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Assessment of the operational and environmental efficiency of agriculture in Latin America and the Caribbean

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Abstract: Governments in Latin America and the Caribbean (LAC) require information that can be used to strengthen environmental agricultural strategies. However, in LAC there is not enough comparative analysis regarding operational performance and environmental performance, which are particularly important for sustainable agriculture. The objective of this study is the measurement of operational, environmental and unified (operational and environmental) efficiency through data envelopment analysis (DEA) for an environmental assessment in the agricultural sectors of eighteen LAC countries. The DEA in this study evaluates each country based on six variables: capital stock, labour, land, consumption of fertilizers, value of the gross agricultural production and agricultural emissions (CO_2eq). This empirical study finds that six LAC countries attained full efficiency in terms of the three efficiency measurements. Three countries exhibit the highest level of unified efficiency, but show some level of inefficiency in the other two measurements (operational and environmental efficiency). In contrast, nine countries failed to achieve the maximum unified efficiency score.

Keywords: agricultural performance, damages to scale, DEA, returns to scale, unified efficiency

The Intergovernmental Panel on Climate Change (IPCC 2014) reported that between 2000 and 2010 the annual greenhouse gas (GHG) emissions caused by human activity increased more than in any previous decade, in spite of regional efforts to reduce them. This increase was mainly due to energy supply (47%), industry (30%), transport (11%) and building (3%) sectors. In fact, GHG emissions have increased in all sectors, except in agriculture, forestry, and others which use soil. Notwithstanding, there is no doubt that agriculture is highly important with respect to GHG emissions (Kuo et al. 2014).

Not all countries contribute to the same extent to GHG emissions. Thus, developed regions with 17% of the world's population produce 43% of the total CO_2 equivalent in metric tons, while developing regions, representing 83% of the world's population, release 57% of these emissions in metric tons (PRB 2014; UNDP 2014). In 2012, the contribution of LAC to GHG emissions amounted to only 9.9% of global emissions. These GHG emissions come from energy use (40.4%), agriculture (19.8%), land-use change and forestry (31.5%), waste (5.3%) and industrial process (3.0%) activities (Sánchez and Reyes 2015).

The growth of the economies of the LAC region experienced a slowdown in 2012, resulting in a 3% reduction in the gross domestic product (GDP) versus the prior year. Nevertheless, despite this decrease in GDP, the agricultural sector only accounted for 5% of LAC's GDP in 2012, a relatively lower level than in previous years (World Bank 2016). The aforementioned takes into account the fact that the annual growth rate of the agricultural sector of the LAC in the last three years was 2.9% higher than the total growth (ECLAC et al. 2015).

LAC faces a background of global economic decline, a loss of buoyancy as world trade contracts, an upswing in adverse climatic events and increased outbreaks of crop pests and diseases that are intensified by a greater variability in the climate. Climate change is now an issue of undoubted relevance and is considered one of the major costs that is affecting

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society today and will continue to have an impact in the future (Cihelková 2011). Thus, reconciling agricultural productivity and environmental performance will be key factors for LAC in tackling the economic slowdown (ECLAC et al. 2013; 2015).

There have been a number of studies that have analysed agricultural productivity in LAC and they have shown different results. Notable among them is Pfeiffer (2003), who estimated a meta-production function to analyse the change in agricultural productivity in the Andean community over the period 1972–2000. Bharati and Fulginiti (2007) also stand out. They used a translog frontier production function to estimate the agricultural productivity in the original Mercosur member countries and later associate members over the period 1972–2002. A feature of both studies is that they concluded that technical progress is the main contributor to agricultural productivity.

Lending support to results obtained from previous studies, Ludena (2010) estimated the total factor productivity growth (TFP) in LAC between 1961 and 2007 using a Malmquist index. His study showed that agricultural productivity growth is due to technical change. In the last two decades of this period agricultural productivity grew at a faster rate as a result of changes in efficiency and mainly because of new technologies.

Looking to provide information on agricultural productivity, Zúniga (2011) performed data envelopment analysis (DEA) to derive a Malmquist index over the period 1994–2010 in Central America. This study confirms that gains in agricultural productivity in the LAC countries in the last decades are associated with new technologies. In this context, this work also concluded that increases in agricultural productivity are due to technical changes and efficiency changes.

A previous study by Solís et al. (2009), using an input-oriented stochastic distance frontier simultaneously with a technical efficiency effects model, concluded that improvements in technical efficiency are financially beneficial to farm households while also contributing to environmental sustainability. This study was performed with the aim of determining the extent to which technical efficiency is related to activities promoted by two natural resource management programs of 639 farms in El Salvador and Honduras.

More recently, Martín-Retortillo et al. (2014) analysed the growth of agricultural production in LAC between 1950 and 2010. The study used Hayami and Ruttan's (1985) induced development model to estimate the evolution of partial productivities of labour and land, and growth accounting methodology to measure the TFP. This work found that the efficiency gains made a modest contribution to the important increase in production, which was mainly caused by the use of capital, along with more moderate increases in the use of land and labour (Martín-Retortillo et al. 2014).

Another study applied a growth accounting approach combined with DEA to measure TFP growth and to break down the contributions of technical change and changes in technical efficiency agricultural to growth in LAC over the period 1980–2012. This study by Nin-Pratt et al. (2015) showed that productivity increased faster in the countries that increased inputs per work than in countries with limited access to capital and land. Besides, it concluded that agricultural growth is mainly due to increases in the consumption of fertiliser, land productivity and the use of capital. Furthermore, these researchers point out that growth patterns have amplified differences in labour productivity among LCA countries.

Focusing on South American countries, a translog production function and a Malmquist index applied by Trindade and Fulginiti (2015) showed that agricultural productivity growth accounted for half of the three-fold increase in agricultural output between 1969 and 2009 and that performance is sensitive to R&D investments in this sector. It also found that there was no evidence of a slowdown in agricultural productivity growth in this region between 2000 and 2009.

However, although recognising the contributions of all of the above-mentioned studies to the assessment of agricultural productivity growth in specific LAC countries, it must be said that these previous studies did not report an environmental performance analysis in agriculture, with the exception of Nin-Pratt et al. (2015) who recently analysed the agro-ecological efficiency in their study of the productivity and performance of agriculture in LAC.

Finally, it is important to point out the contribution of Ebata (2011), who estimated the TFP in the agricultural sector of Central America and the Caribbean over the period 1976–2006, using a translog production function and the Malmquist index approach. In contrast to other studies, this study found that TFP growth rates improved over this period when no externalities were taken into account. Nonetheless, a lower rate of growth was identified between 1992 and 2006 in most countries when CO_2 emissions were included in the analysis.

