# Best Practice for Eco-efficiency and Economic Value of Degradation and Protection of the Environment in Amazonian Agriculture

## Carlos Rosano-Peña[[1]](#footnote-1)

Department of Management, Faculty of Economics, Management and Accounting – FACE, Universidade de Brasília. Campus Universitário Darcy Ribeiro, Brasília - CEP 70910-900. Brasilia – DF, Brazil.

## Abstract

Aiming to assist the sustainability of Amazonia’s agriculture, this article developed an eco-efficiency index, indicating the possible limits to maximize economic and environmental objectives, taking into account the best practices in the municipalities of the region. Shadow prices of degraded areas and forest preservation were also estimated using data envelopment analysis. The results indicate that, on average, the analyzed municipalities are able to expand the production and the forest areas by 38%, and reduce degraded areas and their inputs in the same proportion. The shadow prices allowed the estimation of the anual opportunity cost of the degraded areas and the preservation of the forest. The first, US$1.199.79/ha degraded, represented 1.65% of the annual eco-efficient production, indicating that the internalization of that cost should not be a big burden for the eco-efficient producer. The second cost, US$1,977.93/ha; however, in total values, means a very high value to compensate.

**Key words**:Eco-efficiency, DEA, Shadow price, Agriculture.

**JEL classifications**: Q01, C14, D62.

## Introduction

The world's growing concern with environmental problems resulting from the expansion of the agricultural frontier and intensification of agricultural production in the Brazilian Amazon is notorious. Paradoxically, the "Green Revolution" in the region largely induced deforestation, loss of biodiversity, pollution and depletion of water resources, desertification and soil erosion, the growth of emissions of greenhouse gases and the risk of global climate change (Barreto et al., 2006).

Nevertheless, Brazilian agriculture, as one of the world's largest food exporters, faces yet another challenge: the rising global population and undernutrition or malnutrition plaguing millions of people. It is estimated that global agricultural production will have to increase by 70% to feed a population expected to exceed 9 billion by 2050 (FAO, 2009).

To meet this dual challenge, Brazilian agriculture, especially in the Amazon, must change old strategies and practices into a new paradigm to maintain and expand the achievements of the Green Revolution, while minimizing environmental degradation. A second and even greener revolution is required.

In this regard, decision makers demand answers from academia for the following questions: Is it possible to, simultaneously, maximize economic performance and minimize environmental impacts and use of non-renewable natural resources? How to make the most eco-efficient agriculture? What is the cost of environmental degradation and preservationt? Hence, this research problem focuses on finding answers to these questions.

Numerous theoretical and empirical studies have looked at problems of efficiency and evaluation of environmental impacts (Tyteca, 1996; Bravo-Ureta et al., 2007; Darku et al., 2013). Indeed, due to the complexity of the issue, various, new, non-hierarchized methods have incorporated the environmental impacts in the efficiency analysis.

The production theory perspective encompasses two different approaches. On one hand, research addressing the efficient behavior hypothesis of production units as a *sine qua non* condition for market endurance and the existence of trade-offs between economic and environmental objectives. These works use the traditional production function and total factor productivity, ignoring the externalities inherent to the process. However, the significant increase of undesired products or contaminants makes this approach inadequate and leading to misleading results, since the production units with more restrictions and environmental responsibilities are likely to exhibit lower levels of productivity and efficiency (Pittman, 1983; Ball et al., 2005). This led to the emergence of other approach incorporating the hypothesis of market failures inhibiting efficient behavior, and modeling of a technological frontier multiproduct (with desired and undesired outputs). Thus, it is possible to find the potential to increase the supply of desired products while minimizing both environmental impact and use of production factors: the win-win result.

For the latter, there are recent empirical studies using the Shephard's distance functions (Lampe and Hilgers, 2015). These applications employ both parametric and non-parametric methods starting from different assumptions with, advantages and disadvantages. The first uses the Stochastic Frontier Analysis with a parametric distance function expressing the functional relationship between the products and inputs to represent the boundary of the set of production possibilities and decompose the deviation of the border in stochastic noise and technical inefficiency. This function is estimated basically, by the maximum likelihood method. The second method uses data envelopment analysis and Malmquist Productivity Index (MPI), to model the multiproduct technologies and the internalisation of externalities associated with the production process. To minimize possible specification and unknown errors it uses technology through distance functions, measured with problems of mathematical programming, without the need to pre define a stochastic function of production and type of distribution (behavior). However, being deterministic, it ignores the random disturbances of the production process.

According to Lampe and Hilgers (2015) these tools are predominantly used to study technical efficiency in agriculture. Some analysis of the ecological efficiency with parametric and maximum likelihood methods include: Reinhard et al. (1999), introducing an environmental impact waste as input to measure the environmental efficiency of a number of Dutch dairy farms; Areal et al. (2012), using distance parametric functions in environmental efficiency of British dairy farms. Färe et al. (2006) use distance parametric functions with mathematical programming techniques (deterministic) to estimate the shadow prices of pollutants and levels of eco-efficiency of agriculture in the US states. Regarding the nonparametric perspective with mathematical programming, Ball et al. (2005), assess the dynamics of American agriculture incorporating the environmental impact with the Malmquist Productivity Index; and Picazo-Tadeo et al. (2011), evaluate the eco-efficiency of Spanish agriculture using the DEA.

However, the use of these tools to study eco-efficiency and shadow price of externalities in Brazilian agriculture is still incipient. Regarding the multiproduct stochastic frontier, only Rosano-Peña et al. (2015) used hyperbolic distance functions to estimate the eco-efficiency of Amazonian agriculture. Resende Filho et al. (2011) used linear programming to estimate the translog logarithm input-distance function, and calculate the willingness to pay for water, and technical inefficiencies of producers in public irrigation projects in Sub medium São Francisco River. Among works employing non-parametric methods, it is worth mentioning Padrão et al. (2012), comparing the technical and environmental efficiency of agricultural production in the Amazon and estimating the opportunity cost of the Forest Code using the DEA model; Rosano-Peña et al. (2014) evaluated the eco-efficiency and sustainability of Brazilian state agriculture using directional distance functions with DEA, as well as Campos et al. (2014), who studied the economic and environmental performance of dairy farmers in Minas Gerais using the DEA model.

