Ammonia emissions from livestock production in Chile: an inventory and uncertainty analysis

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Abstract

The objective of this work was to quantify the country's NH₃ emissions from livestock production. This calculation was based on the mass flow of total ammoniacal nitrogen (TAN). The analysis was performed for all 15 geographical regions in Chile. The definition of livestock subcategories was based on data from the Chilean Agriculture and Forestry Census as well as technical reports published by the Chilean National Statistics Institute. Significant differences were observed among the sources of livestock emissions in Chile's regions, and there was high variability depending on the degree of livestock confinement. In 2013, the total calculated emissions were 69.1 kt NH₃/year ($\pm$ 31.1). The O'Higgins Region had the highest NH₃ emissions in Chile, representing 45% of the total. In terms of livestock production, 45% of the emissions were generated by pigs, 22% by poultry, 16% by cattle, 11% by equines and 4% by sheep. Emissions from the TAN that was available during manure and slurry management and the degree of animal confinement were the primary sources of uncertainty. This uncertainty could be greatly reduced by developing regional emission factors and by including the degree of animal confinement in Chile's national statistics such as the Agriculture, Livestock and Forestry Census.

Keywords: Ammonia, livestock, emissions, nitrogen losses, uncertainty

1. Introduction

Gas emissions inventories are commonly used to calculate total national emissions and identify major emission sources to develop abatement policies (Webb and Misselbrook, 2004). The first ammonia

emissions inventories for livestock production were calculated by multiplying the quantity of livestock by an emission factor (EF) for each type of animal. According to Webb and Misselbrook (2004),

this approach does not allow for the identification of significant differences in the potential for NH_3 emissions because of differences in diets, and therefore in the excretion of nitrogen, and differences in livestock or the use of manure in different countries or regions. In general, emissions vary widely from country to country depending on the different livestock sectors present, that is, cattle, sheep, pigs and poultry. These variations are generated by the proportions of each class of livestock and their respective nitrogen excretion and emissions (EAA, 2009), differences in agricultural practices such as livestock housing and manure storage and application (Martínez-Lagos *et al.*, 2010) as well as climate differences (EAA, 2009). The source of NH_3 emissions from manure is nitrogen that is excreted by livestock. Typically, more than half of the nitrogen excreted by mammalian livestock is urine, and between 65 and 85% of the urine is in the form of urea and other relatively mineralized compounds. The urease enzyme rapidly hydrolyzes urea into ammonium carbonate ($(\text{NH}_4)_2\text{CO}_3$) and ammonium ion (NH_4^+), providing the primary source of NH_3 (EAA, 2009). Ammoniacal nitrogen ($\text{NH}_4^+\text{-N}$) and other compounds, including uric acid, quickly decompose into $\text{NH}_4^+\text{-N}$. By contrast, most of the N in mammalian livestock excrement (fecal matter) is not easily degradable (EAA, 2009). Only a small percentage of this N is present as urea or NH_4^+ , and the NH_3 emissions are therefore fairly small for estimating the total ammoniacal nitrogen (TAN) in pastures or housing. However, TAN may be mineralized from fecal N during manure storage and soil application. A recent study quantified the N mineralized rates in permanent grassland fertilized with dairy slurry. In this study the N mineralization ranged between 320–344 kg $\text{NH}_4^+\text{-N ha}^{-1} \text{ yr}^{-1}$ (Martínez-Lagos *et al.*, 2015). Conversely, poultry only produce manure that is primarily made up of uric acid. This compound, along with other labile compounds, can be degraded

into $\text{NH}_4^+\text{-N}$ after being hydrolyzed into urea (Groot Koerkamp, 1994).

Livestock is the greatest source of NH_3 emissions, primarily from manure. In Europe is estimated that 80–90% of all agricultural emissions result from animal production (EAA, 2009). In particular, this sector represents 96% of total French ammonia emissions (Gac *et al.*, 2007), and in Spain, livestock is responsible for 78% of agricultural NH_3 emissions (Gallego *et al.*, 2009). In the United States, Doorn *et al.* (2002) estimated that approximately 80% of ammonia emissions are associated with livestock waste. The most recent studies have replaced emissions sources by animals with specific sources for different stages of manure management. In this work, we estimate the NH_3 emissions generated by livestock in Chile by using a model with a mass flow approach for the total ammoniacal nitrogen throughout a manure management system.

