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Long-term relationships of beef and dairy cattle and greenhouse gas emissions: Application of co-integrated panel models for Latin America

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ABSTRACT

The cattle sector plays a pivotal role in the economies of numerous Latin American and Caribbean countries. However, it also exerts a significant impact on environmental degradation, including substantial contributions to greenhouse gas emissions (accounting for 23.5 % of global livestock emissions) and deforestation (70 % attributed to livestock in South America). This article aims to investigate the complex, long-term, and short-term relationships between population growth, pastureland expansion, deforestation, and the cattle sector in 15 countries across the region, focusing on their effects on greenhouse gas emissions as well as beef and dairy production. Utilizing data from FAOSTAT spanning the period from 1990 to 2019, a cointegrated panel model was developed using the Pooled Mean Group technique, resulting in the estimation of six models. The aggregate-level results for the region reveal the presence of relatively stable long-term relationships. This implies that over time, the influence of population growth, pastureland expansion, and deforestation on greenhouse gas emissions from cattle production tends to diminish in significance. This long-term behavior may be particularly pronounced in countries with more developed cattle sectors, where efforts to mitigate the environmental impacts of cattle production, such as promoting improved forage technologies, silvo-pastoral systems, grazing management practices, and the implementation of policies, regulatory frameworks, and incentives, have gained traction. These progressive countries can serve as regional benchmarks, and the lessons they have learned hold valuable insights for the sustainable intensification of cattle production in countries with less-developed cattle sectors.

1. Introduction

The cattle sector is key for the economy of many countries in Latin America and the Caribbean (LAC). In addition to generating employment and development for large parts of the rural areas in the region, it is one of the main food sources and thus plays a fundamental role for food security [1]. According to the FAO [1], LAC produced 18.82 million tons of beef and 85.54 million tons of raw milk in 2021, which correspond to 57.15 % and 43.28 % of the total production of the American continent, respectively. The

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economic and social importance of the cattle sector, however, contrasts with the negative environmental impacts generated in beef and dairy production systems and along the associated value chains. According to the FAO [2], cattle farming is one of the activities with the greatest impact on greenhouse gas (GHG) emissions, deforestation, loss of biodiversity, and conflicts over land use. Since the 1990s, it is estimated that about 420 million hectares of forest have been lost due to land use changes, and the agricultural sector is held responsible for about 90 % of the deforestation in this period (52.3 % cereal crops, 37.5 % livestock) [3]. In South America, deforestation attributed to the cattle sector reaches close to 70 % while crop production is held responsible for 20 % [2,3].

In LAC, deforestation dynamics have been linked to various determinants related to productive activities, implementation of forest conservation and protection policies, land-use-related conflicts, and illegal activities such as mining and the cultivation of illicit crops. At the country level, several studies have delved into deforestation dynamics. Cattle farming and its relationship with land speculation and land grabbing processes were studied for example in Costa Rica [4] and Colombia [5,6]. In Peru, the expansion of palm, cocoa, and coffee plantations and the presence of artisanal mining [7], and in Colombia, elements such as the armed conflict, the Peace Agreement with the FARC-EP, the cultivation of illicit crops, and the implementation of public policies regarding land distribution and land use [8–13], were identified as factors that influence deforestation dynamics. In Ecuador, deforestation is attributed to factors such as connectivity, population pressure, and territorial conflicts [14], and in Bolivia to weak legislation and institutional limitations in the control of activities that degrade the country's forest cover [15]. Large-scale forest fires and decision making on land use are important determinants in the case of Guatemala [16], whereas in Mexico, factors related to the inadequate planning of agricultural systems, monocultures, and the absence of public policy mechanisms were identified [17]. Finally, in Brazil, large parts of the deforestation are attributed to the illegal expansion of cattle farming in the Amazon region [18]. What most of these studies have in common is that the cattle sector is identified as major driver of deforestation.

Parallel to the increasing levels of deforestation and land use change related to the cattle sector in LAC, GHG emissions from beef and dairy systems have also increased [2]. According to the Intergovernmental Panel on Climate Change (IPCC) [19], within the agricultural sector, livestock are the largest source of GHG emissions globally, which result mainly from enteric fermentation in ruminants and through the decomposition of manure. Ruminants such as cattle are important sources of methane (CH_4) and carbon dioxide (CO_2) emissions. Approximately 25 % of the global CH_4 emissions come from cattle, with enteric fermentation contributing with 80 % and manure management with 20 % [20,21].These emissions contribute significantly to global warming and climate change [22]. LAC stands out for its livestock sector, with a growth rate of 3.7 %, in contrast to the global average of approximately 2.1 %. Despite representing only 13.5 % of the world's population [23], the region contributes significantly to global meat production, accounting for nearly 23 % of the world's beef and buffalo meat. This makes it particularly interesting to examine the impact of this livestock activity on environmental degradation and GHG emissions in the region. According to estimates from IPCC as reported by the Global Livestock Environmental Assessment Model [24], LAC is responsible for generating approximately 1.9 gigatons of $CO_{2eq.}$ out of the global total of 8.1 gigatons from livestock production. Additionally, the region contributes around 23.8 % of the global enteric CH_4 emissions and 5.2 % of the nitrous oxide (N_2O) emissions from manure [24]. Estimations on long-term and short-term effects are of interest in the empirical measurement of cattle farming and its relationship with the environment. Pesaran et al. raise the need to find, from quantitative data, results of interest as a conglomerate, in addition to the diverse empirical applications [25–29]. Although recent studies have explored the relationships between GHG emissions and cattle production [30,31], land use changes [32], or population and economic growth [33–35], it is important to understand the long- and short-term effects of these relationships, especially for LAC where the cattle sector is so relevant in economic, social, and environmental terms. Likewise, it is important to generate evidence that allows for a better understanding of these types of relationships and that serves as an input for the design of policies focused on mitigating the emissions and the effects they cause in the region. Against this background, the present study aims at estimating the effects of population growth, the expansion of pastureland, deforestation, and afforestation on beef and dairy production both in terms of GHG emissions from enteric fermentation and manure management and beef and raw milk production. In the long-term it is evaluated if the variables exert less pressure on the cattle systems and thus the environment (providing stability) with an increasing economic and technical development over time. For this purpose, a co-integrated panel methodology for 15 Latin American countries for the period 1990 to 2019 was applied. The methodology allows for modelling the various relationships over time, i.e., for a period of 30 years, and for identifying trends and differential behaviors among the countries of the region.