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This study uses the nonparametric approach of DEA for environmental assessment to measure operational efficiency, environmental efficiency and unified efficiency, under both operational and environmental efficiency measurements in the agricultural sector of 18 LAC countries. This work also determines the types of returns to scale (RTS) and damages to scale (DTS) in each country in 2012 based on two outputs (value of the gross agricultural production and agricultural emissions (CO_2eq)) and four inputs (fertilisers, capital stock, labour and land). The aim inn this investigation is to identify the most efficient countries and – with this empirical comparison – to provide relevant information to orient the inefficient countries so that they can work on strengthening environmental strategies to reduce their environmental carbon footprint in agriculture and create a sustainable agriculture.

The DEA methodology is widely used and recognised way to measure production efficiency, but it has also been used to evaluate the environmental performance (Scheel 2001; Zhou et al. 2008). Färe et al. (1989, 1993, 1996) were among the earliest authors who used DEA in the context of weak disposability and who employed environmental DEA technology to analyse productivity when some outputs are bad. Since then, different methods have been proposed in order to process the bad outputs in a DEA (Scheel 2001).

Although an environmental assessment model is called for, DEA does not only estimate environmental efficiency in the environmental assessment approach (Dios-Palomares et al. 2014). This approach includes environmental variables and the conventional production variables. That is, the distance that spans the efficient frontier includes operational efficiency, environmental efficiency and unified efficiency, which cannot be separated into an environmental analysis model of these features (Sueyoshi and Goto 2011a; Dios-Palomares et al. 2014). So, a country's environmental performance cannot be determined without first estimating its operational performance.

There has been very little DEA for the environmental assessment approach to measure the environmental efficiency of the agricultural sector in LAC (Dios-Palomares et al. 2014). Thus, this study uses the DEA model for the environmental assessment proposed by Sueyoshi and Goto (2011a; b) to analyse the agricultural sector in LAC. An important feature is the use of DEA-RAM (Range-Adjusted Measurement), first proposed by Cooper et al. (1999), because it can easily incorporate the good output and bad output into a unified treatment. Also, this approach allows the measuring of the type of RTS when handling the good outputs and DTS when handling the bad outputs for environmental assessment (Sueyoshi and Goto 2011a; 2013).

MATERIALS AND METHODS

In our evaluation of the agricultural sectors of LAC countries, it is assumed that there are n countries, ($j = 1, \ldots, n$) and each country uses *input levels* $x_{ik} > 0$ ($i = 1, \ldots, m$) *to produce two kinds of outputs: good outputs* $g_{rk} > 0$ ($r = 1, \ldots, s$) and bad outputs $b_{fk} > 0$ ($f = 1, \ldots, h$). The agricultural sector performance of the kth country is presented as follows.

Operational efficiency in good outputs

This refers to an inefficient country reaching its operational efficiency by decreasing its directional vector of inputs in order to increase its directional vector of good outputs as much as possible. This study therefore evaluates the operational efficiency of the kth country by using a non-radial model as follows:

$$
\begin{aligned}
& Max\ \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g \\
& s.t. \sum_{j=1}^{n} x_{ij}\lambda_j + d_i^x = x_{ik}\ (i = 1, \ldots, m) \\
& \sum_{j=1}^{n} g_{rj}\lambda_j - d_r^g = g_{rk}\ (r = 1, \ldots, s) \qquad (1) \\
& \sum_{j=1}^{n} \lambda_j = 1,\ \lambda_j \geq 0\ (j = 1, \ldots, n) \\
& d_i^x \geq 0\ (i = 1, \ldots, m), d_r^g \geq 0\ (r = 1, \ldots, s)
\end{aligned}
$$

where superscript (g) is used to specify the good outputs. Here, $\lambda = (\lambda_1, \ldots, \lambda_n)^T$ is the jth intensity variable. d_i^x ($i = 1, \ldots, m$) and d_r^g ($r = 1, \ldots, s$) are all slack variables related to the ith input and the good outputs, respectively. Furthermore, the upper and lower bounds of each good output are expressed by $\overline{g}_r = max_j\{g_{rj}\}$ and $\underline{g}_r = min_j\{g_{rj}\}$ and the upper and lower bounds of each input are expressed by $\overline{x}_i = max_j\{x_{ij}\}$ and $\underline{x}_i = min_j\{x_{ij}\}$, respectively. So $R_r^g = 1/[(m + s)(\overline{g}_r - \underline{g}_r)]$ for each r and $R_i^x = 1/[(m + s)(\overline{x}_i - \underline{x}_i)]$ for each i indicate the ranges for good outputs and inputs, respectively.

An operational efficiency score of the specific kth country is measured by $\theta = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*}\right)$ where (*) indicates the optimal values in the model (1). The equation in the parentheses indicates the

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level of inefficiency. The operational efficiency is obtained by subtracting inefficiency from unity.

$$Min \sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sigma \quad (2)$$

$$Min \sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sigma \quad (j = 1, ..., n)$$

$$v_i \geq R_i^x \ (i = 1, ..., m), u_r \geq R_r^g \ (r = 1, ..., s), \sigma\text{: URS}$$

Here, $v_i (i = 1, ..., m)$, $u_r (r = 1, ..., s)$ and σ are the dual variables corresponding to the first, second and third groups of constraints from the primal problem or model (1). Also, URS is unrestricted.

Measurement of the RTS

To explain the RTS measurement it is necessary to describe the economies of scale (SE), which is defined as the quantity of an increase in a good output resulting from a proportional increase in all inputs (Sueyoshi and Goto 2013). After calculating the SE, it is possible to determine the RTS. That is, the RTS measurement aims to make a projection onto the efficient frontier in which each inefficient country evaluated has to project its good outputs.

Hence, to determine the type of RTS, the SE value must be expressed in terms of the efficiency and inefficiency of the kth country. That is, if a kth country is efficient, then the value of the SE is obtained as follows:

$$SE = \left(\sum_{i=1}^{m} v_i^* \left(x_{ik} - d_i^{x*}\right)\right) / \left(\sum_{r=1}^{s} u_r^* \left(g_{rk} + d_r^{g*}\right)\right) = 1/\left(1 + \left(\sigma^* / \sum_{i=1}^{m} v_i^* \left(x_{ik} - d_i^{x*}\right)\right)\right) \quad (3)$$

On the contrary, if a kth country is inefficient, then its projected point on an efficient frontier is found in $\begin{pmatrix} X_k - d^{x*} \\ G_k + d^{g*} \end{pmatrix}$, an optimal solution ($\lambda$, d^{x*}, d^{g*}) of the model (1). That is to say:

$$SE = \left(\sum_{i=1}^{m} v_i^* \left(x_{ik} - d_i^{x*}\right)\right) / \left(\sum_{r=1}^{s} u_r^* \left(g_{rk} + d_r^{g*}\right)\right) \quad (4)$$