1.1. NH_3 emissions from livestock

Several studies have been conducted to estimate the NH_3 emissions from livestock and agricultural sources. According to the estimates of Carew (2010), the 2002 livestock emissions represented 64% of Canada's total emissions, with cattle and pigs comprising the largest sources. In addition, that study provided evidence of marked differences in NH_3 contributions from livestock sources in the eastern and western regions of Canada. In the west, cattle were the primary source of emissions, with 49%, followed by pigs with 12%; in the east, pigs comprised the primary livestock source with 27%, followed by dairy cows with 25%. In the U.K., Webb and Misselbrook (2004) estimated that approximately 60% of livestock emissions came from cattle, and 18 and 12% were generated by poultry and pigs, respectively. Xu *et al.* (2015) performed a study in China, and they

estimated that livestock was responsible for 47.5% of total emission in China; Livestock categories with large NH₃ emissions include poultry, pigs, cattle and sheep, which contribute 34%, 29%, 29% and 4%, respectively. Based on a complete inventory of NH₃ emissions in Galicia (Spain), Gallego *et al.* (2009) found that livestock was responsible for 89.4% of NH₃ emissions, and fertilizers were only responsible for 7%. Similar to Gallego *et al.* (2009), other studies

have reported agricultural and livestock emissions of NH₃. In Athens, Greece, Sotiropoulou *et al.* (2004) estimated that livestock production accounted for 73% of NH₃ emissions in that region, and Martínez-Lagos *et al.* (2010) estimated that in Chile's Los Ríos and Los Lagos regions, emissions from livestock totaled 6.2 kt NH₃-N in 2007. In the latter study, 85% of the emissions came from cattle (Table 1).

Table 1. NH₃ emissions of different countries and regions

Country	Scope	Inventory year	Emissions (kt NH ₃ /year)	Sector	Reference
China	National	2010	10,700	Total	Xu <i>et al.</i> , 2015
			5,100	Livestock	
Greece	National	--	95	Total	Buijsman <i>et al.</i> , 1987
		1996	13	Agriculture	Sotiropoulou <i>et al.</i> , 2004
UK	National	1984	355	Livestock	Ryden <i>et al.</i> , 1987
				Grassland	
UK	National	1999	224	Total	Pain <i>et al.</i> , 1999
UK	National	--	207	Livestock	Webb and Misselbrook, 2004
Canada	National	2002	306	Livestock	Carew, 2010
			110	Fertilizers	
Spain	Galicia	2001	70	Total	Gallego <i>et al.</i> , 2009
French	National	2007	425	Livestock	Gac <i>et al.</i> , 2007
Chile	Los Lagos y Los Ríos	2007	7.5*	Livestock	Martínez-Lagos <i>et al.</i> , (2010)

*Expressed as kt NH₃ from kt NH₃-N·(17/14)

1.2. Methods for determining NH₃ emissions from livestock

According to Webb (2001), livestock N excretion can be calculated by using three different methods. The first is by multiplying the total population of animals in each livestock category by an individual excreted N value that is associated with each type of animal. The second, which uses a “bottom up” approach, estimates N excretion from the balance between the typical

ingested N in the diet and the output into livestock products (milk, meat, etc.). The third method, which is a “top down” method, uses national data about the N in the animal content and production statistics and the N concentration in livestock products (meat, milk, eggs and wool). Similarly, the European Environment Agency (EEA, 2009) proposes three different levels for estimating NH₃ emissions. In the first method, the annual average number of animals in each livestock category is multiplied by a default