2. Cattle farming, GHG emissions, and deforestation

The relationship between cattle farming and the environment is broad and has been studied by numerous scholars [22,30,31, 36–38]. Recent studies [32,34]have not only aimed at identifying the effects of cattle farming on deforestation [39,40] but also at characterizing and quantifying the GHG emissions generated by land use changes and the loss of forest cover associated with cattle farming [41,42] Several studies [6] showed that the intensification of cattle farming has negative effects on the loss of forest cover in Colombia. Along the same lines, Golub et al. [43], in their analysis for the Mato Grosso region in Brazil, found that forest conservation accompanied by intensive cattle production systems is competitive against traditional intensive cattle farming, but that a series of obstacles is limiting this change, such as the perception of producers about land use values.

There is diverse literature on the relationships between GHG emissions from cattle farming and variables such as demographic and economic growth [44–46] land use changes [47], and environmental conservation policies and mitigation of climate change [48–50]. Have projected that GHG emissions from cattle farming will grow as the population increases [31]. In a meta-analysis for LAC, identified three strategies, namely animal breeding, feeds, and ruminal handling, with 34 actions that can be adopted by cattle farmers for the mitigation of CH_4 emissions from ruminants [30]. Other works studied the link between CO_2 emissions and economic and population growth in a data panel for 128 countries for the period 1990–2014, and found that at the global and regional levels, economic and population growth have a positive and significant effect on CO_2 emissions [33]. Along the same lines, estimated that GHG emissions are expected to increase in Latin America because of GDP and population growth [51]. Similar results are presented in a study for the five most populated countries of Asia (China, India, Indonesia, Pakistan, and Bangladesh) on the effects of population density and economic growth on GHG emissions for the period 2001–2014 [35]. Another interesting relationship showed that, in many developed countries, the GHG emissions derived from livestock product and oilseed trade are higher than the emissions from national agriculture [52].

Calvin et al. [32] explored the effect of agriculture, floristry, and other land uses on GHG emissions in Latin America. Significant differences were found between the projections of future emissions with and without climate policies. Regarding land use changes, Rehman [34] explored the influence of forestry, crop production, livestock production, energy use, population growth, temperature, and rainfall on CO_2 emissions in Pakistan. Using series data for the period 1970–2017, it was found that forest production, rainfall, and temperature have a positive effect on CO_2 emissions in the long-term, while population growth has a negative effect. The short-term results show that forestry, crop production, livestock production, population growth, and temperature have an influence on CO_2 emissions. In LAC, research focused on the relationships between GHG emissions and different determinants of deforestation [53–56], such as the implementation of policies, land use changes, growth of the cattle activity, and forest fires [53–56].

Regarding GHG emissions, studies have focused on different perspectives, such as the results of climate regulation policies and emission control on society [43], differentiated effects of economic development on deforestation [46], and the relationship between public spending and deforestation due to land expansion and emissions [47]. Graham et al. [45] present a series of policy alternatives to reduce emissions from deforestation and degradation. Other studies made predictions of emissions based on the Paris Agreement for Southeast Asia [57], experiences and challenges of REDD + mechanisms to control emissions and deforestation [48–50], and the use of economic incentives to reduce emissions [58].Public policy analysis on the effects of conservation initiatives on deforestation and GHG emissions shows that the incentives for agents to reduce emissions depend on the characteristics of individuals, where the efficiency of economic payments decreases if those heterogeneous capacities of the agents are ignored by the policies or programs implemented [59]. Along the same lines, Sheng and Qiu [60] studied the effect of REDD + program incentives on the actors and decision makers involved in reducing GHG emissions. Modelling the decisions of individuals using numerical methods, the authors find that the behavior of landowners in relation to decisions about GHG emission reductions does not depend on their market power and that policy makers must consider multiple factors (emission prices of carbon, credits, opportunity costs, productivity, etc.) within this type of initiatives.

For Mexico, the emissions from enteric fermentation and manure management were estimated at 1926.08 and 62.24 Gg CH_4, respectively [61], and beef cattle farming contributes with 79 % of the CH_4 emissions [62]. Enteric fermentation was also identified the main source of CH_4 emissions in Colombia [42,63]. At the micro level, a life-cycle analysis of a dairy farm in Brazil estimated that CH_4 emissions contribute to climate change with 36.46 % [64]. In Nicaragua, in a sample of 30 cattle farms, significant reductions in CH_4 emissions in cattle farming were achieved among those farmers that used quality forage and good husbandry practices [65].

The relationships mentioned correspond to the empirical evidence for the sector. However, a long-term analysis as provided in the present article can provide evidence of the existence of trends among different variables. Economic development entails the use of cleaner and more efficient technologies that require fewer resources, and it is expected that the pressures exerted by population growth, the extension of pastureland, and deforestation on cattle farming lose influence in the long-term. The present study, however, focuses on a region characterized by countries with heterogeneous cattle farming systems. In other words, at an aggregate level, some countries can mark the long-term trend of others [66–68].

Table 1
Description of the variables.

