Modelling and simulation of the wood biomass supply from the sustainable management of natural forests

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Abstract

Wood biomass is an important energy resource, which can contribute to reduce the dependence on fossil fuels. The research undertakes the microeconomic approach to estimate the technical availability and operational costs of woody biomass production with a higher level of precision than other models present in the literature, as it considers the entire supply chain of the sustainable management of natural forests. This study introduces a tool, which is applied to estimate supply curves and costs of wood biomass extraction from natural forests in the 7th Region of Chile. The simulation indicates that 531,015 tons/year of wood biomass is available in natural forests of the Region under study, with extraction costs ranging from 24.51 to 56.68 US$/ton, or an average total cost of 40.97 US$/ton. The parametric analysis revealed that the maximum admissible distance to the nearest transport route and the transportation costs are the two most influential variables in the estimation of wood biomass supply and cost. Reducing the admissible distance from 5 km to 1 km reduced the availability of biomass by 80%, while a variation of ±50% of transportation costs translated into ±18.3% variation of total extraction costs.

The proposed method can be used to identify the technical-economic potential of wood biomass from natural forests in any commune, province, region, or country; as it has the flexibility to allow tests with multiple scenarios and parameters depending on the specific characteristics of the area to be analyzed. Essentially, the purpose of this tool is to serve the assessment processes of the identification of new wood biomass resources, allowing decision makers to increase the potential of sustainable and cost-effective woody biomass for heat and electricity generation, and at the same time reduce greenhouse gas emissions and the dependence on fossil fuels.

Keywords

Wood biomass; Supply curve; Renewable energy; Sustainability; Heat and power generation; Chile.

1 Introduction

Biomass energy is a key component to meet the United Nations sustainable development goals in terms of energy security and climate change mitigation (Yan et al., 2020). In fact, CO_2 emissions can be reduced by increasing the amount of biomass energy consumption in production processes (Sulaiman et al., 2020). In view of this, many countries have set up targets for the substitution of fossil fuels by bioenergy (Bacovsky et al., 2016; Mandley et al., 2020). Based on a mitigation scenario for the energy sector developed by the International Energy Agency (IEA, 2012), Strapasson et al. (2017) projected the impact of total bioenergy production, predicting a growth of 600% by 2050 compared to 2015 levels. Given the increasing demand for bioenergy resources, forests will be under strong stress in the future. Biomass is the organic resource that mainly comes from living organisms such as plants and animals, and it may be sourced from forest crops and residues, agriculture and residues, marine waste, industrial waste, and co-products (Buonocore et al., 2019; Kalyani and Anitha, 2013; Mola-Yudego et al., 2017). Biomass energy potential is often addressed as the most promising among the renewable energy sources (RES), due to its spread and availability throughout the world (Mobini et al., 2014; Springer et al., 2017). Moreover, it presents the unique advantage among all RES, of being able to provide fuels that can be stored, transported and used far from the point of origin.

In Chile, biomass represents 25% of the primary energy consumption in 2017 (Ministry of Energy, 2018). The same year, the electricity production sector was the largest consumer of biomass with a 53% share of the total stock, followed by the industrial sector with 25%, and the building sector which included commercial, public, and residential buildings with 22% (Ministry of Energy, 2018). The biomass used for electricity generation feeds directly or indirectly 38 power plants of a total installed capacity of 501 MW (Systep, 2020), but it only represents 1.8% of the total installed capacity for power generation in the country as of June 2020 (Generadoras de Chile A.G., 2020). For the residential sector, however, biomass is an essential energy source, as it accounts for 39% of the total energy demand from households (Ministry of Energy, 2018) and almost 73% of their space heating demand (CDT, 2019), surpassing conventional sources such as natural gas, liquefied gas, and electricity. As an abundant resource, biomass can play a strategic role in achieving Chile's energy goals in the domestic sector. Besides, it offers the potential to reduce the country's dependency on fossil fuels imports to generate heat and power, thereby reducing vulnerability to supply disruptions and energy price volatility.