emission factor. The EF includes emissions during ruminant grazing and the application of manure for all livestock categories. In this method, the animal characterization must group livestock that are subject to similar management types. The EF proposed for each livestock category may be found in Sotiropoulou *et al.* (2004) and EEA (2009). The second method uses a mass flow approach based on the concept of total ammoniacal nitrogen (TAN) flow during each stage of manure management. In the first step, the subcategories of homogeneous livestock are defined in terms of the type of diet, excretions, and age/weight range of each animal group. This information is used to calculate N excretions by animal (Nex; kg N animal⁻¹). When there is insufficient national data for this calculation, the methodology recommends the method described by the IPCC (2006) for Nex estimations. Subsequently, the proportion of Nex that is deposited in housing, yards or pastures is calculated, and it is based on the number of days during the year in which the animals are confined. The Nex value in each stage is multiplied by the proportion of TAN (Table 2) to obtain the quantity of TAN deposited during each stage of manure management. The quantities of TAN available in each manure stage (solid and slurry) are multiplied by specific emission factors to obtain the NH₃-N losses from volatilization. Table 2 shows the EFs and TAN for the primary livestock categories. Because the immobilization or loss of TAN reduces the potential for NH₃-N emissions during storage and subsequent dispersion, the model takes into account the amount of TAN that is immobilized in organic material when the manure is managed as a solid. In addition, the method allows for an estimation of the quantity of TAN that is converted into N₂O and NO and N₂, by using emission factors for each gas. The third method is more precise than the second one and does not have any limitations, to the extent that it

can provide demonstrable estimations (EEA, 2009). Emissions can be calculated for a large number of livestock categories, as long as data are available. In this method, the level 2 calculation model can be used as long as there are specific emission factors for each region or if abatement measures are included.

2. Methodology

2.1. Selection of emission sources

Nitrogen excretions (Nex) and the subsequent emissions of NH₃-N vary by livestock species (cattle, pigs, and sheep, among others) (EEA, 2009) and by the diet of the livestock (Webb, 2001). Within one livestock species, there are large differences between animals that are kept for different purposes (dairy cows vs. beef cattle). Therefore, it is necessary when possible to disaggregate the livestock by the type of species and production (EEA, 2009). In this sense, the primary livestock sources established by the EMEP/EEA guide (2009) have been used to select the emission factors. However, a classification has been developed on the basis of Chilean statistical data availability (INE 2007; INE 2013a, b, c, d, e) and IPCC (2006) recommendations for emissions from livestock and manure management. Based on this data, 32 classes of animals were identified. The analysis was performed for Chile's 15 regions, from the Arica and Parinacota Region in the north to the Magallanes and Antarctica Region in the south. Approximately 53% of the productive soil surface in Chile correspond to natural and improved grasslands, and the agricultural soils account for almost 10% of soil surface, being concentrated in Central zone (Muñoz *et al.*, 2010). Volcanic soils are widespread in southern Chile accounting for 60% of the nation arable land. They are characterised by low nutrient availability, high

phosphorus (P) fixation capacity, high organic matter (OM) content and a pH-dependent cation exchange capacity (Alfaro *et al.*, 2006). Mediterranean zone of

Chile there are mainly neutral to alkaline soils, where on high-pH soils may occur nutrient deficiencies such as boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) (Nájera *et al.*, 2015).

Table 2. $\text{NH}_3\text{-N}$ emission factors from manure management and percentages of TAN (adapted from EEA, 2009)

