# HOW MUCH DOES A PIECE OF BIODIVERSITY COST?


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**ABSTRACT**

*Since the 1992 Rio Summit, biodiversity is one of the elements to be considered in natural resource management. The dilemma between economics and ecological aspects should be balanced in many forest projects. While economic issues are dealt with comprehensively through existing techniques, conversely there is a shortage of methodological tools to manage biodiversity aspects.*
*Based on ethical reasons, some first-world people consider that species losses are not economical valuable, as a consequence not having any pay-off tax that can compensate the loss of ecological values. However this philosophical approach totally ignores the actual market forces which are worldwide accepted, so it might be more effective to accept the evidences and make a joint appraisal that balances timber production and biodiversity values.*
*Our approach was applied in a Chilean second-growth Nothogafus forest at Lanco Commune (X Region, 39°15' South latitude) which was cut off and burnt in order to obtain fire woods, temporary crops and meadows. After abandoned, the second-growth Nothofagus woodlands initiated a progress along the ecological chain towards a plesioclimax. Applying Data Envelopment Analysis (DEA) to forest stands as if they were wood production factories, pay-off ratios and substitution prices among forest products and biodiversity levels were obtained.*



*Key words: linear programming model, forest management planning, biodiversity cost, multi-purpose planning*

## INTRODUCTION

Historically forest production was based on timber, firewood, fruits, livestock and hunting; since the late nineteenth century, erosion control, landscape, water supply and landslide suppression were taken into account as environmental services, but no economic quantification was done [1,2]. In 1992 United Nations Conference on Environment and Development in Rio [3], biodiversity emerged as a new environmental service to be considered in territorial projects. However, despite Rio spur, economic appraisal of biodiversity has been assessed with a shortage of liability or not even considered in forest planning and management.

Most of the biodiversity economic approaches have come out from linear programming [4, 5, 6] and multi-criteria decision [5, 7], although during the last decade other methods as neural networks and cellular automata have appeared to solve multiuse forest planning [4, 5]. In some of these approaches biodiversity is managed directly in terms of pieces of livestock and age-classes abundance, being optimized the livestock Net Present Value at the objective function [8]. Other studies add different forest products to the objective function establishing some animal abundance and binary spatial constrains, then after dual system is solved [9, 10] shadow prices are obtained.

In other multi-criteria models, biodiversity issues are considered by means of forest structural diversity index [11] that is admitted to be associated to species biodiversity [12]. However the short biodiversity information collected and used on this approach limits its performance.

Several authors have incorporated environmental restrictions to a linear programming multiple-use forest management model obtaining shadow prices for amenities and services through the dual system [13, 14, 15, 16]. A further approach is to apply goal programming [18] and propose a model that includes biodiversity into a mixed programming structure of forest goals [19].

The most classical models have been made considering as essential the long-term sustainability of forest ecosystems, thus having developed management plans with constraints on wood volume flow, the cash-flow regulation and the continuity volume and age classes, compassing I and II Johnson's models [1, 2]. Belonging to this group, a particular Johnson's model 1 was developed by the authors in second growth *Nothofagus* forest in Lanco Commune where different scenarios of biodiversity and landscape levels along with other wood productions were considered [14]. As a result, a variety of biodiversity indexes were analyzed along the two rotation time horizon. A drawback found at that study was the need to establish some strong assumptions about future vegetation dynamics and make some biodiversity stochastic models which required comprehensive vegetation information. Even though current diversity information is commonly obtained by forest sampling, however past vegetation information has seldom been gathered with enough detail. Moreover, in applying linear programming at long rotation periods, biodiversity indexes had to be estimated in each space-time unit of the forest plan. Although sometimes, when having ancillary and extended information from National forest inventories, the lack of past botanic samples might be overcome by estimating the most likely vegetal succession, this is something that not always can be done.

In order to avoid forecasting vegetation dynamics and taking risks, a biodiversity retrospective analysis can be done, which determines the biodiversity status only based on current forest sample. In this research line Nalle et al. [20] developed a method that combines an economic and ecological model, the latter from the point of view of the conservation of species, and compares cost-effective alternatives via the comparison of cost in the production possibility frontier.

Also Kangas [21] and Kurttila et al. [2222] worked with utility functions to analyze the pay-off between different forest outputs. The utility function facilitates the work task when using multidimensional product function and makes easier to obtain the pay-off between different outputs and inputs.

