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Greenhouse gas emissions and biogas potential from livestock in Ecuador

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ABSTRACT

Greenhouse gas emissions inventories provide a baseline to develop mitigation projects for reducing emissions. However, a detailed inventory of livestock gas emissions is not available for Ecuador. This study attempts to fill this gap. The methodology selected comes from the 2006 Intergovernmental Panel on Climate Change guidelines to quantify emissions from the livestock sector. Tier 1 methodology was implemented using animal census data for the year 2000, and historical temperature data by province. The total methane emissions from enteric fermentation were 5596 $GgCO_2Eq$. Methane emissions from manure came mainly from cattle and swine with 92.4 and 44.3 $GgCO_2Eq$, respectively, and a livestock total of 182 $GgCO_2Eq$. The total direct nitrous oxide (N_2O) emissions from manure management were 172 $GgCO_2Eq$, and total direct and indirect N_2O emissions from manure deposited on soils by grazing livestock were 2176 $GgCO_2Eq$. A further 103 $GgCO_2Eq$ of direct N_2O emissions came from the application of confined-livestock manure to soils. We estimated the total potential reductions in emissions from capturing methane gas from anaerobic digestion of dairy, swine and poultry manure and substituting methane for liquefied petroleum gas (LPG) at 308 $GgCO_2Eq$. The value of the methane produced could amount to US$ 77 M. Alternatively, that same methane gas could be used to generate 275 GWh of electricity. Additional benefits from anaerobic digestion of manure include the recovery of nutrients from the digested effluent, which could be used as biofertilizer and soil amendment. The capture of these greenhouse gases and the use of anaerobic digesters to produce energy and other products seem to have potential in Ecuador. However, lack of experience with anaerobic digestion and biogas production is a great limitation for the implementation of this technology. Also, anaerobic digester designs should be evaluated and modified to fit local needs given the variability of climatic and socio-economic conditions across the country.

Introduction

Although greenhouse gases (GHGs) like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) occur naturally in the atmosphere, human activities have changed their atmospheric concentrations (IPCC, 2006). Agricultural sources are the largest global source of non-CO_2 emissions. Nitrous oxide emissions from agricultural soils and methane from enteric fermentation in livestock account for nearly 70% of the emissions from this category (IPCC, 2006; EPA, 2006).

This document presents a livestock emissions inventory that identifies and quantifies sources of GHGs in Ecuador. This inventory adheres to both 1) a comprehensive and detailed set of methodologies for estimating sources of anthropogenic GHGs, and 2) a common and consistent mechanism that enables parties of the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and GHGs to climate change.

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct radiative effects occur when the gas itself is a GHG and absorbs radiation, such as CO_2. Indirect radiative forcing occurs when chemical transformations of a substance produce other GHGs, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects atmospheric processes that alter the radiative balance of the earth. The Intergovernmental Panel on Climate Change (IPCC) developed the global warming potential (GWP) concept to compare the ability of each GHG to trap heat in the atmosphere relative to other gases (IPCC, 2006).

The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of the trace substance relative to that of 1 kg of a reference gas (IPCC, 2006). The reference gas used is CO_2 and therefore GWP-weighted emissions are measured in gigagrams of CO_2 equivalent ($GgCO_2Eq$). GWP values allow comparisons of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of roughly ±35% (Forster et al., 2007). The effectiveness of different gases at trapping heat in the atmosphere as estimated by EPA (2002) is 1, 21, and 310 for CO_2, CH_4, and N_2O, respectively, calculated over a 100 year time horizon.

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Greenhouse gas emissions in Ecuador

The latest available data on Ecuador's GHG emissions come from the first National Communication on Climate Change (Cáceres-Silva, 2000), which were based on data from 1990 using the IPCC methodology available at the time. It included three GHGs (carbon dioxide, methane, and nitrous oxide) and five sectors (energy, industrial processes, agriculture, land-use change and forestry, and waste management). In 1990, GHG emissions were mainly generated by the energy sector, land-use changes and forestry and, to a lesser extent, the agricultural, industrial, and waste management sectors. Carbon dioxide came mainly from land-use change and forestry (69.5%) and the energy sector (28.8%), which together accounted for almost 97% of the total. Methane emissions came mostly from agricultural activities (about 70%), with waste management accounting for 11.5%, land-use change and forestry for 10.9%, and the energy sector for 7.4% (Cáceres-Silva, 2000). At this time, a detailed inventory for livestock GHG emissions in Ecuador is not available.

The objectives of this study were to: (1) develop a national inventory of GHG emissions from livestock based on the IPCC guidelines; (2) estimate the potential reduction of GHG emissions from implementation of manure management systems that incorporate the production of biogas from anaerobic digestion of livestock manure.

Livestock production in Ecuador

Ecuador, with a land area of 256,370 km^2, is geographically divided into four natural regions: Coast, Andes (highlands), Amazon, and Galapagos Islands. This geography provides diverse climates from tropical to cold, with multiple micro-climates in between. Such variable climates allow for the production of a great diversity of agricultural products and provide potential for several renewable energy technologies (Peláez-Samaniego et al., 2007). From month to month, the mean temperatures at all sites in Ecuador are relatively constant; monthly means do not vary more than 3 °C at any site, and at many sites vary less than 1 °C (Jørgensen and León-Yánez, 1999). Temperature in Ecuador varies rather predictably with altitude. At sea level in coastal Ecuador, the mean annual temperature is about 25 °C. On most tropical mountains, temperature decreases at about 0.5 °C for each increase of 100 m in altitude (Jørgensen and León-Yánez, 1999).

Until the 1980s, livestock were produced primarily for domestic consumption and were one of the few agricultural products found throughout the country. Although animal husbandry was widespread, it was generally practiced on small plots of land (Vera, 2006). However, over the last 20 years, commercial livestock production has increased significantly. Ecuador had about 3.7 million (M) cattle in 1985; by 2005, the number had increased to almost 5 M (Vera, 2006). Currently, livestock represents an important part of the agricultural output, accounting for about 40% of Ecuador's agricultural value added and about 8% of GDP. Over the last decade, it has been one of the fastest growing sub-sectors in agriculture, with poultry averaging 10.3% growth per year (FAO, 2005). Ecuador produced a total of 2 and 2.5 M metric tons (mt) of milk in 2000 and 2004, respectively, and 170,620 and 212,000 mt of beef (Vera, 2006). Expected growth in population and per-capita income are likely to change dietary preferences and thus increase demand for animal products.

The Coast and Amazon regions produce mainly beef and dual-purpose cattle, while dairy are found mostly in the Andes. Cattle graze the coastal land that is otherwise unsuited for agriculture, such as the hilly terrain in Manabí Province, seasonally flooded river plains, or semiarid parts of the far south. Dairy farming in the Andes is typically practiced in fertile valleys, particularly between Riobamba and the Colombian border. Beef cattle are relatively new to the Amazon region, although large areas of land are suitable for grazing.

Methane emissions

Livestock produce methane in two ways: through enteric fermentation and through manure. Enteric fermentation refers to a process whereby microbes in an animal's digestive system ferment food. Methane is produced as a by-product and can be emitted by the animal. The amount of methane that is released depends mainly on the type of digestive tract, and the quality and quantity of the feed consumed. Ruminant livestock (e.g., cattle, sheep) are major sources of methane with moderate amounts produced from non-ruminant livestock (e.g., pigs, horses); poultry is not considered in enteric fermentation emissions (IPCC, 2006, ch. 10; EPA, 2006).