The equations (3) and (4) indicate that the sign of the dual variable (σ) determines the value of SE and the RTS in all efficient and inefficient countries in terms of operational efficiency. Then, assuming a single projection of an inefficient country onto an efficient frontier and a single set of references for the projected country, the model (5) calculates the upper bounds $\bar{\sigma}$ and the lower bounds $\underline{\sigma}$ as follows:

Max/Min σ

s.t. constraints in both (1) and (2)

$$\sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g = \sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sigma \quad (5)$$

Consequently, the type of the RTS for the kth country can be obtained:

(a) Increasing RTS $\leftrightarrow 0 > \bar{\sigma}^* \geq \underline{\sigma}^*$

(b) Constant RTS $\leftrightarrow \bar{\sigma}^* \geq 0 \geq \underline{\sigma}^*$

(c) Decreasing RTS $\leftrightarrow \bar{\sigma}^* \geq \underline{\sigma}^* > 0$

For instance, suppose that a country exhibits increasing RTS in its operational performance. This means that a unit increase in inputs in the agricultural activity should produce good outputs more proportionally than the unit increase in inputs. Accordingly, a country ought to increase its current level of agricultural activity to achieve its operational efficiency in good outputs.

Additionally, a decreasing RTS indicates that a unit increase in inputs produces good outputs, i.e., value of the gross agricultural production in our case, less proportionally than the increase in inputs. However, a constant RTS indicates that a unit increase in inputs increases agricultural production to the same proportion as the increase in inputs.

Environmental efficiency in bad outputs

In contrast, environmental efficiency refers to an inefficient country achieving its environmental efficiency by increasing the directional vector of inputs in order to decrease the directional vector of bad outputs as much as possible. Thus, this study evaluates the environmental efficiency of the kth country by using a non-radial model as follows:

$$Max \sum_{i=1}^{m} R_i^x d_i^x + \sum_{f=1}^{h} R_f^b d_f^b$$

$$s.t. \sum_{j=1}^{n} x_{ij} \lambda_j - d_i^x = x_{ik} \ (i = 1, ..., m)$$

$$\sum_{j=1}^{n} b_{fj} \lambda_j + d_f^b = b_{fk} \ (f = 1, ..., h) \quad (6)$$

$$\sum_{j=1}^{n} \lambda_j = 1, \ \lambda_j \geq 0 \ (j = 1, ..., n)$$

$$d_i^x \geq 0 \ (i = 1, ..., m), d_f^b \geq 0 \ (f = 1, ..., h)$$

where superscript (b) is used in order to specify the bad outputs. Here, $d_f^b (f = 1, ..., h)$ are all the slack variables related to the bad outputs. The ranges for the model (6) are calculated as follows: $R_f^b = 1/[(m + h)(\bar{b}_f - \underline{b}_f)]$ for each f and $R_i^x = 1/[(m + h)(\bar{x}_i - \underline{x}_i)]$ for each i. Furthermore, the upper and lower bounds of each bad output are

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expressed by $\overline{b}_f = max_j\{b_{fj}\}$ and $\underline{b}_f = min_j\{b_{fj}\}$, respectively. Then, the environmental efficiency score (θ) of the kth country is measured by:

$$\theta = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right)$$

The model (6) has the following dual formulation:

$$Min\ -\sum_{i=1}^{m} v_i x_{ik} + \sum_{f=1}^{h} w_f b_{fk} + \sigma$$

$$s.t. - \sum_{i=1}^{m} v_i x_{ij} + \sum_{f=1}^{h} w_f b_{fj} + \sigma \geq 0 \qquad (7)$$

$$v_i \geq R_i^x\ (i = 1, \ldots, m), w_f \geq R_f^b\ (f = 1, \ldots, h), \sigma\text{: URS}$$

Here, $v_i = (i = 1, \ldots, m)$, $w_f = (f = 1, \ldots, h)$ and σ are dual variables corresponding to the first, second and third groups of constraints from the primal problem or model (6). Also, URS is unrestricted.

Measurement of the DTS

This measurement changes the SE concept for a new concept, SD (scale damages). The SD corresponds to the SE in the bad outputs (Sueyoshi and Goto 2013). The DTS measurement aims to indicate a projection onto the efficient frontier in which each inefficient country evaluated has to project its bad outputs.

To obtain the type of the DTS, the value of the SD must be expressed in terms of the efficiency and inefficiency of the kth country. Then, if the kth country is efficient the value of the SD is obtained as follows:

$$SD = \left(\sum_{i=1}^{m} v_i^* \left(x_{ik} + d_i^{x*}\right)\right) / \left(\sum_{f=1}^{h} w_f^* \left(b_{fk} - d_f^{b*}\right)\right)$$
$$= 1/\left(1 - \left(\sigma^* / \sum_{i=1}^{m} v_i^* \left(x_{ik} + d_i^{x*}\right)\right)\right) \qquad (8)$$

On the contrary, if a kth country is inefficient, then its projected point on an efficient frontier is found in $\binom{X_k + d^{x*}}{B_k - d^{b*}}$ of an optimal solution (λ, d^{x^*}, d^{b^*}) of the model (6). That is to say:

$$SD = \left(\sum_{i=1}^{m} v_i^* \left(x_{ik} + d_i^{x*}\right)\right) / \left(\sum_{f=1}^{h} w_f^* \left(b_{fk} - d_f^{b*}\right)\right) \qquad (9)$$

Equations (8) and (9) indicate that the sign of a dual variable (σ) determines the value of the SD and the DTS in all efficient and inefficient countries in terms of environmental efficiency. Then, assuming a single projection of an inefficient country onto an efficient frontier and a single set of references for the country projected, the model (10) calculates the upper bounds $\overline{\sigma}$ and the lower bounds $\underline{\sigma}$, as follows:

Max/Min σ

s.t. constraints in both (6) and (7)

$$\sum_{i=1}^{m} R_i^x d_i^x + \sum_{f=1}^{h} R_f^b d_f^b = -\sum_{i=1}^{m} v_i x_{ik} + \sum_{f=1}^{h} w_f b_{fk} + \sigma \qquad (10)$$

Consequently, the type of the DTS for the kth country can be obtained:

(a) Increasing DTS $\leftrightarrow \overline{\sigma}^* \geq \underline{\sigma}^* > 0$

(b) Constant DTS $\leftrightarrow \overline{\sigma}^* \geq 0 \geq \underline{\sigma}^*$

(c) Decreasing DTS $\leftrightarrow 0 > \overline{\sigma}^* \geq \underline{\sigma}^*$

DTS has an opposite managerial implication for the RTS. Suppose that a country belongs to those with increasing DTS. This means that a unit increase in inputs to agricultural activity produces bad outputs more proportionally than the unit increase in inputs. For this reason, a country should reduce the current size of its agricultural activity to attain its environmental efficiency in bad outputs. Yet this result indicates that this country ought to use technological innovations in agricultural activity in order to reduce its bad outputs – agricultural emissions (CO_2eq) in our case.