Filling an important literature gap on eco-efficiency and pricing of externalities in the Amazon, the present study has the following objectives. Innitialy, to estimate an eco-efficiency indicator for the Amazon agriculture that, satisfying the great concept of Pareto, simultaneously maximizes the economic and environmental objectives, with reference to best practices in the local municipalities. In this regard we use the DEA method with directional distance functions, from classic variables of agricultural activity and internalization of two externalities (one positive and one negative). Subsequently, after the virtual correction of eco-inefficiency using best practices, we estimate the shadow prices of externalities, taking advantage of the slope of the projection on the eco-efficient production frontier and the properties of duality of DEA linear programming problems. This approach allows calculating the opportunity costs (economic value) of degraded land and forest preservation, while testing the feasibility of internalization of detected externalities.

This study is divided as follows: Section 2 provides a review of concepts and measures of efficiency and shadow price; Section 3 describes the object and the study parameters; Section 4 shows the search results and, finally, section 5 presents the main conclusions.

## Methodology

Farming is a multifunctional activity with a strong impact on the ecosystem. It uses a set of production factors (including natural resources) and generate two types of complementary products. One intended to satisfy human needs (food and raw materials), primarily, through market and price mechanisms. The other is the side effect imposed on third parties not included in the individual cost of production due to lack of market and well-defined property rights. Not internalized in the cost, this is called externality: it can be negative, when generating costs for society (eg pollution, biodiversity loss and soil degradation), or positive, when generating social benefits, such as ecosystemic services in areas of environmental preservation of rural properties.

The technology used in this process is peculiar to each case and, in this sense, is an unknown. Therefore, the generic way to describe the technology is the production possibilities set (PPS). This set includes vectors used inputs (***x*** Є and outputs produced (***u*** Єin i Decision Making Units - DMUs within a certain period of time. Here ***u*** = (***y***, ***b***), ***y*** is the desired output subvetor, ***b*** is the unwanted and m = p + q. Formally, PPS = {(***x****,* ***y****,* ***b***): ***x*** can produce (***y****,* ***b***)  ***x****,* ***y****,* ***b***≥0}.

In addition to the classical properties formulated by Grosskopt (1986), the PPS must meet three additional ones, recorded by Picazo-Tadeo et al. (2012):

1. The economic activities always generate impacts on the ecosystem, so that the only alternative to not polluting the environment is not producing. That is, both outputs are complementary and there are no technologies 100% clean. This property is called null jointness.
2. Existing ecological efficiency, the reduction of both types of outputs is possible, but isolated elimination of unwanted products is impossible. This means that the elimination of pollutants involves compensation (trade off), a cost measured in terms of opportunities as the value at which the product (*y*) must be reduced to mitigate the environmental impact. This value is called the shadow price and represents the cost of environmental degradation to the producer (Fare & Grosskopf, 1998). This property is called weak disposability of outputs.
3. In the absence of echo-efficiency, it is possible to generate a larger amount of pollutants (*b*) with the same amount of *x* and *y*. Therefore, the reduction of the undesirable output does not imply a decrease of desirable product and the opportunity cost of reducing the environmental impact is zero, in this case. This property is named strong disposability of desired products.

The PPS properties determine a multidimensional space and a frontier formed by the axes of the variables involved (***x****,* ***y****,* ***b***).

The frontier corresponds to the largest allowable output level with certain levels of input and undesirable product or, alternatively, the smaller amount of inputs and byproducts possible to produce a given output vector. This means that eco-efficient DMUs form the frontier of the PPS and there is only *weak* disposability. The subset of inefficient units is located between the frontier and the axes, showing strong disposability. Therefore, eco-inefficiency of a DMU can be measured by its distance to the frontier. In other words, one can measure the eco-inefficiency of a DMU by comparing its performance with best practices.

Therefore we can reason the concept of eco-efficiency as the ability of a company or an economy (DMU) to produce a given amount of desired product with the least amount of inputs and environmental impact, or, similarly, the power to maximize production with a given quantity of inputs and unwanted by-products. Thus, the optimal eco-efficiency, associated with a given combination of inputs is achieved in the efficient frontier of the PPS, an optimal point of Pareto, when no other production process or combination of processes can produce the same output level, impacting less environment and using less inputs.

In this sense, though necessary, eco-efficiency is not sufficient to achieve sustainability (Callens and Tyteca, 1999). Not enough because the minimum values of environmental impact of eco-efficiency are determined in relation to a sample of DMUs, not the universe, and disregard the planet's ability to absorb and support this "minimum" value. Furthermore, the concept is broader sustainability, including social aspects.

One of the most appropriate models for characterizing the PPS and estimating the eco-efficiency measures is the directional distance function developed by Chung, Färe and Grosskopf (1997) and Färe and Grosskopf (2000) to include unwanted products. It is an alternative to Shephard's radial distance functions which treats both desirable and undesirable outputs asymmetrically. It stands out as one of the most flexible ways to optimize multiple goals. It also allows defining *a priori* different projection directions on the efficient frontier by a directional vector (g = -g*x*, g*y*, -g*b*), offering a range of options to meet the ecological efficiency which can also improve a group of variables without affecting the behavior of others.

The directional distance function can be expressed as follows:

[***x****,* ***y****,* ***b***;, )]=Max{β:(***x***β, ***y***+β, ***b***) Є PPS} (1)

In the expression (1), β, the optimum value to be estimated, indicates the maximum attainable expansion of desirable outputs in the gy direction and the largest feasible contraction of undesirables and inputs in gb and gx directions, respectively, when the direction of the vector, *a priori* defined by the researcher, is (, . Therefore, β is greater than, or equal to, zero, β = 0 means the unit is efficiently evaluated; and β > 0 is inefficient.

Figure 1 graphically illustrates other projections on the border of an inefficient unit (a) which, using a given amount of inputs, produces a desirable output (*y*) and an undesired by-product (b). In this case, the directional output distance function can use three different directional vectors given in (2), for projecting the points on the efficient frontier R, S and T, respectively. It is observed that, for each directional vector set previously, the directional distance functions project A to efficient arc SR, which implies an increase of y and / or a decrease in b, satisfying the Pareto optimal. Furthermore, as the different directions lead to specific points of the border, each has a different tangent. Thus, these points will not have equal marginal rates of substitution and shadow prices. Note that, the lesser the pollution of a DMU, the greater must be the slope of the tangent and the shadow price.

|  |  |
| --- | --- |
| [*x,y,b*;)]=Max{β:( *x*, *y*+β, *b*) Є CPP} | (2) |
| [*x,y,b*;)]=Max{β:( *x*, *y*+β, *b*) Є CPP} |
| [*x,y,b*;)]=Max{β:( *x*, *y*, *b*) Є CPP} |

*y*

R

T

S A

*b*

**Figure 1.** The efficient frontier of the PPS and different projections of the directional output distance function.

In estimating the shadow price of undesirable by-products, an important property of the directional distance function lies in its duality (Lee et al., 2002; Färe et al., 2004). According this property, the solution of the profit-maximization problem can be found from the distance function to outputs formulated by:

|  |  |
| --- | --- |
|  | (3) |
| s.t. |  |
| [***x****,****y****,****b***;, )]=1 |  |

Where **P**x and **P**y is the price vectors (assumed equal to market) of the desired outputs and inputs respectively and **P**b the shadow prices of undesired products.