The application of production function theory to Chinese forest regions was made by Kao et al. [23, 24] who used the Data Envelopment Analysis (DEA) to set up the production frontier. DEA has been used for a long time to study company efficiency, but it has never been used before to evaluate forest management. The advantage of using DEA is the wide availability of common tools and useful documentation to analyze inefficiencies, production factors and decision makers [25, 26] even in forest companies [27].

Our approach has been originated as a translation of the production possibility frontier theory to the forestry field, considering each forest stand as if it was a factory where timber and biodiversity are produced from rainfall, soil nutrients and sunlight. After establishing the production possibility set, the most efficient forest stands, where timber and biodiversity are efficiently jointly produced, are found. As a consequence, although only timber has a market price, biodiversity price can be obtained by analyzing the pay-off marginal cost between outputs at the efficient frontier.

## SECOND GROWTH NOTHOFAGUS FOREST AT LANCO COMMUNE

The study area is located in the Lanco commune - X Region - in Chile (Figure 1) and it consists of all the area covered by “roble-raulí-coihue” second growth forests within the commune. The basic information used in this work comes from the forest inventory carried out by FDI-CORFO [28] and the Chile’s Vegetation Resources Survey [29, 30]. The area covered by “roble-raulí-coihue” second growth forests in the Lanco commune is 7,976.6 ha.

The Lanco commune is located in the northern limit of the X region of Los Lagos, at an average latitude of 39º15´ South. The X region is characterized by a high annual rainfall, a pretty short dry summer period of two months and it has been classified within the South Macroclimatic Region among the six macro climatic regions that make up Chile [3131]. According to Schlatter et al. [32], the Lanco commune is placed in the South macroclimatic area and mainly in a homogeneous growth zone from the climatic point of view. It is characterized by an annual average 2,450 mm rainfall, a 1.5 month dry period, a -6º C annual absolute minimum temperature and a 160 days/annum frost free period.

Our study was carried out in a second–growth *Nothofagus* forest generated by means of extensive burns at the early twentieth century. The collected information has been filed in a database with 604 registers related to forest stands with different features and area [28, 29, 30, 33].

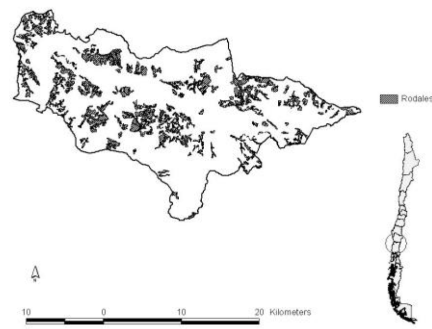


Figure 1. Study area

## APPLYING DATA ENVELOPMENT ANALYSIS TO DETERMINE PRODUCTION FRONTIER

DEA (Data Envelopment Analysis) is a method belonging to multi-criteria linear programming which maximizes the ratio between outputs and inputs for a set of decision maker units (DMU) [25, 26]. The first applications of DEA were addressed to identify efficient points in cases where the objective function consists of goals (outputs) of a “the-more-the-better” nature in combination with resources (inputs) of a “the-less-the-better” nature, however step by step DEA was spreading out its applications from cost-benefit assessment to efficiency assessment in not-for-profit organizations [26, 34, 35, 36]. Nowadays DEA is a technical paradigm applied in many sectors and aims [37]. In our case we used DEA in the context of efficiency production theory based on Charnes, Cooper and Rhodes’s studies (CCR) [34] and Banker, Charnes and Cooper’s (BCC) [35] production efficiency analysis, but we consider the technical efficiency of forest stands when producing jointly timber and biodiversity from ecological inputs such as soil nutrients, water, and solar energy.

Each forest stand has the aim of maximizing its outputs ($y_1$, $y_2$), volume timber and vegetation richness from the resources provided: precipitation, sunlight and quality soil site ($x_1$, $x_2$, $x_3$).

