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# ECO-EFFICIENCY OF FORESTRY COMPANIES AROUND THE WORLD: A DATA ENVELOPMENT ANALYSIS

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## ABSTRACT

**Objective:** to evaluate and compare the economic, environmental, and eco-efficiency of companies operating in the forestry sector and fill the gap in relation to the lack of information about the theme.

**Theoretical framework:** increased awareness of society around the traditional productive model and its impact on the environment demands that companies associate business competitiveness with environmental responsibility. Therefore, the disclosure of information and the analysis of it using methods such as the eco-efficiency approach are important to monitor the performance of companies.

**Methods:** the Data Envelopment Analysis method was used with three proposed models: economic (desirable output); environmental with undesirable variables; and eco-efficiency model with desirable and undesirable variables.

**Results and conclusions:** results show that the years 2009-2010 and 2016-2017 were more favorable to technical efficiency, while ecological efficiency was higher from 2010 to 2012. Meanwhile, the highest average eco-efficiency score was registered in 2013. In the 11 years analyzed, Portugal, Canada, United Kingdom, Australia, South Africa, and Spain stood out as the most eco-efficient countries.

**Research implications:** the eco-efficiency approach demonstrated and discussed in this research can be used to monitor forestry companies' performance taking into account their productivity and environmental impact reduction.

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**Originality/value:** this study presents a comprehensive evaluation of silviculture companies worldwide using the technical, environmental, and eco-efficiency models. Analyses are based on financial and environmental data of 82 publicly listed companies from 23 countries, including developed and developing economies and cover the period of 11 years (2009 to 2019).

**Keywords:** Cellulose, CO2, Sustainability, Productivity.

**ECOEFICIÊNCIA DE EMPRESAS FLORESTAIS EM TODO O MUNDO: UMA ANÁLISE DE ENVELOPAMENTO DE DADOS**

**RESUMO**

**Objetivo:** avaliar e comparar a eficiência econômica, ambiental e ecológica das empresas que atuam no setor florestal e preencher a lacuna em relação à falta de informações sobre o tema.

**Referencial teórico:** a crescente conscientização da sociedade sobre o modelo produtivo tradicional e seu impacto no meio ambiente exige que as empresas associem a competitividade empresarial à responsabilidade ambiental. Portanto, a divulgação de informações e a análise delas por meio de métodos como a abordagem da ecoeficiência são importantes para monitorar o desempenho das empresas.

**Métodos:** foi utilizado o método Data Envelopment Analysis com três modelos propostos: econômico (output desejável); ambiental com variáveis indesejáveis; e modelo de ecoeficiência com variáveis desejáveis e indesejáveis.

**Resultados e conclusões:** os resultados mostram que os anos de 2009-2010 e 2016-2017 foram mais favoráveis à eficiência técnica, enquanto a eficiência ecológica foi maior de 2010 a 2012. Entretanto, a maior pontuação média de ecoeficiência foi registrada em 2013. Nos 11 anos analisados, Portugal, Canadá, Reino Unido, Austrália, África do Sul e Espanha se destacaram como os países mais ecoeficientes.

**Implicações para a pesquisa**: a abordagem de ecoeficiência demonstrada e discutida nesta pesquisa pode ser usada para monitorar o desempenho das empresas florestais, levando em conta sua produtividade e a redução do impacto ambiental.

**Originalidade/valor:** este estudo apresenta uma avaliação abrangente das empresas de silvicultura em todo o mundo usando os modelos técnico, ambiental e de ecoeficiência. As análises são baseadas em dados financeiros e ambientais de 82 empresas de capital aberto de 23 países, incluindo economias desenvolvidas e em desenvolvimento, e abrangem o período de 11 anos (2009 a 2019).

**Palavras-chave:** Celulose, CO2, Sustentabilidade, Produtividade.



## 1 INTRODUCTION

As a tool for attributing to all productive agents the responsibility for maintaining environmental externalities at acceptable levels, the eco-efficiency approach measures the level of sustainable development considering economic impact, resources involved, and environmental impact (Zhang et al., 2021). Recently, the methodology has been successfully employed in academia, see, for example, de Araújo et al. (2021), and Zhu et al. (2022). In this context, the present research innovates and contributes to the literature by analyzing eco-efficiency in the forestry sector globally. Further, the study compares and discusses the economic and environmental efficiency, and eco-efficiency among companies.

Eco-efficiency refers to the creation of value with the least impact, that is, associating business competitiveness with environmental responsibility, so that the least possible damage is caused to the planet in the operational activity, this way creating a sustainable productive model (WBCSD, 2016). It reveals itself as a change of paradigm in the world economic model, which demands a change in how companies communicate with the market. In addition to economic and financial indicators, such as annual balance sheets and income statements, the market is increasingly requiring the disclosure of reports containing social and environmental information, for example, the Global Reporting Initiative (GRI, 2022). Recent studies by Gomes et al. (2015) and Prudêncio et al. (2020) analyze GRI reporting data from publicly listed companies and show that stakeholders react to negative environmental disclosures and that larger and better performing companies are more likely to disclose social and environmental information.

Nonetheless, criticisms have been made of companies who attempt to disclose information that only seeks to improve their image in the eyes of stakeholders, without highlighting in their reports data that actually contribute to the understanding of their environmental conduct toward sustainable development, for example, pollutant emission indicators (Mussoi, 2010). In this context, the eco-efficiency indicator presents an alternative for the disclosure of meaningful information regarding the environmental and economic performance of companies. The methodology provides a weighted comparability tool that accounts for the capacities and resources of each organization, and balances energy efficiency and polluting waste generated in the productive process (Van Zwieten et al., 2010).

We stress that, overall, the various economic sectors generate important economic impacts that also influence the quality of the environment by reducing carbon footprint with, for example, solid and organic waste management (Obersteiner et al., 2021). Therefore, there is a need for measuring economic performance while at the same time producing goods and services with less energy, resource, waste, and emissions (Luptacik, 2000).

Particularly in the agribusiness context, which includes the forestry sector, eco-efficiency has been applied more commonly in local and regional analyses rather than globally. For example, the study of Basset-Mens et al. (2009), which compares eco-efficiency between conventional and organic milk production, and Iribarren et al. (2011), who evaluated eco-efficiency in a large number of dairy farms, but their conclusions do not allow for global comparability.

The forestry sector is one of the main productive sectors that has been experiencing exponential growth in the world, especially the subsector of paper and cellulose production with high expansion and significant income from internal consumption and exportation in several countries when compared to other activities (Morgan and Daigneault, 2015; Susilawati and Kanowski, 2020). The application of intelligent mechanisms to assess environmental impacts derived from manufacturing activity is increasingly necessary (Haggith et al., 2018). Thus, cleaner production may be a parameter for trading a product and attracting stakeholders.

Although studies mention the eco-efficiency in the forestry sector in specific cases, see, for example, Sporcic et al. (2009) and Luptacik (2000), the main challenge is to measure eco-efficiency with companies' microdata and provide indicators to support decision-making and define economic policies. The authors further highlight issues related to the lack of assessments and market prices for the wastes and emissions. Koskela (2015) stresses that, although economic performance is associated with the definition of eco-efficiency, there is no consensus as to the operational estimation of this indicator. The author analyzed forestry industries in Finland using the Delphi panel technique, and indicators were determined based on specialists' evaluation. The study highlights the importance of comparing companies in this sector, not only in Finland but also around the world.

Accordingly, the present study aims to expand the research frontier by evaluating and comparing the efficiency of silviculture companies worldwide in a comprehensive way. To this end, we calculate three types of efficiency, technical, environmental, and eco-efficiency, for companies that operate in the forestry sector around the world using the Data Envelopment Analysis (DEA) approach proposed by Charnes et al. (1978). Results are based on the analysis of financial and environmental data of 82 publicly listed companies from 23 countries, including developed and developing economies and cover the period of 11 years (2009 to 2019). To the best of our knowledge, such a comprehensive study has never been conducted before.

The remaining of this study is structured as follows. Section 2 brings a review of relevant DEA related literature. Section 3 discusses some extensions to the DEA model when undesirable outputs are considered, as well as the eco-efficiency DEA models. Section 4 describes the employed methodology, while Section 5 presents and discusses the results. Finally, Section 6 presents the study conclusions and recommendations for future research.

## 2 DATA ENVELOPMENT ANALYSIS

The DEA model defines inputs and outputs to estimate the efficiency frontier, and in studies that use the DEA methodology to calculate eco-efficiency and environmental and economic efficiency, a wide range of variables are considered (see, for example, Dyckhoff and Allen (2001); Kuosmanen and Kortelainen (2005); Barba-Gutierrez et al. (2009); Iribarren et al. (2011); Oggioni et al. (2011); Picazo-Tadeo et al. (2011); Gomez-Limon et al. (2012); Picazo-Tadeo et al. (2012); Huang et al. (2014); Yin et al. (2014); Lorenzo-Toja et al. (2015).