Management of animal manure also results in methane emissions. Methane production depends on the type of manure management system used. Dry systems include solid storage, dry feedlots, deep pit stacks, and daily spreading of the manure. In addition, unmanaged manure from animals grazing on pasture falls into this category. Liquid management systems use water to facilitate manure handling. These liquid/slurry systems use concrete tanks and/or lagoons to store flushed and scraped manure (EPA, 2008). Intensive swine production systems are used by large commercial companies in Ecuador. These production systems rely on liquid manure management systems (CDM, 2005). Similar production systems are used in commercial dairy operations. Small farmers use mainly dry manure management systems.

The quantity of methane emitted from manure management operations is a function of three primary factors: the type of treatment or storage facility, the ambient climate, and the composition of the manure. Methane production is minimal under dry conditions. When manure is stored or treated in liquid systems such as lagoons, ponds or pits, anaerobic conditions develop and the decomposition process results in methane emissions (IPCC, 2006, ch.10). Ambient temperature and moisture content also affect methane formation, with higher ambient temperature and moisture conditions favoring methane production. The composition of manure is directly related to animal type and diet. For example, milk production in dairy cattle is associated with higher feed intake, and therefore higher manure excretion rates than non-dairy cattle. Also, supplemental feeds with higher energy content generally result in a higher potential for methane generation per unit of waste excreted than lower quality pasture diets. However, some higher energy feeds are more digestible than lower quality forages, which can result in less overall waste excreted. Ultimately, a combination of all these factors affects the actual emissions from manure management systems (IPCC, 2006; EPA, 2006).

Nitrous oxide emissions

Livestock also produce the GHG, nitrous oxide, through manure. Globally, agricultural production accounts for 65% of anthropogenic N_2O emissions, the great majority from land change, synthetic fertilizer and manure application (IPCC, 2007). For manure, nitrous oxide generation is a function of the composition of the manure, the type of bacteria involved in the decomposition process, and the oxygen and liquid content of the manure.

Direct N_2O emissions occur via combined nitrification and denitrification of nitrogen contained in the manure. The emission of N_2O from manure during storage and treatment depends on the nitrogen and carbon content of manure, and on the duration of storage and the type of treatment (IPCC, 2006). Indirect emissions from manure management result from leaching, runoff and volatile nitrogen losses that result in N_2O emissions offsite. Volatile nitrogen emissions occur primarily in the forms of ammonia and NO_x which are highly volatile and easily diffused into the surrounding air (Asman et al., 1998), and then redeposited as NH_4^+ and NO_3^- on soils and waters.

In soils, the emissions of N_2O that result from anthropogenic N inputs occur directly and indirectly. Direct N_2O emissions from soils come mostly from N added to the field in chemical fertilizers; the rest comes from manure deposited by grazing animals and from managed manure applied to soils that follow the same nitrification-denitrification process. Indirect emissions refer to NH_3 and NO_x redeposition as NH_4^+ and NO_3^- to soils and waters. The widespread and poorly controlled use of animal waste as fertilizer can lead to substantial direct emissions of nitrous oxide from agricultural soils. Indirect emissions from soils occur mainly from nitrogen leaching and runoff from agricultural soils (Steinfeld et al., 2006).

Replacing fossil fuels

Energy is necessary for development. However, the provision of energy should be sustainable economically, socially, and environmentally. The production of primary energy in Ecuador was 10.73 M tons of oil equivalent (Toe) in 2004, representing an increase of 5% compared to 2000 (Peláez-Samaniego et al., 2007). More than 82% was from oil and only 14% from renewables (wood, sugarcane bagasse, and hydropower). While Ecuador is an oil exporting country, given the lack of refining capacity it imports petroleum-derived fuels for thermal generation to compensate for its insufficient hydropower generation capacity, as well as for the automotive sector (Peláez-Samaniego et al., 2007). Also, Ecuador has a policy of subsidizing all oil derivatives both imported and produced domestically, at high economic costs (Peláez-Samaniego et al., 2007). Subsidies for fuels and electricity currently represent about 25% of the national budget. Those resources could instead play an important role in the development of local renewable energy projects in Ecuador.

According to the National Energy Balance (MEM, 2003), 388,000 Toe of firewood were consumed during 2000 in the residential sector and 36,000 Toe in the manufacturing sector. In 2000, only 4% of the primary energy came from wood (MEM, 2003), compared to 48% in 1970 and 20% in 1984 (Aguilera, 1998). Most of the firewood use has been replaced by the use of liquefied petroleum gas (LPG) for domestic uses. LPG consumption has grown 7% annually (2003–2006). However, this demand has been covered by imports of LPG rather than by an increase in domestic production (Peláez-Samaniego et al., 2007). Statistics show that the residential sector accounts for 59% of the LPG consumption in Ecuador and that LPG is mainly used for cooking (Ríos et al., 2007). The subsidized price to the public is US$ 1.60–1.70 for a 15 kilogram LPG tank, while the international market price fluctuates between US$ 5.40 and 11.40. In total LPG subsidy, the government spent US$ 391 and 531 million in 2006 and 2007, respectively (Hurtado, 2008).

Ecuador has the potential to increase the production and use of renewable energies, especially in rural areas. Sources of particular interest for expansion are sugarcane bagasse, windpower, solar, and new hydropower for electricity generation; ethanol and biodiesel for the automotive sector; and methane capture for electricity generation and to replace LPG (Peláez-Samaniego et al., 2007; MEER, 2009).

New energy policies, such as Regulation CONELEC-004/04 (CONELEC, 2006a), establish the conditions for selling electricity to the national grid in order to encourage the development of new projects involving the use of renewable energy. “Matriz Energética del Ecuador al 2020” (MEER, 2009) is also expected to stimulate the development of renewable electricity. These new policies include increased investments and the payment of premium rates for electricity generated from renewable sources. Co-generation of electricity using sugarcane bagasse is also expanding. In 2000, 318,000 Toe of sugarcane bagasse were used to produce electricity, which represents less than 5% of the total bagasse available for electricity generation (MEM, 2003); the rest was burned for steam generation or discarded. In 2005, there was an increase of 5.82% in power production by non-utility generators, mainly from sugarcane bagasse, with small wind- and hydro-power complementing the total increase (Peláez-Samaniego et al., 2007). The present generation capacity from sugarcane is just over 40 MW, out of a total of 3567 MW installed capacity in 2005 (CONELEC, 2006b). This power is used at the mill and the excess is sold to the grid. In addition, there are various projects for landfill gas recovery from municipal landfills, including in Guayaquil (ERG, 2007a), Cuenca (ERG, 2007b), and other cities.