Variable	Description	Abbreviation	Unit of measurement
Net forest conversion	Proxy for deforestation	DEF	1,000 ha
Population	Total population (indicator for population growth)	POP	# of people
Forest land	Area of forest land (indicator for afforestation)	FL	1,000 ha
Pastureland	Area of pastureland (indicator for the extension of pastureland)	PL	1,000 ha
GHG emissions from beef cattle, direct emissions	Emissions from beef cattle, direct emissions (N_20) (manure management)	EBC_MM	1,000 tons
GHG emissions from dairy cattle, direct emissions	Emissions from dairy cattle, direct emissions (N_20) (manure management)	EDC_MM	1,000 tons
GHG emissions from beef cattle, direct emissions	Emissions from beef cattle, direct emissions (CH_4) (enteric fermentation)	EBC_EF	1,000 tons
GHG emissions from dairy cattle, direct emissions	Emissions from dairy cattle, direct emissions (CH_4) (enteric fermentation)	EDC_EF	1,000 tons
Beef production (beef cattle)	Meat production (beef cattle)	PR_BC	tons
Raw milk production (dairy cattle)	Raw milk production (dairy cattle)	PR_DC	tons

3. Material and methods

3.1. Data sources

The data used in this article was derived from FAOSTAT [69] and is described in Table 1. Net forest conversion was used as a proxy for deforestation. Furthermore, population, forest land, pastureland, production volumes of beef and raw milk, and GHG emissions from beef and raw milk production, both from manure management and enteric fermentation, were included as variables. It should be noted that the variables on GHG emissions were obtained in volume units of N_20 and CH_4. These variables are considered relevant to study the long-term relationships between GHG emissions from the cattle sector and the other variables. Information was consulted for the period from 1990 to 2019 for 15 Latin American countries, namely Argentina, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, and Venezuela. These countries were selected due to the importance of cattle farming in both socio-economic and environmental terms. In these countries, the cattle sector plays an important role for food security, employment and income generation, and rural development, and strongly contributes to the agricultural and national GDPs. Likewise, the sector generates negative environmental externalities, such as GHG emissions from enteric fermentation and manure or the expansion of the agricultural frontier at the expense of forests (i.e., in the Amazon region and Central America). This list of countries thus includes those with the largest cattle herds of the region, as well as those with the largest impacts on the environment.

3.2. Econometric model

Given the structure of the data, the most appropriate methodology to examine the relationships between cattle farming (GHG emissions and production) and the explanatory variables described in the previous section is a panel data model. This approach is designed for cross-sectional and temporal unit-of-measure analysis. The panel data method varies depending on the size of the data, its heterogeneity, and stationarity [29]. Therefore, a heterogeneous panel data is applied in this study, which makes it possible to identify both long- and short-term relationships. In other words, the model recognizes the global effects for the conglomerate of 15 countries of analysis in the long-term, but also allows identifying the effects by country in the short-term. As previously stated, there is information for 15 Latin American countries with data from 1990 to 2019. Therefore, the model to be estimated is:

$$Y_{it} = \alpha_i + \beta_i X_{it} + u_{it} \tag{1}$$

Where Y_{it} is the dependent variable, which represents various variables to be estimated, such as the GHG emissions generated from beef and raw milk production, and total beef and raw milk production of country i in year t. For its part, X_{it} refers to the explanatory variables of the model, such as population, pastureland, forest land, and net forest conversion. Therefore, there are six specifications that will be estimated:

Model 1

$$ln\ EBC\_MM_{it} = \alpha_i + \beta_1\ ln\ POP_{it} + \beta_2\ ln\ PL_{it} + \beta_3\ ln\ DEF_{it} + \beta_4\ ln\ FL_{it} + u_{it} \tag{2}$$

Model 2

$$nEDC\_MM_{it} = \alpha_i + \beta_1\ ln\ POP_{it} + \beta_2\ ln\ PL_{it} + \beta_3\ ln\ DEF_{it} + \beta_4\ ln\ FL_{it} + u_{it} \tag{3}$$

Model 3

$$lnEBC\_EF_{it} = \alpha_i + \beta_1\ ln\ POP_{it} + \beta_2\ ln\ PL_{it} + \beta_3\ ln\ DEF_{it} + \beta_4\ ln\ FL_{it} + u_{it} \tag{4}$$

Model 4

$$lnEDC\_EF_{it} = \alpha_i + \beta_1\ ln\ POP_{it} + \beta_2\ ln\ PL_{it} + \beta_3\ ln\ DEF_{it} + \beta_4\ ln\ FL_{it} + u_{it} \tag{5}$$

Model 5

$$lnPR\_BC_{it} = \alpha_i + \beta_1\ ln\ POP_{it} + \beta_2\ ln\ PL_{it} + \beta_3\ ln\ DEF_{it} + \beta_4\ ln\ FL_{it} + u_{it} \tag{6}$$

Model 6

$$ln\ PR\_DC_{it} = \alpha_i + \beta_1\ ln\ POP_{it} + \beta_2\ ln\ PL_{it} + \beta_3\ ln\ DEF_{it} + \beta_4\ ln\ FL_{it} + u_{it} \tag{7}$$

Where EBC_MM_{it} represents the GHG emissions generated from manure management of cattle for beef production, EDC_MM_{it} the GHG emissions generated from manure management of cattle for raw milk production, EBC_EF_{it} the GHG emissions generated from enteric fermentation of cattle for beef production, EDC_EF_{it} the GHG emissions generated from enteric fermentation of cattle for raw milk production, PR_BC_{it} and PR_DC_{it} refer to the variables production of beef and raw milk in tons, respectively. These are the dependent variables of the six models. The explanatory variables include POP_{it}, which is the total population estimate by country, PL_{it}, which is the amount of land used for pastures, FL_{it}, which is the amount of land covered by forests, and DEF_{it}, which refers to the net forest conversion (as a proxy for deforestation). Furthermore, for $i = 1,2,3,\ldots,N$, N refers to the number of countries in the sample, and for $t = 1,2,3,\ldots,T$, T refers to the number of years of available data. The variables are expressed in logarithms to facilitate the interpretation of the results. A more detailed development of the equations is provided in Appendix 1.