Dyckhoff and Allen (2001) highlight that the DEA modeling for environmental efficiency or ecological models should consider desirable inputs and outputs together with undesirable ones such as $CO_2$ emission, which was employed as one of the environmental variables in the study of Kuosmanen and Kortelainen (2005).

Barba-Gutierrez et al. (2009) used a proxy of environmental impact as the input variable and retail price as the output variable. Iribarren et al. (2011) employed as inputs diesel, electricity, water, plastic silage, corn silage, grass silage, alfalfa and, as output variable the amount of product produced. Oggioni et al. (2011) studied the relationship between workforce, installed capacity, energy, and materials as inputs, and $CO_2$ and amount of production as outputs. The study of Picazo-Tadeo et al. (2011) considered as input variables the amount of seeds, nitrogen, phosphorus, pesticides, and energy, and as output variables the number of sales, associated subsidies, agri-environmental payments, and efficiency values. The relationship between consumed energy, fertilizers, pesticides, workforce, energy, and fixed land, considered as inputs, and energy fixed and exported by the harvested production and agricultural production, considered as outputs, was explored in the study of Gomez-Limon et al. (2012).

Picazo-Tadeo et al. (2012) applied the eco-efficiency indicator to measure the relationship between environmental pressure and added value and net result. Huang et al. (2014) studied the relationship between environmental pollutants and production value and Gross Domestic Product (GDP). Yin et al. (2014) used the indicator to study the relationship between energy consumption, material, water, greenhouse gas emissions, and damages in the ozone layer, as inputs, and GDP indicators, amount of product by service produced, net sales, and added value, as outputs. Lorenzo-Toja et al. (2015) considered as inputs the electricity use, chemical products consumption, and iodine production, and as outputs, the kilograms of suspended solids, treated water, and removed PO4. Further, Hu and Liu (2017) used the DEA approach to measure eco-efficiency by using, jointly, the added value of production and reduction of environmental impact.

According to Banker et al. (1984), the mathematical modeling used in DEA aims to analyze the efficiency of ex post facto management performance. One assumes, beyond efficacy (achievement of objectives) and productivity (better use of resources for production), the technical efficiency, and the current productivity level is compared to what could be more adequate. Such an efficiency measure may be oriented to reduce inputs or to increase product/output given a Decision Making Unit (DMU). For Dellnitz et al. (2018), the most popular DEA models are named CCR (developed by Charnes, Cooper, and Rhodes), CRS (constant return to scale), BCC (created by Banker, Charnes, and Cooper), and VRS (variable returns to scale).

To calculate the model, we assume *n* DMUs, denoted by (*j* = 1,2, . . ., *n*), each using *m* inputs (*i* = 1, 2, . . ., *m*) and producing *k* desirable (denoted by *r* = 1, 2, . . ., *k*) and *p* undesirable outputs (*s* = 1, 2, . . ., *p*). $Xi\,j \geq 0$ is the *i*-th input for the *j*-th DMU and $X \in R^{mxn}$, $Y^g \in R^{kxn}$, and $Y^b \in R^{pxn}$ are matrices composed of non-negative elements, containing the observed input and desirable and undesirable output measures for the DMUs.

In the original model, without undesirable outputs, proposed by Charnes et al. (1978), the efficiency measure of a DMU is defined as the ratio between the weighted sum of (desirable) outputs and the weighted sum of inputs subject to the restriction that the corresponding proportion for each DMU is lower or equal to one. The model defines optimal non-negative weights for the inputs and outputs according to each DMU.

Following the traditional DEA model and applied research related to technical efficiency and eco-efficiency demonstrated by Luptacik (2000), Dyckhoff and Allen (2001), Picazo-Tadeo et al. (2011), and Hu and Liu (2017), we employed the corresponding dual model, also called envelope model, for technical efficiency analysis. For elaboration, we denoted the assessed DMU by '0':

$$max_{\theta,\lambda,s^g,s^-} \quad \theta - \varepsilon\left(\sum_r S_r^g + \sum_i S_i^-\right) \tag{1}$$

Subject to

$$\sum_j \lambda_j y_{rj}^g - s_{r0}^g = y_{r0}^g \quad (r = 1,2,\dots,k) \tag{2}$$

$$\theta x_{i0} - \sum_j \lambda_j x_{ij} - s_i^- = 0 \quad (i = 1,2,\dots,m) \tag{3}$$

$$\lambda \geq 0 \quad (j = 1,2,\dots,n) \tag{4}$$

$$s_r^g \geq 0 \quad (r = 1,2,\dots,n) \tag{5}$$

$$s_i^- \geq 0 \quad (i = 1,2,\dots,n) \tag{6}$$

Where

λ denotes the weights for the DMUs, $s-$ is an input slack vector, and $s^g$ is a slack vector for (desirable) output. A DMU is efficient if the following two conditions are met:

a) $\theta^0 = 1$

b) $s_i^{-0} = s_r^{g^0} = 0$ for every *i* and *r* with subscript "0", denotes the optimal solution for the (1)- (6) problem.

The $\theta_0^o$ (scalar) variable provides the ratio of all inputs for $DMU_0$ that must be sufficient – in comparison with the efficient units – to achieve the levels of output. In other words, $1 - \theta_0^0$ gives the proportional reduction needed for all inputs from the assessed $DMU_0$ to be efficient (input-oriented model). The slacks different from zero and $\theta^o < 1$ value identify the sources and inefficiency values for each input and output of the assessed DMU.

Restriction (3) implies that even after the proportional reductions of all inputs, the assessed inputs from $DMU_0$ cannot be lower than the inputs $\Sigma\lambda_j x_{ij}$ ($i$ = 1, 2,..., $m$) of the composite unit. The same happens with restriction (2), where the (desirable) outputs from $DMU_0$ cannot be higher than the (desirable) outputs $\Sigma_j\lambda_j y_{rj}^g$ (r=1,2,...,$k$) of the composite unit. The $DMU_0$ will be efficient when it is impossible to build a composite unit that surpasses $DMU_0$. Positive values of $\lambda_j$ provide the linear combination of DMUs at the efficiency frontier closest to $DMU_0$ (the group of pairs for $DMU_0$). Thus, equations (1) - (6) build the piecewise linear envelopment surface.

## 3 DEA METHOD FOR ECO-EFFICIENCY

Technical efficiency is calculated using the traditional CCR model as defined in the literature by Charnes et al. (1978) and presented in equations (1)-(6). However, for calculating the eco-efficiency indicator undesirable outputs need to be included in the model, following the DEA model construction perspective of Luptacik (2000).

Luptacik (2000) named the model ecological efficiency, which is defined as the ratio between the weighted sum of outputs and the weighted sum of undesirable outputs. The model simultaneously considers inputs and outputs, either desirable or undesirable. We treat $CO_2$ emissions as inputs in the sense that we wish to expand the desirable outputs and reduce the undesirable outputs and inputs.

This idea takes the following model:

$$max_{u,v,d} \quad h_0 = \frac{\sum_r u_r y_{r0}^g}{\sum_i v_i x_{i0} + \sum_s d_s y_{s0}^b} \tag{7}$$

Subject to:

$$\frac{\sum_r u_r y_{rj}^g}{\sum_i v_i x_{ij} + \sum_s d_s y_{sj}^b} \leq 1 \quad (j = 1,2,\dots,n) \tag{8}$$

$$u_r = \varepsilon \quad (r = 1,2,\dots,k) \tag{9}$$

$$v_i = \varepsilon \quad (r = 1,2,\dots,m) \tag{10}$$

$$d_s = \varepsilon \quad (r = 1,2,\dots,p) \tag{11}$$

The transformation produces the following multiplier problem:

$$max_{\mu,v,\delta} \quad h_0 = \sum_r \mu_r y_{r0}^g \tag{12}$$

Subject to:

$$\sum_r \mu_r y_{rj}^g - \sum_s \delta_s y_{sj}^b - \sum_i v_i x_{ij} \leq 0 \quad (j = 1,2,\dots,n) \tag{13}$$

$$\sum_i v_i x_{i0} + \sum_s \delta_s y_{sj}^b = 1 \tag{14}$$

$$\mu_r \geq \varepsilon \quad (r = 1,2,\dots,k) \tag{15}$$

$$v_i \geq \varepsilon \quad (i = 1,2,\dots,m) \tag{16}$$

$$\delta_s \geq \varepsilon \quad (s = 1,2,\dots,p) \tag{17}$$

And the following envelope model:

$$max_{\theta,s^g,s^b,s^-} \quad \theta - \varepsilon\left(\sum_r S_r^g + \sum_s S_s^b + \sum_s S_j^-\right) \tag{18}$$