The basic mathematical formulation of DEA lets each DMU (each forest stand) *'i'* to select the most suitable weights in order to achieve the best production efficiency score $\theta_i$ , but subject to the following constraints: 1) all inputs, outputs and weights are positive, and 2) the efficiency index $\theta_i$ is between 1 and 0. Therefore it can be expressed as:

$$\max \quad \theta_i = \frac{\sum_{j=1}^{m} u_{ji} \cdot y_{ji}}{\sum_{k=1}^{r} v_{ki} \cdot x_{ki}} \qquad \forall\, i = 1,2,...,n$$

$$subject\ to \quad \frac{\sum_{j=1}^{m} u_{ji} \cdot y_{ji}}{\sum_{k=1}^{r} v_{ki} \cdot x_{ki}} \le 1$$

$$and \quad u_{ji}, v_{ki} \ge 0 \quad \left(j = 1,2,...,m; k = 1,2,...,r\right)$$

Where $m$ is the number of outputs considered, $r$ is the number of inputs and $n$ the number of DMUs. The output weights or technical production coefficients are denoted by $u_{ji}$ and the input weights are denoted by $v_{ki}$, both can be considered as "virtual prices" of outputs and inputs, respectively. The system solution provides the maximum efficiency index for each forest stand $\theta_i$ , the optimal values for the technical production coefficients $u_{ji}$ $v_{ki}$, the marginal cost, and some slack $s$ and dummy variables λ which will provide the distance between a given inefficient DMU and the actual production frontier.

The main outcomes are the efficiency indexes $\theta_i$ that summarize the degree of inefficiency in each forest stand; the closer to 1 it is, the greater the efficiency. A forest stand with an index of 1 means that uses water, nutrients and sunlight in an optimal way to jointly get the maximum biodiversity level and the maximum timber production. In addition, the product of the input weight multiplied by the level of use also reveals which resources are the ones that affect efficiency and which ones make no difference.

Nevertheless the DEA system has not a unique way of finding a solution. In fact, two approaches can be used depending on whether it maximizes outputs anchoring inputs or maximizes efficiency by minimizing inputs subject to a baseline. The first one is called input-oriented CCR, because the input radial anchor is used to analyze input scale-efficiency. The second path is named output-oriented CCR [36], because facilitates the output analysis near optimal inputs.

The formulation of input-oriented CCR is:

$$\max \quad \sum_{j=1}^{m} u_{ji} \cdot y_{ji} \qquad \forall\, i = 1,2,...,n$$

$$subject\ to \quad \sum_{k=1}^{r} v_{ki} \cdot x_{ki} = 1$$

$$-\sum_{k=1}^{r} v_{ki} \cdot x_{ki} + \sum_{j=1}^{m} u_{ji} \cdot y_{ji} \le 0$$

$$u_{ji}, v_{ki} \ge 0 \quad \left(j = 1,2,...,m; k = 1,2,...,r\right)$$

As we can observe in the second constraint, inefficient points are enveloped under the most efficient points, so that the method is named Data Envelopment Analysis. This system is linked to its dual at the point solution set that can be expressed as follows:

$$\min \quad \theta_i = \frac{\sum_{j=1}^{m} u_{ji} \cdot y_{ji}}{\sum_{k=1}^{r} v_{ki} \cdot x_{ki}} \qquad \forall\, i = 1,2,...,n$$

*subject to*

$$\theta_i \cdot x^*_{ki} - \sum_{i=1}^{n} x_{ki} \cdot \lambda_i = s^-_{ki} \ge 0 \quad ; \quad k = 1,2,...,r$$

$$\sum_{i=1}^{n} y_{ji} \cdot \lambda_i - y^*_{ji} = s^+_{ji} \ge 0 \quad ; \quad j = 1,2,...,m$$

$$\lambda_i \ge 0 \quad \left(i = 1,2,...,n\right)$$

$$x^*, y^* \quad are\ the\ primal\ solutions$$

In DEA each decision maker is left choosing what weight vector prefers, which can be interpreted as forest stands use inputs the best possible way to obtain the largest timber volume and the highest biodiversity. Nevertheless not all DMUs are able to reach the highest efficiency, becoming inefficient DMUs with $\theta_i<1$. For these inefficient DMUs, DEA provides the slack-variables ($s$, $\lambda$) that are useful for analyzing the inefficient causes, for identifying the reference efficient points ($\lambda_i>0$) and the improving range. Other useful outcome is the contribution made by each resource to achieving a standard goal.

Based on the efficiency index $\theta_i$, a preference ranking can be built, which will state the forest stand efficiency for jointly producing woods and biodiversity.