Additionally, a decreasing DTS means that a unit increase in inputs produces bad outputs less proportionally than the increase in inputs. Nevertheless, a constant DTS means that a unit increase in inputs produces agricultural emissions (CO_2eq) in the same proportion as the increase in inputs.

Unified efficiency measurement

The operational and environmental efficiency approach is first presented in a separate treatment. Nonetheless, the main purpose of the DEA for the environmental assessment is to calculate both of the measures in a unified treatment because a production activity produces not only good outputs but also bad outputs.

The resulting model (11) unifies model (1) and (6) in such a manner that the integration provides a single set of intensity variables to produce a unified (operational and environmental) efficiency, i.e., model (11) can express the two efficient frontiers in a single set of intensity variables. Also, the direction of the possible projection in model (11) includes both of the operational and environmental efforts of the adaptive strategy for environmental protection (Sueyoshi and Goto 2011b).

Then, this study evaluates the unified efficiency of the kth country by using the model as follows:

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$$Max\ \sum_{i=1}^{m} R_i^x (d_i^{x+} + d_i^{x-}) + \sum_{r=1}^{s} R_r^g\ d_r^g + \sum_{f=1}^{h} R_f^b\ d_f^b$$

$$s.t. \sum_{j=1}^{n} x_{ij}\ \lambda_j - d_i^{x+} + d_i^{x-} = x_{ik}\ (i = 1, \dots, m)$$

$$\sum_{j=1}^{n} g_{rj}\ \lambda_j - d_r^g = g_{rk}\ (r = 1, \dots, s)$$

$$\sum_{j=1}^{n} b_{fj}\ \lambda_j + d_f^b = b_{fk}\ (f = 1, \dots, h) \qquad (11)$$

$$\sum_{j=1}^{n} \lambda_j = 1, \lambda_j \geq 0\ (j = 1, \dots, n)$$

$$d_i^{x+} \geq 0\ (i = 1, \dots, m), d_i^{x-} \geq 0\ (i = 1, \dots, m)$$

$$d_r^g \geq 0\ (r = 1, \dots, s) \text{ and } d_f^b \geq 0\ (f = 1, \dots, h)$$

where superscripts (g) and (b) are used in order to specify the good outputs and bad outputs, respectively. Here, d_i^x related to the ith inputs is separated into its positive and negative part (d_i^{x+} and d_i^{x-}). The input slacks in the first group of constraints in model (11) indicate $d_i^{x+} - d_i^{x-} = d_i^x$. The variable transformation of input slacks requires the nonlinear conditions: $d_i^{x+} - d_i^{x-} = 0$ ($i = 1, \dots, m$), which indicate that the two slack variables are mutually exclusive. Then, a simultaneous occurrence of both $d_i^{x+} \geq 0$ and $d_i^{x-} \geq 0$ is excluded from the optimal solution of model (11).

To satisfy the nonlinear condition in model (11), this study used the following two computational alternatives:

First, solve the model (11) with $d_i^{x+} - d_i^{x-} = 0$ ($i = 1, \dots, m$) as a nonlinear condition in a programming problem.

Second, put $d_i^{x+} \leq Mz_i^+$, $d_i^{x-} \leq Mz_i^-$, $z_i^+ + z_i^- \leq 1$, z_i^+ and z_i^- : binary ($i = 1, \dots, m$) into the model (11) and solve the model with the side constraints as a mixed integer programming problem. M stands for a very large number that need to determine before the computational operation.

Thus, unified (operational and environmental) efficiency is measured by:

$$\theta = 1 - \left[\sum_{i=1}^{m} R_i^x (d_i^{x+*} + d_i^{x-*}) + \sum_{r=1}^{s} R_r^g\ d_r^{g*} + \right.$$
$$\left. + \sum_{f=1}^{h} R_f^b\ d_f^{b*}\right]$$

Data

This study includes eighteen LAC countries: Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru and Uruguay. The variables that are to be analysed were obtained from the Food and Agriculture Organization of the United Nations (FAOSTAT 2016) and Nin-Pratt et al. (2015) for the year 2012. They include four conventional input variables (capital stock, labour, land and consumption of fertilisers) and two outputs (value of the gross agricultural production and agricultural emissions (CO_2eq)). The definitions of these variables are given below.

Inputs

Capital stock: The FAO statistics division has compiled an updated dataset of capital stock in agriculture from 1975 to 2007 using 2005 constant prices as the base year. The data for the year 2012 were obtained from the study of Nin-Pratt et al. (2015). They used figures of gross fixed capital stock formation. This measures the value of the existing fixed assets of farmers over a given period with each asset valued at new prices. Capital stock has two components: (1) *crop capital* covering land developments, plantation crops and machinery and equipment; (2) *livestock* including animal inventory and livestock fixed assets.

Labour is the total economically active population in agriculture in thousands of peoples. The data refer to the 5th edition of the International Labour Organization, revised in 2009. *Land* includes arable land, permanent crops and permanent meadows and pastures, and it is expressed in thousands of hectares.

Consumption of fertilisers refers to the quantity of nitrogen (N), phosphate (P_2O_5) and potash (K_2O) and is expressed in tons. In this study, the consumption of fertilisers represents the increase of soil yield. The application of fertilisers is responsible for a portion of GHG emissions, yet the other inputs of this study are assumed to also affect the level of GHG emissions (IPCC 2006; Solazzo et al. 2016).

Good output

The value of gross agricultural production is expressed in millions of USD, based on the constant price of 2004–2006. It includes crop and livestock production. According to FAOSTAT (2016), the value of gross production is obtained by multiplying the gross production in physical terms by the output prices at the farm gate. As a result, it measures production in monetary terms at the farm gate level. Since the intermediate uses within the agricultural sector (seed and feed) were not subtracted from the production data, this value of the production aggregate refers to the notion of gross production.

Bad output

Agricultural emissions are expressed in gigagrams CO_2 equivalent (CO_2eq), and are those reported in

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the FAOSTAT domains of emissions from land use consistent with the IPCC. These are the bad output directional vectors of models 6 and 11. This variable includes crop and livestock production, forestry and associated land-use changes. According to the IPCC (2006), in agricultural emissions the key greenhouse gases of concern are CO_2, N_2O and CH_4. Still, agricultural GHG emissions are dominated by non-CO_2 gases, namely methane (CH_4) and nitrous oxide (N_2O), produced as a result of crop and livestock production and management activities. This variable comprises data on GHG emissions formed in the different agricultural sub-domains, giving a picture of the contribution to the total amount of GHG emissions from agriculture (FAO 2014).