The relevance of the implementation of methods for non-stationary and heterogeneous panels should be noted. The non-stationarity and the presence of temporal relationships in the data panel implies the need to differentiate short- and long-term effects and, at the same time, allow the estimated coefficients to differ per panel analysis unit, given the implicit heterogeneity. For this, Pesaran and Smith [70] propose the Mean-Group (MG) method, where the coefficients vary between groups and the value of the coefficient for the panel is an average of all the coefficients calculated separately. Another alternative is the Pooled Mean-Group (PMG) estimation method [25,26] which brings the same benefits as the MG estimation but imposes certain restrictions for the long-term effects in the panel. For this study both the MG and PMG estimations could be considered since they allow the panel to be estimated under the conditions of the available data. To select the best model and estimate the short- and long-term effects adequately, the following steps were considered beforehand.

i) Testing for slope homogeneity and cross-section dependency of data
ii) Testing for the presence of unit roots in the data panel
iii) Testing for the existence of cointegration between the variables
iv) Identifying the best model between MG and PMG
v) Estimating the long- and short-term effects of the chosen model

The slope homogeneity tests identify an adequate specification of the model, in such a way that differences between the units of analysis are evaluated, in this case countries. The test makes it possible, for example, to show whether the effects of the variables population and deforestation on GHG emissions and cattle production are the same for all countries. A priori, it is considered that the null hypothesis should be rejected, since the effects by individual or country tend to be different or heterogeneous [71]. For its part, cross-section dependency poses a characteristic of the panel data structure since it contrasts whether there are relationships between countries [72]. For the presence of cointegration, unit root tests of the panel are proposed [73]. In case non-stationary series are found, the panel cointegration test proposed by Pedroni [74,75]is applied. Finally, identifying the presence of cointegration in the panel, the models are estimated by MG and PMG, to then choose the best one based on a Hausman test. In this way, the long- and short-term results for the selected models are obtained. In any case, the model would consider what has already been mentioned: heterogeneity and non-stationarity.

3.3. Study limitations

There exist some difficulties in the selection of the variables of interest. The information available on FAOSTAT by country can be compiled by the Intergovernmental Panel on Climate Change (IPCC) classification of Agriculture, Forestry, and Other Land Uses (AFOLU), which identifies the type of activity by land use, as well as the share this activity contributes to the overall GHG emissions. In this sense, the cattle sector generates more GHG emissions than accounted for in this study, since they are not only generated on-farm but also along the entire value chain. Likewise, in cattle farming there are different types of sources of GHG emissions, such as enteric fermentation, manure management, deposition in pastures, and emissions from agricultural residues, among others. The reason for considering only some and not all these GHG emission sources in the present study lies in the availability of data on FAOSTAT. Various studies suggest that cattle are among of the main sources of CH_4 emissions, which is reported as emission data from enteric fermentation and manure management. Although the FAO makes periodical publications on the subject, there are studies that delve into the analysis of GHG emission sources at the country level. In China, for example, GHG emissions were calculated from 1991 to 2019, identifying cattle and poultry as main emitters, contributing with 39.53 %, 46.5 %, and 37.4 % of the total GHG emissions of the agricultural sector in 1991, 2003, and 2019, respectively [76]. A study from South Africa estimated that in 2019, cattle farming produced 35.37 million tons of carbon dioxide equivalent (CO_2e), from which 65.54 % correspond to methane from enteric fermentation and 4.34 % to nitrous oxide (N_2O) from manure management. Commercial beef production was identified to be the main contributor to the total GHG emissions generated by the cattle sector [77]. Although not complete, the selection of the GHG sources in this study represent a major proportion of the overall GHG emissions generated by the cattle farming.

Furthermore, constraints around data sources need to be considered, as information on deforestation, pastureland, and forests is limited for the period from the 1990s onwards, while information on GHG emissions from cattle (for both beef and raw milk) is available since 1961. This implies that the analysis of the relationship could be addressed in greater detail if data for deforestation were available for the period before 1990. An alternative is data imputation. However, it can bring more difficulties than benefits in the empirical analysis, since there would be approximately 30 data for the 15 study countries, which would impute an entire data panel. It is important to highlight that the information on the deforestation variable is available in the form of averages from the 1990s to 2010 and on a five-year basis from 2010 to 2019. The underlying difficulties generated by this occur in the variability of the panel and in that the estimates show some degree of bias. Despite these limitations, the presented results can generate information and ideas related to the studied problem and contribute to discussions on future research.

Regarding the methodology used in this study, the ability to find long-term relationships can cause ignorance of processes specific to each country and that relationships are assumed based on data from some countries but not all of them. Cointegration tests give hints of long-term relationships, but it is difficult to irrefutably assume them. A possible solution lies in including a greater number of temporal and country data. It is important to clarify that the use of panel models is justified despite these restrictions. The methodology allows for estimations in a more consistent way compared to the temporal data structures by country. This is due to the increase in the number of observations and the interdependence between countries with respect to the relationships of the variables of interest [72]. It is thus a more robust estimation method. The limitations are typical of the scope of the empirical tools to capture the real relationships in the phenomena of interest. However, these techniques give clues to the underlying relationships in panel data.

It is important to mention that the source of information is based on the IPCC Tier method, specifically the Level 1 approach (Tier 1). This is the simplest and most basic level [78]. This is due to its simplified assumptions, as it assumes that emissions per animal do not vary and are the same for all animal categories. Additionally, it only allows for the identification of changes in trends over time due to changes in the number of animals, making it unable to detect the impacts of mitigation actions. The Level 2 approach (Tier 2) is a methodology with more disaggregated data, which increases the accuracy of estimates. These developments are incorporated into the Global Livestock Environmental Assessment Model (GLEAM), which provides detailed estimates of GHG emissions and emission intensities for major products, agricultural systems, and regions [79]. Its strength compared to previous models lies in its incorporation of geographical profiling, considering factors like climate, soil quality, and land use. It also employs a life cycle assessment method to capture all emission sources throughout the supply chain [79]. The choice between Tier 1 and Tier 2 ultimately depends on the type of analysis being conducted. In the present case, the sample under analysis spans a 30-year period, and the sheer volume of data required necessitates the use of the more basic methodology to ensure an adequate number of observations for analysis. While the method used for these data does not allow for the identification of the impact of mitigation actions, it does establish a relationship between the number of animals and the long-term trends in relevant variables [78]. This enables the examination of emissions variables' behavior in relation to livestock production.

4. Results

The complex relationships between cattle farming (GHG emissions and production) and variables such as population growth, the expansion of pastureland, afforestation, and deforestation pose challenges in the fight against climate change, highlighting the importance of analysis, i.e., for Latin America, where cattle farming plays a strong social and economic role.