Reducing greenhouse gas emissions

Cost-effective technologies are available that can stem GHG emissions growth by recovering methane and using it as a renewable energy source (Wilkie, 2008). The most common of these technologies are anaerobic digesters. Anaerobic digestion technology refers to the production of a combustible gas (biogas) and a digestate (biofertilizer) by a process called anaerobic digestion, which is the microbial degradation of organic matter under oxygen-free conditions. Using anaerobic digestion, we can generate biogas from readily available animal manures, crop residues, and industrial and municipal wastes (Wilkie, 2006). Generally, biogas contains methane (>60%), carbon dioxide (<40%), water vapor and traces of hydrogen sulfide (<1%). The biogas can be used as a fuel source for cooking, heating or cooling or to generate electricity for local needs or for sale to the electrical grid, and the digestate can be used in a number of ways as a nutrient source or soil amendment (EPA, 2002; Wilkie, 2006). Environmental benefits of anaerobic digestion include waste stabilization, odor control, pathogen reduction, reduced impact of waste emissions, and maximization of resource recovery (Wilkie, 2005a). For example, after anaerobic digestion of livestock manure, the resulting effluent is a good source of mineralized nutrients and organic matter (Wilkie, 2008).

Materials and methods

Greenhouse gas emission estimation

The estimated GHG emissions from livestock were calculated following the IPCC, 2006 guidelines to estimate a country's GHG emissions national inventory (IPCC, 2006, ch. 10–11). The guidelines offer three different levels of sophistication depending on the available data. Tier 1 uses emission factors based on empirical analysis and models provided by the IPCC (IPCC, 2006, ch. 10). The Tier 1 methodology was selected to estimate the emission values due to the limited availability of data on the values of the various parameters and emission factors required for the livestock sector. All the results are presented in gigagrams (Gg), a unit used by IPCC and internationally to present GHG emissions (IPCC, 2006; Velychko and Gordiyenko, 2007).

The potential of producing methane from manure depends on the specific composition of the manure which in turn depends on the composition and digestibility of the animal diet. The amount of methane produced during decomposition is also influenced by the climate and the manner in which the manure is managed. The management system determines the water content of the manure, with higher water levels excluding oxygen and resulting in higher emissions. Climate factors include temperature and rainfall. Optimal conditions for methane production include an anaerobic water-based environment, a high level of nutrients for bacterial growth, a neutral pH (close to 7.0), warm temperatures, and a moist climate (EPA, 2008). All these factors are taken into consideration in the IPCC Tier 1 methodology.

Because emissions from manure are highly temperature dependent, it is good practice to estimate the average annual temperature associated with the locations where manure is produced. Instead of using a unique temperature factor for the entire country, we calculated the historical mean annual temperature for each province in Ecuador (Fig. 1) from CLIMWAT, the Food and Agriculture Organization (FAO) climatic database (CLIMWAT, 2009). By doing this, we reduced the error introduced when a single temperature value for the entire country is used to select the methane and nitrous oxide emissions factors provided by the IPCC methodology.

Livestock production

Number of heads and animal category were obtained from Ecuador's 2000 National Agricultural Census (CNA in Spanish) (SICA, 2002). These data were organized by province and by animal category for use in conjunction with the temperature data obtained above (Table 1). Following IPCC, 2006 methodologies, a complete list of all livestock populations that have default emission factor values was developed (e.g., dairy cows, other cattle, sheep, goats, horses, mules and asses, swine, and poultry). More detailed categories were used when data were available. For example, more accurate emission estimates were made for layers and broilers raised in large commercial operations. Emissions from chicken raised in small lots were calculated separately as the waste characteristics among these different populations vary significantly. In this study, dairy refers to pure-breed dairy cows only, which are managed differently than other cattle. Dairy raised commercially in stalls use higher quality feed inputs and specialized manure/waste management systems. Under cattle, we included beef, dual-purpose, and dairy breeds that are not pure or are raised under conditions different to those described for dairy.

Methane emissions

Methane emissions from enteric fermentation

From the CNA, we obtained the total number of heads organized by animal category and province. We obtained the enteric fermentation methane emission factor ($EF_{(T)}$) for each animal category from the IPCC guidelines (IPCC, 2006, table 10.10) prior to the 2009 revision of the document. The differences in the emission factors are driven by differences in feed intake and feed characteristic assumptions; IPCC (2006) gives emission factors for typical regional (South America) conditions. The equation for Tier 1 calculations of methane emissions from enteric fermentation is presented below (IPCC, 2006, eq. 10.19).

$$CH_{4Enteric} = \sum_{(T)} \frac{\left(EF_{(T)} \cdot N_{(T)}\right)}{10^6} \qquad (1)$$

where:

$CH_{4Enteric}$	CH_4 emissions from enteric fermentation, $GgCH_4\ yr^{-1}$ by province
$EF_{(T)}$	emission factor for the defined livestock category, $kgCH_4\ head^{-1}\ yr^{-1}$ by province
$N_{(T)}$	the number of head of livestock for category T in the province
T	category of livestock

Methane emissions from manure

Default emission factors by average annual temperature are given by IPCC for each of the recommended livestock categories. Emission factors represent the range in manure volatile solids content and in manure management practices used in each region, as well as the difference in emissions due to temperature. The temperature data was based on national meteorological statistics (CLIMWAT, 2009), and the average annual temperature by province was calculated (Fig. 1). We used CNA data for the total number of heads by livestock category and province. The emission factors ($EF_{(T)}$) used in this study come from the 2006 IPCC guidelines (IPCC, 2006, tables 10.14, 10.15, 10.16). The equation below was used to calculate CH_4 emissions from manure management (IPCC, 2006, eq. 10.22):

$$CH_{4Manure} = \sum_{(T)} \frac{\left(EF_{(T)} \cdot N_T\right)}{10^6} \qquad (2)$$

where:

$CH_{4Manure}$	CH_4 emissions from manure management, $GgCH_4\ yr^{-1}$ by province
$EF_{(T)}$	emission factor for the defined livestock category, $kgCH_4\ head^{-1}\ yr^{-1}$ by province
$N_{(T)}$	the number of head of livestock for category T in the province
T	category of livestock

Nitrous oxide emissions

Nitrous oxide emissions are separated into emissions from manure management and emissions from manure deposited on or applied to soils. Manure management emissions refer to the estimated N_2O produced, directly and indirectly, during the storage and treatment of manure. The N_2O emissions generated by manure deposited in 'pasture, range, and paddock' systems are calculated separately (IPCC, 2006). Further, N_2O emissions from application of manure to soils are also calculated separately.

Manure management emissions of N_2O for Ecuador were calculated using the manure management system usage percentages provided by IPCC (IPCC, 2006, tables 10A-4 to 10A-8). For dairy, 64% confinement and 36% in pasture was used. For horses, sheep and turkeys, the same percentages as cattle were used (99% pasture, 1% other management system). For swine, layers, and broilers, 100% confinement was assumed. Soil emissions of N_2O were calculated for all livestock categories produced mainly under the 'pasture, range, and paddock' system, subtracting the percentage reared under other systems.

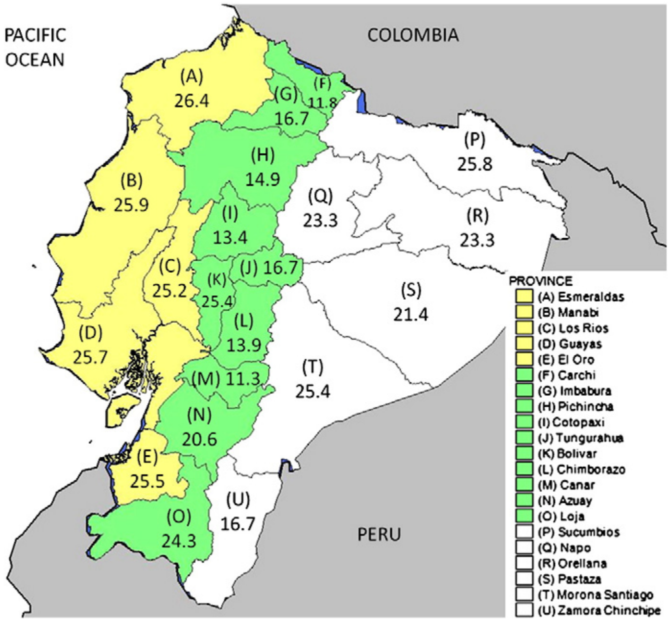

Fig. 1. Historical average annual temperature (°C) in Ecuador by province.