Subject to:

$$\sum_j \lambda_j y_{rj}^g - s_r^g = y_{r0}^g \quad (r = 1,2, \dots, k) \tag{19}$$

$$\theta y_{s0}^b - \sum_j \lambda_j y_{sj}^b - s_s^b = 0 \quad (s = 1,2, \dots, m) \tag{20}$$

$$\theta x_{i0} - \sum_j \lambda_j x_{ij}^b - s_i^- = 0 \quad (i = 1,2, \dots, m) \tag{21}$$

$$s_r^g \geq 0 \quad (r = 1,2, \dots, k) \tag{22}$$

$$s_s^b \geq 0 \quad (s = 1,2, \dots, p) \tag{23}$$

$$s_i^- \geq 0 \quad (i = 1,2, \dots, m) \tag{24}$$

In this model, the DMU simultaneously reduces the inputs and emissions to increase eco-efficiency. Considering that the DEA models produce the best possible result for each decision-making unit, the eco-efficiency measured by models (12) - (17) and (18) - (24) cannot be lower than that obtained by the composition of technical and ecological efficiencies, as defined by Luptacik (2000).

The present study defines the eco-efficiency variable as the ratio between the firm's revenue and $CO_2$ emissions. Accordingly, revenue is denoted by the *r* variable generated in production processes by a set of $k = 1, \ldots, K$ firms in the forestry sector. Additionally, the production process generates a set of $n = 1, \ldots, N$ environmental emissions, denoted by $p = (p_1, \ldots, p_n)$.

Following Kuosmanen and Kortelainen (2005) and Picazo-Tadeo et al. (2011), the eco-efficiency of firm k is defined as:

$$Ecoefficiency_k = \frac{r_k}{P(p_k)} \tag{25}$$

## 4 MATERIALS AND METHODS

Table 1 presents the descriptive statistics for the variables used to estimate the applied models. The variables revenue, asset, and operating expense are in US$. The $CO_2$ emissions are measured in tons and the Eco-efficiency in US$/tons.[9]

**Table 1.** Variables descriptive statistics

| Year | Variable | Mean | Median | Std. dev. | Skewness | Kurtosis | N |
|---|---|---|---|---|---|---|---|
| 2009 | Eco-efficiency | 4,589 | 3,232 | 5,115 | 2.96 | 8.82 | 31 |
| | Asset | 7,046,764,014 | 5,002,800,000 | 6,451,966,481 | 1.37 | 0.84 | 31 |
| | Operating expense | 5,202,619,740 | 3,344,545,000 | 4,680,173,271 | 1.62 | 2.61 | 31 |
| | CO2 | 2,129,021 | 1,123,000 | 2,748,683 | 2.33 | 5.72 | 31 |

[9] Differently from economic information, which publicly listed companies are obliged to publish, ecological and eco-efficiency indicators are not mandatory. Therefore, there is no standardization regarding these variables, which considerably impacted the data collection, and a relative analysis of the information available.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Total revenue | 5,426,977,362 | 3,686,061,989 | 4,887,583,852 | 1.76 | 3.51 | 31 |
| 2010 | Eco-efficiency | 5,085 | 3,457 | 5,856 | 2.97 | 8.47 | 36 |
| | Asset | 6,961,327,433 | 5,040,981,410 | 6,106,219,620 | 1.41 | 1.15 | 36 |
| | Operating expense | 5,227,727,280 | 3,628,430,500 | 4,539,020,251 | 2.03 | 5.31 | 36 |
| | CO2 | 2,196,834 | 1,241,009 | 2,835,077 | 2.51 | 7.21 | 36 |
| | Total revenue | 5,659,755,684 | 4,135,460,500 | 4,830,162,609 | 2 | 5.07 | 36 |
| 2011 | Eco-efficiency | 6,030 | 4,347 | 6,724 | 2.7 | 7.59 | 38 |
| | Asset | 7,325,265,262 | 5,188,010,908 | 6,538,737,025 | 1.38 | 1.12 | 38 |
| | Operating expense | 5,600,418,150 | 3,968,050,000 | 4,808,803,487 | 1.7 | 3.45 | 38 |
| | CO2 | 2,261,480 | 955,377 | 3,203,836 | 2.7 | 8.7 | 38 |
| | Total revenue | 5,983,301,823 | 4,373,566,000 | 5,104,453,276 | 1.79 | 4.01 | 38 |
| 2012 | Eco-efficiency | 6,276 | 3,481 | 7,892 | 3.03 | 10.56 | 44 |
| | Asset | 7,497,529,207 | 5,402,956,220 | 6,758,786,150 | 1.54 | 2.32 | 44 |
| | Operating expense | 5,359,477,741 | 3,820,969,660 | 4,580,497,414 | 1.29 | 1.09 | 44 |
| | CO2 | 2,223,211 | 884,104 | 2,996,797 | 2.5 | 7.79 | 44 |
| | Total revenue | 5,644,852,934 | 4,203,089,131 | 4,682,183,415 | 1.37 | 1.6 | 44 |
| 2013 | Eco-efficiency | 12,711 | 3,792 | 44,548 | 6.02 | 36 | 45 |
| | Asset | 7,744,560,638 | 5,709,913,465 | 6,587,471,536 | 1.5 | 2.25 | 45 |
| | Operating expense | 5,452,438,893 | 4,163,600,000 | 4,405,793,388 | 1.46 | 2.29 | 45 |
| | CO2 | 2,296,785 | 1,192,045 | 2,943,639 | 2.38 | 7.23 | 45 |
| | Total revenue | 5,873,832,080 | 4,682,624,890 | 4,652,702,179 | 1.52 | 2.68 | 45 |
| 2014 | Eco-efficiency | 11,203 | 4,218 | 36,361 | 6.29 | 39.79 | 50 |
| | Asset | 6,788,364,106 | 4,576,847,855 | 5,957,377,379 | 1.44 | 2.07 | 50 |
| | Operating expense | 5,034,293,463 | 4,008,450,000 | 4,213,107,949 | 1.59 | 3.39 | 50 |
| | CO2 | 2,150,007 | 1,253,622 | 2,680,477 | 2.19 | 6.13 | 50 |
| | Total revenue | 5,433,599,944 | 4,239,800,000 | 4,464,763,116 | 1.59 | 3.43 | 50 |
| 2015 | Eco-efficiency | 9,646 | 3,547 | 33,071 | 6.41 | 41.34 | 52 |
| | Asset | 6,761,413,269 | 4,424,734,108 | 6,420,414,247 | 1.64 | 2.74 | 52 |
| | Operating expense | 4,558,431,951 | 3,588,629,500 | 3,731,578,562 | 1.4 | 2.44 | 52 |
| | CO2 | 2,151,798 | 1,025,728 | 2,627,789 | 1.97 | 4.66 | 52 |
| | Total revenue | 4,986,642,584 | 3,962,085,500 | 4,045,107,394 | 1.41 | 2.51 | 52 |
| 2016 | Eco-efficiency | 9,617 | 2,947 | 35,136 | 6.71 | 45.35 | 56 |
| | Asset | 6,597,347,774 | 4,159,801,500 | 6,548,467,414 | 1.69 | 3.31 | 56 |
| | Operating expense | 4,217,228,437 | 3,015,317,150 | 3,642,608,702 | 1.56 | 2.7 | 56 |
| | CO2 | 2,230,071 | 943,483 | 2,799,334 | 1.78 | 2.97 | 56 |
| | Total revenue | 4,589,488,238 | 3,276,985,145 | 3,833,483,802 | 1.52 | 2.7 | 56 |
| 2017 | Eco-efficiency | 9,231 | 4,218 | 27,620 | 6.83 | 48 | 62 |
| | Asset | 6,367,543,175 | 4,601,585,000 | 6,466,004,243 | 1.9 | 4.34 | 62 |
| | Operating expense | 4,407,838,959 | 3,323,162,515 | 3,876,963,484 | 1.53 | 2.66 | 62 |
| | CO2 | 1,884,034 | 791,091 | 2,556,956 | 2.18 | 5.04 | 62 |
| | Total revenue | 4,855,888,912 | 3,709,733,697 | 4,179,392,124 | 1.54 | 2.85 | 62 |
| 2018 | Eco-efficiency | 8,294 | 3,843 | 23,048 | 7.13 | 53.43 | 72 |
| | Asset | 6,162,310,113 | 3,671,050,677 | 6,536,339,590 | 1.8 | 3.64 | 72 |
| | Operating expense | 4,283,980,771 | 3,247,341,791 | 4,036,247,417 | 1.54 | 2.57 | 72 |
| | CO2 | 1,874,716 | 749,355 | 2,750,111 | 2.35 | 5.56 | 72 |
| | Total revenue | 4,747,755,007 | 3,511,186,500 | 4,428,309,058 | 1.59 | 3.05 | 72 |
| 2019 | Eco-efficiency | 7,877 | 3,229 | 22,756 | 7.1 | 54.09 | 81 |
| | Asset | 6,261,036,645 | 3,594,640,382 | 7,064,075,003 | 1.78 | 3.05 | 81 |
| | Operating expense | 4,007,005,432 | 2,566,125,597 | 3,961,389,964 | 1.62 | 3 | 81 |
| | CO2 | 1,819,583 | 775,338 | 2,614,736 | 2.37 | 5.82 | 81 |
| | Total revenue | 4,361,863,782 | 2,859,732,000 | 4,317,230,290 | 1.65 | 3.21 | 81 |