4.1. Descriptive statistics

Before estimating the model, some descriptive statistics are presented for the entire panel. Although they do not consider time and heterogeneity of the countries, it is a first approximation to characterize the data. Table 2 shows the means, standard deviations, and minimum and maximum values of the variables. Beef and raw milk production generate on average 1,192,000 and 172,000 tons of GHG emissions from enteric fermentation, respectively. GHG emissions from manure management are much lower, with mean values for beef and raw milk production of 630 and 260 tons, respectively. On the other hand, the average deforestation is 122,787 ha per country. The average production of beef and raw milk is 964,339 and 4,025,363 tons, respectively. The average amount of land used for pastures and forests are32,227,000 and 122,787,000 ha, respectively. The population variable, as expected, has a large dispersion with respect to its central value.

4.2. Methodological steps and econometric results

i) Testing for slope homogeneity and cross-section dependency of data

The first step in the methodology is the testing of the homogeneity hypothesis for the effects of the variables between the units of analysis. In this case, the null hypothesis of homogeneity in the slopes for all models is rejected (see Table A1). Therefore, a disparate relationship between countries is proposed or differential effects can be expected in the six models. This is expected, since there is no reason to assume that each country presents the same effects as the others.

Likewise, cross-section dependency tests are conducted which indicate the relationships between countries and interdependence in the data panel. Here, the null hypothesis of independence is rejected only for the models of GHG emissions from milk production, which is why relationships between countries are identified for these cases (see Table A2). In this sense, the null hypothesis is not

Table 2
Descriptive statistics.

Variable	Description	Obs.	Mean	Std. dev.	Min	Max
POP	Total population (indicator for population growth)	450	32,681,868	48,000,000	2,470,946	211,000,000
PL	Area of pastureland	450	32,226.55	46,801.88	314.70	178,444.00
DEF	Net forest conversion	450	122,786.80	320,813.80	0.00	1,605,106.00
FL	Area of forest land	450	62,283.41	129,684.10	588.38	588,898.00
EBC_MM	GHG emissions from beef cattle, direct emissions (N_20) (manure management)	450	0.07	0.13	0.00	0.63
EDC_MM	GHG emissions from dairy cattle, direct emissions (N_20) (manure management)	450	0.03	0.05	0.00	0.26
EBC_EF	GHG emissions from beef cattle, direct emissions (CH_4) (enteric fermentation)	450	1,191.91	2,359.82	27.99	11,123.37
EDC_EF	GHG emissions from dairy cattle, direct emissions (CH_4) (enteric fermentation)	450	171.66	351.55	5.83	1,672.50
PR_BC	Meat production (beef cattle)	450	964,338.50	1,991,873.00	15,339.00	10,200,000.00
PR_DC	Raw milk production (dairy cattle)	450	4,025,363.00	6,947,198.00	113,000.00	35,900,000.00

rejected in the case of GHG emissions from beef production, nor are the models of beef and milk production.

ii) Testing for the presence of unit roots in the data panel

For the evaluation of the unit root of the models, it is found that all variables of interest, except population, are non-stationary and have a unit root. This means that the time series have some pattern of behavior and the mean and variance do not remain constant but have considerable changes in the analyzed period. Given this, the first difference of all variables with unit roots is taken and the test is repeated. We find that the variables in first differences are all stationary (see Table A3). Therefore, it is possible to estimate cointegrated models.

iii) Testing for the existence of cointegration between the variables

Based on the cointegration tests (see Table A4), it is found that for both GHG emissions from beef cattle due to manure management and enteric fermentation, a cointegration relationship is presented with the model variables. On the other hand, the models for GHG emissions generated from manure management and enteric fermentation in the production of raw milk present a cointegration relationship, since four estimators are statistically significant. Similarly, this occurs with the beef and milk production models, with four and five coefficients supporting it, respectively. In this sense, for all the models there is at least one coefficient that rejects the null hypothesis of no cointegration, for which cointegration relationships can be assumed for all the models.

iv) Identifying the best model between MG and PMG

After identifying the presence of long-run relationships for the variables of interest and for the various models, the best estimation model must be identified. Therefore, a Hausman test is performed to choose between the PMG and MG models, and thus estimate the effects of each of the models and identify if there are long-term effects between cattle farming (GHG emissions and production) and the variables of interest. The results of the Hausman test (see Table A5) show that the best model to estimate is PMG.

v) Estimating the long- and short-term effects of the chosen model

Table 3 presents the general results of the short- and long-term estimations for the six models. In general, the short-term effects are not statistically significant at the 5 % level. Significant results occur only in the two manure management GHG emissions models for the population and forest land variables. However, they do not present the expected signs. Given this, the analysis of short-term effects is further broken down by country (see Tables 4 and 5).

The estimation of long-term effects presents a greater number of significant coefficients than the short-term ones. Therefore, it allows extracting some results of interest. The impact of population growth on both GHG emissions from cattle production and beef and dairy production levels tends to stabilize in the long-term, or in other words its fluctuation reduces. This is shown by the coefficients in the six models, which have values that range between −1.41 and 2.54. The same happens with the expansion of pastureland, since although a positive effect predominates, it is small and ranges between −2.15 and 2.66. Deforestation also seems to lose influence on cattle farming in the long-term, since the coefficients do not exceed 1.19 in any case. Finally, the estimates suggest that the growth of forest land reduces cattle farming in the long-term. The most consistent results were obtained by running a one-lag empirical specification.

Table 4 shows the error correction terms and their statistical significance by country, both for the beef and raw milk production models. The results of this analysis were also obtained within the framework of the dynamic panel methodology. For beef production, there are no long-term relationships for Costa Rica and Panama, whereas for raw milk production, there are none for Colombia, El Salvador, Mexico, Panama, Peru, and Venezuela. So, for this set of countries, there would be no incidence of the explanatory variables of the models on the production of beef or raw milk in a long-term scenario. The most representative results of the estimation show that Argentina presents long-term relationships in both models. The coefficients are 0.22 and 0.24, indicating that the adjustment period to long-run equilibrium in the event of any shock to the system is similar in the beef and dairy sectors, namely about 4 years (for example, $1/0.24 = 4.1$ years and $1/0.22 = 4.5$ years). This means that disturbances in raw milk or beef production generated by variables such as

Table 3
Estimation of short- and long-term effects.