Table 1
Livestock numbers (values are per 1000 head) by category and province in Ecuador (based on 2000 livestock data, SICA, 2002).

Province	Dairy	Cattle	Swine	Sheep	Goats	Donkeys	Horses	Mules	Layers	Broilers	Chicken	Ducks	Turkeys
(A) Esmeraldas	0.52	218.87	41.28	1.03	0.37	1.31	17.46	7.30	15.68	34.22	267.79	20.77	4.26
(B) Manabí	1.54	782.05	189.41	0.24	4.28	26.01	43.05	34.83	3443.16	187.52	1436.52	73.99	17.45
(C) Los Rios	0.68	117.12	58.25	0.60	0.83	1.44	19.59	3.26	34.47	135.75	723.58	48.83	8.36
(D) Guayas	4.89	339.91	125.87	2.60	19.22	8.07	40.90	6.26	238.64	1998.52	1030.30	128.48	41.05
(E) El Oro	0.21	162.26	39.96	6.04	1.27	1.89	6.98	6.31	152.36	252.79	211.18	8.45	1.76
Coast Total	7.84	1620.20	454.77	10.52	25.96	38.72	127.97	57.96	3884.30	2608.79	3669.36	280.52	72.88
(F) Carchi	4.04	89.74	15.82	2.95	0.21	0.36	8.94	0.17	221.00	137.27	102.48	0.95	0.57
(G) Imbabura	2.58	102.48	40.23	35.11	6.33	2.18	10.83	2.38	47.26	1081.17	231.73	1.81	1.30
(H) Pichincha	16.70	427.88	189.10	61.37	7.07	5.37	31.24	8.50	3491.68	13,326.50	613.16	13.20	5.03
(I) Cotopaxi	1.13	192.00	104.03	217.25	5.60	21.78	14.59	6.39	385.57	74.06	440.39	5.85	3.76
(J) Tungurahua	0.44	150.82	89.88	90.57	1.54	16.20	9.89	0.95	1948.61	50.71	342.60	2.92	0.93
(K) Bolivar	0.39	196.14	84.09	78.13	0.64	4.64	18.62	12.75	0.00	5.66	522.49	13.88	4.15
(L) Chimborazo	1.50	245.29	142.79	328.02	11.77	43.50	17.70	1.63	54.26	344.33	388.06	6.05	2.64
(M) Cañar	1.18	138.59	52.26	72.68	0.56	0.77	11.41	1.67	28.83	95.34	241.78	7.38	0.93
(N) Azuay	2.34	339.46	130.11	169.92	7.53	1.90	35.21	5.45	25.93	0.00	737.39	11.03	3.09
(O) Loja	0.34	361.12	137.90	52.57	110.40	37.70	30.77	16.56	5.62	354.66	857.17	17.39	14.73
Andes Total	30.62	2243.52	986.22	1108.55	151.64	134.40	189.19	56.45	6208.76	15,469.69	4477.24	80.45	37.13
(P) Sucumbíos	0.00	49.59	15.15	1.77	0.07	0.12	7.68	1.19	0.76	1.44	190.14	2.95	0.36
(Q) Napo	0.07	50.91	3.95	1.00	0.08	0.17	4.96	0.91	0.00	19.87	84.24	1.73	0.24
(R) Orellana	0.33	35.61	8.75	0.41	0.03	0.07	4.65	1.02	0.00	5.04	149.68	2.68	0.13
(S) Pastaza	0.00	26.82	3.16	0.42	0.05	0.07	5.83	0.78	0.00	40.48	76.21	2.08	0.49
(T) Morona Sant.	0.00	229.21	28.49	1.96	0.15	0.17	22.82	3.49	1.05	70.36	250.97	21.30	3.30
(U) Zamora Chi.	0.15	130.53	14.79	2.78	0.13	1.22	8.38	5.26	0.00	15.36	153.72	8.33	2.52
Amazon Total	0.55	522.67	74.29	8.33	0.51	1.81	54.32	12.65	1.80	152.54	904.96	39.06	7.04
Galapagos	0.00	11.10	2.46	0.00	0.24	0.28	0.65	0.10	0.00	3.74	21.52	0.43	0.04
Total	39.01	4397.50	1517.74	1127.41	178.35	175.21	372.13	127.16	10,094.86	18,234.76	9073.07	400.46	117.08

Nitrous oxide emissions from manure management

For direct emissions, the Tier 1 method entails multiplying the total amount of N excretion (from all livestock categories) in each type of manure management system by an emission factor for that type of manure management system (IPCC, 2006 eq. 10.25). Emissions are then summed over all manure management systems, as shown in Eq. (3). The Tier 1 method is applied using IPCC default N_2O emission factors, default nitrogen excretion data, and default manure management system data for each livestock category (IPCC, 2006, tables 10A-4 to 10A-8).

$$N_2O_{D(mm)} = \left[\sum_S \left[\sum_T \left(N_{(T)} \bullet Nex_{(T)} \bullet MS_{(T,S)}\right)\right] \bullet EF_{3(S)}\right] \bullet \frac{44}{28} \qquad (3)$$

where:

$N_2O_{D(mm)}$	direct N_2O emissions from manure management by province, $kgN_2O\ yr^{-1}$
$N_{(T)}$	number of head of livestock for category *T* in the province
$Nex_{(T)}$	annual average N excretion per head of category *T* by province, $kgN\ animal^{-1}\ yr^{-1}$
$MS_{(T,S)}$	fraction of total annual nitrogen excretion for each livestock category *T* that is managed in manure management system *S* by province, dimensionless
$EF_{3(S)}$	emission factor for direct N_2O emissions from manure management system *S*, $kgN_2O–N/kgN$
S	manure management system
T	category of livestock
44/28	factor for conversion of $N_2O–N$ emissions to N_2O emissions

Indirect N_2O emissions from manure management result from leaching, runoff and volatile nitrogen losses that occur primarily in the forms of ammonia and nitrogen oxides (NO_x). This is a fraction of excreted organic nitrogen that is mineralized to ammonia nitrogen during manure collection (IPCC, 2006). We used the Tier 1 methodology to estimate indirect N_2O emissions from manure management. However, based on the available data the values obtained for this emissions fraction were negligible and are not reported in this paper.