Livestock	TAN (%)	Manure management	EF (% of TAN)	
			Slurry	Solid manure
Dairy cows	0.6	Housing	0.20 (0.10-0.40)	0.19 (0.10-0.38)
		Yard	0.30 (0.15-0.60)	0.30 (0.15-0.60)
		Storage	0.20 (0.10-0.40)	0.27 (0.14-0.54)
		Spreading	0.55 (0.28-0.75)	0.79 (0.40-0.85)
		Grazing	0.10 (0.05-0.20)	0.10 (0.05-0.20)
Other cattle	0.6	Housing	0.20 (0.10-0.40)	0.19 (0.10-0.38)
		Yard	0.53 (0.27-0.75)	0.53 (0.27-0.75)
		Storage	0.20 (0.10-0.40)	0.27 (0.14-0.54)
		Spreading	0.55 (0.28-0.75)	0.79 (0.40-0.85)
		Grazing	0.06 (0.03-0.12)	0.06 (0.03-0.12)
Fattening pigs (8-110 kg)	0.7	Housing	0.28 (0.14-0.56)	0.27 (0.14-0.54)
		Yard	0.53 (0.27-0.75)	0.53 (0.27-0.75)
		Storage	0.14 (0.07-0.28)	0.45 (0.23-0.90)
		Spreading	0.40 (0.20-0.80)	0.81 (0.41-0.90)
Sows (to 8 kg)	0.7	Housing	0.22 (0.11-0.44)	0.27 (0.14-0.54)
		Storage	0.14 (0.07-0.28)	0.53 (0.27-0.75)
		Spreading	0.29 (0.15-0.58)	0.45 (0.23-0.90)
Sheep and goats	0.5	Housing		0.22 (0.11-0.44)
		Yard		0.75 (0.38-0.90)
		Storage		0.28 (0.14-0.56)
		Spreading		0.90 (0.45-0.95)
		Grazing		0.09 (0.05-0.18)
Horses, mules, and asses	0.7	Housing		0.22 (0.11-0.44)
		Storage		0.35 (0.18-0.70)
		Spreading		0.90 (0.45-0.95)
		Grazing		0.35 (0.18-0.70)
Laying hens	0.7	Housing		0.41 (0.21-0.82)
		Storage		0.14 (0.07-0.28)
		Spreading		0.69 (0.35-0.80)
Broilers	0.7	Housing		0.28 (0.14-0.56)
		Storage		0.17 (0.09-0.34)
		Spreading		0.66 (0.33-0.75)

2.2. Emissions calculation

The calculation was performed by using a mass flow approach to find the total ammoniacal nitrogen (TAN) throughout each stage of manure management (EEA, 2009). An approach based on the total N was not considered because the calculation of $\text{NH}_3\text{-N}$ is also used by the IPCC (2006) to estimate N_2O emissions. The definition of livestock subcategories was based on data from the 2007 Chilean Agriculture and Forestry Census (INE, 2007) and from technical reports published by the Chilean National Statistics Institute (INE), including the Bovine Livestock Survey (INE, 2013e) and the annual report on Poultry (INE, 2013b) and Pig Farms (INE, 2013a). The quantity of nitrogen excreted (N_{ex}) by each animal is the product of the rate of N excretion ($\text{kg N (1000 kg animal)}^{-1} \text{ day}^{-1}$) that is obtained from the IPCC (2006) and the average mass by type of animal. Data provided by Luengo and Morales (1999) were used to obtain the average mass of beef cattle, and IPCC (2006) data that had been recommended for Latin America were used for pigs, sheep, goats, equine animals, and poultry. In the absence of data, nitrogen excretions were obtained from Gallego *et al.* (2009). To estimate the nitrogen excretion loads in housing and during grazing, the degree of confinement results (the time during which the cows are not grazing) presented by Carrillo *et al.* (2011) were used for central-southern Chile (Metropolitan, Maule, and Bio-Bio regions); for southern Chile (Los Ríos and Los Lagos regions),

we used findings by Smith *et al.* (2002). The emission factors of $\text{NH}_3\text{-N}$, N_2O , NO and N_2 that were generated by the TAN that was available during slurry and manure storage were obtained from the EMEP/EEA guide (2009) and the IPCC (2006). The fractions of TAN mineralization in the slurry ($f_{\text{min}}=0.1$) and its immobilization in the solid manure ($f_{\text{imm}}=0.0067$) were used to estimate the TAN mineralization and immobilization during storage (EEA, 2009). These emissions were calculated because during this stage, N_2O , NO and N_2 emissions are generated from TAN, thereby reducing the availability of nitrogen in the application phase. The emission factors used for N_2O , NO and N_2 were those recommended by the EMEP/EEA guide (2009) for each type of manure. Figure 1 is a diagram of the nitrogen routes that were included in the methodology for estimating NH_3 emissions. Table 2 summarizes the primary emission factors considered in this study. The emissions generated in yards were not included because of a lack of information, and for this reason, the manure was distributed between grazing and housing. All the information was processed in a Microsoft Excel 2011 spreadsheet, generating a matrix of 101 columns and 35 rows. The rows correspond to the different livestock classes, and the columns contain the inventory data, IPCC (2006) and EEA (2009) equations, and calculations of the different sources of uncertainty. The spreadsheet was replicated for each region of Chile, and the totals for each region were added together to create national data.