According to the literature, woody biomass resources can cover a significant part of primary energy consumption (Bildirici and Özaksoy 2016, Proskurina 2016, Kovalyshyn 2019). Using a spatial equilibrium model based on biophysical and technical cost information, Lauri et al. (2014) predict that wood biomass could satisfy 18% of the global and 74% of South America primary energy consumption in 2050. The cost of production is a crucial factor to consider when the purpose is to increase the use woody biomass as a biofuel, as it can be influenced by accessibility limitations or the demand for alternative uses. Thus, special attention must be given to the cost-effectiveness of biomass compared to other conventional energy sources. In Chile, as in many cases, the limiting factor is not the amount of biomass, but its accessibility and associated production costs, such as the cost of harvesting labour, machine tools and transportation. The latter is a key issue when analysing the strategy for wood biomass extraction, not only because of the economic aspects but also because of the environmental impacts associated with the use of fossil fuel in transportation.

Estimates of the gross wood biomass potential of natural forest management in Chile range from 2.6 GW to 4.7 GW (Ríos et al., 2013, Leiva et al., 2008, Gysling et al., 2017). However, as these studies only quantified the gross potential of the resource and ignored to consider the technical or economic restrictions of the supply chain, there is a gap in the true representation of the potential and implications this energy source could have on the country's energy matrix. Therefore, it is necessary to carry out studies to assess the biomass supply at the local level to have a clear understanding of the market and the impact it may have in relation to externalities, such as the possibility of reducing greenhouse gases and particulate matter emissions resulting from biomass combustion.

The supply of forest wood biomass for a region or country can be described as the centralized representation of the operational costs and the technical availability of production of all the forests present in one determined area. The lack of such information has a negative impact on the growth of the wood biomass sector for heat and power generation, as it represents a constraint that can repel new business engagement and prevent the introduction of public policies aiming to promote the use of wood energy. In Chile, current policies rather aim to mitigate the environmental impacts of the wood biomass sector, particularly with Law 20.283 for the recovery and sustainable management of natural forests (Schlegel, 2020) and air quality management plans for the control of air pollution episodes (Jorquera, 2018), but do not actually set the scene to ensure the growth of the sector for heat and power generation.

The objective of this study is to develop a model that allows to simulate both the technical capacity and operational costs for the supply of wood biomass from natural forests for any region, province, or community of interest. Essentially, the proposed tool aims to provide crucial information capable of drawing attention towards the technical-economic potential of woody biomass for heat and power generation, and spur investors and regulatory bodies to make the most of this energy resource, which is increasingly prevalent to reduce greenhouse gases emissions and the dependence of fossil fuels. The present study focuses on woody biomass, which can be generated directly by the sustainable management of natural forests. This includes split logs, felling and harvesting residues (i.e., bark, branches, crowns, stumps), and wood processing (i.e., sawdust, woodchips). Natural forest management uses the waste from forests of non-industrialized native species, which should not be confused with protected forests or reserves.

The paper is organised as follows: Section 2 introduces some of the literature on the subject, followed by the proposed methodology in section 3; the methodology is then employed for estimating the biomass supply from the sustainable management of natural forests for the 7th Region of Chile, and section 4 presents a discussion about the findings; finally, section 5 presents the concluding remarks.

2 Literature review

2.1 Identification of the needs and opportunities

At the national level, there is documentation on the theoretical amount of wood biomass available from natural forest management; however, there is no information on the technical potential (i.e., technologically possible to extract) and economic cost (i.e. cost of obtaining) of the resource for the entire country. Due to the lack of information on the technical-economic potential of this energy source, private companies are less keen to invest, and it is more difficult for public institutions to make policy decisions in order to regulate and harvest the maximum benefit from this energy resource. In this regard, there is a need to build a model capable of simulating the technical capacity and the costs associated with the extraction of wood biomass. Such a model can lead to the graphical representation of supply curves for this energy source throughout the country.