Nitrous oxide emissions from grazing animals and soils

Nitrous oxide emissions generated by manure in “pasture, range, and paddock” systems occur directly and indirectly from the soil. In its most basic form, direct N_2O emissions from manure deposited to soils are estimated following Eq. (4) (IPCC, 2006, eq. 11.1):

$$N_2O{-}N_{PRP} = \left[\left(F_{PRP,CPP} \bullet EF_{3PRP,CPP}\right) + \left(F_{PRP,SO} \bullet EF_{3PRP,SO}\right)\right] \qquad (4)$$

where:

$N_2O{-}N_{PRP}$	annual direct $N_2O–N$ emissions from urine and dung inputs to grazed soils, $kgN_2O–N\ yr^{-1}$
F_{PRP}	annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, $kgN\ yr^{-1}$ (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)
EF_{3PRP}	emission factor for direct N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals, $kgN_2O–N\ (kgN\ input)^{-1}$; (IPCC, 2006, table 11.1) (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)

Conversion of the $N_2O–N_{PRP}$ emissions to N_2O emissions for reporting purposes is performed by multiplying the $N_2O–N_{PRP}$ by a conversion factor of 44/28.

Direct emissions also come from “applied organic N fertilizer” (F_{ON}), which refers to the amount of organic N inputs applied to soils other than by grazing animals. This includes applied animal manure and is calculated using the following equation (IPCC, 2006, eq. 11.1):

$$N_2O{-}N_{Ninputs} = [F_{ON} \bullet EF_1] \tag{5}$$

where:

$N_2O{-}N_{Ninputs}$ annual direct N_2O–N emissions from N inputs to managed soils, kgN_2O–N yr^{-1}
F_{ON} annual amount of animal manure N applied to soils, kgN yr^{-1}
EF_1 emission factor for N_2O emissions from N inputs, kgN_2O–N $(kgN\ input)^{-1}$ (IPCC, 2006, table 11.1)

Conversion of N_2O–$N_{Ninputs}$ emissions to N_2O emissions for reporting purposes is performed by multiplying the N_2O–$N_{Ninputs}$ by a conversion factor of 44/28.

F_{ON} is estimated based on the amount of managed manure N available (N_{MMS_Avb}) for soil application calculated from equation 10.34 in Chapter 10 (IPCC, 2006). For the N-loss of swine manure on dry lot manure management, the N-loss fraction for dairy cows on dry lots was used since the required N-loss fraction was not given in IPPC (2006, ch. 10). Also, since a large portion of swine were placed in the "other" manure management category, that did not have emission factors, we applied the emission factor for liquid storage. Likewise, broiler and layer populations under "dry lot" (no emission factor) were assumed to use solid storage, where an emission factor existed.

Indirect N_2O emissions from soils occur from the deposition of NH_3 and nitrogen oxides (NO_x), and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. Urine and dung N deposited on pasture, range and paddock by animals contribute to indirect N_2O emissions from soils. Indirect N_2O emissions from soils are estimated as follows (IPCC, 2006, eq. 11.9):

$$N_2O_{(ATD)}{-}N = [F_{PRP} \bullet Frac_{GasMS}] \bullet EF_4 \tag{6}$$

where:

$N_2O_{(ATD)}{-}N$ annual amount of N_2O–N produced from atmospheric deposition (ATD) of N volatilized from managed soils, kgN_2O–N yr^{-1}
F_{PRP} annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kgN yr^{-1}
$Frac_{GasMS}$ fraction of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_3 and NO_x, kgN volatilized $(kgN\ deposited)^{-1}$
EF_4 emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kgN_2O–N $(kgNH_3\text{–}N + NO_x\text{–}N\ volatilized)^{-1}$

Conversion of $N_2O_{(ATD)}$–N emissions to N_2O emissions for reporting purposes is performed by multiplying the $N_2O_{(ATD)}$–N by a conversion factor of 44/28.

Energy and fertilizer value of biogas production

In this study, we calculated the potential savings in energy consumption from substituting LPG with biogas. LPG is a fossil fuel commonly used in rural areas in Ecuador. We also calculated the value of electricity that could be produced from captured biogas. Additionally, we calculated the value of nutrients (chemical fertilizers) that could be replaced by using the biodigester effluent (also known as *biol* in Spanish) as biofertilizer for agricultural production. However, this is not intended to be a detailed analysis of the economic benefits or costs associated with the use of biogas for energy production or the use of other by-products.

Methane capture

Due to their production and management conditions, three livestock categories – dairy, swine, and poultry (broilers and layers raised in intensive conditions) – provide the best opportunity for the treatment of manure using anaerobic digestion systems. The volume of methane produced from anaerobic digestion was calculated based on the amount of manure recovered (70%), the conversion efficiency from volatile solids (VS) to biogas, and the methane content in the biogas (for each category). The amounts of VS generated by animal category were obtained from the IPCC guidelines (IPCC, 2006, tables 10A-4 through 10A-9). The conversion efficiency of VS varies by animal category. The values for digester conversion of VS to biogas calculated by Kumar and Biswas (1982) are 60, 63, and 70%, respectively for dairy, swine, and poultry. The Clean Development Mechanism (CDM) methodology AMS-III.D uses a value of 40% for dairy and other cattle (CDM, 2009). In our calculations, we used the Kumar and Biswas (1982) values for all categories except for dairy, for which the CDM value was used. CDM (2009) estimates that 70% of the VS is delivered to the digester; the rest is lost due to handling, weather, etc. Most authors assume biogas methane content of 60–65% (Ghose et al., 1979; Aubart and Fauchille, 1983; Li Sui Fong et al., 1986; Engler et al., 1999; Itodo and Awulu, 1999) and 65% was used for calculations in this study. After the volume of methane was calculated, we determined the total energy contained in the biogas. Biogas has 21,345 to 22,207 kilojoule per cubic meter (kJ/m^3) (600–650 BTU/cuft). We then estimated the equivalent volume of LPG that would produce the same energy. The international cost of LPG per million BTUs was US$ 20.47 as of December 2008, according to the U.S. National Propane Gas Association (NPGA, 2008). We also calculated the electric power that could potentially be produced by using biogas as fuel in electric generators; we assumed a conversion efficiency of 25%. Biogas is an alternative to replace LPG as a cooking fuel for small farmers, and also to provide electricity generation for medium and large operations.

Macronutrients capture

The potential savings from replacing chemical fertilizers with biofertilizer were obtained by calculating the percentage of macronutrients: nitrogen (N), phosphorus (P), and potassium (K), contained in the manure. Nutrient concentrations in manure per animal category were obtained from ASAE (2005), using regional VS excretion data from IPCC (2006). These coefficients were multiplied by the volatile solids per head by animal category obtained from IPCC (2006). Then, the total amount of macronutrients was multiplied by the number of heads for dairy, swine, and poultry, assuming 70% recovery of the manure. That value was again multiplied by the cost of synthetic fertilizer per unit of nutrient: US$ 600, 800, and 600 per ton of N, P, and K respectively, as of spring 2009 (Schnitkey, 2009).

Results

Methane emissions

The emissions of methane from enteric fermentation estimated for the livestock sector in Ecuador for 2000 and its CO_2 equivalent are presented in Table 2. Cattle were the largest emitter with 246 $GgCH_4$ or 5171 $GgCO_2Eq$. The total enteric fermentation emissions for the same year represented 5596 $GgCO_2Eq$.