Model	lnPOP		lnPL		lnDEF		lnFL		ECT
	LR	SR	LR	SR	LR	SR	LR	SR	
lnEBC_MM	−1,41***	−6,22	2,66***	−0,60	0,199	76,58	−2,11***	−2,51	−0.15**
lnEDC_MM	0,41	−21,18***	0,06	−0,01	1,19***	−16,09	0,60	163,99***	−0.47***
lnEBC_EF	0,97***	−0,89	−2,15***	0,13	0,22**	42,32	−1,79***	80,63	−0.20***
lnEDC_EF	0,46	−20,09***	0,08	0,07	1,17***	−19,15	0,66	159,28***	−0.46***
lnPR_BC	1,00***	−0,57	0,53***	−4,72	0,19**	27,87	−1,87***	55,24	−0.43***
lnPR_DC	2,54***	−11,71*	0,31**	−1,36*	0,89***	−21,85	3,41***	61,90*	−0.26***

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; LR = long-term; SR = short-term; ECT = Error correction term.

Table 4
Error correction term by country for the beef and raw milk production models.

Country	ECT	
	lnPR_BC	lnPR_DC
Argentina	−0,22**	−0,24**
Bolivia	−0,43***	−0,57***
Brazil	−0,48***	−0,15**
Colombia	−0,24**	−0,08
Costa Rica	−0,29	−0,41***
Ecuador	−0,67***	−0,80***
El Salvador	−0,71***	−0,23
Guatemala	−0,21**	−0,46***
Honduras	−0,66***	−0,53***
Mexico	−0,40***	−0,07
Nicaragua	−0,51***	−0,21***
Panama	−0,12	−0,08
Paraguay	−0,34**	−0,30***
Peru	−0,38***	−0,04
Venezuela	−0,73***	−0,18*

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; ECT = error correction term.

Table 5
Short-term country effects for the beef and raw milk production models.

Country	lnPOP		lnPL		lnDEF		lnFL	
	lnPR_BC	lnPR_DC	lnPR_BC	lnPR_DC	lnPR_BC	lnPR_DC	lnPR_BC	lnPR_DC
Argentina	25,55**	−13,09	−0,97	−4,07*	0,06	0,13	4,29	34,28**
Bolivia	−5,67	−51,41**	1,02	−3,74	0,11	1,14***	23,79	132,53**
Brazil	−12,49**	−10,49**	−3,72	−0,01	0,01	−0,02	5,35	20,42*
Colombia	3,79	−19,24	0,91	−2,73	−0,24**	−0,04	14,34	−197,38
Costa Rica	5,20	1,48	2,29	−0,81	0,01	0,004	61,08	408,01***
Ecuador	−25,82***	−29,71**	−0,09	−0,21	−0,13*	−0,39***	0,77	62,49
El Salvador	−49,24***	−15,89	−0,27	−0,21	418,42	−328,25	734,67***	55,16
Guatemala	−31,05***	−30,76**	1,03***	−0,04	−0,08	−0,04	−7,75	46,12***
Honduras	33,98***	27,64***	−0,44	−0,41	0,42	−0,11	−6,76	277,71**
Mexico	4,89	0,19	0,18	−0,06	0,03	−0,02	44,12**	−3,76
Nicaragua	17,64	−55,12***	−1,11	2,58	−0,26***	−0,09	−2,54	9,21
Panama	9,30	31,06	−0,75	−0,20	0,02	0,19	−10,61	55,15
Paraguay	18,54*	−4,21	−0,18	0,50**	−0,23	−0,22	−7,41	5,28
Peru	−5,45***	−3,43*	1,65***	−0,17	0,01	−0,06	−39,28*	7,23
Venezuela	2,26	−2,75	−70,50**	−10,87	−0,01	−0,01	14,54	16,03

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

population, pastureland, or deforestation take between 4 and 4.5 years to correct. Brazil has a faster adjustment period in beef production (1/0.48 = 2 years), but a slower one in milk production (0.15 = 6.6 years). For both models in Ecuador, El Salvador, and Honduras, there are relatively fast adjustment periods of about two years.

Table 5 shows the short-term effects by country, according to the beef and raw milk production models. Most of the results are not statistically significant. However, some elements can be extracted. In Honduras and Argentina, the positive association between population growth and beef production is the most robust in the region. Regarding the pastureland variable, the coefficients are small except for the outlier of Venezuela. For deforestation there is little significance, and the coefficients are less than 1.14. Very few statistically significant results are found for the forest land variable and those that are significant do not contribute in terms of interpretation, given the atypical magnitude of the coefficients. Based on the panel data, it appears that the deforestation variable better captures the impact on production than the forest land variable.

5. Discussion

This document analyzed the short- and long-term effects of population growth, deforestation, and the expansion of pastureland and forest land on the cattle activity in Latin America, both in terms of GHG emissions and beef and raw milk production. The most relevant effects occur in the long-term, at an aggregate level for the 15 countries of analysis, and for beef production.

It is estimated that over the period of analysis, a population growth of 1 % decreases the methane emissions derived from manure management in beef production by 1.41 % and increases those derived from enteric fermentation by 0.97 %. These results are consistent with other panel data studies from different regions of the world, which have evaluated the relations between productive activities and GHG emissions. A study from south-eastern Europe, for example, highlights a positive long-term relationship between CO_2 emissions and variables such as income, electricity consumption, and agricultural production. The relation is especially high for income, where a 1 % growth leads to increased emissions of 2.33 % [66]. An analysis for 28 countries of the Union for the Mediterranean (UfM) showed that in the long-term, a population growth of 1 % decreases CO_2 and CH_4 emissions by 0.25 % and 0.038 %, respectively, because of technological advances and new regulations, which reduce the impact of economic activities on the environment [67]. This might also be the cause for the results of the present study: On the one hand, there are countries with strong technical and political advances in cattle production, such as Brazil, Uruguay, Costa Rica, and Argentina, which may pave the way towards stability in the long-term [80,81]. On the other hand, in countries with less efficient and productive cattle systems, such as Colombia or the Central American countries, long-term stability can only be achieved through the implementation of new public policies that focus on a transition towards more sustainable production systems, i.e., those that include improved forages, silvo-pastoral systems, agroforestry arrangements, and improved grazing management, among others [79,80].

