literature (Table 5). Although there is no local empirical data to prove them, these assumptions were analysed and approved with the members of the focus group and with INIAP researchers.
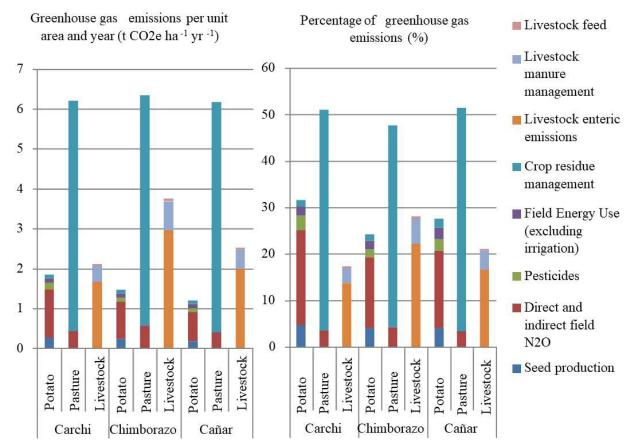

Figure 3. Greenhouse gases emissions in the representative locations of mixed farming systems in the Central Andes; units in left panel, percentages in right panel.

Table 5. Costs and benefits at level of farm of mitigation measures selected.

Measures	Costs (%)	Benefits (%)	Source of data
M1		Labour and machine cost reduced by 20%. Increased yield of 13%.	Koga *et al.*, 2003
M2	5% increase in costs of planting. Reduction of crop yield 7%.	Reduced use of nitrogen 10%.	MacLeod *et al.*, 2010
M3		Reduced use of nitrogen 15%.	MacLeod *et al.*, 2010
M4		Reduced use of nitrogen 60%. Labour and machine cost reduced by 5%. Small yield increase (5%).	MacLeod *et al.*, 2010
M5	Yield unaffected but tubers are bigger and 15% higher price. 8% increase use nitrogenous fertilizer and 25% potassium fertilizer. 33% less incidence of Phytophthora infestans. Insect control not necessary.	Machine cost reduced by 20%. Labour cost reduced by 48%.	Chulde, 2005; INIAP, 2013; Zangeneh *et al.*, 2010
M6	Lower yield than conventional varieties (Fripapa, Superchola) (30% less)	Reduced use of fertilizers 30% (fewer days of fertilization). Reduced spraying pest management 30% (resistant varieties).	INIAP, 2013
M7	Increased fertilizer cost 50%	Yield increase 2%. Half number of fertilization labour.	MacLeod *et al.*, 2010

Costs and benefits were used as input data to calculate the net margin per farm and hectare in each case study by using the optimization model (net margin maximization). The change in net margin was defined as the cost or benefit of implementing a particular mitigation measure. Negative changes in net margin mean cost savings and positive changes mean more expensive measures (Table 6).

Cost-effectiveness of the mitigation measures to guide policy choices

In Fig. 4, the rate of change in total costs depending on changes in GHG reduction and the relative rate of increase of marginal cost observed. In all scenarios of our study, MACC have negative slopes. Each point represents a mitigation measure, differentiated by the implementation cost per tonne of reduced CO_2e (y-axis) and the quantity of reduced CO_2e emissions (x-axis). Measures below the x-axis are cost-effective, for example removing emissions and representing positive changes in net margin.

Regarding the cost-effectiveness of the mitigation measures to guide policy choices, our results showed that the MAAC of Cañar (the blue curve in Fig. 4) was steeper because of the use of few agricultural inputs. MACC analysis showed that the potential for reducing

emissions in farms with high inputs consumption exceeds the abatement potential of farms with low consumption. Thus, in the scenario with high inputs consumption (Carchi, mainly) the cost to reduce 2 ton CO_2e ha^{-1} would be USD 300 ton^{-1} CO_2e, while in the case of farms with low inputs consumption (Cañar) the effort to reduce 0.7 ton CO_2e ha^{-1} would be, equally, about USD 300 ton^{-1} CO_2e.

The abatement potential between different geographical areas can be represented for the same MACC. An alternative representation of the cost heterogeneity is presented in Fig. 5, which contains the results of the three locations in regional MACC. The results showed considerable geographical variability. Management of organic soils, reduced tillage and crop residues management in Cañar is more profitable than in Carchi and Chimborazo. Manure management is profitable only in Carchi (USD -7.7 ton^{-1} CO_2e. In Chimborazo and Cañar, even for low levels of mitigation, the marginal abatement cost is positive (respectively USD 8.9 ton^{-1} CO_2e and USD 4.2 ton^{-1} CO_2e). Therefore, in the Andes, it would be expected that the marginal abatement cost range will be USD 4-8 ton^{-1} CO_2e.