As said above, two approaches are included into DEA, the input-oriented models that minimize input and maximize output jointly, and the output-oriented DEA that maximizes outputs while using no more than observed amount of any input. This second DEA understanding can be very suitable to forest stand performance, because inputs are not controlled by forest stands – inputs depend on environmental and ecological conditions- as well as they cannot be used beyond a provided amount.

The output-oriented DEA model is established by:

$$\max \quad \eta_i = \frac{\sum_{k=1}^{r} v_{ki} \cdot x_{ki}}{\sum_{j=1}^{m} u_{ji} \cdot y_{ji}} \qquad \forall\, i = 1,2,...,n$$

*subject to*

$$x_{ki}^{*} - \sum_{i=1}^{n} x_{ki} \cdot \mu_i = t_r^{-} \geq 0 \quad ; \quad k = 1,2,...,r$$

$$\eta_i \cdot y_j^{*} - \sum_{i=1}^{n} y_{ji} \cdot \mu_i = t_j^{+} \leq 0 \quad ; \quad j = 1,2,...,m$$

$$\mu_i \geq 0 \quad (i = 1,2,...,n)$$

$$x^{*}, y^{*} \quad \text{are the primal solutions}$$

This expression shows how efficiency is forced to reach the maximum inputs, but constrained to be less than input-oriented optimum ($x_{ki}^{*}$) and outputs should be more than input-oriented optimum ($y_{ki}^{*}$). In output-oriented efficiency indicator is $\eta=1/\theta$, thus the more inefficient a stand is, the higher the score $\eta$ and in frontier points $\eta=\theta=1$.

Both oriented DEA BCC approaches allow building the efficiency production frontier comprised of linear pieces between efficient points. Also convexity constrains have to be established in the system.

## A FOREST STAND AS AN EFFICIENT PRODUCTION FACTORY

Our thesis is that forest stands work as factories where timber and biodiversity are produced. Each forest stand has a capacity to produce biomass only limited by ecological factors as rainfall, sunlight and soil quality. However this primary production can be addressed to different outputs: saw timber, firewood, pulpwood, secondary vegetation (richness and abundance), bushes, meadows, etc…

In our approach it is considered that each forest stand manages efficiently its inputs, although not all stands reach an optimal output combination. Consequently, it seems that DEA BCC output-oriented theory should be more suitable for forest stands than input-oriented DEA.

DEA was applied to 604 forest stands(DMU) belonging to Lanco Commune which had been previously inventoried to estimate their main forest features: wood volume (VOL, $m^3$/ha), tree richness (IRE, number of tree species), stand area (SUP, ha), basal area (BA, summation of all tree sections at 1.30 meter high in a hectare, $m^2$/ha), tree density (DEN, number of trees per hectare), mean squared tree diameter (DMC, cm), forest stand age (E, years), dominant tree height (H, meters), quality site index (QI, adimensional) and radiation index (RI, adimensional). The two last variables were obtained by transforming raw variables; QI was obtained by applying $\ln(QI)=7.0+\ln(H_0)-(E_i/E_0)$ [14, 38, 39] and reflects the forest stand site quality, the QI range in Lance Commune was from 12.67 (poor sites) to 12.98 (rich sites). The RI deals with forest stand sunlight and was obtained as the complement to one of the crown cover, $RI=(BA_{Max}-BA_i)/BA_{Max}$ where $BA_i$ is the basal area, which varied from 14.7 to 43m2/ha.

According to the forest growth theory an increment in some input, whether soil quality (QI) or sunlight (RI), must produce an increment in wood volume and/or biodiversity. All forest stands inputs and outputs are positive, so that DEA requirements seem to be fulfilled.

After applying DEA BCC output-oriented method, the efficient production frontier, made up of all the efficient points, was obtained. In a two-output graph, the efficient points were drawn and marginal production costs were calculated for both outputs (figure 2). Based on this two-output graph, it was possible to discriminate two zones, a zone where both outputs grew together and other where outputs showed a competitive performance, appearing a pay-off marginal cost between them.

Although the quantitative interchange ratio between outputs (timber volume per richness unit) is obtained directly this way, the economic effects depend on the kind of wood to be lost, because wood prices depend on tree diameter and height. In Lanco area, wood products are classified in four classes according to their dimensions (diameter× length): firewood (5cmØ×1.10mL) 22.20$/m$^3$, pulpwood (10cmØ×2.44mL) 19.70$/m$^3$, saw wood (18cmØ×3.30mL) 48.90$/m$^3$, pealing wood (32cmØ×4.10mL) 73.30$/m$^3$ [28, 29, 30, 33, 40, 41].