Table 3. Matrix used to assess the data source quality (Gallego *et al.*, 2009)

	1	2	3	4	5
RELIABILITY	Verified data ^a based on measurement	Verified data partly based on assumptions or non-verified ^b data based on measurements	Non-verified data partly based on a hypothesis	Qualified estimation (e.g., industrial, agriculture)	Non-qualified estimate of unknown data origin
Uncertainty factor (U ₁)	1	1.05	1.1	1.2	1.5
TEMPORAL CORRELATION	≤ 3 years difference from reference year	≤ 6 years difference from reference year	≤ 10 years difference from reference year	≤ 15 years difference from reference year	≤ 15 years difference from reference year
Uncertainty factor (U ₂)	1	1.03	1.1	1.2	1.5
GEOGRAPHICAL CORRELATION	Data from area under study	Average data from a larger area that includes the area of study	Data from a smaller area than the area under study or from a similar area ^c		Data from an unknown or distinctly different area
Uncertainty factor (U ₃)	1	1.01	1.02		1.1
..					

^aVerified data: published in public environmental reports of companies, official statistics; ^bNon-verified data: personal information by letter, fax or e-mail; ^cSimilarity expressed in terms of environmental legislation

2.3. Calculating uncertainty

The calculation of uncertainty is a fundamental stage in developing an emissions inventory because of the variety of data that must be managed and the wide range of information sources. Therefore, uncertainty values have been established for each of the calculations. For the emission factors and data obtained from the EMEP/EEA (2009) and IPCC (2006), we used the uncertainty values provided by those methodologies.

Frequently, the uncertainty data on quantities or inputs and outputs cannot be derived from the information available because there is only one source of information that provides the average value without information about the uncertainty of that value (Frischknecht *et al.*, 2007). For this type of information, the uncertainty was estimated by following the matrix proposed by Frischknecht *et al.* (2007) and adapted by Gallego *et al.* (2009). This matrix had been used in Chile by Muñoz *et al.* (2015) and defines uncertainty in relation to the reliability, temporality and geography parameters.

Frischknecht *et al.* (2007) also establish basic uncertainty factors in association with the demand for energy, transportation, waste management, resource consumption, and the emissions of water, air and soil contaminants. The values that are established will vary if the emissions, demand or consumption are generated during a process, by combustion, or by agriculture (Gallego *et al.*, 2009). In the latter case,

Frischknecht *et al.* (2007) propose basic uncertainty values (U_b) of 1.2 for contaminant emissions (CO_2 , NH_3 , N_2O , etc.) from agriculture and 1.5 for the sources of energy used in agricultural activities. Uncertainty values for reliability (U_1), temporality (U_2), geography (U_3) and basic uncertainty (U_b) are used to calculate the square of the standard geometric deviation (95% confidence interval) with Equation 1.

$$\sigma_g^2 = \exp \sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_b)]^2} \quad (1)$$

The uncertainties for each inventory datum, scientific article or assumption were calculated by using the uncertainty factors (Table 3) and Equation 1.

Once the data uncertainties and emission factors were calculated for each category, the uncertainties of the total NH_3 emissions were calculated for the inventory by using the propagation of error methodology proposed by the IPCC (2006). This methodology was used because there is sufficient information about data uncertainty, emission factor averages and standard deviations, and the equations for combining inputs to obtain NH_3 emissions. These factors are the primary requirements of the IPCC (2006) for applying the methodology. The propagation of error equation provides two rules for combining uncertainties for multiplication and addition. In the first case, when combining multiplications, Equation 2 is used. In this equation, U_i represents the percentage of uncertainty associated with each of the quantities and U_{total} is

the percentage of uncertainty in the product of the quantities.

$$U_{\text{total}} = \sqrt{U_1^2 + U_2^2 + U_3^2 \dots + U_n^2} \quad (2)$$

Equation 3 is used when uncertain quantities have to be combined by adding or subtracting. In this equation, the U_{total} is the percentage of uncertainty in the product of the quantities, U_i corresponds to the percentage of uncertainty associated with each quantity, and x_i are the uncertain quantities.

$$U_{\text{total}} = \frac{\sqrt{(U_1 \cdot X_1)^2 + (U_2 \cdot X_2)^2 + \dots + (U_n \cdot X_n)^2}}{|X_1 + X_2 + \dots + X_n|} \quad (3)$$

Figure 1. Nitrogen flows in the manure management system.