The most efficient measures in terms of potential and cost reduction were the management of organic soils (M1) and reduced tillage (M5), which had the lowest negative costs and the greatest reduction in CO_2 emissions. Costs and benefits of reduced tillage and

crop residue use were derived from studies conducted in Ecuador specifically under the "Huacho rozado" system (INIAP, 2013).

Additionally, there may be mitigation options with mitigation potential, but they cannot be adopted by the farmers, due to the high costs or due to socioeconomic
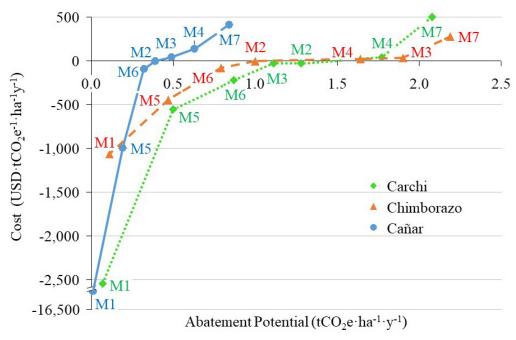

Figure 4. Marginal abatement cost curve (MAAC) for potato-milk system in the Central Andes. M1, management of organic soils; M2, multipurpose fodder trees; M3, manure management; M4, grazing management, pasture improvement and fertilization; M5, reduced tillage + use of crop residues; M6, cropland management agronomy; and M7, nutrient management.

Figure 5. Accumulated abatement for the potato-milk system in the Central Andes. Assuming 100% applicability by farmers depending on the area in each zone, approximately 97,234 ton CO_2e yr^{-1} would be mitigated nationally, equivalent to 46% reduction in agricultural emissions for a total of 210,000 ton CO_2e yr^{-1} (see Table 7). M1, management of organic soils; M2, multipurpose fodder trees; M3, manure management; M4, grazing management, pasture improvement and fertilization; M5, reduced tillage + use of crop residues; M6, cropland management agronomy; and M7, nutrient management.
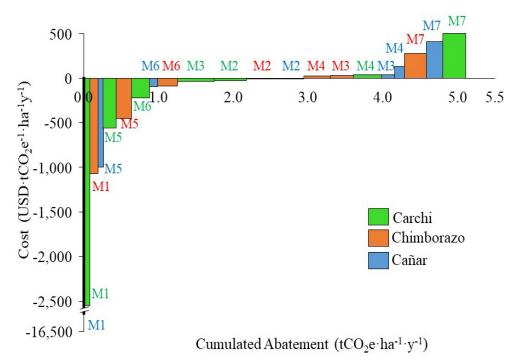
Table 6. Changes in the net margin of the representative farms between baseline scenario and mitigation scenarios in the selected locations in the Central Andes.

| Measures | Site | Size of the representative farm (ha) | Changes for the representative farms | | |
			Net margin farm⁻¹ (USD yr⁻¹)	Net margin per land unit (USD ha⁻¹ yr⁻¹)	Variation in the net margin of farmers (USD ha⁻¹ yr⁻¹)
Baseline scenario	Carchi	11.03	6,109.85	539.26	
	Chimborazo	4.69	1,104.00	235.40	
	Cañar	7.03	1,904.32	270.88	
M1	Carchi	11.03	8,187.58	722.65	-183.38
	Chimborazo	4.69	1,676.00	357.40	-121.99
	Cañar	7.03	2,683.30	381.69	-110.81
M2	Carchi	11.03	6,166.87	544.30	-5.03
	Chimborazo	4.69	1,113.00	237.25	-1.84
	Cañar	7.03	1,907.00	271.30	-0.41
M3	Carchi	11.03	6,196.95	546.95	-7.69
	Chimborazo	4.69	1,062.00	226.46	8.95
	Cañar	7.03	1,874.00	266.59	4.29
M4	Carchi	11.03	5,900.35	520.77	18.49
	Chimborazo	4.69	1,038.00	221.30	14.10
	Cañar	7.03	1,778.00	252.95	17.94
M5	Carchi	11.03	8,796.91	776.43	-237.16
	Chimborazo	4.69	1,863.00	397.20	-161.79
	Cañar	7.03	3,198.00	454.84	-183.95
M6	Carchi	11.03	7,046.38	621.92	-82.66
	Chimborazo	4.69	1,228.00	261.88	-26.48
	Cañar	7.03	1,990.00	283.02	-12.14
M7	Carchi	11.03	4,353.81	384.27	154.99
	Chimborazo	4.69	726.00	154.82	80.58
	Cañar	7.03	1,285.00	182.84	88.05

factors of the farmers in each region. This would be considered as an implementation barrier, which will generate inequality among farmers of the three regions. An analysis of implementation barriers could be relevant for a better understanding of the reasons why farmers do not adopt these mitigation practices.