Methane emissions from manure are shown in Table 3. Cattle and swine manures were the largest emitters of methane with 92.4 and 44.3 $GgCO_2Eq$, respectively. Three species (cattle, swine, and horses) represented 82% of the total manure methane emissions in 2000. Results shown in Figs. 2 and 3 indicate that two of the coastal provinces, Guayas and Manabí, are among the highest CH_4 emitters for swine and cattle manure. This result is produced by a combination of high average temperatures and the number of animals. As stated

Table 2
Methane emissions from enteric fermentation in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock Category[a]	Number of Animals (×1000)	Enteric methane emissions (GgCH$_4$)	(GgCO$_2$Eq)
Cattle	4398	246.26	5171.5
Horses	372	6.70	140.7
Sheep	1127	5.64	118.4
Dairy	39	2.46	51.6
Donkeys	175	1.75	36.8
Swine	1518	1.52	31.9
Mules	127	1.27	26.7
Goats	178	0.89	18.7
Total		266	5596

[a] Poultry (layers, broilers, chicken, ducks and turkeys) are not considered significant enteric methane emitters.

Table 3
Methane emissions from manure of both pastured and confined livestock in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock Category	Number of Animals (×1000)	Methane emissions from manure (GgCH$_4$)	(GgCO$_2$Eq)
Cattle	4398	4.40	92.35
Swine	1518	2.11	44.29
Horses	372	0.66	13.95
Broilers	18,235	0.41	8.55
Layers	10,095	0.30	6.36
Chicken	9073	0.27	5.72
Donkeys	175	0.15	3.13
Sheep	1127	0.14	2.93
Mules	127	0.13	2.77
Dairy	39	0.05	1.00
Goats	178	0.03	0.63
Turkeys	117	0.01	0.22
Ducks	400	0.01	0.17
Total		8.67	182

before (Livestock production in Ecuador), temperature decreases at around 0.5 °C for each increase of 100 m in altitude. Hence, the provinces in the Andes have lower mean annual temperatures (Fig. 1), which translate into lower factors for GHG emissions. However, these differences are most noticeable when wet manure management systems are used (e.g., swine). This analysis is useful for determining where and for which animal categories one should prioritize the implementation of methane capture programs in Ecuador.

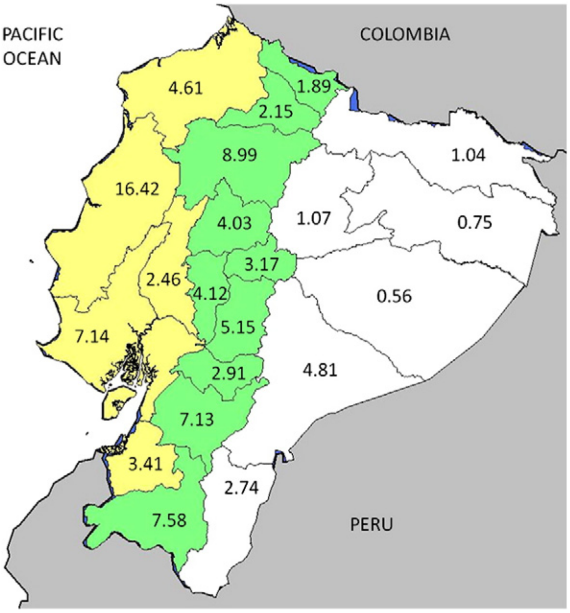

Fig. 2. Methane emissions in GgCO$_2$Eq from cattle manure by province in Ecuador (based on 2000 livestock data, SICA, 2002).

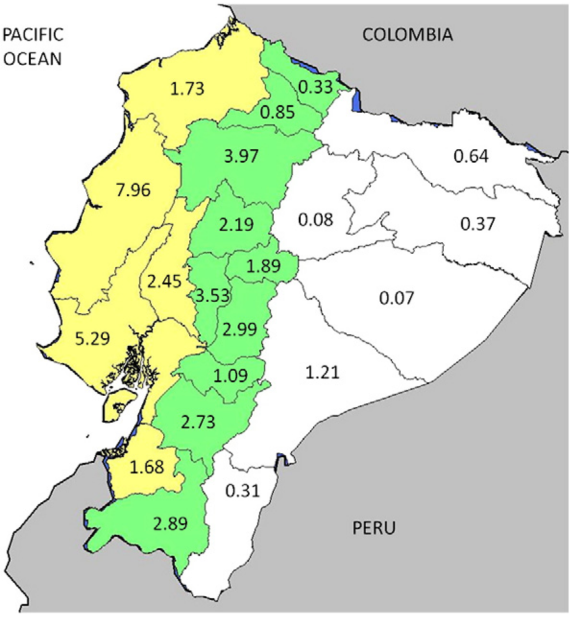

Fig. 3. Methane emissions in GgCO$_2$Eq from swine manure by province in Ecuador (based on 2000 livestock data, SICA, 2002).

Nitrous oxide emissions

Manure emissions of N$_2$O estimated for livestock manure management in Gg of N$_2$O and CO$_2$ equivalent are presented in Table 4. The total direct emissions from livestock manure management were 172 GgCO$_2$Eq.

Direct and indirect N$_2$O emissions from manure deposited on soils by grazing livestock is presented in Table 5. This table excludes values for the livestock categories assumed to be managed intensively (dairy, swine, and poultry (layers plus broilers)), for which liquid or solid manure management systems are often used. Most of the livestock in Ecuador is maintained on pasture systems. Table 6 presents the direct N$_2$O emissions from confined-livestock manure that is applied to soils.

As shown in Table 7, methane from enteric emissions is the largest contributor to livestock GHG emissions in Ecuador, at 68%. Methane from manure (182 GgCO$_2$Eq) and direct N$_2$O (172 GgCO$_2$Eq) emissions from animal manure management account for 4.3%. This

Table 4
Direct N$_2$O emissions from livestock manure management in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock Category[a]	Number of Animals (×1000)	Direct N$_2$O emissions from manure management (GgN$_2$O)	(GgCO$_2$Eq)
Swine	1518	0.44	137.55
Broilers	18,235	0.05	15.89
Layers	10,095	0.04	13.11
Cattle	44	0.01	4.29
Turkeys	116	<0.01	0.52
Horses	4	<0.01	0.36
Sheep	11	<0.01	0.33
Dairy	25	<0.01	0.13
Total		0.56	172

[a] Direct N$_2$O emissions from chicken, goats, donkeys, mules and ducks were not significant.

Table 5
Direct and indirect N_2O emissions from manure deposited on soils by grazing livestock in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock Category[a]	Number of Animals (×1000)	Direct N_2O emissions from deposited manure (GgN_2O)		Indirect N_2O emissions from deposited manure (GgN_2O)	
		(GgN_2O)	(GgCO_2Eq)	(GgN_2O)	(GgCO_2Eq)
Cattle	4354	5.54	1717.07	0.55	171.71
Horses	368	0.23	72.44	0.05	14.49
Sheep	1116	0.21	65.67	0.04	13.13
Chicken	8982	0.15	47.62	0.02	4.76
Donkeys	173	0.06	18.63	0.01	3.73
Mules	126	0.04	13.52	0.01	2.70
Goats	177	0.04	13.03	0.01	2.61
Dairy	14	0.03	9.59	<0.01	0.96
Ducks	396	0.01	1.60	<0.01	0.32
Turkeys	1	0.01	2.10	<0.01	0.21
Total		6.33	1961	0.70	215

[a] Swine, layers and broilers are assumed to be not pastured and not emitters.

is due to the fact that manures produced by the main animal species are managed under systems that generate low methane quantities. However, direct N_2O emissions from manure deposited on soils by grazing animals represent almost 24% of total GHG emissions from livestock in Ecuador.