**Source:** Elaborated by the authors (2023)

The database consists of data from publicly listed companies in the forestry sector from 2009 to 2019, available on the Thomson Reuters platform, which was arranged annually based on the availability of environmental data The desirable output considered is the industry's revenue and the undesirable output the $CO_2$ emissions. As inputs, we considered the operating expense and the firms' total assets.

Data correlation is an important factor to be considered for data envelopment analysis. Figure 1 presents a polynomial regression between revenue and $CO_2$ emissions and the correlation between expense and revenue. The polynomial function initially shows a strong positive correlation between revenue and $CO_2$ emissions, however, as revenue increases this correlation tends to ease.

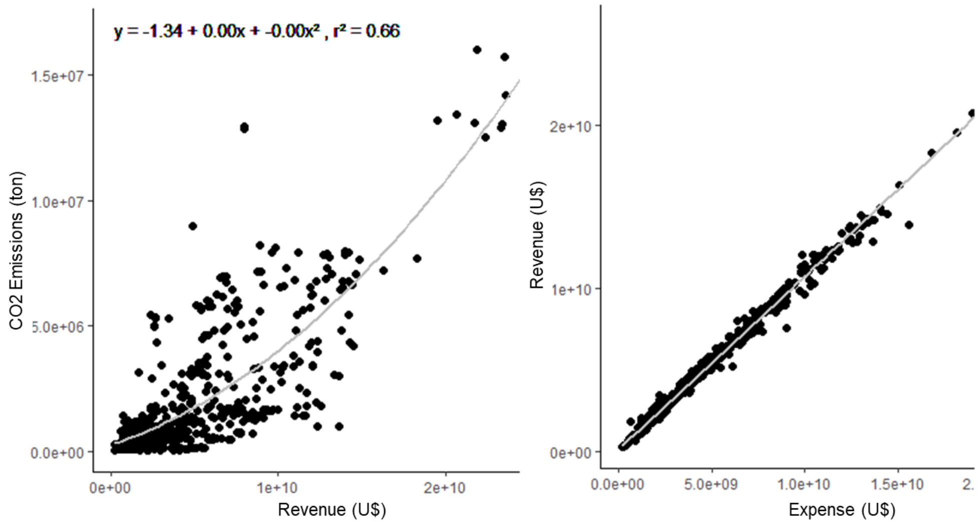


**Fig 1.** Polynomial regression and correlation
Source: Elaborated by the authors (2023)

The choice of inputs and outputs for the three specified models were based on the studies of Yin et al. (2014), Wang et al. (2015), Augustynczik et al. (2018), and Petrov et al. (2019) for model 1(technical or economic efficiency); Sueyoshi and Goto (2011) and Wang et al. (2015) for model 2(environmental or ecological efficiency); and Picazo-Tadeo et al. (2011), Oggioni et al. (2011), and Chen and Jia (2017) for model 3(eco-efficiency).

For Model 1 (Technical Efficiency) we defined the following function:

$$Revenue_{it} = f\,(Asset_{it} + Expense_{it})$$

Where:

The revenue of firm *i* at time *t* is the output and the assets and expenses of firm *i* at time *t* are inputs in the model. For Model 2 (Ecological) we consider $CO_{2it}$ emissions as undesirable input and the firm's revenue as output, with the objective of directly relating an undesirable input and its impact on the result of firm *i* at time *t*, as per:

$$Revenue_t = CO_{2t}$$

For Model 3 (Eco-efficiency), as per equation (25), the output considered is the ratio between revenue and $CO_2$ emissions of firm *i* at time *t*, and the inputs are $CO_{2it}$ emissions (undesirable) and revenue of firm *i* at time *t*:

$$Eco\text{-}efficiency = CO_{2it} + Revenue_{it}$$

After defining the models, the estimations were performed using the R programming language, and the Benchmarking[10] package by Bogetoft and Otto (2010). Data Envelopment Analysis provides a relative assessment of performance (benchmarking), which highlights the leading firms in the segment according to the analyzed variables and specified models. Bogetoft and Otto (2010) report that despite some criticisms, the use of DEA for DMU ranking offers a valuable tool to identify DMUs with 100% relative efficiency that can become role models. The assessment of relative performance, or benchmarking, was conducted according to Charnes et al. (1984) and Lins et al. (2003), performing the ranking of firms serving as benchmarks for other companies in the sector.

[10] More details see: https://cran.r-project.org/web/packages/Benchmarking/index.html

## 5 RESULTS AND DISCUSSION

The initial analysis indicates that between 2009 and 2012 the eco-efficiency indicator measured by the $\frac{r_k}{P(p_k)}$ ratio was quite low. From 2013, the eco-efficiency proxy increases significantly and reaches levels considerably higher than those at the beginning of the investigated period. The boxplot presented in Figure 2 illustrates the companies that stood out in the relation between $CO_2$ emissions and firm revenue from 2013. Further, as shown in Table 1, 2013 had the highest mean eco-efficiency value among all years analyzed.

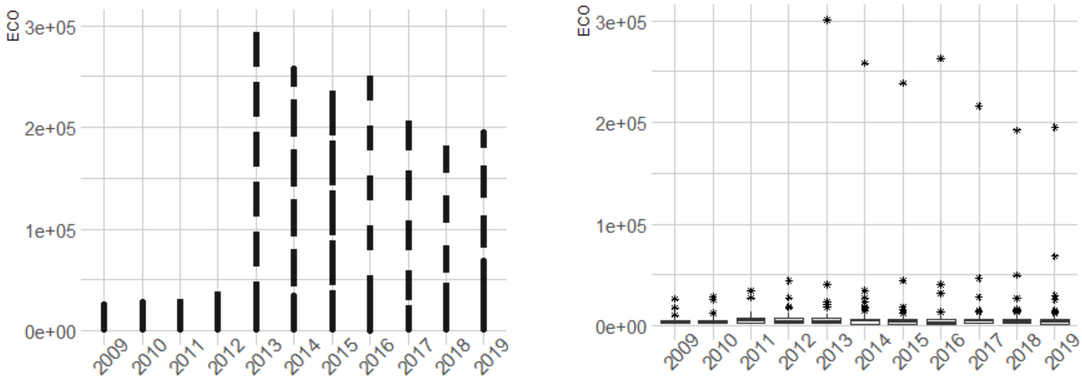


**Fig 2.** Ecoefficiency ratio during the analyzed period
Source: Elaborated by the authors (2023)

Table 2 brings the results for the efficiency score obtained by companies in the forestry sector in each model, in the period from 2009 to 2019. According to the results, 2019 recorded the lowest mean technical efficiency value at 0.9055, with a standard deviation of 0.07, and a minimum value of 0. Interestingly, 2019 registered the lowest mean values for the variables revenue and expense (see Table 1). The highest mean for the technical efficiency model was obtained in 2013 at 0.9599.