The IPCC guidelines for national GHG emissions for agriculture consider that emissions have a linear relationship with the size of the economic activity. That is, an increase in agricultural activity will produce a proportional surge in GHG emissions (Solazzo et al. 2016). In this respect, GHG emissions in LAC have historically been dominated by land use, land-use change and agriculture and forestry (IICA 2015). Enteric fermentation and manure emissions from livestock-rearing is the largest source of total agricultural emissions in LAC (FAO 2014).

Livestock breeding results in the release of CH_4 from enteric fermentation and N_2O from the excreted nitrogen, as well as from nitrogenous chemical fertilisers (N) used to produce feed for many animals. The utilisation of manure and nitrogen fertilisers on agricultural land increases N_2O emissions. Moreover, N_2O and CO_2 are released during the production of chemical nitrogen fertilisers (UNEP 2012).

For the reader who is interested in the mathematical details of these models, several files have been created using the Wolfram Mathematica programme. These are available upon request.

RESULTS AND DISCUSSION

The efficiency measurements of the agricultural sector in 18 LAC countries are presented in Table 2. The second column shows the operational efficiency and the third column shows the environmental efficiency, which have been calculated using models (1) and (6), respectively. Also, the fourth and fifth columns present the unified (operational and environmental) efficiency that was obtained using model (11).

Figure 1 shows that Argentina, Belize, Bolivia, Brazil, Costa Rica, the Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Panama and Uruguay attained the maximum operational efficiency score (1.0000) in 2012. These countries exhibited the highest agricultural production with the lowest consumption

Table 1. Variables of the agricultural sector during 2012 for 18 LAC countries

Country	Fertilizers	Capital stock	Labor	Land	Agricultural production	Agricultural Emissions (CO_2eq)
Argentina	1 403 678	70 471	1 388	149 254	39 609 904	105 825
Belize	10 689	227	32	160	185 608	319
Bolivia	35 294	10 805	2 056	37 596	3 732 400	23 342
Brazil	13 195 074	233 127	10 478	275 607	145 545 149	444 704
Chile	527 415	22 692	957	15 755	8 583 679	11 518
Colombia	1 178 948	112 632	3 484	42 618	14 014 336	52 263
Costa Rica	172 725	2 365	317	1 812	3 061 382	3 394
Dominican Republic	59 571	11 024	438	2 352	2 824 180	7 692
Ecuador	291 420	21 182	1 219	7 507	7 335 057	13 734
El Salvador	121 630	2 454	577	1 572	1 196 889	2 826
Guatemala	266 966	10 679	2 148	3 809	4 744 677	8 387
Honduras	84 806	4 536	662	3 235	2 191 396	5 851
Mexico	1 814 509	126 536	7 708	106 705	38 098 572	82 661
Nicaragua	76 914	6 316	343	5 103	1 609 347	7 759
Panama	23 424	3 927	244	2 257	990 944	3 489
Paraguay	367 780	10 207	851	21 500	4 282 544	25 127
Peru	432 667	24 533	3 728	24 332	9 613 351	23 450
Uruguay	338 213	23 312	184	14 230	4 391 247	23 848

Source: According to the FAOSTAT and Nin-Pratt et al. (2015)

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Table 2. Efficiency measurements of the agricultural sector for 18 LAC countries in 2012

Country	Operational efficiency	Environmental efficiency	Unified efficiency as nonlinear programming	Unified efficiency as mixed integer programming
Best efficiency levels in all the efficiency measurements:				
Argentina	1.0000	1.0000	1.0000	1.0000
Belize	1.0000	1.0000	1.0000	1.0000
Bolivia	1.0000	1.0000	1.0000	1.0000
Brazil	1.0000	1.0000	1.0000	1.0000
Costa Rica	1.0000	1.0000	1.0000	1.0000
Mexico	1.0000	1.0000	1.0000	1.0000
Highest level of unified efficiency, but showing some inefficiency level in the other two measurements:				
Chile	0.9882	1.0000	1.0000	1.0000
Dominican Republic	1.0000	0.9716	1.0000	1.0000
Ecuador	1.0000	0.9740	1.0000	1.0000
Inefficiency scores under the unified efficiency measurement:				
Panama	1.0000	0.9883	0.9985	0.9985
El Salvador	0.9888	1.0000	0.9904	0.9904
Honduras	1.0000	0.9819	0.9877	0.9877
Nicaragua	0.9908	0.9673	0.9849	0.9849
Guatemala	1.0000	1.0000	0.9660	0.9660
Paraguay	0.9726	0.9206	0.9390	0.9390
Peru	0.9351	1.0000	0.9388	0.9388
Uruguay	1.0000	0.9186	0.9358	0.9358
Colombia	0.8604	1.0000	0.8784	0.8784
Average	*0.9853*	*0.9846*	*0.9789*	*0.9789*

of inputs, thus improving their agricultural competitiveness. They are followed by Nicaragua, El Salvador and Chile, with relatively small performances in terms of their operational efficiency, with efficiency levels of 0.9908, 0.9888 and 0.9882, respectively. This indicates that these countries made progress in improving their operational efficiencies by attaining a high operational efficiency of agricultural production. These three countries are followed by Paraguay with an efficiency score of 0.9726. Finally, Peru and Colombia had a lower operational efficiency, with efficiency levels of 0.9351 and 0.8604, respectively.

Figure 2 shows the environmental efficiency of the evaluated countries in relation to their performance in reducing agricultural emissions of CO_2 eq, which is measured using model (6). The results indicate that 11 countries, including Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, El Salvador, Guatemala, Mexico and Peru attained the maximum efficiency level (1.0000), i.e., these countries have per-