## RESULTS FOR ONE OUTPUT TIMBER PRODUCTION

Firstly, a DEA BCC output-oriented was applied to the 604 forest stands of Lanco Commune, obtaining only four efficient forest stands: no.425 (377 m$^3$/ha, 39 year), no.587 (336.9 m$^3$/ha, 45 year), no.602 (360 m$^3$/ha, 46 year) and no.604 (216.8 m$^3$/ha; 48 year). The efficiency score ($\theta$) ranged from to 1 to 3.84, having a median of 1.78.

Sunlight input slacks were positive and quality site slacks are always nearly cero, which was interpreted as water and soil were ever optimized, so that efficiency score mainly depended on a good sunlight management.

Looking into the obtained efficiency scores, some negative significant correlation were achieved; efficiency indices were strongly and negatively correlated to forest stand diameter DMC (r=-0.609), age (r=-0.789) and dominant tree height (r=-0.810), and slightly correlated to richness (r=-0.171), conversely efficiency index was positively linked to QI (0.766) and RI (0.798). On the other hand no correlation was found to forest stand density (r=0.073) or stand area (r=0.012). As a result, efficiency depends on stand age and inputs use.

## RESULTS FOR ONE OUTPUT BIODIVERSITY PRODUCTION

When only biodiversity was considered, in terms of number of tree species living in a forest stand, the most efficient stands were no.568 (15 species, 44 year), no.587(8 species, 45 years), no.602 (15 species, 46 years) and no.604(15 species, 48 years), repeating three out of four from the classification based on timber volume production.

At the biodiversity output solution, efficiency score is slightly and negatively correlated to timber volume (r=-0.131), forest stand diameter (r=-0.276), age (r=-0.233), and tree height (r=-0.231), but positively to stand density (r=0.257) and site index QI (r=0.234). No correlation was found between inefficiency and sunlight index RI (r=0.017) or stand area (r=0.041).

## RESULTS FOR JOINT PRODUCTION: TIMBER AND BIODIVERSITY

At this scenario the maximal efficiency index stands were no.568, no.587, no.602 and no.604, the same ones which were obtained for the biodiversity output scenario.

Inefficiency scores were negatively related to richness (r=-0.769), basal area (r=-0.410), forest stand volume (r=-0.579), diameter (r=-0.511), age (r=-0.572) and tree dominant height (r=-0.575). Correlations were positive between inefficiency and density (r=0.233), QI (r=0.567) and RI (r=0.410).

Analyzing how output increments might affect the joint production on the production frontier (Figure 2), we obtained that both timber and biodiversity production can be jointly improved from 3 to 11 richness biodiversity but, for a richness level greater than 11, each richness unit is linked to a pay-off cost. Biodiversity increment can be reached through three different paths: first, a timber volume loss of 4.15 m$^3$/unit to reach a forest stand of 26.2cmØ DCM; second, a volume loss of 13.78 m$^3$/unit to reach a forest stand of 23.4cmØ DCM; and third, a volume loss of 40.05 m$^3$/unit to reach a forest stand of 33.4cmØ DMC. In all three cases different proportions of tree classes should be cut in order to transform the forest from the initial forest stand features (stand no.425 with DCM=19.8cm) to the final forest stand features with a richness of 15 species, stand no.602 ( DCM = 26.2cm ), no.568 ( DMC = 23.4cm ) and no.604 ( DMC = 33.4cm )[42, 43].

Each forest stand diameter distribution was modeled by means of Weibull functions [28, 44,45 46], so that we could calculate how the diameter distribution should change to transform forest stand no.425 into a diameter pattern similar to forest stands no.602, no.568 and no.604.

Following the first path, 17m$^3$ should be cut distributed as 81% firewood, and 29% pulp wood; on the second path the distribution of cuttings was 56% firewood, 39% pulp wood, 5% saw wood, and on the third path felling should be done only on 100% fuel wood trees.

Finally, the cost of adding a new species by improving biodiversity level was obtained. As a result from 3$^{rd}$ to 11$^{th}$ species no pay-off cost should be imputed, but after 11$^{th}$ species the biodiversity marginal cost is 91.27$/species per hectare on the first path, 310.76$/species per hectare on the second path and the highest cost was 889.11 $/species per hectare on the third path.