The Lagrangian function of (3) is:

|  |  |
| --- | --- |
| [***x,y,b*;**, )]-1) | (4) |

Where λ is the Lagrangian multiplier.

The first order conditions are:

|  |  |
| --- | --- |
| ==0 | (4.1) |
| ==0 | (4.2) |
| ==0 | (4.3) |
| =[***x****,****y****,****b***;, )]-1=0 | (4.4) |

Here it is assumed that the conditions of second-order for (4.3) are satisfied under the condition of quasi-concavity of directional outputs distance function. From the solution of (4), the relative shadow price of an undesirable product and a desirable product is deduced using the ratio of the first order conditions (4.2) and (4.1), namely:

|  |  |
| --- | --- |
|  | (5) |

The shadow price of undesirable output can be interpreted as the opportunity cost of reducing an additional unit of environmental impact in terms of loss of a desirable product, keeping constant the level of eco-efficiency and the behavior of other variables.

Similarly, one can infer the shadow price of a positive externality. It expresses the loss of potential gain by the choice to increase the generation of positive externality. It defines the marginal rate of transformation of the desired other. This shadow price is defined as

|  |  |
| --- | --- |
|  | (6) |

Functions distance and shadow prices can be estimated with parametric and non-parametric methods. As mentioned earlier we use the DEA. In this application, shadow prices can be obtained for each DMU from the calculation of the following linear programming problem (LPP):

|  |  |
| --- | --- |
| =(***x****,****y****,****b***;, )=Max β | (7) |
| s.a: |  |
|  |  |
|  |  |
|  |  |
|  |  |

Where:

***x***i, ***y***i and ***b***i denote, respectively, the vector of inputs, desired production and un- desired production of the **ith** DMU evaluated;

**X**, **Y** and **B** are, respectively, the matrices of the inputs: good outputs and bad outputs of the evaluated DMU;

**z** is a vector of intensities used to weight the diffent DMUs in the formation of the reference frontier.

The equivalent to **z** in the dual of linear programming problem (7) indicates the absolute shadow price for each output and each input in determining the eco-efficiency. It tells how the eco-efficiency could be increased if it were raised to the desired output or reduced environmental impacts and inputs. The shadow prices of the constraints (7.1) and (7.2) are respectively and . It is expected that the first absolute shadow price is positive, since an increase of y should increase the eco-efficiency, and the second negative, since a reduction in emissions should increase that environmental economic performance. Therefore, it is assumed negative shadow price on (5), and positive on (6).

Weak disposability and null-jointness properties are imposed in expression (7) through the strict equality (=) of the undesirable outputs constraint (restriction 7.2). These properties allow the accurate estimation of the shadow prices when the PPL and its border take the form in Figure 1.

But what happens if the PPS is represented in Figure 2, where the biggest producer is not the biggest polluter, i.e. when there is a set of DMUs "super-polluting". We call super-polluting those units that use obsolete technologies and, for a given input level, give off more than the most polluting efficient unit.

*y*

D

C

B E

F

(-gb, gy) A I

45º H

bD *b*

**Figure 2.** PPS with "super-polluting" units and downward-sloping segments.

In Figure 2, the PPS is described with a desired output (y) on the ordinate, and a pollutant (b) on the abscissa, for a given level of input (*x*). Thus, A, B, C, D, E, F are the extreme points forming the boundary of the PPS and units which maximize *y* for a given level of *b*. However, only A, B, C, D form the ecoefficient frontier, where D is the efficient unit with the highest emission level. All units to the right of D can be considered "super-polluting" units and in this sense, the *b*D level can be used to set the maximum pollution, as it does not compromise the efficiency and maximum productivity.

According to Picazo-Tadeo and Prior (2009), when the PPS includes super-polluting units, the LPP (7) should consider the points E and F eco-efficient because they are extreme positions. In addition, the LPP will project point I in the end of segment, with negative slope. Thus, the relative shadow price of pollution (*b*) and the marginal rate of substitution between desired and undesired products of points E, F and I, will be positive. In other words, ecoefficient units can increase an environmental degradation while reducing the desirable production. This contravenes the optimum principle in the sense of Pareto.

To correct this problem, Arandia and Aldanondo-Ochoa (2011), according to Färe et al. (2006), treat pollution as input and exchange constraint (7.2) through (8.2) as in the following LPP:

|  |  |
| --- | --- |
| =(***x****,****y****,****b***;, )=Max β | (8) |
| s.a: |  |
|  |  |
|  |  |
|  |  |
|  |  |

## This model will project the inefficient units and "super polluters" in the efficient frontier, however, can give those provisions a null shadow price. To alleviate this problem the PPL was carried out (8) a second time after projecting the inefficient units in the border considering the existing slacks.

## Agrarian system object of study and variables

This research targets farming in the 528 municipalities comprising the Amazon biome, according to the Ministry of Environment of Brazil.

This biome is a set of regions interconnected by the Amazon Rain Forest and the river basin of the Amazon River. Its huge area (4.1 million km2, or 49.9% of the Brazilian territory) shelters 21 million people living in towns and villages in nine states (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins, Maranhão and Mato Grosso).

From the 70’s, the public policies of tax incentives, land grant, infrastructure construction and deployment of technologies have transformed the Amazon in one of the major expanding agricultural frontiers in Brazil.

In the 1990’s, the suspension of tax and financial subsidies made the region autonomous as to economic rationality. The agricultural census shows that, from 1995 to 2006, growth rates in the Amazon were higher than other Brazilian regions. This rapid growth took place mostly from cattle farming and soybean production. In the intercensal period, cattle herds increased 59.3%, reaching 57 million heads, requiring on average 1ha of pastures (natural and cultured) per animal. In the same period, soybean planted area grew 38% to 4.4 million ha, yielding around 2.550-3.000 t/ha (Domingues et al., 2012).