Figure 2. Percentage distributions of NH₃ emissions in Chile for different livestock in 2013.

Figure 3. Contribution of NH_3 emissions by different livestock by region in Chile, 2013.

3. Results and Discussion

3.1. Distribution of NH_3 emissions by type of livestock

In 2013, the livestock emissions totaled 69,148 t NH_3 . The origins of these emissions were primarily pigs (46%), beef poultry (22%), cattle (16%), equine animals (11%) and sheep (4%) (Figure 2). The remaining quantified livestock (camelids, goats, rabbits, boar and deer) contributed just 1% of livestock emissions in Chile. In the case of pigs, 73% of emissions correspond to fattening pigs, and this category contributes 33% of livestock emissions nationally. However, most authors have identified cattle as the primary source of NH_3 emissions (Carew, 2010; Gallego *et al.*, 2009; Webb and Misselbrook,

2004), a trend that is common in the majority of countries (EEA, 2009).

In the case of Chile, where cattle emissions are 10.9 kt NH_3 annually (Table 4), cattle represent the third most important source of NH_3 . In this category, 68.2% (10.6 kt NH_3 /year) of emissions are generated by dairy cows and the remaining 31.8% comes from meat production. Within dairy livestock, milk animals contribute the greatest emissions, at 65.2% of the total (4.9 kt NH_3 /year). In beef production, 60.5% of emissions are generated by nurse cows, heifers and young bulls. In terms of the distribution of emissions during grazing and housing, there are significant differences at the national level because the degree of confinement varies throughout the country. For example, in the Valparaíso, Metropolitan

and O'Higgins regions, dairy cows are housed for approximately 270 days/year, such that 69% of their emissions occur during housing and 31% occur during grazing. In the Bio-Bio Region, dairy cows are confined for approximately 131 days of the year, generating 46% of their emissions during housing and 54% during grazing. In regions further to the south, such as La Araucanía, Los Ríos and Los Lagos, dairy cows are confined for approximately 44 days per year, generating 20% and 80%, 39% and 61%, and 41% and 59% of their emissions occur during housing and grazing, respectively. This trend of higher NH_3 emissions within housing is expected and occurs in most countries (EEA, 2009).

In housing, the highest NH_3 emissions are generated during ground applications of slurry (E_{E6}) and manure (E_{E3}), for totals of 21% and 24%, respectively. The lowest emissions during housing occur during the storage stage, with 6% for solid manure (E_{E5}) and 10% for the slurry (E_{E2}). This trend occurs because part of the TAN is mineralized during storage and another part is transformed into N_2O , NO and N_2 .

In poultry production, which is the second largest source, at $15.5 \text{ kt } \text{NH}_3 \text{ year}^{-1}$, the livestock are always confined. The greatest source of emissions in this group is broilers, with 71% of NH_3 emissions and 34.7 million heads in 2013, followed by egg layers, with 29%. In this category, the principal emissions are generated during manure application (51%) followed by the deposit of manure in housing (40%). The remaining 9% is generated during manure storage.

3.2. Geographic distribution of emissions

Similar to the results obtained in Canada by Carew (2010), livestock emissions vary greatly throughout Chile (Figure 3). Out of all Chile's emissions, the largest percentage is generated in the O'Higgins Region (45%), followed by the Metropolitan Region

(16%), Los Lagos (9%) and Bio-Bio (6%) (Figure 3 and Table 4). The results for the O'Higgins Region are strongly influenced by pig production (Figure 3). In 2013, pig production in Chile consisted of 2.9 million heads and was concentrated in the O'Higgins Region, which had 74% of national production. For this reason, the O'Higgins Region contributes the largest quantity of NH_3 emissions from livestock in Chile. In O'Higgins, more than 2 million heads of fattening pigs contribute 55% of the region's emissions, broiler chickens account for 21% and pigs used for reproduction represent 17%. In terms of the distribution of pig emissions, 100% originates in housing because their production is completely confined. This situation is quite different from that which occurs with cattle because the degree of confinement varies greatly depending on the geographic location of the livestock.