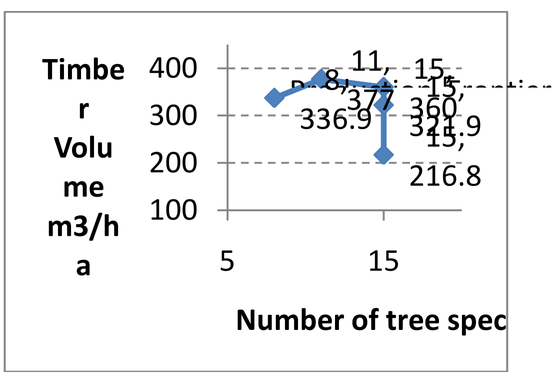


Figure 2. DEA Production Frontier

According to these results, the interchange ratio between timber production and biodiversity (species richness) is 42.12m$^3$/species at richness 8, 34.27m$^3$/species at richness 11 and 24.00m$^3$/species at richness 15, and the average of interchange ratio for inefficient richness is 25.38m$^3$/species.

**DISCUSSION**

DEA method has provided a very intuitive procedure to find the efficient forest stands (θ=1), which will be a reference to inefficient forest stands characterized by the shortage of output or a waste of inputs. The knowledge of the inefficiency cause can provide tools to manage the forest, so forest thinning can be prescribed when the inefficiency cause was a low IR, or fertilization or soil labors could be applied when IQ was low. In addition, each inefficient forest stand has a set of reference efficient ones from which further dasometric and ecological features can be investigated. This information can be used to improve forest management of inefficient stands.

According to the results, a constant relationship appeared between efficiency index and age stand, the bigger the age the lower the efficiency index which is understood, as a general statement, as timber volume is growing steady and species are being added to the forest stand along time. As a consequence, it seems more suitable to compare forest stands with a similar age, which might enforce the site quality index (QI) as an important factor in forest efficiency.

The amount of money obtained as biodiversity trade-off varied from 91.27$/ha·year (high dense and young forest stands) to 889.11$/ha·year (low dense and old forest stands), similar figures to those estimated by Kurttila et al.[22], who reported in 2005 a subsidy taxes for biodiversity temporary protection from 137.75$/ha·year to 171.10$/ha·year, and for permanent protection from 551.00$/ha·year to 845.35$/ha·year.

Otherwise Rojas et al. [14], applying multicriteria linear programming Johnson model I [1] with a biodiversity constrain of 80% of maximum biodiversity (3 species), obtained 10% volume reduction. When Rojas et al. [14] results were applied to two arbitrary forest stands, no.10 and no.297, two pay-off prices of 260.1$/ha·year at no.10 forest stand and 274.4$/ha·year at no.297 forest stand were obtained. Applying at the same stands output-oriented BCC DEA, the pay-off cost to production frontier were 429.95$/ha·year and

603.77$/ha·year, respectively. Nevertheless this cost might be partially imputed to pay-off biodiversity increment but also to the stand inefficiency because neither no.10 or no.297 forest stands belong to the production frontier, so, if inefficiency cost is discounted, by prorating the biodiversity pay-off would be 257.45$/ha·year and 361.54$/ha·year, respectively, which are figures similar to those obtained applying DEA.

## CONCLUSIONS

The output-oriented DEA BCC results were helpful and suitable for analyzing timber production and biodiversity environmental services. Although this work is a first time study, it seems to be a promising method to analyze natural resource efficiency, actual costs and prices in multiple-use forests, achieving interchange inputs and outputs ratios and pay-off prices easily.

The method provides information about whether forest stands are efficient using waters, nutrients and sunlight and helps to find out the closer efficient forest stands and the pattern of improving production.

Obtained values of biodiversity costs are within a liable and reasonable range to be applied to natural resource accounting. In spite of the above written, effects of age should be considered more deeply, trying to get biodiversity cost into natural age-class separately.

As an important result, we can state that, in second growth *Nothofagus* forests in Lanco Commune, for a vegetation richness level between 3 and 11, timber production and biodiversity can be increased simultaneously, but on the production frontier, for a biodiversity level over 11, the increment of a biodiversity unit means a timber volume loss. According to the obtained results, this trade-off ratio varies from 4.05$m^3$/species to 40.5$m^3$/species, that is meant in dollars from 91.27$/species to 889.11$/species.

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