According to the Institute of Applied Economic Research - IPEA (2013), the low price of land and increasing demand on domestic and foreign markets also explain the rapid growth of Amazon agriculture. These factors combined increased the region's competitiveness, even with higher operational and logistic costs and expensive agrochemicals to correct the low natural soil fertility.

The latest agricultural census (IBGE, 2010) also shows a high concentration of land in the region. In 2006, properties with less than 100ha represented 72.7% of total and occupied only 13.1% of the total studied area, while those larger than 1.000 ha, made up 2.1% representing 58.7 % of the total area.

This unequal distribution explains the heterogeneous technology used in Amazon agriculture. Firstly, producers with high expertise using capital-intensive technologies, making transplant embryos and genetic selection of high-yielding matrixes use the latest technologies in agriculture. On the other hand, a large majority of small producers use outdated, predatory technologies, such as slash and burn.

According to the National Institute of Amazonian Research (Val and Santos, 2011), small producers commonly use itinerant plantation. It begins clearing 1 to 2ha of forest, sale of fine wood and fire. At first, fire increases soil fertility and allows crops for 2-3 consecutive years. However, as fertility decreases significantly, it is common to leave the area fallow for 10 years, and deforest and burn a new 1 or 2 ha tract. This cycle ends with the farmer returning to the starting area, to burn vegetation regenerated in the fallow time. This practice of rotation has three undesirable consequences: i) requires 6 times more land than actually planted; ii) leads, regularly, to deforestation of more than the 20% limit defined by the Forest Code; iii) The land, bare of forest cover and organic matter, rapidly deplete. High rainfall and high temperatures year-round force land abandonment, since the cost recovery is higher than the acquisition of new areas (Val and Santos, 2011).

However, deforestation, burning and soil degradation are not exclusive to small producers. 2006 census confirms that 28% of the areas of rural properties in the study are degraded lands. This value is larger than the total area of small farms (13.1%), as previously seen. Therefore, it is not appropriate to target solely small farmers as the main actors of deforestation, burning and soil degradation.

The World Bank, supports this conclusion by pointing to large and medium-sized livestock as the main responsible for environmentally adverse practices (Margulis, 2003), motivated by the high profitability of Amazon livestock related to traditional regions.

However, the World Bank study, finds controversy in the literature regarding rates of returns of agricultural activities in the Brazilian Amazon. Some studies suggest low rates of return, which decompensate high environmental losses from deforestation, burning and soil degradation.

Regrettably, data on annual cash flows are not available to estimate internal rates of return (IRR). Nevertheless, the most recent census (IBGE, 2010) allows estimation in annual gross profit based on revenue, as follows: calculation of gross profit, discounting total value of production from the value of cost, without discounting the depreciation of capital and the price of land; later, the result is divided by the total value of production. Even as a partial and annual rate, it is useful to compare performance levels. Table 1, makes it clear that the average rates in the Amazon states (37%) is higher than the average in other states (28%), reinforcing the World Bank's conclusions.

**Table 1**. Annual gross profit rate on agricultural revenue of states.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| States of the Amazon Biome | | Other states | | | |
| Annual gross profit rate | | Annual gross profit rate | | Annual gross profit rate | |
| Rondônia | 39,41 | Piauí | 17,89 | Espírito Santo | 40,65 |
| Acre | 45,79 | Ceará | 60,77 | Rio de Janeiro | 40,40 |
| Amazonas | 61,92 | Rio Grande do Norte | 15,78 | São Paulo | 22,58 |
| Roraima | 34,94 | Paraíba | 46,54 | Paraná | 29,88 |
| Pará | 59,46 | Pernambuco | 44,17 | Santa Catarina | 42,19 |
| Amapá | 78,67 | Alagoas | 47,39 | Rio Grande do Sul | 26,69 |
| Tocantins | -13,25 | Sergipe | -22,70 | Mato Grosso do Sul | 13,48 |
| Maranhão | 36,29 | Bahia | 13,64 | Goiás | 20,04 |
| Mato Grosso | -7,90 | Minas Gerais | 10,25 | Distrito Federal | 31,45 |
| Average of the Biome | 37,26 | Average of the states that form the other biomes | | | 27,84 |

### 3.1 Variables

The empirical analysis is based on the 2006 agricultural census (IBGE, 2010) for the 528 municipalities comprising the Amazon. The research considers the classical inputs and outputs of the sector, but innovates by incorporating a positive externality and one negative. As in most cases (Gomes, 2008), the inputs used in the model were: ***x*1** – Property Labor in number of workers; ***x*2** - Capital estimated by the depreciation -10% of the value of fixed assets; ***x*3** - Total area (ha) of the establishments; ***x*4** - Other current expenditure called spending on costing. The outputs consider three types of products: ***y*1** - desirable Product - Total value of production; ***y*2** - Environmental desirable product - forest areas and natural forests (ha) preserved in properties; ***b*1** - environmental undesirable product - Areas of degraded lands (ha) in the properties (census does not include abandoned land).

## 4. Results

From data described in the previous section, we reached the results analyzed in two parts. The first examined the eco-efficiency indexes. The second the shadow prices and costs of conservation and environmental degradation.

### 4.1. Eco-efficiency index

For every 528 municipalities, eco-efficiency indexes were obtained by solving the PPL (8). Table 2 shows results by states.The state of Acre is the most eco-efficient and Maranhão and Tocantins the most eco-inefficient. Mato Grosso boosts the most eco-efficient municipalities.

**Table 2**. Mean eco-efficiency indexes in% of municipalities by states

|  |  |  |  |
| --- | --- | --- | --- |
| States (number of municipalities belonging to the biome) | Average | Standard deviation | No. of eco-efficient municipalities |
| Acre (22) | 17,96 | 0,1390 | 2 |
| Amapá (16) | 19,27 | 0,1625 | 4 |
| Amazonas (62) | 30,24 | 0,2188 | 2 |
| Maranhão (102) | 60,0 | 0,2047 | 2 |
| Mato Grosso (86) | 26,51 | 0,2144 | 13 |
| Pará (143) | 34,55 | 0,1856 | 10 |
| Rondônia (52) | 44,88 | 0,1519 | 0 |
| Roraima (15) | 26,21 | 0,2175 | 2 |
| Tocantins (30) | 50,71 | 0,1379 | 0 |
| Amazon biome as a whole (528) | 38,20 | 0,2321 | 35 |

Note, also, that 38.20% is the average eco-efficiency rate of all municipalities in the Amazon. This value suggests that, on average, municipalities may increase the total output value (***y*1**) and the areas intended for forest (***y*2**) by 38% and reduce degraded areas and inputs, accordingly. Therefore, if the world production of food is to increase 70% by 2050 to meet world´s population growth, in 2006, the studied municipalities could already have reached more than half of that number by only imitating the local best practices in 35 eco-efficient municipalities. In addition, the eco-efficiency would improve compliance of areas of preserved forests stipulated by the Forest Code. According to 2006 census, only 10 municipalities in the Amazon preserve areas larger than, or equal to, 80%, minimum percentage required by law.