It is reiterated again that caution should be exercised when interpreting these results, as the source of information corresponds to a basic and less detailed level. However, given the availability of the data, the analysis provides relevant insights. With that in mind, the results indicate that a 1 % expansion of pastureland increases the methane emissions from manure management by 2.66 % and decreases those related to enteric fermentation by 2.15 %. The increase in the emissions from manure management identified in the present study might be related to a growing cattle herd resulting from the expansion of pastureland, a phenomenon widely documented in literature for several of the analyzed countries [6,82–85]. The decrease in emissions from enteric fermentation might be explained by improvements in forage quality and grazing management over time because of technological advances, which increase production efficiencies and contribute to reducing GHG emissions. This includes for example new forage varieties and hybrids, silvo-pastoral systems, and rotational grazing – innovations that are being pushed for adoption in cattle systems in the countries of analysis since several decades [81,82,86–88]and have shown to reduce the emissions from enteric fermentation [30,89–92]. This result is in line with a study on the influence of economic growth on CO_2 emissions in Brazil, India, China, and South Africa for the period is from 1971 to 2013, where it was found that a 1 % increase in cattle production increases emissions by up to 15.8 % in the long-term. The study concludes that these economies are in a stage of development in which economic growth has a significant impact on the environment, and that a transition towards cleaner and more efficient technologies is needed [93,94].

An increase in deforestation has effects on both the emissions from beef and raw milk production: In the case of raw milk production, both emissions from enteric fermentation and manure management increase (by 1.19 and 1.17 %, respectively), while in beef production only the emissions from enteric fermentation increase (by 0.22 %). This might be related to a growth in the cattle herd on deforested areas, which often are not planted with productive forages nor follow adequate pasture management practices, i.e., when cattle are used as placeholder in land speculation processes, and thus increase GHG emissions [5]. On the other hand, if the land used for forests is increased by 1 %, for example through afforestation efforts, the emissions from beef production decrease by 2.11 and 1.79 % for manure management and enteric fermentation, respectively. This shows that the cattle activity is strongly related to deforestation in the region, which is in line with the findings from other studies on the subject [6,37,95–98], and that adequate public policies or monitoring can contribute to reducing the emissions from deforestation related to cattle production, among other environmental benefits such as biodiversity conservation, for example through land-sparing [99–102] and sustainable intensification approaches [103].

The results for the short-term effects of the measured variables on cattle production and emissions in LAC are heterogeneous and little statistical significance was found. Despite this, the estimation of the adjustment periods to long-run equilibrium in the event of any shock to the system by country are provided, which estimate how long it takes the cattle sector (beef and raw milk production) to return to its original trend, after an unexpected change in the explanatory variables happens. According to the results, if disturbances in the population, pastureland, deforestation, and afforestation variables occur, cattle production adjusts over a period of 2–6 years. The estimated adjustment periods are consistent with the findings from other studies [68].

Studies agree that in the short-term, the economic activity has a significant impact on GHG emissions. However, the most important results suggest that in the long-term, there is a tendency towards stabilization. This applies particularly to developed countries and to those that count on strong environmental regulations, suggesting that developing countries have a bigger challenge to control their emissions in the long-term [67].

On the other hand, as mentioned in the study's limitations, the Tier 2 method is more efficient. For instance, when estimating methane emissions, it yields more accurate results that enable better monitoring of the livestock activity [2]. Consequently, these tools allow for a more in-depth exploration of the observed relationships, using more recent temporal information. Several studies have delved into this approach [104–106]).

In the present article, the estimates showed results with some similarities. In the short-term, there are heterogeneous results for the countries. In the long-term, trends towards stabilization are observed with small or even negative coefficients. The findings thus indicate that both technological development and improvements in regulatory frameworks in the long-term can a) help in reducing the pressure population growth, pastureland expansion, and deforestation have on cattle production systems and hence, the environment, and b) contribute towards achieving stability.

6. Conclusions

This article provided an analysis of the relationship of the cattle sector and the environment. It was evaluated how population growth, pastureland expansion, and deforestation affect cattle production and greenhouse gas emissions from the cattle sector in the short- and long-term with a data panel for 15 Latin American countries over a period of 30 years. The results show that cattle production in the region is very heterogeneous, and some countries have a stronger participation of more technology-intensive production systems, whereas in others production levels and efficiencies lag behind. The estimation of a panel allows to reflect this heterogeneity but also shows a path towards stability in the long-term, meaning that population growth, pastureland expansion, and deforestation, over time, tend to be related less with the GHG emissions generated by the cattle sector. This long-term behavior may be marked by countries with a more developed cattle sector, i.e., those that focus on reducing the impacts of cattle production on the environment, for example through supporting the adoption of improved forage technologies, silvo-pastoral systems, and grazing management practices, or the development of regulatory frameworks and incentives. These countries can serve as regional benchmarks and decision-makers from countries with a less-developed cattle sector can learn from their experiences.

This suggests that long-term scenarios for those countries with less efficient and sustainable cattle sector should be further investigated. A large-scale study that focuses on the cattle production units as unit of analysis for the entire region can provide a better understanding of the relationships between cattle production and the environment. Econometric advances and increasingly sophisticated computational techniques can contribute strongly to this endeavor, but more complete sources of information are needed. The results of this study can be used as a starting point for future research, such as a) further assessments of the general trends at the country level, b) assessments of other units of analysis and other sources of information, and c) expanding the techniques for empirical analysis.

The present study is a contribution to the field since it allows for comparisons to be made at the regional level in relation to GHG emissions and cattle farming. The study provides an understanding of the dynamics of the sector in the region, where cattle farming is a determining productive activity in the generation of GHG emissions. This is a growing topic of interest considering both the importance of the cattle sector in Latin America and the growing demand for the conservation of natural resources and sustainable production systems that support the mitigation of GHG emissions. Nevertheless, it is essential to delve more deeply into these dynamics using other methodologies and sources of information that allow for result comparisons. Recent developments such as FAO-GLEAM provide an opportunity to further explore these aspects.

Data availability statement

Data will be made available on request.