According to information from the Ministry of Environment of Ecuador (MAE, 2011), 210,000 ton CO_2e yr⁻¹ were generated by the agriculture sector in 2011. The GHG mitigation analysis without considering adoption barriers or costs, and assuming total adoption of practices by farmers, shows that approximately 97,234 ton CO_2e yr⁻¹ would be reduced in the Central Andes (specifically in regard to Ecuador), that is equivalent to 46% reduction in agricultural emissions generated in 2011 (Table 7). The analysis in relative terms (Table 8)

Table 7. National mitigation potential of mixed farming systems in the Andes assuming 100% applicability.

| Measures | Abatement potential tonnes CO_2e yr⁻¹ | | | |
	Northern zone (12,398 ha)	Central zone (30,191 ha)	Southern zone (6,622 ha)	Central Andes (49,211 ha)
M1	867.86	3,321.01	66.22	4,255.09
M2	2,107.66	6,340.11	463.54	8,911.31
M3	2,975.52	7,849.66	728.42	11,553.60
M4	6,075.02	19,322.24	860.86	26,258.12
M5	5,331.14	10,868.76	1,191.96	17,391.86
M6	4,587.26	9,359.21	860.86	14,807.33
M7	3,843.38	8,755.39	1,456.84	14,055.61
Total abatement with all options	25,787.84	65,816.38	5,628.70	97,232.92

Table 8. National mitigation potential of mixed farming systems in the Andes in relative (percentage) terms assuming 100% of applicability.

Measures	Abatement potential (%)			
	Carchi	Chimborazo	Cañar	Andean region
M1	0.41	1.58	0.03	2.03
M2	1.00	3.02	0.22	4.24
M3	1.42	3.74	0.35	5.50
M4	2.89	9.20	0.41	12.50
M5	2.54	5.18	0.57	8.28
M6	2.18	4.46	0.41	7.05
M7	1.83	4.17	0.69	6.69
Total abatement	12.28%	31.34%	2.68%	46.30%

indicates that, the application of measures M4 (grazing management) and M5 (reduced tillage), would reduce agricultural emissions by 12.5% and 8.28%, respectively, of the total emissions generated by agriculture in the year 2011.

Discussion

We calculated costs and benefits only in the first year of potato and milk production. Indirect and social costs/benefits are excluded from the analysis and ignore the interaction of measures (MacLeod *et al.,* 2010), since we have not found a detailed assessment of interaction factors in the literature. We have considered the opinion of farmers in the selection of mitigation measures, and we have given value to expert opinion on climate change and in the potato-milk system according to technical, social and economic aspects. Expert judgement was used to estimate the costs and benefits, in particular for the effect of cropland management agronomics when farmers adopt new varieties.

Our analysis is limited to the effects on farms and does not take into account before or after effects (*i.e.* fertilizer production) nor emissions mitigation benefits related to enteric fermentation of livestock. We considered mitigation measures related only to the potato crop and pasture in the mixed systems. Defining the baseline in the Andean agricultural potato and milk systems allowed for the characterization of current potato-milk farming systems. Our results indicated that potato and milk yield heterogeneity is due to agronomic, climate, socio-economic and institutional (*i.e.* public support) differences. Potato cultivation, in many cases, is associated with grass cultivation for milk production.

Resource efficiency measures can be implemented in mixed farming systems to help reconcile competing objectives of yield improvements and reduction of external costs. The analysis responds to the need to demonstrate the possibilities for sustainable intensification, allowing the Andes to meet economic growth ambitions for the sector.

Emissions attributed to fertilizer use in pastures were not significant, however direct and indirect emissions of N_2O from the excessive application of fertilizer in the potato crop reached 20%. This low contribution was expected, since pastures are least fertilized in the Andes. The main fertilisation input is the residual fertilizer from the potato crop (Barrera *et al.*, 2004).

Using the Cool Farm Tool model, we estimated the emissions in the baseline scenario. When interpreting these results, it should be taken into account that in all scenarios of our study MACC have negative slopes. This is consistent with the microeconomic production theory of diminishing marginal returns or increasing marginal cost, which states that in the production process, when some inputs remain fixed, each additional unit of a variable factor provides a smaller benefit (diminishing return/increasing cost) at the margin. The abatement potential of a measure decreases or the cost increases when the measure´s abatement activity level increases (Balana *et al.*, 2012). The implication is that the cost of reducing each additional input in farms when the input current level is already low is increased substantially (Cayambe *et al.*, 2015).

Farmers that use few agricultural inputs (nitrogenous fertilizer principally) find it more expensive to reduce GHG emissions, equivalent to USD 428.57 ton[-1] CO_2e. But for the farmer who uses many agricultural inputs, it is much cheaper to reduce emissions because for each tonne of GHG reduced, the cost is lower, equivalent to USD 150 ton[-1] CO_2e.