**Table 2.** Results of the estimated models by year

| Year | n | Model | Mean | Median | Std. dev. | Min | Max |
|---|---|---|---|---|---|---|---|
| 2009 | 31 | Technical | 0.92827 | 0.93731 | 0.073 | 0.73625 | 1 |
| | | Environmental | 0.60242 | 0.5538 | 0.28464 | 0.17429 | 1 |
| | | Eco-efficiency | 0.22938 | 0.15542 | 0.26479 | 0.04775 | 1 |
| 2010 | 36 | Technical | 0.95965 | 0.96788 | 0.04541 | 0.80325 | 1 |
| | | Environmental | 0.6235 | 0.56276 | 0.26861 | 0.20405 | 1 |
| | | Eco-efficiency | 0.20534 | 0.12371 | 0.25169 | 0.03313 | 1 |
| 2011 | 38 | Technical | 0.94268 | 0.95067 | 0.05399 | 0.74346 | 1 |
| | | Environmental | 0.56792 | 0.46946 | 0.28714 | 0.1527 | 1 |
| | | Eco-efficiency | 0.21483 | 0.1514 | 0.25034 | 0.03353 | 1 |
| 2012 | 44 | Technical | 0.93369 | 0.94767 | 0.06181 | 0.76452 | 1 |
| | | Environmental | 0.52967 | 0.44769 | 0.29938 | 0.09703 | 1 |
| | | Eco-efficiency | 0.23182 | 0.10649 | 0.29851 | 0.02301 | 1 |
| 2013 | 45 | Technical | 0.95991 | 0.959 | 0.03918 | 0.85918 | 1 |
| | | Environmental | 0.57663 | 0.51982 | 0.28021 | 0.09395 | 1 |
| | | Eco-efficiency | 0.10956 | 0.01295 | 0.28302 | 0.00296 | 1 |
| 2014 | 50 | Technical | 0.94928 | 0.95151 | 0.04523 | 0.82638 | 1 |
| | | Environmental | 0.52913 | 0.45468 | 0.28118 | 0.09353 | 1 |
| | | Eco-efficiency | 0.1143 | 0.01719 | 0.27133 | 0.00195 | 1 |
| 2015 | 52 | Technical | 0.94905 | 0.95641 | 0.04761 | 0.81618 | 1 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Environmental | 0.48585 | 0.42988 | 0.26977 | 0.07434 | 1 |
| | | Eco-efficiency | 0.06436 | 0.01815 | 0.19156 | 0.00218 | 1 |
| 2016 | 56 | Technical | 0.95755 | 0.96316 | 0.04319 | 0.78458 | 1 |
| | | Environmental | 0.49695 | 0.4516 | 0.28664 | 0.07814 | 1 |
| | | Eco-efficiency | 0.06152 | 0.01674 | 0.18491 | 0.00206 | 1 |
| 2017 | 62 | Technical | 0.93176 | 0.94371 | 0.06281 | 0.77149 | 1 |
| | | Environmental | 0.47504 | 0.43254 | 0.27794 | 0.07057 | 1 |
| | | Eco-efficiency | 0.07968 | 0.02762 | 0.18025 | 0.00407 | 1 |
| 2018 | 72 | Technical | 0.91492 | 0.91913 | 0.07845 | 0.51127 | 1 |
| | | Environmental | 0.38592 | 0.33817 | 0.26161 | 0.06041 | 1 |
| | | Eco-efficiency | 0.08668 | 0.02995 | 0.17344 | 0.0032 | 1 |
| 2019 | 81 | Technical | 0.90552 | 0.92121 | 0.07785 | 0.59042 | 1 |
| | | Environmental | 0.37185 | 0.31681 | 0.27815 | 0.04252 | 1 |
| | | Eco-efficiency | 0.08997 | 0.03218 | 0.17037 | 0.00318 | 1 |

**Source:** Elaborated by the authors (2023)

Differently, the highest mean value for the ecological model was achieved in 2010 (0.6235), while 2019 had the lowest mean (0.3718). The standard deviation was recorded at 0.2686 and 0.2781 for the years 2010 and 2019 respectively.

Lastly, the eco-efficiency model presented the lowest levels of efficiency when compared to the previous two models. As shown in Table 2, all mean scores for the eco-efficiency model are below 0.24, with the lowest mean value registered in 2016 at 0.0615 and the highest mean value recorded in 2012 at 0.2318.

The proportion of companies that reached maximum technical efficiency scores, relative to the total of observations, were higher in the years 2009 and 2013at 32.26% and 31.11% respectively. Figure 3 shows, for the entire analyzed period, the number of times that companies achieved the highest level of technical efficiency by country. We highlight the United States (47 times), United Kingdom (19 times), Canada (11 times), and Brazil and Australia (7 times each). Among the countries with the largest forest areas in the world (Russia, Brazil, Canada, United States, and China, respectively), according to FAO (2016), only Russia did not present a company with a maximum technical efficiency score.

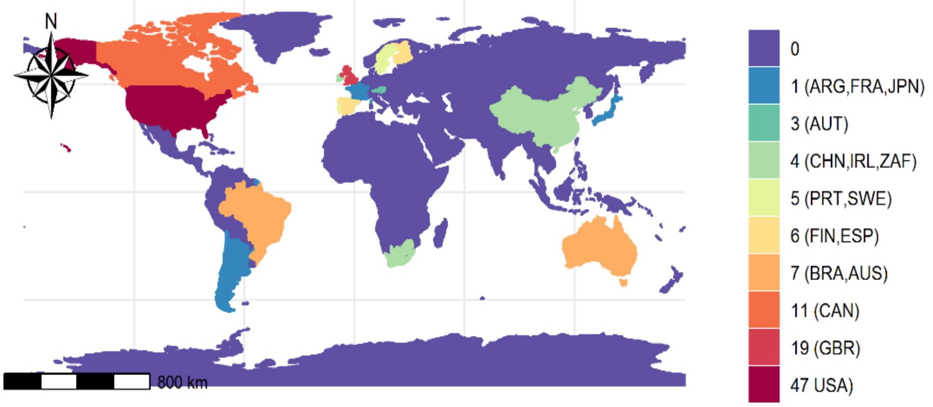


**Fig 3.** Technical efficiency between 2009 to 2019
Note: ARG – Argentina, FRA – France, JPN – Japan, AUT – Austria, CHN – China, IRL – Ireland, ZAF – South Africa, PRT – Portugal, SWE – Sweden, FIN – Finland, ESP – Spain, BRA – Brazil, AUS – Australia, CAN – Canada, GBR – United Kingdom, and USA – United States
**Source:** Elaborated by the authors (2023)

It is important to highlight that the silviculture activity is not only economically relevant but also environmentally since the planted area acts directly on carbon sequestration. Recently, the production of cellulose and paper has become an increasingly significant source of exportation in several countries (Susilawati and Kanowski, 2020), and may have contributed to the result recorded for the United States, United Kingdom, and Canada, essentially.

Following, the percentage of companies that achieved maximum ecological efficiency as per the DEA model, compared to the total of annual observations, was higher in 2010 and 2012 with16.67% and 15.91% respectively. Figure 4 illustrates, by country, the total number of times that companies achieved maximum ecological efficiency scores during the years analyzed. The best ranking countries were United States (18 times), Australia (10 times), United Kingdom (8 times), and Canada (7 times). These countries were also best classified in the previous technical efficiency map, except for Brazil which is not among the best ranking countries according to the ecological efficiency model.

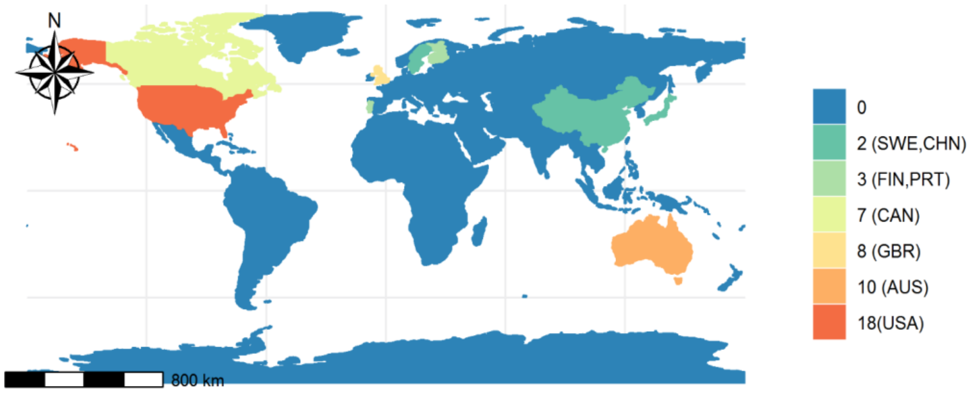


**Fig 4.** Ecological efficiency between 2009 to 2019
Note: SWE – Sweden, CHN – China, FIN – Finland, PRT – Portugal, CAN – Canada, GBR – United Kingdom, AUS – Australia, and USA – United States
**Source:** Elaborated by the authors (2023)

Brazil has the second largest forest area in the world (FAO, 2016) and, compared to other countries with a traditional silviculture sector, Brazil has great potential to grow in the forestry industry due to the existence of vast land and a climate favorable to forestation. Data from the Parana Association of Forest-Based Companies - APRE (2018) reveal that the Brazilian leadership in the forestry sector is largely attributed to investments in technology and better forest management practices by companies in the sector, in addition to favorable climate and soil. Despite that, Valverde et al. (2015) stress that Brazilian lack of public policies encouraging sustainable development and the country's low participation in environmental global commitments discourage investors. This is further evidenced by the absence of Brazilian firms in the ecological efficiency model and eco-efficiency model presented next.