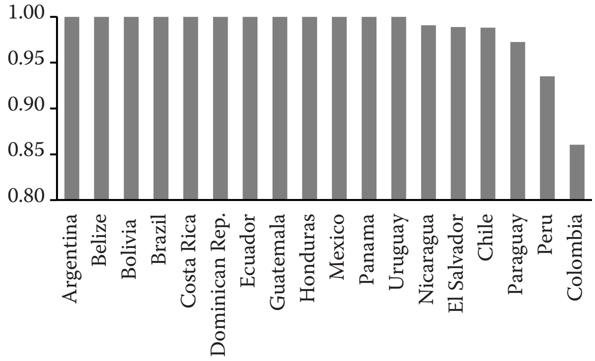

Figure 1. Operational efficiency

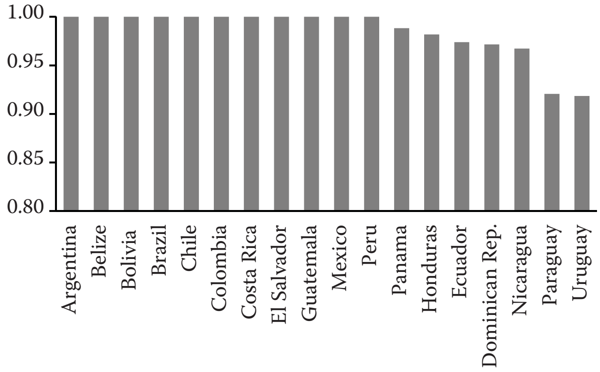

Figure 2. Environmental efficiency

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formed well in environmental efficiency compared to the other countries that were evaluated in this study. They are followed by Panama and Honduras, with efficiency levels of 0.9883 and 0.9819, respectively. Thus, the performance of these countries in reducing agricultural emissions of CO_2 eq. is comparatively high. These countries are followed by Ecuador, the Dominican Republic and Nicaragua, with efficiency levels of between 0.96 and 0.77. Paraguay and Uruguay had the lowest environmental efficiencies: 0.9206 and 0.9186, respectively.

In the preliminary results, operational and environmental efficiencies were treated separately. Still, the main objective of this study was to measure the unified efficiency because a production activity produces not only good outputs but also bad outputs. The unified efficiency is the integration of both the operational and environmental efficiency and provides a comprehensive evaluation of the performance of the agricultural sector by taking into account the efforts towards achieving specific agricultural production goals as well as, in an appropriate form, the environmental regulation targets that aim to reduce the agricultural emissions of CO_2 eq.

Figure 3 shows that Argentina, Belize, Bolivia, Brazil, Chile, Costa Rica, the Dominican Republic, Ecuador and Mexico attained the highest unified (operational and environmental) efficiency level (1.000), i.e., to improve their efficiency in agricultural activity and to satisfy the environmental targets, these countries pay attention not only to obtaining the highest agricultural production, but also to reducing the agricultural emissions of CO_2 eq. They are followed by Panama, El Salvador, Honduras and Nicaragua, with 0.9985, 0.9904, 0.9877 and 0.9849, respectively. The results show that these countries made progress in improving their agricultural goals by attaining a comparatively high unified (operational and environmental) efficiency. They are followed by Guatemala, with an efficiency score of 0.9660. Paraguay, Peru, Uruguay and Colombia had the lowest unified efficiencies, which ranged between 0.87 and 0.93.

Table 2 indicates that in 2012, the averages of the operational efficiency (0.9853) and environmental efficiency (0.9846) were relatively high when measured separately. However, the unified efficiency (0.9789) is still of a lower magnitude than the operational efficiency and environmental efficiency. In any case, it can be seen in Figure 4 that the operational efficiency became more balanced than the environmental and unified efficiency among the 18 LAC countries. This finding indicates that the 18 LAC countries have been primarily oriented towards satisfying their agricultural production goals and, secondly, their agricultural-environmental targets.

The radar chart (Figure 4) and Table 2 show three groups of countries. The first includes Argentina, Belize, Bolivia, Brazil, Costa Rica and Mexico. The second group is made up of Chile, the Dominican Republic and Ecuador. The last group includes Panama, El Salvador, Honduras, Nicaragua, Guatemala, Paraguay, Peru, Uruguay and Colombia.

The first group exhibits the best status, its countries having attained the maximum efficiency under the three models when compared to the other countries analysed. Nevertheless, achieving the maximum efficiency does not mean that they have reached the maximum efficiency in a real situation of agricultural productivity and environmental performance and,

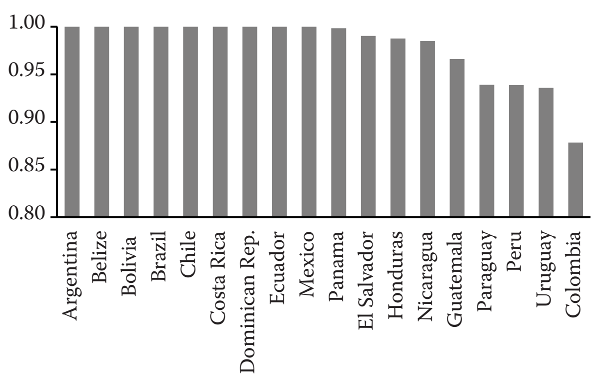

Figure 3. Unified (operational and environmental) efficiency

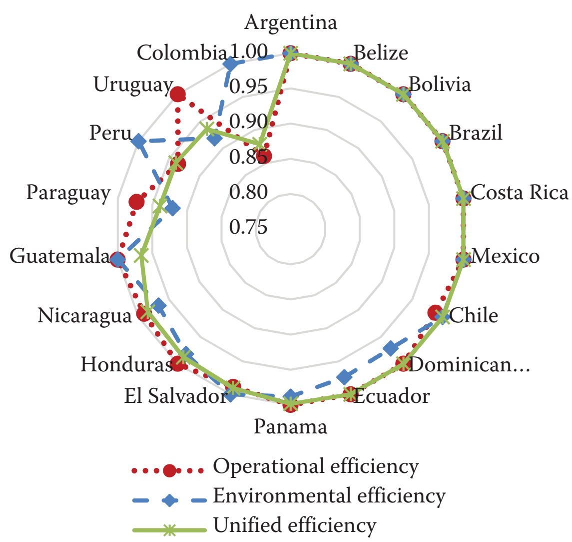

Figure 4. Comparison of the efficiency measurements for 18 LAC countries

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therefore, have no problems in terms of operational and environmental efficiency (Montoya and Soto 2010).

However, despite the slow growth of the LAC economies in 2012 (World Bank 2016), the results are a sign of the macroeconomic strength in each country. It must thus be concluded that these countries are concerned about confronting the important challenge of reducing their environmental carbon footprint – which is caused by unsustainable production practices – and are applying technological innovations in order to reconcile agricultural productivity and environmental performance. For that reason, these countries should be used as a benchmark for those countries that do not achieve maximum efficiency in all three models of this study and as guidance as they seek to improve their efficiency levels in the agricultural sector.

According to McCarthy (2014) and the World Bank et al. (2014), LAC countries have many types of strategies that constitute better agricultural practices. These already exist in different regions and are used to differing extents by farmers in their efforts to reconcile their agricultural productivity and their environmental performance. The first group of countries have for many years been developing better agricultural practices to improve their environmental performances in accordance with their national circumstances (World Bank et al. 2014). Nonetheless, the number of strategies used by them is related with the progress of their environmental regulation policies and their economic strength (CAF 2013). The priorities of each country are thus reflected in the results of this study over the period evaluated.