The use of biomass from the sustainable management of natural forests represents an opportunity to sell energy in the range of US$ 251 million and US$ 1,600 million for the electricity sector, considering the most conservative estimates of the usable gross potential of 2,597 MWe (Ríos et al., 2013), based on the following assumptions:

- There is a technical-economic capacity to extract biomass from 10% up to 50% of the feasible technical potential estimated by the Universidad Austral de Chile (Ríos et al., 2013).
- Uptime of 8,400 hours annually per MW installed (i.e., hours per year that the plant is operating).
- Plant factor of 80% (i.e., amount of MWh generated per MWh theoretical design).
- Sale price of energy at 144.3 US$/MWhe (i.e. the average of the marginal cost for the last ten years (Systep, 2016)).

Another possible economic or social opportunity that would result from the use of wood biomass from the sustainable management of natural forests as a source of electricity is an investment of US$ 700 million to US$ 3,500 million in biomass power plants, based on the following assumptions:

- An investment of US$ 2,700 per kWe installed for power plants using forest residue (CNE, 2015).
- The installation of 10% to 50% of the feasible technical potential (Ríos et al., 2013).

In addition to the production, sale, and investment in power generation projects, using biomass is a great opportunity for job creation in extraction work on the field, the conservation and maintenance of natural forests, and it offers a series of economic benefits to the surrounding communities. Simulating the operational costs and the technical availability of production requires an analysis and simulation model that can:

- Carry out a territorial analysis of the forests;
- Simulate the availability of biomass;
- Determine a supply centre;
- Simulate the operational costs by forest;
- Simulate the supply curves based on the operational costs and the technical availability of the wood biomass production of forests.

2.2 Market supply modelling and analysis

The market supply curve (i.e., graphic representation of the market offer) is defined by the relationship between the availability and costs from all the actors. The modelling of the market supply curve necessarily involves the microeconomic or operational analysis of each actor. This consists of gathering the short-term microeconomic particularities of all the actors in a single data set. The market supply curve modelled with this approach is defined and restricted by the sum of the different sellers' supply curves horizontally.

In order to model the supply curve of a company involved in a market with perfect competition (i.e., where the company does not influence the price or the cost factors of production), it is necessary to take into account the interest of commercial companies. Commercial agreements are generally obtained if companies can secure a certain benefit from their operations and productions. Thus, the seller's supply curve can be defined according to the short-term microeconomic approach, which is that the selling price is equal to the quantity ratio at which the seller would offer the products. Despite the lack of homogeneity in the studies reviewed, most of them carried out the following stages in the estimation of the market supply (Sommer, 2009; Furubayashi and Nakata, 2018):

a) Identify potential biomass suppliers and their location;
b) Determine the amount of biomass available from each source;
c) Estimate the costs associated with the delivery of the resource (extraction and transport);
d) Establish a hierarchy of suppliers based on their selling price;
e) Create the market supply curve.

In order to simulate the availability and costs of delivering forest wood biomass, it is necessary to understand the logistics chain that allows its extraction and delivery (Sanchez-García et al., 2017).

2.3 Forest biomass and natural forest

Biomass resources from forests such as split logs, felling, harvesting residues, and wood processing have been widely documented and validated at the national level (Bertran and Morales, 2008). These are resources that have the economic and logistical support of the main forestry companies, which use the majority of their wood waste in generating heat and power for their own processes (Bertran and Morales, 2008). The existing data on the biomass of the natural forest are closely related to the gross availability, location, and legal feasibility of operating the resource, with only one pilot study that has been done on the costs and the technical availability for the 14th Region of Chile (Ríos et al., 2013).

The main potential source of wood biomass in Chile is from the management of natural forests (Pontt, 2008). The main objectives of the management are to improve the conditions inside the forests and extract high quality wood. At the international level, it is observed that the processes that simulate the production of biomass from the forests are: harvest, management of the forest interior, transformation (i.e., physical processes to splinter the material), loading, and transport of the material (Cabrera et al., 2011; Perez-Verdin et al., 2017; Cozzi et al., 2013). In Turkey, Eker et al. (2017) predicted yield and extraction costs throughout the supply chain of residual woody biomass that involve harvesting, collection, pre-processing, chipping and transportation. Biomass in the form of woodchip, bale and pellet was investigated with road, railway and waterway transportation options, and results indicated that the total cost including chipping, transportation and other indirect costs can reach 75€/dry tons.