Although companies in the forestry sector usually show a higher level of environmental responsibility, they still pollute via, for example, the production of residues, consumption of energy coming from fossil fuels, water usage, and greenhouse gas emissions. Thus, economic efficiency must be linked to environmental efficiency, creating the denominated eco-efficient companies.

Regarding the eco-efficiency DEA model, the proportion of companies that achieved maximum efficiency score, in relation to the total number of companies in each year, was registered in 2009 and 2012 at 9.68% and 11.36% respectively. Meanwhile, the lowest proportion is found for 2019, with only 2 of the 81 companies (2.47%) analyzed that year achieving eco-efficiency.

Figure 5 shows, in the period from 2009 to 2019, the total number of times that companies of each country achieved the highest level of eco-efficiency. We highlight Portugal (10 times), Canada (8 times), United Kingdom (5 times), and Australia (4 times). According to Ferreira et al. (2019), Portugal has a strong forestry sector that contributes about 5% to the country's total foreign exchange revenue, and production is exported to more than 140 countries. Our results show that forestry companies in Portugal are not solely concerned about increasing revenue and economic output but also about environmental aspects such as reducing greenhouse gas emissions.

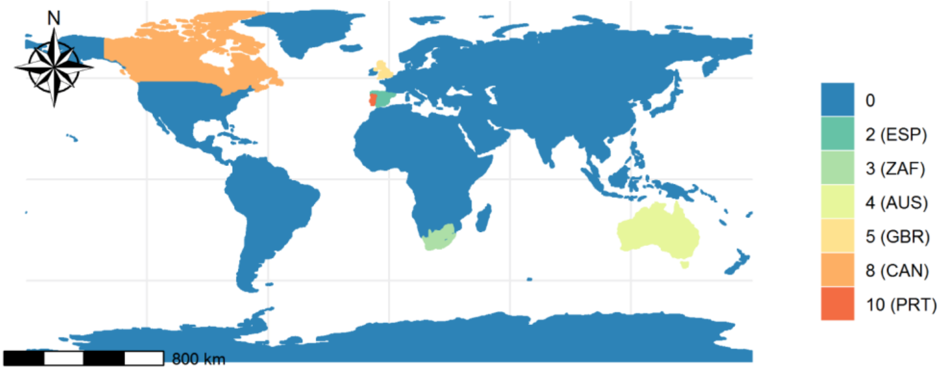


**Fig 5.** Eco-efficiency between 2009 to 2019
Note: ESP – Spain, ZAF – South Africa, AUS – Australia, GBR – United Kingdom, CAN – Canada, and PRT – Portugal
**Source:** Elaborated by the authors (2023)

Among the 3 models presented, the eco-efficiency one has the lowest proportion of companies that reached maximum efficiency results in the 11 years analyzed. In total, organizations reached efficiency 32 times, against 48 and 103 in the ecological and technical efficiency models respectively.

Figure 6 shows the comparison of the mean and standard deviation between the three efficiency models. As illustrated, during the period analyzed, the highest means were achieved in 2010 and 2013 for the technical efficiency model, 2009 and 2010 for environmental efficiency, and 2009 to 2012 for the eco-efficient model. Such a result may indicate greater environmental concern by the companies in this sector in the past, which has been steadily decreasing in recent years.

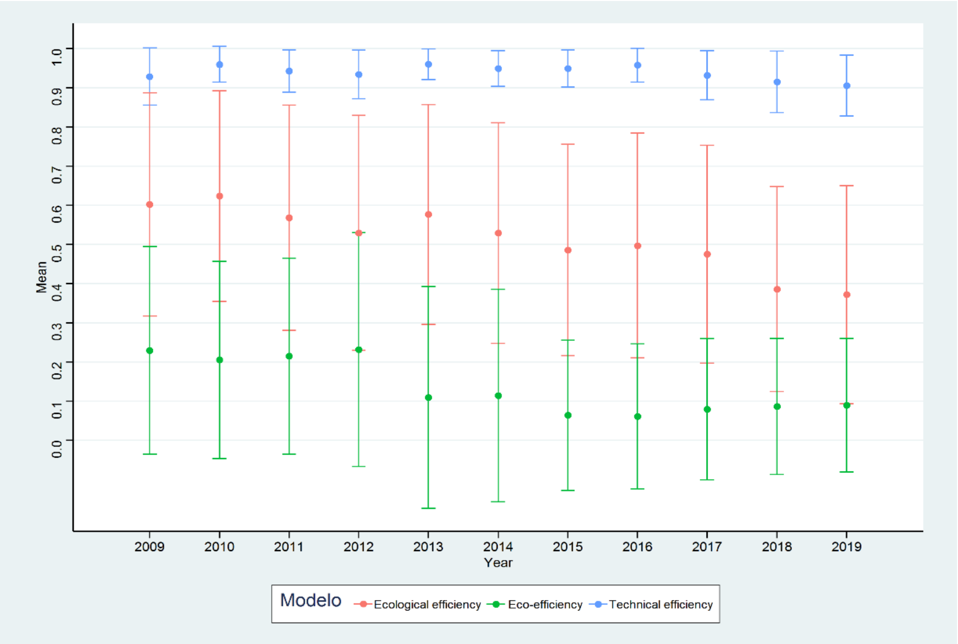


**Fig 6.** Average efficiency score comparison.
**Source:** Elaborated by the authors (2023)

According to Vellani (2009), companies seeking to improve eco-efficiency tend to increase their environmental expenditures. A better eco-efficiency indicator means an increase in revenue and/or decrease in carbon gas emissions and, to do that, environmental expenditures must be combined with clean energy technology usage, which reduces greenhouse gas emissions.

Another important analysis refers to the identification of companies considered the best benchmark for others in the period analyzed. As usual, results from most DEA models analysis reveal more than one DMU tied at maximum efficiency which makes it difficult to rank the DMUs. We followed the benchmarking procedure described by Charnes et al. (1984) and Lins et al. (2003) which ranks the firms based on the number of times an efficient firm is selected as a target by the inefficient companies. The results of such analysis are presented in tables A1, A2, and A3 of the appendix.

The firms considered the best benchmarks in the silviculture sector in terms of technical efficiency were Brambles Ltd (Australia), in the years 2009, 2010, 2013, and 2015; Holmen AB (Sweden), in the years 2011 and 2019; Packaging Corp of America (United States), in 2012 and 2014; and Norbord Inc (Canada), from 2016 to 2018. Three companies were considered the best benchmarks according to the eco-efficiency model in the period, one from Australia and two from Canada. Brambles (Australia), which was considered the best benchmark in terms of technical efficiency in some years, also appears as the best benchmark in terms of eco-efficiency from 2009 to 2012. Further, Intertape Polymer Group Inc (Canada) is considered the best benchmark in 2014, while the company CCL Industries Inc, also from Canada, ranks best in 2013 and from 2015 to 2019.

It is important to note that Russia, Brazil, United States, and China appear, together with Canada, as the countries with the largest forest area in the world (FAO, 2016). In this context, Canadian companies' eco-efficiency performance is notable as indicated by the highest number of benchmarks and in more recent years (2013 to 2019), which may be the result of national public policies and better executive management.

The list of the best environmental efficiency benchmarks is composed of the following firms: Crown Holdings Inc, from United States (2009 and 2010); Toyo Seikan Group Holdings Ltd, from Japan (2011 and 2012); Sealed Air Corp, from United States (2013 and 2014); Svenska Cellulosa SCA AB, from Sweden (2015); Amcor PLC, from United Kingdom (2016); Ball Corp, from United States (2017); and Intern. Marine Containers Group, from China, in more recent years (2018 and 2019).

It is important to highlight that China is the main paper producer in the world (111.2 million tons) and the fourth largest producer of cellulose (16.8 million tons) (IBA/PoyryABRAF, 2016). The performance of the Chinese company as the best benchmark in terms of environmental efficiency in more recent years may be a consequence of the adoption of a more strict program that regulates discharges in the paper and cellulose industry that some provinces in China have implemented, for example, Shandong Province (Wang et al., 2011). Further, studies such as the one from Song et al. (2013) and Chen and Jia (2017) indicate that, aside from economic interest, ecological concern must be an important item on the agenda of companies in this industry. The paper and cellulose industry in China has been growing accordingly to world climate action expectations. At the same that China is the developing country that most emits pollutants, it is also a leader in the sector of renewable energies (Hurri, 2020).