Table 3 shows the absolute values of the improvements required for the eco-efficiency of the Amazon municipalities. These results were obtained considering both the eco-efficiency indexes (β) and the slacks estimated by PPL (8). The Pará state boosts the highest number of eco-inefficient municipalities. In the opposite direction, Acre and Amapá, are the most ecoefficient states. Generally, the economy of economic and environmental resources is substantial and evident and it is important to note that the degraded areas would be reduced to 23,000 ha. The economic growth potential of production and conservation areas are no less relevant (R$4 billion and 7 million ha, respectively). Thus, the preserved areas could increase from 40% to 49% of the size of farms.

### 4.2. Shadow price and opportunity cost

### The section begins with the analysis of results of shadow prices obtained by running the LPP (8) twice. The first calculation measured the eco-efficiency indexes and improvements that project the inefficient units on the border presented in the previous section. After correcting inefficiency, the second turn allowed to estimate the absolute and relative shadow prices of degradation and protection of the environment. This procedure reduces the slacks of variables involved and the number of shadow prices with null value.

### Shadow prices are measured by the slope of a tangent in the projection on the efficient frontier of the PPS, or from the marginal rate of transformation of the products involved, thus indicating the marginal revenue that each eco-efficient production unit has to give up to reduce an additional unit of degraded areas or to preserve an additional unit of forest, *ceteris paribus*. Therefore, the valuation performed is focused on the production theory whose values do not represent the availability, from the consumer’s point of view, to pay for environmental services.

Table 4 shows the results of synthesized relative shadow prices of degraded areas and costs.

The results of shadow prices for degradation provide several pieces of evidence. First, as expected, none of their values were positive, indicating that in eco-efficiency, reduction of the degraded area is incompatible with the expansion of production. Second, we observe a large dispersion around the average. This is explained by the wide variation in the slope of the efficient frontier of the PPS towards *y*1 and *b*1. Third, there is a downward trend in the shadow price. On the one hand, municipalities with low levels of degraded lands have more inclined tangents and tend to have high shadow prices, confirming that the producer has to make a greater effort to reduce these prices. On the other hand, municipalities with high levels of degradation exhibit descending slope and lower shadow prices, which may be zero. This indicates that they have negligible costs to reduce degradation. When the slope and hence the shadow price are zero, the evaluated units show slacks. They are found in the so called weak efficiency frontier and can be categorized as super polluters.

Table 4 indicates Pará state has the highest average in the shadow price compared to states with municipalities in the Amazon biome. By contrast, Amapá has the lowest average in the shadow price. The explanation lies in the fact that the state had the highest level of degraded area relative to the level of production. Table 4 also shows that the regional average was R$ 6,972,590.31/ha. These results are overvalued and strongly influenced by the high values of shadow prices in municipalities with low levels of degraded land.Therefore, this price should not be multiplied by the degraded areas to find the opportunity cost of degradation of the municipalities.

The opportunity cost of degradation is understood as the sum of the marginal revenue that the producer has to give up to reduce an additional hectare of degraded land, up to reduce to zero this degradation. That is, the costs were calculated using the definite integrals of the regression function in the range [0.1, value of the degraded area of the municipalities].

The equation for the best-fitting trend curve was Psb = 336,681.61 (b-0.469) with coefficients significantly different from zero and R2 = 0.18. Although this curve has a low R2, it is the most efficient estimate, since it passes through the estimated averages of shadow prices for each value of degraded land. In addition, R2 shows that 18% of the variation around the average of degraded land is explained by the variation of shadow prices, leaving 82% of the variation of other factors, including market failures.

Thus, the costs of degradation were calculated for municipalities. It should be noted that because this value represents the additional cost to produce without degrading the land, it must be assumed by the producer, if the degradation is prohibited. As shown in Table 4, this cost is concentrated in Pará, Mato Grosso and Maranhão. For the whole Amazon it is worth R$321,904,434.99, equivalent to 2.10% of the value of production of 2006. As this is cost reduction of 124,214 ha degraded, it is R$ 2,591.55/ha.

Interestingly, this cost is close to that of recovery of degraded areas in the biome. According to Townsend et al. (2009), the value for the recovery of degraded pastures may reach R$2,250.00/ ha in the region.

Moreover, comparing the costs of degradation with the price for the bare and regularized land in Pará, for example, it is evident the high propensity to abandon degraded land. According to Brito and Cardoso (2015), land values practiced in 2011 by the Institute of Lands of Pará had an average of R$325.00/ha with a minimum and a maximum of R$110 and R$522 respectively. The National Institute of Colonization and Agrarian Reform finds R$709/ha with a minimum of R$22 and R$1,722 as maximum. This undoubtedly may help explain why Pará has the largest degraded area in the Amazon.

Still, confronting this cost with the total value of production, it is clear that the impact of the immediate incorporation of this expenditure may be negligible in revenue of some municipalities and states, but must compromise the viability of others. This is evidenced by comparing the costs of degradation in % of total production with the gross profit rate recorded in Table 1. However, this impact could be reduced with an eco-efficient production. For the entire region, the cost of degradation (R$321,904,434.99), is equivalent to 1.65% of the value of eco-efficient production. Therefore, internalization of that cost should not be a problem for the eco-efficient producer.

The estimated shadow prices for environmental preservation are recorded in Table 5. They show some highlights. First, all the values were positive, as expected, indicating that, with eco-efficiency, there is a trade-off: the increase of the forest should generate a reduction in production value. Second, it notes that the magnitudes of their means and their standard deviations are smaller than the values of the shadow price of degraded areas, indicating a smaller variation of the slope of the efficient frontier of the CPP in the direction of y1 and y2. Therefore, it is evident that increasing the preserved area has a smaller impact on production that reducing degraded. Moreover, the inclination of this tangent line descends as it reduces forested areas. But when the tangent and the shadow price of environmental preservation are null, the unit has slacks and is designed in the call weak efficient frontier, indicating potential to increase the forested area without changing the level of production.