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Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Danny Fernando Sandoval: Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Conceptualization. **Jhon Jairo Junca Paredes:** Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Conceptualization. **Karen Johanna Enciso Valencia:** Formal analysis. **Manuel Francisco Díaz Baca:** Formal analysis. **Aura María Bravo:** Formal analysis. **Stefan Burkart:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Stefan Burkart reports financial support was provided by CGIAR Consortium. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

The main aspects of the econometric model are presented below [29]. If an autoregressive distributive lag is assumed, the dynamic panel specification is:

$$y_{it} = \sum_{j=1}^{p} \lambda_{ij} y_{i,t-j} + \sum_{j=0}^{q} \delta_{ij}^{'} X_{i,t-j} + \mu_i + \epsilon_{it} \tag{A1}$$

where:

i: 1, 2, ….., N groups.
t: 1, 2, ….., T periods.
$X_{i,t}$: k x1 vector of explanatory variables.
δ_{ij}: k x1 coefficient vectors
λ_{ij}: scalars
μ_i: group-specific effect

If the variables in equation (A1) are I(1) and cointegrated, then the error is I(0). Thus, these variables have the capacity to respond to deviations from the long-term equilibrium. This implies an error correction model. Therefore, equation (A1) can be reparametrized into the following error correction equation:

$$\Delta y_{it} = -\varnothing_i \left(y_{i,t-1} - \theta_i^{'} X_{it}\right) + \sum_{j=1}^{p-1} \lambda_{ij}^{*} \Delta y_{i,t-1} + \sum_{j=0}^{q-1} \delta_{ij}^{*} \Delta X_{i,t-j} + \mu_i + \epsilon_{it} \tag{A2}$$

where:

$$\varphi_i = -\left(1 - \sum\nolimits_{j=1}^{p} \lambda_{ij}\right).$$

$$\theta_i = \sum_{j=0}^{q} \delta_{ij} \Bigg/ \left(1 - \sum\nolimits_{k} \lambda_{ik}\right).$$

$$\lambda_{ij}^{*} = -\sum\nolimits_{m=j+1}^{p} \lambda_{im}.$$

$$j = 1, 2, \ldots, p-1.$$

$$\delta_{ij}^{*} = -\sum_{m=j+1}^{q} \delta_{im} \; j = 1, 2, \ldots, q-1.$$

θ_i: error-correcting speed of adjustment. If it is equal to zero, then there would be no evidence for a long-term relationship.
$\theta_i^{'}$: contains the long-term relationships between the variables.

There is a PMG estimator that combines both pooling and averaging. This estimator allows the relevant elements to differ across the groups but constrains the long-term coefficients to be equal across groups [25,26,29]. Since equation (A2) is nonlinear in the parameters, Pesaran et al. [26] propose a maximum likelihood method to estimate the parameters, as expressed in equation (A3):

$$l_T(\theta^{'}, \varphi^{'}, \sigma^{'}) = -\frac{T}{2} \sum_{i=1}^{N} \ln\left(2\pi\sigma_i^2\right) - \frac{1}{2} \sum_{i=1}^{N} \frac{1}{\sigma_i^2} \{\Delta y_i - \varphi_i \xi_i(\theta)\}^{'} H_i \{\Delta y_i - \varphi_i \xi_i(\theta)\} \tag{A3}$$

where:

$$i = 1, \ldots, N.$$

$$\xi_i(\theta) = y_{i,t-1} - X_i \theta_i.$$

$$H_i = I_T - W_i \left(W_i^{'} W_i\right) W_i.$$

I_T: identity matrix of order T.

$$W_i = \left(\Delta y_{i,t-1}, \ldots, \Delta y_{i,t-p+1}, \Delta X_{i,t-1}, \ldots, \Delta X_{i,t-q+1}\right).$$

Stata software offers computational facilities to obtain these results. A detailed analysis of these technical aspects can be found in Blackburne and Frank [29].

Appendix 2

Table A.1
Slope homogeneity tests

	Delta	P-value
lnEBC_MM	35,45	0,0000
lnEDC_MM	31,63	0,0000
lnEBC_EF	30,34	0,0000
lnEDC_EF	31,39	0,0000
lnPR_BC	33,59	0,0000
lnPR_DC	34,03	0,0000

Table A.2
Cross-section dependency tests

	Statistics	P-value
lnEBC_MM	1,60	0,1096
lnEDC_MM	2,03	0,0422
lnEBC_EF	1,58	0,1123
lnEDC_EF	2,10	0,0357
lnPR_BC	0,93	0,3525
lnPR_DC	−0,56	1,4277

Table A.3
Unit root tests

	Level		First difference	
	Z-statistics	P-value	Z-statistics	P-value
lnEBC_MM	1,29	0,9029	−10,34	0,0000
lnEDC_MM	−0,14	0,4410	−11,01	0,0000
lnEBC_EF	1,33	0,9095	−10,47	0,0000
lnEDC_EF	−0,04	0,4812	−10,87	0,0000
lnPR_BC	0,67	0,7487	−10,47	0,0000
lnPR_DC	−0,77	0,2187	−10,17	0,0000
lnPOP	−16,01	0,0000	*	*
lnPL	2,56	0,9948	−8,10	0,0000
lnFL	5,78	1,0000	−1,68	0,0458
lnDEF	1,58	0,9435	−11,23	0,0000

Table A.4
Cointegration tests

Model	Panel				Group		
	V	RHO	T	ADF	RHO	T	ADF
lnEBC_MM	0,41	0,39	−1,93**	−0,24	1,65**	−1,44*	0,44
lnEDC_MM	1,39*	−0,93	−4,14***	−2,59***	0,46	−3,92***	−3,27***
lnEBC_EF	0,42	0,33	−2,00**	−0,36	1,59*	−1,50*	0,34
lnEDC_EF	1,39*	−0,84	−4,02***	−3,16***	0,55	−3,76***	−3,82***
lnPR_BC	0,96	−0,16	−3,23***	−3,19***	1,26	−3,11***	−3,17***
lnPR_DC	1,82**	−0,71	−3,14***	−1,87**	0,44	−2,94***	−3,00***

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table A.5
Hausman tests

	Statistics	P-value
lnEBC_MM	1,67	0,7966
lnEDC_MM	3,05	0,5498
lnEBC_EF	2,02	0,7322
lnEDC_EF	2,04	0,7281
lnPR_BC	1,62	0,8056
lnPR_DC	1,25	0,8705

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