Song et al. (2013), employed the DEA model with economic and environmental variables to analyze provinces in China and highlighted the importance of adopting environmental protection measures respecting the province’s local policies. Chen and Jia (2017) stated that, in China, there is a strong demand for the responsible use of natural resources and environmental pollution in the forestry industry. Further, Wang et al. (2013) stress that the provinces of Beijing, Shanghai, and Guangdong were benchmarks for other regions due to their energy and environment efficiency, while most Chinese regions are solely interested in technological innovations.

By comparing the three models (technical, ecological, and eco-efficiency), the United States, one of the largest producers of paper and cellulose, stands out in the technical and ecological efficiency models (as illustrated in Figures 3 and 4), but does not perform well according to the eco-efficiency model (Figure 5). The United States is the leader in cellulose production (48.5 million tons) and the second largest paper producer (72.4 million tons), behind only China (IBA/PoyryABRAF., 2016). This emphasizes the strong exploratory production model adopted by this country in the forestry industry, which may result in environmental damage to the world as a whole (Silva, 2019).

It is important to note the positive performance of Australia, Canada, and United Kingdom in the three efficiency models. Australia, which holds approximately 3% of the world`s forest area (FAO, 2016), presents highly efficient firms in all that are benchmarks of technical efficiency and eco-efficiency. Carberry et al. (2013) stress that Australia`s agenda includes the development of novel technology to strengthen agriculture and environmental conservation, which is reflected in the results presented in this study.

Further, Canada is also one of the world's largest producers of paper and cellulose, and, according to the results, the country presented high performance companies that serve as benchmarks in technical efficiency and eco-efficiency analyses. The efficiency demonstrated by Canadian companies might be a consequence of the commercial partnership and technological sharing agreements between the country and its neighbor, United States. Hussain and Bernard (2017) highlight in their study that Canadian firms were working together with North American ones regarding productivity in the paper and cellulose industry, while at the same time learning from companies from Nordic countries such as Finland and Sweden, which presented a high performance in the technical and ecological efficiency models.

The United Kingdom is also among the most efficient countries according to all three models. According to Green et al. (1994), this may be a response to a longstanding work that this country has carried out to encourage technological innovation efforts. The author highlight that British companies invested in research and development aimed at ecologically friendly products and processes, as a response to governmental environmental pressures. Forestry companies from Sweden also presented high efficiency levels according to the technical model and the ecological efficiency model. In this case, the results might be related to the implementation of public policies targeting energy efficiency in the country as discussed by Blomberg et al. (2012).

The paper and cellulose companies that achieved high technical, ecological, and eco-efficiency scores are mainly from Australia, Canada, and United Kingdom. These countries are known for having effective public policies that support and encourage investments in green technology. In Europe, the countries considered most eco-efficient, in addition to the United Kingdom, are Portugal and Spain. Besides Canada and Australia, companies from South Africa also appear on the eco-efficiency map. During the period analyzed, South Africa received investments from European and North American forestry companies due to the high productivity and low cost of South African forest lands (McEwan et al., 2020), this had a significant positive impact on the paper and cellulose industry development in the country.

Finally, the technical efficiency, ecological efficiency, and eco-efficiency maps for the analyzed period confirm some behaviors in the forestry industry. The United States presents highly economic efficient and environmentally efficient companies but lacks eco-efficient firms. Forestry companies in Brazil only show positive technical efficiency performance, which demonstrates insufficient investment in environmental actions possibly related to poor government management.

## 6 CONCLUSIONS

This study performs a comprehensive analysis of more than 80 silviculture companies in 23 countries during the period between 2009 to 2019. The DEA methodology is employed to explore efficiency from three different perspectives technical, ecological, and eco-efficient. According to the results, the highest mean eco-efficiency was achieved in 2013. The countries considered most eco-efficient in the forestry sector were Portugal, Canada, United Kingdom, Australia, South Africa, and Spain.

Regarding the environmental aspect, recent years show a reduction of tons of $CO_2$ emissions compared to the beginning of the analyzed period, which may be a result of the commitment made in Paris in 2015 by the sector companies.

The eco-efficiency model results present important information about the forestry industry around the world. The United States, despite its tradition in the forestry sector, did not present eco-efficient companies in the analyzed period. Companies from other countries are designated as performance parameters in this aspect for usually presenting higher investments in clean technologies and waste treatment, at times resulting from more rigorous public policies and/or cultural behavior. Interestingly, different from United States, results for Canada demonstrate that forestry companies in the country tend to pursue productivity while respecting and preserving the environment.

Lastly, this study is limited by the number of observations with available environmental information since the disclosure of such data is still not compulsory in many countries. As suggestions for future investigations, it is important to highlight the relevance of carrying out qualitative studies in companies considered eco-efficient, in order to understand their strategies and production processes.

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# PPENDIX 1

**Table A1.** Benchmarks technical efficiency

| Year | Q* | Company (Efficiency) | Country | Year | Q* | Company (Efficiency) | Country |
|---|---|---|---|---|---|---|---|
| 2009 | 11 | Brambles Ltd | AUS | 2015 | 11 | Avery Dennison Corp | USA |
| | 10 | Packaging Corp of America | USA | | 8 | Amcor PLC | GBR |
| | 9 | Ball Corp | USA | | 7 | Mondi PLC | GBR |
| | 9 | International Paper Co | USA | | 6 | Suzano SA | BRA |
| | 6 | NineDragonsPaper(Hold.)-HK | CHN | | 4 | International Paper Co | USA |
| | 6 | Crown Holdings Inc | USA | | 1 | Sonae Industria Sgps SA | PRT |
| | 4 | Essentra PLC | GBR | | 0 | Mpact Ltd | ZAF |
| | 3 | Svenska Cellulosa SCA AB | SWE | 2016 | 19 | Norbord Inc | CAN |
| | 2 | Mayr Melnhof Karton AG | AUT | | 16 | Brambles Ltd | AUS |
| | 1 | DS Smith PLC | GBR | | 14 | Universal Forest Products Inc | USA |
| 2010 | 18 | Brambles Ltd | AUS | | 14 | Packaging Corp of America | USA |
| | 18 | Ball Corp | USA | | 10 | UPM-Kymmene Oyj | FIN |
| | 12 | Essentra PLC | GBR | | 9 | Mondi PLC | GBR |
| | 11 | Stora Enso Oyj | FIN | | 7 | Viscofan SA | ESP |
| | 6 | Empresas CMPC SA | CHL | | 5 | Klabin SA | BRA |
| | 4 | Lee& ManPaperManufac.Ltd-HK | CHN | | 5 | Winpak Ltd | CAN |
| | 4 | Sonoco Products Co | USA | | 4 | Western Forest Products Inc | CAN |
| | 1 | Crown Holdings Inc | USA | | 4 | Amcor PLC | GBR |
| | 1 | International Paper Co | USA | | 3 | International Paper Co | USA |
| | 0 | DS Smith PLC | GBR | | 2 | Smurfit Kappa Group PLC | IRL |
| | 21 | Holmen AB | SWE | | 2 | Sonae Industria Sgps SA | PRT |
| 2011 | 15 | Aptargroup Inc | USA | | 2 | Avery Dennison Corp | USA |
| | 14 | Ball Corp | USA | 2017 | 27 | Norbord Inc | CAN |
| | 13 | International Paper Co | USA | | 16 | Suzano SA | BRA |
| | 6 | Mayr Melnhof Karton AG | AUT | | 13 | Universal Forest Products Inc | USA |
| | 6 | Essentra PLC | GBR | | 11 | Packaging Corp of America | USA |
| | 4 | Silgan Holdings Inc | USA | | 9 | West Fraser Timber Co Ltd | CAN |
| | 3 | Crown Holdings Inc | USA | | 9 | UPM-Kymmene Oyj | FIN |
| 2012 | 19 | Packaging Corp of America | USA | | 9 | Mondi PLC | GBR |
| | 19 | Ball Corp | USA | | 9 | Myers Industries Inc | USA |
| | 17 | Brambles Ltd | AUS | | 8 | Lee& ManPaperManufac.Ltd-HK | CHN |
| | 13 | International Paper Co | USA | | 7 | Corticeira Amorim SGPS SA | PRT |
| | 11 | Klabin SA | BRA | | 4 | Boise Cascade Co | USA |
| | 8 | Viscofan SA | ESP | | 3 | International Paper Co | USA |
| | 5 | Mayr Melnhof Karton AG | AUT | | 2 | Sonae Industria Sgps SA | PRT |
| | 4 | Mpact Ltd | ZAF | | 1 | Stora Enso Oyj | FIN |
| | 3 | Amcor PLC | GBR | | 0 | Smurfit Kappa Group PLC | IRL |
| 2013 | 23 | Brambles Ltd | AUS | | 0 | Amcor PLC | GBR |
| | 19 | Ball Corp | USA | | 0 | Avery Dennison Corp | USA |
| | 16 | Norbord Inc | CAN | 2018 | 36 | Norbord Inc | CAN |
| | 7 | Canfor Corp | CAN | | 28 | Suzano SA | BRA |
| | 5 | Amcor PLC | GBR | | 23 | West Fraser Timber Co Ltd | CAN |
| | 5 | International Paper Co | USA | | 18 | Oeneo SA | FRA |
| | 4 | Klabin SA | BRA | | 13 | UPM-Kymmene Oyj | FIN |
| | 3 | Viscofan SA | ESP | | 10 | Universal Forest Products Inc | USA |
| | 3 | Svenska Cellulosa SCA AB | SWE | | 8 | IG Design Group PLC | GBR |
| | 3 | Avery Dennison Corp | USA | | 8 | International Paper Co | USA |
| | 1 | Smurfit Kappa Group PLC | IRL | | 6 | Avery Dennison Corp | USA |
| | 0 | Mpact Ltd | ZAF | | 5 | NineDragonsPaper(Hold.)-HK | CHN |
| | 0 | Mondi PLC | GBR | | 4 | Mondi PLC | GBR |
| | 0 | Crown Holdings Inc | USA | | 4 | Amcor PLC | GBR |
| 2014 | 27 | Packaging Corp of America | USA | | 3 | Packaging Corp of America | USA |
| | 18 | Brambles Ltd | AUS | | 0 | Sonae Industria Sgps SA | PRT |
| | 16 | Intertape Polymer Group Inc | CAN | | 0 | Boise Cascade Co | USA |
| | 16 | Viscofan SA | ESP | 2019 | 66 | Holmen AB | SWE |
| | 15 | Amcor PLC | GBR | | 45 | Universal Forest Products Inc | USA |
| | 9 | Avery Dennison Corp | USA | | 35 | Myers Industries Inc | USA |
| | 8 | Svenska Cellulosa SCA AB | SWE | | 17 | Packaging Corp of America | USA |
| | 5 | Klabin SA | BRA | | 16 | International Paper Co | USA |
| | 3 | International Paper Co | USA | | 13 | Mondi PLC | GBR |
| | 0 | Mpact Ltd | ZAF | | 4 | Miquel y Costas & Miquel SA | ESP |
| 2015 | 19 | Brambles Ltd | AUS | | 3 | Smurfit Kappa Group PLC | IRL |