The analysis by state shows that Mato Grosso has the highest opportunity cost to increase the forest, while Maranhão, Amapá and Acre have the lowest shadow prices. The regional average was R$3,960.04/ha/year.

The shadow prices have allowed to estimate the opportunity costs of environmental preservation. These were assessed following the same procedure used in the estimation of environmental degradation costs, i.e. calculating the definite integrals of the equation representing the relationship between the shadow price (Ps*y*2) and preserved land with forests (*y*2) in the range [0.1, value of municipal forest in ha] and excluding the municipalities with Ps*y*2 = 0.

The best-fitting trend curve was Ps*y*2 = 1,810.27 (*y*20.05) with estimators significantly different from zero and R2 = 0.015. In this case, although there is a low R2, the functional relationship is also the most efficient, for the reasons explained above. Thus, R2 shows that 1.5% of variation around the average of the area preserved is explained by the variation of shadow prices, leaving 98.5% of the variation to other factors, including market failures.

This procedure led to two opportunity costs of forest preservation revealed in Table 5.

1. The costs of existing conservation areas is R$132 billion and, the preservation of 32,203,404.10 ha, is consistent with the unitary cost of R$4,125.89/ha.
2. The total cost of preserving 80% of the area of the property, as the law requires. This cost reached R$274 billion, compatible with the preservation of 64.234.327.69 ha, at R$4,272.32/ha.

**Table 3**. Improvements to the efficiency of biome municipalities by states

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| States | *x*1 – Labor (people) | *x*2 –Capital (1000 R$) | *x*3 – Área (ha) | *x*4 – Costing (1000 R$) | *b*1 - Degraded Areas (ha) | *y*2 - Preserved areas (ha) | *y*1- Production (1000 R$) |
| Rondônia | -130,800.15 | -599,486.04 | -347,4587.65 | -382,976.45 | -6,376.32 | 1,028,878.72 | 661,448.25 |
| Acre | -28,778.29 | -117,719.13 | -529,741.52 | -32,268.11 | -3,381.55 | 269,945.07 | 71,976.38 |
| Amazonas | -134,792.49 | -78,063.78 | -971,469.70 | -73,045.60 | -5,096.36 | 320,880.89 | 195,616.34 |
| Roraima | -6,581.93 | -27,769.07 | -526,641.10 | -19,445.83 | -755.65 | 142,373.22 | 26,087.47 |
| Pará | -325,139.82 | -816,963.77 | -8,248,000.02 | -847,288.04 | -46,962.56 | 2,481,080.91 | 1,398,922.89 |
| Amapá | -4,502.20 | -7,230.94 | -154,937.91 | -3,585.94 | -823.70 | 37,819.02 | 7,644.76 |
| Tocantins | -23,490.21 | -130,974.04 | -1,405,944.80 | -136,759.73 | -1,438.19 | 284,956.61 | 172,436.54 |
| Maranhão | -312,913.19 | -199,237.53 | -3,208,110.30 | -237,339.27 | -8,411.70 | 429,240.23 | 737,048.91 |
| Mato Grosso | -65,975.11 | -724,458.17 | -6,583,662.66 | -2,237,835.86 | -27,467.93 | 2,157,065.46 | 974,246.73 |
| Biome Total | -1,032,973.39 | -2,701,902.47 | -25103095.66 | -3970544.83 | -100,713.95 | 7,152,240.14 | 424,5428.89 |

**Table 4**. Shadow price and costs of degraded areas in the Amazon

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| States | Average of Shadow Price of the degraded area at R$ / ha | Current Production R$1000 | Current Degraded Areas (ha) | Cost to fully reduce the degraded area at R$ (in % of production) |
| Rondônia | -1,194,325.45 | 1,465,836.44 | 6,823.62 | 68,771,884.48 (4.69) |
| Acre | -1,049,167.73 | 389,289.68 | 3,728.10 | 49,832,243.22 (12.80) |
| Amazonas | -1,812,698.70 | 673,841.27 | 5,961.82 | 63,999,299.19 (9.50) |
| Roraima | -2,296,569.19 | 121,250.17 | 875.00 | 22,974,294.65 (18.95) |
| Pará | -19,995,647.85 | 5,040,446.55 | 51,531.85 | 201,655,865.21 (4.00) |
| Amapá | -265,074.80 | 101,676.77 | 1,668.36 | 32,445,047.51 (31.91) |
| Tocantins | -7,930,550.91 | 349,864.72 | 1,590.11 | 31,622,921.36 (9.04) |
| Maranhão | -561,188.02 | 1,340,493.18 | 10,482.82 | 86,436,950.35 (6.45) |
| Mato Grosso | -3,495,621.77 | 5,840,228.49 | 41,551.14 | 179,845,245.58 (3.08) |
| Biome (standard deviation) | -6,972,590.31 (109,246,049.15) | 15,322,927.26 | 124,212.82 | 321,904,434.99 (2.10) |

**Table 5**. Shadow price, cost of forest conservation and emissions avoided in tons of carbon to the fulfillment of the 80% target of the total area

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| States | Shadow price of preservation in R $ / ha | Current Preserved Areas (ha) | Total area of properties in ha | The cost of the existing protected áreas in R $ | Total cost of preserving 80% of the area of property in R $ | Emissions of carbon avoided in tons with 80% of the area of property |
| Rondônia | 4,325.25 | 2,856,050.56 | 8,433,867.76 | 10,426,719,937.05 | 25,724,918,617.34 | 6,544,681.38 |
| Acre | 3,904.12 | 2,145,881.38 | 3,528,542.74 | 7,721,773,167.73 | 10,299,368,657.80 | 2,738,149.17 |
| Amazonas | 4,269.97 | 1,777,847.90 | 3,668,753.07 | 6,336,935,068.33 | 10,729,719,641.34 | 2,846,952.38 |
| Roraima | 2,989.85 | 766,277.63 | 1,717,531.97 | 2,617,649,168.77 | 4,834,239,584.07 | 1,332,804.81 |
| Pará | 3,889.55 | 8,533,522.49 | 22,925,330.66 | 32,924,370,771.28 | 73,548,836,663.35 | 17,790,056.59 |
| Amapá | 3,550.22 | 384,886.10 | 873,788.50 | 1,269,855,523.14 | 2,376,878,799.49 | 678,059.88 |
| Tocantins | 3,615.03 | 640,709.71 | 2,688,151.28 | 2,169,008,428.35 | 7,739,312,662.11 | 2,086,005.39 |
| Maranhão | 2,763.64 | 848,320.53 | 5,239,556.44 | 2,912,837,063.91 | 15,602,029,783.14 | 4,065,895.80 |
| Mato G rosso. | 2,695.21 | 14,249,907.80 | 31,222,387.19 | 56,421,865,584.47 | 101,742,249,188.08 | 24,228,572.46 |
| Biome (standard deviation) | 3.960,04 (2,780.98) | 32,203,404.10 | 80,297,909.61 | 132,867,827,655.88 | 274,446,570,198.21 | 62,311,177.86 |