For cattle, the highest emissions are generated in central-southern Chile, where the Los Lagos, Los Ríos, Bio-Bio and La Araucanía regions contribute the most, at 41%, 21%, 11% and 8%, respectively. In general, grazing emissions tend to be lower than those generated during housing. This trend occurs because the $\text{NH}_4\text{-N}$ in urine is deposited directly onto the pasture and rapidly absorbed by the soil, preventing volatilization. During housing, the NH_3 emission factors increase with the number of days in confinement, a relation that has been put forth by the European Environmental Commission (2009). In this sense, the livestock emissions per animal in central-southern Chile (from the Bio-Bio Region to the Magallanes Region) are significantly lower than the emissions generated in the northern part of the country. This fact is important if one considers that the national emissions inventories conducted by governments generally use less sophisticated methods (Level 1) based on emissions factors per animal such as $39.3 \text{ kg } \text{NH}_3/\text{animal/year}$ (EEA, 2009). However,

this value varies significantly depending on the production strategy in each region and the size of the animal. The latter aspect could be important for the competitiveness of the livestock industry in central-southern Chile, particularly because the international trend is moving towards environmental product declarations (EPD) with quantitative information about product environmental performance over the life cycle. In this sense, production systems with lower degrees of confinement would generate a smaller environmental impact in categories such as eutrophication and acidification

In Chile, the emissions per animal are highest in the north and lowest in the south. This trend occurs because there is more intensive grazing in the regions of central-southern Chile, and only some livestock groups (dairy) are housed for prolonged periods of time (Smith *et al.*, 2002). By contrast, milk production systems in northern Chile with intensive confinement are predominant (Carrillo *et al.*, 2011). Therefore, each zone influences the emissions of ammonia, and NH_3 emission factors have been determined to vary significantly by zone and their respective production characteristics (Table 5).

Although the degree of confinement is a determinant of the quantity of ammonia emissions, this information is not included in Chile's national statistics. In this sense, the precision of the results could be significantly improved if the National Agriculture and Livestock Census were to incorporate information about the days of animal confinement

3.3. Uncertainty of the results

Based on the data analysis, the national emissions of ammonia have an uncertainty of $\pm 45\%$ as shown in

Table 4; in other words, 69.1 ± 31.1 kt NH_3 /year. The highest uncertainties occur for the goat ($\pm 81.6\%$), deer ($\pm 77.1\%$) and camelid ($\pm 76.7\%$) categories. However, these uncertainties do not significantly affect the final result because of the low contribution to NH_3 emissions from these categories. Perhaps the most important result is for cattle, with an uncertainty of $\pm 55.4\%$ (6.06 kt NH_3 /year). This category is heavily influenced by beef cattle, with uncertainties of up to 84%, primarily because of uncertainties related to the N excreted per animal (52%) and N emission factors from TAN that are available in grazing (60%). There is high uncertainty for excreted N because its value is the production of the N excretion rate (IPCC, 2006) and the average mass per animal. Both values are obtained from published sources and combined to obtain the uncertainty of excreted N. In this category, individual uncertainties become increasingly important because of the smaller quantity of calculation operations (equations) required to quantify the final emissions of NH_3 . Undoubtedly, determining the N excreted per animal and local (regional) emission factors of N from the available TAN would greatly improve the certainty of the results included in national inventories. In the case of dairy animals, which have an uncertainty that is close to 44%, the primary sources of uncertainty are the N excreted per animal, the N emission factors from TAN during the manure and slurry management stages, and the degree of animal confinement. As in the case of livestock for meat production, determining the excreted N per animal and the N emission factors from the available TAN would greatly improve the certainty of the results. Along with these parameters, the degree of animal confinement should be included in national livestock surveys (censuses).