| | | | | | | |
|---|---|---|---|---|---|---|
| 16 | Packaging Corp of America | USA | | 1 | Oji Holdings Corp | JPN |
| 15 | Intertape Polymer Group Inc | CAN | | 1 | Boise Cascade Co | USA |
| 15 | Viscofan SA | ESP | | 0 | Celulosa Argentina SA | ARG |
| 11 | UPM-Kymmene Oyj | FIN | | 0 | Avery Dennison Corp | USA |

*Number of inefficient companies that selected this efficient company as a benchmark target.

**Table A2.** Benchmarks environmental efficiency

| Year | Q* | Company (Efficiency) | Country |
|---|---|---|---|
| 2009 | 26 | Crown Holdings Inc | United States of America |
| | 14 | Brambles Ltd | Australia |
| | 13 | International Paper Co | United States of America |
| | 1 | Essentra PLC | United Kingdom |
| 2010 | 26 | Crown Holdings Inc | United States of America |
| | 16 | Stora Enso Oyj | Finland |
| | 14 | Brambles Ltd | Australia |
| | 4 | International Paper Co | United States of America |
| | 0 | Sonae Industria Sgps SA | Portugal |
| | 0 | Essentra PLC | United Kingdom |
| 2011 | 22 | Toyo Seikan Group Holdings Ltd | Japan |
| | 22 | Amcor PLC | United Kingdom |
| | 10 | Brambles Ltd | Australia |
| | 10 | International Paper Co | United States of America |
| | 0 | Sonae Industria Sgps SA | Portugal |
| | 0 | Essentra PLC | United Kingdom |
| 2012 | 25 | Toyo Seikan Group Holdings Ltd | Japan |
| | 17 | Amcor PLC | United Kingdom |
| | 13 | Brambles Ltd | Australia |
| | 12 | Stora Enso Oyj | Finland |
| | 7 | International Paper Co | United States of America |
| | 0 | Sonae Industria Sgps SA | Portugal |
| | 0 | Essentra PLC | United Kingdom |
| 2013 | 23 | Sealed Air Corp | United States of America |
| | 19 | Amcor PLC | United Kingdom |
| | 14 | Stora Enso Oyj | Finland |
| | 13 | Brambles Ltd | Australia |
| | 7 | International Paper Co | United States of America |
| | 2 | CCL Industries Inc | Canada |
| 2014 | 28 | Sealed Air Corp | United States of America |
| | 27 | Svenska Cellulosa SCA AB | Sweden |
| | 18 | Brambles Ltd | Australia |
| | 12 | International Paper Co | United States of America |
| | 5 | CCL Industries Inc | Canada |
| 2015 | 46 | Svenska Cellulosa SCA | Sweden |
| | 35 | Brambles Ltd | Australia |
| | 13 | International Paper Co | United States of America |
| | 2 | CCL Industries Inc | Canada |
| 2016 | 40 | Amcor PLC | United Kingdom |
| | 28 | Avery Dennison Corp | United States of America |
| | 20 | International Paper Co | United States of America |
| | 11 | Brambles Ltd | Australia |
| | 3 | CCL Industries Inc | Canada |
| 2017 | 55 | Ball Corp | United States of America |
| | 38 | Brambles Ltd | Australia |
| | 20 | International Paper Co | United States of America |
| | 3 | CCL Industries Inc | Canada |
| 2018 | 68 | China International Marine Containers Group Co Ltd | China |
| | 39 | CCL Industries Inc | Canada |
| | 30 | International Paper Co | United States of America |
| 2019 | 71 | China International Marine Containers Group Co Ltd | China |
| | 45 | Brambles Ltd | Australia |

| | | | |
|---|---|---|---|
| | 30 | Westrock Co | United States of America |
| | 3 | International Paper Co | United States of America |
| | 2 | CCL Industries Inc | Canada |

*Number of inefficient companies that selected this efficient company as a benchmark target.

**Table A3.** Benchmarks eco-efficiency

| Year | Q* | Company (Efficiency) | Country |
|---|---|---|---|
| 2009 | 22 | Brambles Ltd | Australia |
| | 14 | Sonae Industria Sgps SA | Portugal |
| | 6 | Essentra PLC | United Kingdom |
| 2010 | 29 | Brambles Ltd | Australia |
| | 16 | Sonae Industria Sgps SA | Portugal |
| | 4 | Essentra PLC | United Kingdom |
| 2011 | 31 | Brambles Ltd | Australia |
| | 18 | Sonae Industria Sgps SA | Portugal |
| | 4 | Essentra PLC | United Kingdom |
| 2012 | 34 | Brambles Ltd | Australia |
| | 23 | Sonae Industria Sgps SA | Portugal |
| | 0 | Mpact Ltd | South Africa |
| | 0 | Viscofan SA | Spain |
| | 5 | Essentra PLC | United Kingdom |
| 2013 | 41 | CCL Industries Inc | Canada |
| | 1 | Mpact Ltd | South Africa |
| | 2 | Viscofan SA | Spain |
| | 1 | Essentra PLC | United Kingdom |
| 2014 | 5 | Intertape Polymer Group Inc | Canada |
| | 46 | CCL Industries Inc | Canada |
| | 1 | Sonae Industria Sgps SA | Portugal |
| | 9 | Mpact Ltd | South Africa |
| 2015 | 50 | CCL Industries Inc | Canada |
| | 12 | Sonae Industria Sgps SA | Portugal |
| 2016 | 54 | CCL Industries Inc | Canada |
| | 21 | Sonae Industria Sgps SA | Portugal |
| 2017 | 60 | CCL Industries Inc | Canada |
| | 30 | Sonae Industria Sgps SA | Portugal |
| 2018 | 70 | CCL Industries Inc | Canada |
| | 37 | Sonae Industria Sgps SA | Portugal |
| 2019 | 79 | CCL Industries Inc | Canada |
| | 47 | Sonae Industria Sgps SA | Portugal |

* Number of inefficient companies that selected this efficient company as a benchmark target.