Therefore, farms applying high amounts of inputs may reduce their emissions at a lower cost, while farms already using low amounts of inputs might face higher costs in order to further reduce their CO_2e emissions. This means that in the study region, farms with less use

of inputs are already operating more efficiently with respect to emissions (that is, less emissions per output produced) than those with greater use of inputs, as their practices reduce emissions and do not increase them.

The results showed that the greatest potential for mitigation is achieved with measures applied on farms with large cultivated areas (*i.e.* Carchi and Chimborazo); these areas utilize more inputs and have higher CO_2e emissions and greater potential for mitigation. Cañar applied small amounts of inputs, and mitigation is more expensive. This result seems to be in line with previous investigations which found that potato systems with low inputs have high costs per tonne of CO_2e reduction compared to intensive farming for which mitigation is more cost effective (Cayambe *et al.*, 2015).

The results in Fig. 5 demonstrated heterogeneity of GHG mitigation options in the Central Andes of Ecuador, both in the abatement potential and in the costs. Therefore, any public policy before being implemented must be considered through the application of policy instruments that allow knowing the implementation barriers, climatic conditions, and sociodemographic data, among other characteristics of the areas under analysis.

After considering the relative cost of emissions mitigation support policy development, we observed that five of the seven mitigation measures simulated - management of organic soils, reduced tillage + crop residues, cropland management agronomy, multipurpose fodder trees, and manure management - have negative costs (*i.e.* < 0 USD ton^{-1} CO_2e), and thus could be candidates for policy or training programs. It is important to note that monetary costs and benefits are only one aspect of implementation.

Lack of knowledge is a fundamental barrier to the support of mitigation policies that reduce agricultural emissions. Therefore, it is essential to promote technologies that use inputs more efficiently and promote markets that support potato production since it is more environmentally friendly as well as attempt to maintain farmers´ current wellbeing by diversified economic activities, considering that potatoes and milk are staple foods in the Andes diet.

Our work supports a multitude of agricultural studies, including recently published (Eory *et al.,* 2018; Barnes *et al.,* 2019; Sapkota *et al.,* 2019), that emphasise the role of mitigation measures to address other problems, such as soil fertility, nutrient recycling, or water efficiency. A fundamental question is: why should a farmer change a management practice to reduce emissions when he/she has not done so before? Here, we explored some economic aspects of implementing regional measures. Further studies that focus on the understanding of social, technical, and market barriers

to implementation will be essential to define policies for multiple benefits. Choices in the future are affected by local factors which indirectly influence national support for mitigation policies. To this end, further evaluations of farmers' choices seem to be particularly appropriate.

In terms of wellbeing, equity, and social justice, although it was not the objective of this research, the barriers implementation were analysed and presented in the study area, which could hinder any intention to apply the public policy in environmental terms and delay social equity through emission reduction programs to mitigate climate change. Lucas (2006) mentions that the success of the application of public policy comes from social inclusion based on the synergistic and integrated delivery of practices worked in consensus with farmers. Governments at the local, regional, national, and international levels need to learn from farmers and integrate practical approaches to environmental justice as a sustainable development policy. Therefore, if there are barriers to implementation, it will be difficult to carry out public policy. This is why the farmers' opinion regarding the barriers to implementation was considered to ensure the adoption of mitigation options raised in consensus with farmers and promote equity and social justice.

Finally, our results indicated the potential for reducing emissions in farms with high inputs consumption exceeds the abatement potential of farms with low consumption. This also demonstrates there are implications in terms of well-being. That is, if low-input farms are also those managed / owned by poorer households, the costs would be higher for the most economically disadvantaged and lower for the owners of larger cultivated areas. Despite this, these findings in the Central Andes of Ecuador reveal there is an opportunity for a great impact on reducing emissions through small changes in agricultural practices. The most efficient measures in terms of abatement potential and costs were M1 and M5. Management of organic soils (M1) had the lower negative costs. Reduced tillage (M5) was the option that reduced the largest volume of emissions and in turn offered cost savings for farmers. Adopting these measures would imply profit increase while reducing emissions and they may be targeted by policies and support in order to increase their adoption.

This study did not evaluate the barriers to adopting mitigation options; however, several studies mention that socio-economic data (gender, age, educational level), characteristics of the farm (farm size, type of farm), behavioural characteristics (Moran *et al.*, 2011, de Oliveira Silva *et al.*, 2015), socio-psychological factors can influence the adoption or rejection of environmental practices (Roca, 2012; Rajaee *et al.*, 2019),

and even cooperative membership is a positive and significant determinant of adoption of sustainable production practices overall (Bro *et al.*, 2019). Additionally, institutional and legal barriers (Chong, 2014), high cost of farm inputs, limited access to weather information, are aspects that must be analysed before implementing a public policy on a large scale.

Acknowledgements

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