Potential benefits of biogas production

While enteric fermentation is a major source of livestock methane emissions, there is little potential for capturing this methane. In contrast, manure can be collected and treated using anaerobic digestion systems to produce methane-rich biogas. Three animal categories were selected for this analysis: commercial dairy farms that manage manure mainly under wet conditions; broilers and layers (poultry) grown in intensive conditions where the manure can be collected in a central facility; and swine, including intensive production facilities that manage manure under wet conditions and small production units where manure can be easily collected since animals are enclosed in small areas. For this analysis, we assumed that biogas from medium and large operations would be used mainly on-farm, directly as gas for heating or indirectly to generate electricity. Excess electricity could be sold to the national grid. The production of biogas on small farms could be for on-farm uses like cooking, water heating, and lighting. While biogas use on medium and large-scale farms may not actually displace LPG consumption, it will still displace fossil fuel consumption (heavy oil) to make electricity and the emission reductions associated with LPG displacement are a conservative estimate of this emission reduction.

We estimated a total annual biogas production potential from livestock manure of 105.6 M m^3, which is equivalent to 3971 terajoules (TJ) of methane. Compared to the same energy content of LPG, this will have a value of US$ 77 M as of spring 2009 (Table 8). More detailed economic analysis of the cost of implementing anaerobic digestion systems is needed to determine the true benefits of replacing LPG with biogas.

Table 6
Direct N_2O emissions from the application of confined-livestock manure to soils in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock Category[a]	Number of Animals (×1000)	Direct N_2O emissions from applied manure (GgN_2O)	(GgCO_2Eq)
Swine	1518	0.22	67.61
Broilers	18,235	0.06	17.17
Layers	10,095	0.03	10.85
Dairy	25	0.02	6.60
Turkeys	116	<0.01	0.48
Total		0.33	103

[a] Direct N_2O emissions from applied manure of cattle, horses and sheep were not significant.

Table 7
Summary of GHG emissions from livestock in Ecuador (based on 2000 livestock data, SICA, 2002) and comparison to previous studies.

Emissions	Current study Percent	Current study GgCO_2Eq	Previous studies 1990[a] GgCO_2Eq	Previous studies 2000[b] GgCO_2Eq
Methane from enteric fermentation	68.0	5596	281	6940
Methane from manure	2.2	182	NA[c]	250
Direct N_2O from manure management	2.1	172	NA	380
Direct N_2O from manure applied to soil as amendment or fertilizer	1.3	103	NA	NA
Direct N_2O from manure deposited on soils by grazing animals	23.8	1961	NA	NA
Indirect N_2O from manure deposited on soils by grazing animals	2.6	215	NA	NA
Total	100	8229	NA	NA

[a] Based on 1990 livestock data (Cáceres-Silva, 2000).
[b] Based on 2000 livestock data (EPA, 2006).
[c] NA, data not available.

Additionally, we estimated the CO_2 emissions from the LPG that would be displaced by biogas. The default emission factor for LPG is 63,100 kgCO_2/TJ (IPCC, 2006, table 2.2). By replacing LPG with biogas, the total annual reduction of CO_2 emissions could reach 248 GgCO_2Eq (Table 9). Instead of using LPG and producing emissions of fossil CO_2, the CO_2 emitted from using biogas will be recirculated into a short carbon cycle: atmospheric CO_2–plants–animals–manure. Also, using this biogas as fuel eliminates methane emissions that would otherwise have come from the manure of dairy, swine and poultry (see Table 3).

Alternatively, biogas can be used to generate electricity. For comparison, we calculated the monetary value of electricity that could be generated from biogas (Table 10), assuming that typical biogas electrical generators run at 25% efficiency and the cost of electricity in Ecuador to be US$ 0.20 per kilowatt hour (kWh) (CONELEC, 2006a). The potential for electricity generation from 105.6 M m^3 of biogas is 275 gigawatt-hours (GWh) with a value of US$ 55 M. Ultimately, the cost effectiveness of electric generation depends on infrastructure, equipment installation and maintenance costs of biogas-electricity systems, as well as the rate that distribution companies will pay for

Table 8
Energy potential of biogas production from manure of confinable livestock in Ecuador (based on 2000 livestock data, SICA, 2002) and the equivalent LPG value.

Livestock Category	Biogas (M m^3)	Methane (TJ)	LPG Eq. (M US$)
Dairy	7.6	284	5.5
Swine	48	1801	35
Poultry[a]	50	1886	36.5
Total	105.6	3971	77

[a] Poultry refers to broilers and layers grown in intensive conditions.

Table 9
Potential reduction in GHG emissions from LPG replacement with methane from manure of confinable livestock in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock Category	LPG Eq. (GgCO_2Eq)	Avoided methane (GgCO_2Eq)	Total GHG reduction (GgCO_2Eq)
Dairy	18	1.00	19
Swine	114	44.29	158
Poultry[a]	116	14.90	131
Total	248	60.20	308

[a] Poultry refers to broilers and layers grown in intensive conditions.

Table 10
Potential electricity production from methane from manure of confinable livestock in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock Category	Methane (TJ)	Electricity Eq. (GWh)	Value (M US$)
Dairy	284	19	4
Swine	1801	125	25
Poultry[a]	1886	131	26
Total	3971	275	55

[a] Poultry refers to broilers and layers grown in intensive conditions.

electricity. Economic feasibility analysis should be conducted before implementing any methane-to-electricity project.

Biofertilizer is a by-product of biogas production from livestock manure. The content of macronutrients varies depending on the animal genetics, diet and management practices. Marchaim (1992) described the main uses of digested slurry and the economic importance of the digested slurry in developing countries. The current use of animal manure in Ecuador allows some of the nutrients contained in the manure to displace synthetic fertilizer. However, by increasing nutrient availability, anaerobic digestion enhances nutrient uptake so that significant levels of synthetic nutrient replacement are possible. The results shown in Table 11 indicate the amount of nutrients captured as well as the avoided cost of buying synthetic fertilizers. The annual amounts of nutrients were 22.5, 4.8, and 4.5 Gg with values of US$ 15.9 M, 9.3 M, and 3.2 M for nitrogen, phosphorus, and potassium, respectively.

Commercial fertilizer production also requires major inputs of fossil fuels, particularly natural gas for ammonia production. GHG emissions consist primarily of CO_2 emitted during the consumption of fossil fuels used in the various production processes and transport of raw materials. GHG emission factors associated with the production of a range of nitrogen, phosphate and multi-nutrient fertilizers vary greatly depending on production system and plant efficiency. For example, for nitrogen fertilizers, emission factors range from 857.5 to 7615.9 g CO_2Eq per kg N; the lower value excludes N_2O emissions (Wood and Cowie, 2004). More analysis is needed to estimate emissions reductions from replacing synthetic fertilizers with biofertilizers.