Notes: R$2.16 per US$1.00, average exchange rate, in 2006

It is interesting to note that the costs of forest preservation are within the expected values, and not much less than the productivity of the annual crops rotation of soybean-corn-rice in R$/ha. In the Amazon, soybeans, up to 120-day cycle, generate, approximately, R$1,400.00/ha (50 bags/ha x R$28.00/bag). The corn productivity, up to 120-day cycle, is R$2,620.00/ha (110 bags/ha x R$24.00) and the rice yield, up to 140-day cycle, is R$1,988.00/ha (60 bags/ha x R$33.00) (Townsend et al., 2009). The three together make for the value of R$6,008.00/ha.

In other words, these costs represent the impact of forest regulation in the revenue of Amazon agricultural production. Moreover, these values can be interpreted as the cost of free generation of positive externalities, a part of the countless environmental benefits taking into account the impact of preserved forest in biodiversity, conservation of water resources, the emission of greenhouse gases, the global climate change, etc.

In this sense, on one hand, the negative externalities should be internalized and, on the other, the positive compensated.

These reimbursements for environmental services provided by farmers can be operationalized through the Clean Development Mechanism (CDM) established by the Kyoto Conference, Japan, in 1997. Through the CDM, developed countries can, through financial compensation to developing countries, discount credits should their emissions exceed the pre-established quotas at such conference. This compensation primarily considers the benefits of preservation, resulting from carbon sequestration.

This work adopted the latter value to estimate the carbon emissions avoided with the preservation of 80% of the total area of the rural property. However, it is necessary to emphasize that this value considers only the avoided emissions of carbon related to forest preservation, not taking into account the emission of greenhouse gases (GHG) avoided by increasing the cattle herd and the land use change.

Table 5 shows that the highest values of annual avoided emissions correspond to the municipalities of Mato Grosso and Pará, states with the largest number of municipalities in the studied biome, while Amapá has the lowest value. The sum of the region stood at 62,311,177.86 tons of C.

According to the Brazilian National Economic and Social Development Bank (BNDES, 1999), the estimated market value of certified emission reductions (CER) of greenhouse gases is between US$5.00 and US$ 15, 00 per ton of carbon reduced. By taking the average value (US$10.00), the amount associated with carbon sequestration in 80% of the areas of the properties reaches US$623,111,778.57, equivalent to R$1,345,921,441.72.

This amount represents 0.5% of the opportunity cost of preservation of 80% of the area of the property (R$274 billion), confirming the uselessness to conserve natural forest areas with the prevailing prices in the carbon market. Therefore, it is unlikely that the implementation of the Brazilian mechanism to buy and sell emissions, postponed to 2017, can resolve the problem of compensation for environmental services generated by producers preserving forests in the Amazon.

However, areas of preserved forest (32,203,404.10 ha), with a sunk cost of R$ 132,867,827,655.88 can generate, following the same reasoning, R$305,932,339.00 in certified emission reductions (CER) of greenhouse gases. This value is very close to cover the costs of reducing degraded areas (R$321,904,434.99). Thus, the compensation CER can be awarded to producers intended to solve the problem of degraded areas.

**5. Conclusions**

This study estimated an eco-efficiency index, shadow prices and costs of degradation and environmental conservation in the Amazon, from the theory of production and nonparametric method of Data Envelopment Analysis with directional distance functions. It fills an important gap in the study of economic and environmental efficiency and pricing of positive and negative externalities in Brazilian agriculture.

The results indicate that on average the analyzed municipalities can raise production and forest areas by 38% and reduce degraded areas and inputs accordingly. These indicators reinforce the initial hypothesis that the formulation of policies consistent with the maximization of social welfare is possible, to optimize both economic and environmental objectives. Therefore, it can be concluded that the discussion of economic and environmental issues does not necessarily result in a zero-sum game.

The shadow prices of degraded land allowed to estimate various opportunity costs of this externality. The cost resulted in 1.65% of the annual output value of eco-efficiency or R$ 2,591.55/ha (US$ 1,199.79). Therefore, internalization of that cost should not be a big problem for the eco-efficient producer.

Moreover, the shadow price of forest preservation indicated R$4,272.32/ha (US$ 1.977.93) as the unitary cost to conserve 80% of the area of the properties. The total values resulted in a very high value to compensate. Even reimbursing the damage avoided by carbon sequestration, the possible revenue generated from carbon credits is insufficient to cover the costs to preserve the forest. Consequently, it is implausible that the implementation of the Brazilian mechanism to buy and sell emissions can solve the problem of compensation of free environmental services generated by producers who preserve forests in the studied biome.

**References**

Arandia, A., Aldanondo-Ochoa, A., 2011. Pollution shadow prices in conventional and organic farming: An application in a mediterranean context. Spanish Journal of Agricultural Research, 9, 363-376.

Areal, F. J., Tiffin, R., Balcombe, K. G., 2012.Provision of environmental output within a multi-output distance function approach. Ecological Economics, v. 78, p. 47-54, June.

Ball, V. E., Färe, R., Grosskopf, S., Zaim, O., 2005.Accounting for Externalities in the Measurement of Productivity Growth: The Malmquist Cost Productivity Measure. Structural Change and Economic Dynamics 16, p.374-394.

Banco Nacional de Desenvolvimento Econômico e Social – BNDES, 1999. Efeito Estufa e a Convenção sobre Mudança do Clima. Rio de Janeiro: BNDES e Ministério da Ciência e Tecnologia – MCT.

Barreto, P., Souza Jr., C., Anderson, A., Salomão, R., Wiles, J. Nogueron, R., 2006. Human Pressure on the Brazilian Amazon Forest Biome. Imazon, WRI, Greenpeace. Belém, Pará.