The second group of countries includes Chile, the Dominican Republic and Ecuador, which attained the maximum efficiency level (1.0000), but show some inefficiency level in the other two measurements. It is important to note that Chile exhibits a better environmental status because its environmental efficiency is always greater than its operational efficiency. However, from the unified efficiency point of view, the results concerning these countries represent important progress towards reconciling agricultural productivity and environmental performance and towards conforming with changes in environmental regulations.

The third group (Panama, El Salvador, Honduras, Nicaragua, Guatemala, Paraguay, Peru, Uruguay and Colombia) failed to reach the maximum unified efficiency score. However, Guatemala exhibits the highest score of operational efficiency and environmental efficiency when these are measured separately (1.000), which indicates that this country needs to continue its efforts in combining both operational and the environmental efficiency. Furthermore, environmental efficiency in El Salvador, Peru and Colombia is always greater than the operational efficiency, which demonstrates a better status for environmental protection.

Moreover, operational efficiency in Panama, Honduras and Uruguay is always greater than the environmental efficiency, which indicates that these countries are primarily concerned with achieving the highest agricultural production and secondly with satisfying the environmental regulation targets. Nicaragua and Paraguay have the worst scores as they do not reach any of the three efficiency measurements.

Slack values under the unified (operational and environmental) efficiency

Particularly under good conditions, all efficient countries have null slack values. Any country that does not have null slack values is inefficient, and the higher the slack values, the lower the efficiency of the evaluated country. Specifically, the input slack value is simply the extent to which a specific country has fallen short in achieving the maximum efficiency (1.000). So, the stacked bar chart (Figure 5) and Table 3 provide inefficient countries with strategic guidance on how they should vary the amount of inputs to improve their unified efficiency measurements.

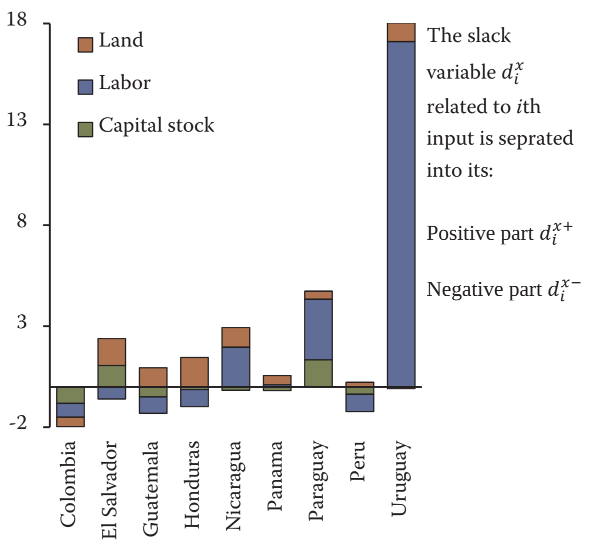

Figure 5. Slacks for the 9 LAC countries that exhibit inefficiency levels under the unified efficiency frontier

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Table 3. Slack values of inputs for the 9 inefficient LAC countries under the unified (operational and environmental) efficiency

Country	The directional vector of inputs is divided into two types: d_i^{x+} and d_i^{x-}								Agricultural production	Agricultural emissions (CO_2eq)
	fertilizers		capital stock		labor		land			
Colombia	0.00	0.00	0.00	0.82	0.00	0.68	0.00	0.46	0.00	0.28
El Salvador	0.00	0.00	1.06	0.00	0.00	0.60	1.32	0.00	0.68	0.00
Guatemala	0.00	0.00	0.00	0.49	0.00	0.82	0.94	0.00	0.01	0.00
Honduras	0.00	0.00	0.00	0.14	0.00	0.84	1.46	0.00	0.03	0.00
Nicaragua	0.00	0.00	0.00	0.17	1.97	0.00	0.97	0.00	0.31	0.00
Panama	0.00	0.00	0.00	0.18	0.10	0.00	0.46	0.00	0.00	0.00
Paraguay	0.00	0.00	1.34	0.00	3.00	0.00	0.40	0.00	1.07	0.00
Peru	0.00	0.00	0.00	0.37	0.00	0.86	0.22	0.00	0.06	0.00
Uruguay	0.00	0.00	0.00	0.09	17.10	0.00	0.93	0.00	0.87	0.02

In the inputs variables, the left column is for the (+) part and the right is for the (–) part, which symbolize the slacks of inputs under unified efficiency, respectively

Table 3 shows the slack values related to the input separated into its positive (d_i^{x+}) and negative (d_i^{x-}) parts, which are mutually exclusive. Therefore, El Salvador and Paraguay must increase the amount of capital stock by 1.06 and 1.34, respectively, because they have failed to use the capital stock at an optimal level. In contrast, capital stock should decrease in countries such as Colombia (0.82), Guatemala (0.49), Honduras (0.14), Nicaragua (0.17), Panama (0.18), Peru (0.37) and Uruguay (0.09), due to the incorrect use or overuse of their capital stock.

Table 3 also shows that Nicaragua, Panama, Paraguay, and Uruguay should improve their labour by 1.97; 0.10; 3.0; and 17.1, respectively, which indicates that the use of a suboptimal level of labour represents a weakness for these countries. On the other hand, labour must be decreased or managed more productively in countries such as Colombia (0.68), El Salvador (0.60), Guatemala (0.82), Honduras (0.84) and Peru (0.86), which implies that these countries are not properly managing their labour.

From Table 3, it can be seen that Colombia should decrease or centre its efforts in the agricultural area by 0.46, implying that the land is still being overused. On the contrary, land is still being used at a suboptimal level, and land management should be improved in countries such as El Salvador (1.32), Guatemala (0.94), Honduras (1.46), Nicaragua (0.97), Panama (0.46), Paraguay (0.40), Peru (0.22) and Uruguay (0.93). For example, in the case of land, this means that better management and a combination of new agricultural technologies represents an opportunity to expand agricultural land, improve efficiency and create a sustainable agriculture focused on the environment.

Measurement of the RTS and DTS

Table 4 shows the RTS and DTS measurements, which provide countries with strategic guidelines on how to improve efficiency measurements by controlling the size of agricultural activity, and provides direction on whether a country should introduce technological innovation for environmental protection.