Discussion

Comparison to previous studies

Comparing the results of this study with those presented by EPA (2006), we find that EPA's non-CO_2 emission estimates for Ecuador's livestock sector (based on 2000 livestock data) are consistently greater than our values (Table 7). EPA also used the IPCC, 2006 Tier 1 methodology to estimate emissions. However, the difference between EPA's and this study is the source and detail of the data. EPA used year 2000 livestock numbers for the whole country from the FAO Statistical Database (FAOSTAT) and countrywide mean annual temperature to obtain the emission factors. In contrast, we used data by province for this study. For Ecuador, the EPA (2006) report shows methane emissions from enteric fermentation of 6940 compared to our estimate of 5596 GgCO_2Eq. Methane emissions from manure follow the same trend, with EPA reporting emissions of 250 compared to 182 GgCO_2Eq from this study. A separate estimate for enteric methane emissions (based on 1990 data) is reported in a previous study (Cáceres-Silva, 2000) that indicated only 281 GgCO_2Eq came from that source, a value that is 20 times lower than our estimate. This discrepancy may be due to Cáceres-Silva's (2000) use of 1990 animal census data and earlier IPCC methodology. According to IPCC (2006), more detailed data on number of animals and temperature provide more accurate estimates of methane emissions.

Estimates for direct N_2O emissions from managed manure were also lower in our study than found by EPA (2006), principally due to the use of different animal number statistics. In EPA's study, the CO_2Eq emissions from direct N_2O were higher than CO_2Eq methane emissions from manure (Table 7), while our data gave the opposite result, presumably due to our choices of manure management systems. Implementation of anaerobic digestion can eliminate manure methane emissions but the impact of the technology on direct N_2O emissions from manure management is not clear. The IPCC methodology gives no means to account for N_2O emissions from digester effluent, or from the application of digester effluent onto soils.

Benefits of biogas production

Ecuador's first National Communication on Climate Change lists biogas production from animal manure as one of the approaches to reduce GHG emissions from the agricultural sector. It was considered to be an approach with high viability index, positive environmental impact, and positive socio-economic importance (Cáceres-Silva, 2000). Benefits of disseminating the use of anaerobic digesters in the rural sector could be: 1) replacement of firewood (where this is used) with biogas as a cooking fuel, thus improving indoor air quality and reducing tree cutting; 2) utilization of biofertilizer to replace synthetic nutrients and minimize soil and water degradation. These actions could potentially reduce direct and indirect GHG emissions.

Biogas production from anaerobic digestion of livestock manure could potentially provide significant energy to replace LPG or electricity in Ecuador. Biogas produced from small biodigesters could provide cooking fuel and replace LPG consumption. Likewise, electricity could be produced from biogas-powered generators, particularly where larger livestock production systems are available, displacing electrical production using heavy oil. Ecuador has a target of 90% electrification in rural areas by 2015, from 79% in 2006; (CONELEC, 2006b). This represents a challenge for centralized power distribution due to long distances (e.g. Amazonian region) and difficult topography (e.g. Andean highlands), and might be better served by distributed power systems. For example, in the Amazonian region most of the electricity is provided by thermal generation from heavy oil. Access to electric power is also related to the size of the productive unit; 17% of the agricultural producers with less than 10 hectares (Ha) do not have access to electricity, and this number grows to 25% if farms with less than 50 Ha are considered.

Economic evaluation studies have shown the importance of using biogas as well as biofertilizer (TAKUMA, 2004; Wilkie, 2008; Pipatmanomai et al., 2009). An additional benefit would be the reduction of LPG and electricity subsidies, allowing the use of these resources elsewhere within the country. Financial resources used to import refined petroleum products for energy generation could be better employed to finance and promote the development of biogas systems. Commercial fertilizer costs are highly variable and worldwide demand for petroleum and food may push fertilizer prices higher. Hence, in developing countries the benefits of using biofertilizers could be advantageous for some producers (Schnitkey,

Table 11
Potential fertilizer value of effluents from digestion of confinable livestock manure as replacement of synthetic fertilizers in Ecuador (based on 2000 livestock data, SICA, 2002).

Livestock	Nitrogen		Phosphorus		Potassium	
Category	(Mg)	(M US$)	(Mg)	(M US$)	(Mg)	(M US$)
Dairy	1730	1.2	300	0.6	397	0.3
Swine	12,200	8.6	1970	3.8	413	0.3
Poultry[a]	8550	6.1	2570	4.9	3680	2.6
Total	22,480	15.9	4840	9.3	4490	3.2

[a] Poultry refers to broilers and layers grown in intensive conditions.

2009). Further benefits that this study does not cover include improvements in water quality by reducing the amount of nutrients leached into the soil, and health benefits by reducing pathogens in the environment (Agoramoorthy and Hsu, 2008).

Barriers to implementation

Barriers to implementation of biogas production in Ecuador include capital costs, uncertain animal production, fossil fuel subsidies, and lack of public awareness. There is little experience of dealing with biogas production in Ecuador as projects have been conducted on a limited scale, and without widespread diffusion of the technology. Outreach programs are needed therefore to promote the use of this technology. Steps to support the adoption of anaerobic technology include: foster methane capture and utilization research, and increase dissemination of existing data; disseminate anaerobic digestion technological models for farms with different modernization levels and sizes, and coordinate the current efforts being made by different institutions and organizations.

There are different approaches to estimate the cost of implementing biodigestion systems at different scales (Seyoum, 1988; TAKUMA, 2004; Aguilar and Botero, 2006; Pipatmanomai et al., 2009). Factors supporting digestion systems include increasing energy costs, the elevated cost of fertilizers and soil amendments, and the possibility of selling carbon credits. One potential program to support biogas development in Ecuador is the Clean Development Mechanism (CDM, 2009) which includes the commercialization of certified emissions reductions (CERs). Through this system, companies in developing countries can sell CERs based on emissions reductions achieved, for example by reducing methane and nitrous oxide emissions as well as offsetting CO_2 emissions by using biogas as fuel or for electricity generation. Revenues from CERs improve the economics of biogas projects and hundreds of animal manure treatment projects involving biogas recovery and use have been implemented worldwide through the CDM in the last few years. Further analysis should be performed to quantify the real economic benefits of biodigestion systems in Ecuador.

Concluding remarks

Biogas production technology should be evaluated and modified to fit local conditions given the variability of climatic and socio-economic conditions across the country and the size of the livestock operations. There are many different digester designs available including covered lagoon digesters, complete mix digesters, plug-flow digesters, fixed-film digesters and bag digesters (mainly for small farms) (Wilkie, 2005b). These designs correspond to the farm characteristics and practices, for example, farm scale, weather conditions, type of manure management system, *inter alia*. Technically, it is more feasible to install anaerobic digesters in large and medium size farms, since these farms often use manure management techniques based on liquid flushing. They normally use water to remove excrement which is later discharged to lagoons. This practice does not necessarily occur in “small” farms due to the lack of water or because it is more profitable to use dry manure management methods such as excreta scraping, shoveling or sweeping.

Livestock management in Ecuador offers opportunities for reducing GHG emissions and the manures from confined dairy, swine, broilers and layers offer the most readily available source for biogas production to minimize methane emissions and replace some fossil fuel usage. While other livestock present some challenges for manure collection, small farm-scale digesters can still play a role in production of biogas from manure and plant residues to displace the use of LPG for cooking. At least 308 $GgCO_2Eq$ could be avoided if manure from confined livestock were converted into biogas and used for replacing fossil energy sources. The use of digester effluent to displace synthetic fertilizer inputs to agricultural land could potentially result in further reductions in GHG emissions.

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