Bravo-Ureta, B.E., Solís, D., Moreira, V.H., Maripani, J.F., Thiam, A., Rivas, T.E., 2007. Technical efficiency in farming: A meta-regression analysis. J. Prod. Anal. 27:57-72.

Brito, B., Cardoso Jr., D., 2015. Regularização fundiária no Pará: Afinal, qual o problema? Belém: Imazon.

Callens, I., Tyteca, D., 1999. Towards indicators of sustainable development for firms. A productive efficiency perspective. Ecological Economics, 28, p. 41-53.

Campos, S. A. B., Coelho, A. B., Gomes, A. P., Mattos, L. B., 2014. Eficiência e custos associados à adequação ambiental para a produção láctea em Minas Gerais. Organizações Rurais & Agroindustriais, v. 16, n. 3, p. 324-342.

Chung, Y., Färe, R.; Grosskopf, S., 1997. Productivity and Undesirable Outputs: A Directional Distance Function Approach. Journal of Environmental Management, 229–240.

Darku, A.B., Malla, S., Tran, K.C., 2013. Historical Review of Agricultural Productivity Studies. Alberta, Canada: CAIRN Research Network.

Domingues, M. S., Bermann, C., 2012. O arco de desflorestamento na Amazônia: da pecuária à soja.Ambient. soc., São Paulo,  v. 15, n. 2, p. 1-22, Aug.

FAO, 2009. How to Feed the World in 2050. Paper Prepared for the High Level Expert Forum. Rome 12-19 October 2009: [s.n.].

Färe, R., Grosskopf, S., 2000. Theory and application of directional distance functions. Journal of Productivity Analysis, v. 13, p. 93-103.

Färe, R., Grosskopf, S., 2004. New directions**:** efficiency and productivity. Boston/London/Dordrecht: KluwerAcademic Publishers.

Färe, R., Grosskopf , S., Weber , W. L., 2006. Shadow prices and pollution costs in US agriculture. Ecol Econ., 56, p. 89-103.

Gomes, E., 2008. Uso de modelos DEA em agricultura: uma revisão da literatura. *Engevista*, v. 10, n. 1, p. 27-51, junho.

Grosskopf, S., 1986. The Role of the Reference Technology in Measuring Productive Efficiency. The Economic Journal, 96, 499-513, June.

Instituto Brasileiro de Geografia E Estatística -IBGE., 2010.Censo Agropecuário 2006. Rio de Janeiro.

Instituto De Pesquisa Econômica Aplicada (IPEA)., 2013. Caracterização e Análise da Dinâmica da Produção Agropecuária na Amazônia Brasileira: Uma análise a partir do Censo Agropecuário 2006. Relatório de Pesquisa. Brasília.

Lampe, H. W., Hilgers, D., 2015. Trajectories of efficiency measurement: A bibliometric analysis of DEA and SFA. *European Journal of Operational Research*, 240, Issue 1, 1, January.

Lee J.D., Park J.B., Kim T.Y., 2002. Estimation of the shadow prices of pollutants with production/environment inefficiency taken into account: a non-parametric directional distance function approach. J Environ Manage 64, 365-375.

Margulis, S., 2003. Causas do desmatamento da Amazônia brasil*eira*. Brasília, Banco Mundial.

Padrão, G. A., Campos, S. A. C., Lirio, V. S., Márcio Lopes Da Silva, M.L., 2012. Environmental efficiency and opportunity cost of the Forest Code for the Amazon. RIO+20 - International Society for Ecological Economics Conference. Rio de Janeiro, [s.n.]

Picazo-Tadeo, A. J., Beltrán-Esteve, M., Gómez-Limón, J. A., 2012. Assessing eco-efficiency with directional distance functions. European Journal of Operational Research, v. 220(3), p. 798-809.

Picazo-Tadeo, A. J., Gómez-Limón, J. A., Reig-Martínez, E., 2011. Assessing farming eco-efficiency: A Data Envelopment Analysis approach. Journal of Environmental Management, 92, p. 1154-1164.

Picazo-Tadeo, A. J., Prior, D., 2009. Environmental externalities and efficiency measurement. Journal of Environmental Management, v. 90(11), p. 3332-3339.

Pittman, R. W., 1983. Multilateral productivity comparisons with undesirable outputs. Energy Journal, v. 93, p. 883–891.

Reinhard, S., Lovell, C. A. K., Thijssen, G., 1999. Econometric Estimation of Technical and Environmental Efficiency: An Application to Dutch Dairy Farms. American Journal of Agricultural Economics, v. 81, p. 44-60.

Resende Filho, M. A., Araujo, F. A., Silva, A. S.,  Barros, E. S., 2011. Precificação da água e eficiência técnica em perímetros irrigados: uma aplicação da função insumo distância paramétrica. Estud. Econ. [online], vol.41, n.1.

Rosano-Peña, C, Serrano, A. L. M., Britto, P. A. P., 2015. Uma medida da Sustentabilidade Ambiental da Agropecuária Amazônica Utilizando Fronteiras Estocásticas Multiprodutos. Anais. Belo Horizonte/MG, XXXIX ENANPAD, Set.

Rosano-Peña, C., Guarnieri, P., Sobreiro, V.A., Serrano, A. L., Kimura, H., 2014. A Measure of sustainability of Brazilian agribusiness using directional distance functions and data envelopment analysis. International Journal of Sustainable Development and World Ecology, v. 21.

Townsend, C. R. et al., 2009. Aspectos econômicos da recuperação de pastagens no bioma Amazônia. Porto Velho, RO: Embrapa Rondônia.

Tyteca, D., 1996. On the measurement of the environmental performance of firms: a literature review and productive efficiency perspective. Journal of Environmental Management 46, 281–308.

Val, Adalberto Luis; Santos, Geraldo Mendes dos. (Org.), 2011.GEEA - Grupo de Estudos Estratégicos Amazônicos, Caderno de Debates. TOMO IV. Manaus: INPA.

1. Email Correspondence: gmcrosano@gmail.com

   Acknowledgments:

   The author acknowledges the financial support of the FAP-DF and is grateful to Leopoldo Costa Junior, Danielle Sandi Pinheiro, Neantro Saavedra-Rivano, Rodrigo Andrés de Souza Peñaloza and Marcondes M. de Araujo for comments and suggestions. [↑](#footnote-ref-1)