Firstly, Belize, Nicaragua and Panama exhibit increasing RTS, which indicates that the proportion of agricultural production is more than the increase in all factors of production. Thus, it is better for these countries to increase agricultural activity in order to enhance their operational performance. Also, these countries number among those with decreasing DTS from the perspective of the environmental performance. Decreasing DTS indicates that an increase in all factors leads to a less than proportional increase in pollution. This finding puts these countries at an advantage when compared to the others: they can increase their agricultural activity by maintaining their current technological innovation because their pollutant discharge is decreasing. Nonetheless, it is important to highlight than an increase in agricultural activity without considering technological innovation is not recommended in the long-term for the environmental protection.

The above countries are followed by the Dominican Republic and Honduras with constant RTS, which indicates that agricultural production changes proportionally as all factors change. Theoretically, these countries may maintain their level of agricultural activity to sustain their operational performance. However, they exhibit decreasing DTS. Therefore,

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Table 4. RTS under operational efficiency and DTS under environmental efficiency

Country	RTS	DTS
Belize	increasing	decreasing
Nicaragua	increasing	decreasing
Panama	increasing	decreasing
Dominican Republic	constant	decreasing
Honduras	constant	decreasing
El Salvador	increasing	constant
Bolivia	constant	constant
Costa Rica	constant	constant
Chile	decreasing	constant
Colombia	decreasing	constant
Guatemala	decreasing	constant
Argentina	constant	increasing
Brazil	constant	increasing
Uruguay	constant	increasing
Ecuador	decreasing	increasing
Mexico	decreasing	increasing
Paraguay	decreasing	increasing
Peru	decreasing	increasing

RTS = return to scale, DTS = damage to scale

it is suggested that these countries increase their agricultural activity rather than simply maintain the current level; this, in turn, will lead to an increase in the wage bill. Alternatively, they should use technological innovation for environmental protection.

Chile, Colombia and Guatemala exhibit decreasing RTS, which indicates that the proportional increase in agricultural production is less than the increase in all the factors of production. Theoretically, the result indicates that further pursuing large-scale agricultural activity is not to be recommended from the operational performance point of view. Meanwhile, El Salvador exhibits increasing RTS. However, Bolivia and Costa Rica are characterised by constant RTS.

All of these countries exhibit constant DTS from the perspective of the environmental performance. This finding implies that the discharge of pollutants changes in proportion to the changes in all factors. The contribution of LAC to the GHG emissions was determined to be only 9.9% of global emissions (Sánchez and Reyes 2015); further, it has also contracted in 2015 (–0.6%) and 2016 (–1.0%); thus, the countries in this region need to keep pace with other nations and to register positive growth so as to improve their economic situation (United Nations 2017). Consequently, it is better for these countries to promote agricultural economic growth through technological innovation rather than simply maintaining or even decreasing their level of agricultural activity. That is, technological innovation can contribute not only to enhancing their operational performance, but also their environmental performance.

Lastly, the results also show that Argentina, Brazil and Uruguay exhibit constant RTS. Meanwhile, Ecuador, Mexico, Paraguay and Peru exhibit decreasing RTS. Furthermore, the results show that their discharge of pollutants is increasing due to their increasing DTS. Increasing DTS indicates that the pollution increases more than proportionally in response to an increase in the factors of production. In both cases, pursuing large-scale agricultural activity is associated with a very quick increase in pollution due to their increasing DTS. Thus, it is strongly recommended for all these countries to use technological innovation to reduce pollution.

CONCLUSIONS

In this study, we used DEA environmental assessment to measure operational efficiency, environmental efficiency and unified (operational and environmental) efficiency of agriculture in 18 LAC countries in 2012, and, through an empirical comparison, we also identified the type of RTS and DTS for each efficiency measurement.

The empirical comparison shows that six countries fulfil the three efficiency measurements. Argentina, Belize, Bolivia, Brazil, Costa Rica and Mexico exhibit the best agricultural performance. The empirical evidence showed that these countries are not only concerned about increasing agricultural production, but also about controlling their agricultural emissions (CO_2eq). Also, three countries, including Chile, the Dominican Republic and Ecuador exhibit the highest level (1.000) of unified efficiency, but they also show some degree of inefficiency in the other two measurements.

On the other hand, Guatemala exhibits the highest scores of operational efficiency and environmental efficiency when measured separately (1.000), but shows inefficiency in the unified efficiency measure. Some countries, such as Panama, Honduras and Uruguay, have become more efficient in agricultural production, i.e., operational efficiency (1.000). El Salvador, Peru and Colombia, meanwhile, have become more efficient in controlling their agricultural emissions (CO_2 eq), i.e., environmental efficiency (1.000). In addition, the empirical evidence shows that

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Nicaragua and Paraguay do not attain the maximum efficiency in any of the efficiency measurements that were analysed. i.e., they have the worst status. Hence, these countries may be able to improve their agricultural performance if they introduce better and more environmentally-friendly agricultural practices.

Seven countries exhibited decreasing RTS: Chile, Colombia, Guatemala, Ecuador, México, Paraguay and Peru. Seven countries also exhibited constant RTS: Argentina, Bolivia, Brazil, Costa Rica, the Dominican Republic, Honduras and Uruguay. Four countries, meanwhile, exhibited increasing RTS: Belize, Nicaragua, Panama and El Salvador. The economic implications are that these countries need to decrease, maintain and increase, respectively, the current level of agricultural activity from the perspective of operational performance.

In the DTS measurement, five countries exhibited decreasing DTS: Belize, Nicaragua, Panama, the Dominican Republic and Honduras. Six countries exhibited constant DTS: El Salvador, Bolivia, Costa Rica, Chile, Colombia and Guatemala. Furthermore, seven countries exhibited increasing DTS: Argentina, Brazil, Uruguay, Ecuador, Mexico, Paraguay and Peru. The economic implications are that these countries could vary the level of agricultural of activity, or alternatively, should use technological innovation in agriculture to further enhance environmental performance. Nonetheless, technological innovation will be the main tool for improving their unified (operational and environmental) efficiency of the agricultural activity.

This study has some limitations that must be pointed out. Firstly, the DEA model for the environmental assessment of this study does not take into account other agri-environmental variables such as water use and energy use. Second, only the year 2012 has been evaluated, i.e., a year characterised by a slowdown of growth in LAC. The main reason for this was the lack of data for all the LAC countries evaluated in this study. Therefore, this empirical study has not identified improvements or changes in efficiency that occurred over the years in each evaluated country.

Thus, a comprehensive assessment of the agricultural performance of LAC countries would be necessary in order to arrive at a broader understanding of the unified (operational and environmental) efficiency of each country. Future research using DEA for environmental assessment might include a larger number of years in the analysis. In such a study, the efficiency measurements of the agricultural sectors in LAC countries would be compared and the empirical comparison of these important evaluations would provide governments with information that will help them in developing strategies to strengthen the environmental efficiencies of their agricultural sectors.

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