Table 4. National inventory of NH₃ emissions from livestock by region for 2013 in Chile

	NH ₃ emissions from Chile by region ^a (t NH ₃ /year)															Total	Unc. (t NH ₃ /year)	Unc. (%)
	XV	I	II	III	IV	V	M	VI	VII	VIII	IX	XIV	X	XI	XII			
Cattle	-	-	-	-	-	352	635	309	433	882	1,208	2,270	4,448	236	165	10,939	±6,058	±55.4
Pigs	24	40	52	39	105	211	3,881	23,062	872	1,206	331	356	829	28	17	31,056	±12,210	±39.3
Poultry	-	771	-	-	441	1,025	5,739	6,934	163	462	12	-	-	-	-	15,545	±8,321	±53.5
Sheep	21	0	0	0	0	0	0	139	90	42	39	35	51	276	2,077	2,769	±564	±20.4
Equine	9	5	17	119	695	661	599	655	1,319	1,249	754	348	556	298	248	7,532	±2,929	±38.9
Camelids	339	252	55	1	3	3	1	5	4	2	11	8	8	2	5	698	±536	±76.7
Goats	5	2	5	19	240	29	7	12	24	24	24	8	9	10	0	417	±340	±81.6
Rabbits	2	15	19	6	6	6	13	12	3	7	5	1	2	0	0	98	±41	±42.0
Wild boar	-	-	0	-	0	-	2	-	2	8	10	7	9	0	-	39	±28	±72.7
Deer	-	-	-	-	-	0	-	-	5	2	6	1	40	-	-	54	±42	±77.1
Total	400	1.085	148	183	1.492	2.287	10.877	31.128	2.914	3.885	2.401	3.034	5.951	850	2.513	69,148	±31,069	±44.9
(%)	0.6	1.6	0.2	0.2	2.2	3.3	15.7	45.0	4.2	5.6	3.8	4.4	8.6	1.2	3.6			

a XV: Arica y Parinacota; I: Tarapacá; II: Antofagasta; III: Atacama; IV: Coquimbo; V: Valparaíso; M: Metropolitana; VI: O'Higgins; VII: Maule; VIII: Bío-Bío; IX: La Araucanía; XIV: Los Lagos; X: Los Ríos; XI: Aysén; XII: Magallanes y Antártica. Unc.: Uncertainty

Table 5. NH₃ emission factors for cattle for the different Chilean regions (zones) and animal weights

Dairy cows	Regions (kg NH ₃ animal ⁻¹ year ⁻¹)							
	V	M	VI	VII	VIII	IX	XIV	X
Cows (400 kg)		29.2			16.8		9.0	
Cows (300 kg)		21.9			12.6		6.8	
Calves (207 kg)		15.1			8.7		4.7	

4. Conclusions

This analysis has provided the basis for determining the principal sources of NH₃ emissions from livestock in Chile and their geographic distribution. Thus, it was determined that livestock emission sources vary greatly throughout Chile, with large differences

among emission quantities by region and the livestock sources that generate them. The total emissions for 2013 were estimated to be 69.1 kt NH₃, with the largest portion coming from the O'Higgins Region, which generates 45% of the total livestock emissions in the country. Pig production is the primary source of emissions by animals, with 45% of the national

total. Cattle represent the third most important source nationally, and their NH_3 emissions vary greatly by geographic location, although they are concentrated primarily in central-southern Chile. The primary regional differences are related to variations in livestock management systems, in that the degree of animal confinement strongly influences NH_3 emission factors and the confinement level increases successively from the north to the south of the country. Thus, it was determined that the N, the N emission factors excreted from TAN available during manure and slurry management and the degree of animal confinement are the primary sources of uncertainty, for a total of 44.9% of the national livestock inventory. This percentage could be significantly reduced if regional emission factors are developed and if the degree of animal confinement is included in the information gathered as part of the national statistics in Chile, such as the Agriculture, Livestock and Forestry Census.

Acknowledgments

The authors are grateful for financial support from FONDEF Project D07I1096 from CONICYT, Chile.

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