2.4 Logistics chain

Studies performed in Chile on this subject have mentioned logistics chain processes such as harvest, material handling within the forest, the transformation of biomass, and transport to supply centres (Ríos et al., 2013, Bertran and Morales, 2008). The following describes each of the processes.

Thinning is the selective removal of trees, primarily undertaken to improve the growth rate or health of the remaining trees. This results in a higher volume and larger diameter of good quality timber being harvested from a crop, which commands a higher price from the future transformation processes. The wood harvested from thinning is still of good quality, particularly for split logs, wood chips, and pellets production (Espinosa et al., 2000). The operational costs of thinning are closely related to the internal conditions of the forest, especially the prevailing slope of the terrain (Ríos et al., 2013; Cabrera et al., 2011) and distance to the nearest transport route (Cozzi et al., 2013). Some studies assume that the cost of felling trees (thinning) is a sunk cost by biomass producers (Bertran and Morales, 2008; Perez-Verdin et al., 2017) since the objective of thinning is to get larger and higher priced trees. Other studies state that the cost of thinning must be absorbed proportionally by biomass producers (Ríos et al., 2013).

Stacking consists of the gathering and transformation of material for the later stages of the logistics chain (Bertran and Morales, 2008). The transformation process can be done thanks to the equipment used during harvests, such as the felling axe, the handsaw, or machinery tools like the chainsaw, the cutting-saw, or the sawmill (Cabrera et al., 2011). The gathering can be done using small trucks or excavators, or traditional methods such as the use of oxen (Carey Briones et al., 2006). The complexity of this process is determined mainly by the predominant slope in the forest (Cabrera et al., 2011) and the distance to the extraction route (Cozzi et al., 2013).

Chipping involves crushing or mulching the material in the forest. This process can optimise transportation costs. When the material is crushed, it can occupy all the available volume in the trucks, considerably reducing costs for distances greater than 30 km (Cabrera et al., 2011).

Transport links the logistics chain between suppliers and clients through the complex network of existing roads. Due to the relatively high density of the wood, the cost of transportation generally represents a large share of the final wood cost (Bertran and Morales, 2008; Perez-Verdin et al., 2017). The analysis of the transport routes to be used is usually done through the GIS software (Geographic Information System), a process in which the distance between the forest and the destination of the wood biomass is optimised (Ríos et al., 2013). None of the previously mentioned processes consider the economic retribution to forest owners. However, several studies analyse and quantify the payments to forest owners per ton of extracted material (Ríos et al., 2013; Perez-Verdin et al., 2017) as a cost component to be covered by the biomass bidders.

2.5 Technical feasibility of extraction

The technical feasibility of wood biomass extraction is usually defined by the slope and distance to the nearest forest route. The average slope is an essential factor to determine the operational feasibility since high slope terrains make the thinning and stacking processes more complicated to execute. The operational labour costs are closely proportionate to the average slope of the area of operation. Studies indicate that forests with slopes between 30% and 50% are usually discarded, as they do not represent any economic interest (Cabrera et al., 2011; Cozzi et al., 2013).

The distance to the nearest route is another variable that determines the operational feasibility of harvesting wood biomass from a forest. Operation costs are calculated depending on the distance to the nearest route and ease of access to the area. Ríos et al. (2013) determined for the 14th Region that all forests within a 5 km radius to any route should be considered for operations.

In order to understand how much biomass can be obtained from the total amount available, the literature uses the utilisation factor, which can simulate the percentage of extractable biomass from the forests without disturbing their internal ecosystems (Bertran and Morales, 2008). The usage values of extractable biomass are in a range between 50% and 90% for each forest analysed.

2.6 Energy implications of biomass

The energy implications of biomass begin with an analysis of its characteristics, which define the combustion power of the wood biomass fuels extracted from natural forests of Chile. The calorific value is defined as the magnitude of the combustion enthalpy produced by the fuel (Moran et al., 2004). Enthalpy is defined as a property of materials determined by the combination of internal energy, pressure, and volume of the system, which can be calculated as follows:

$$H = U + P \cdot V \quad (1)$$

where H is the system enthalpy in MJ, U is the system internal energy in MJ, P and V stand for the system pressure in Pa and volume in m^3, respectively.

The enthalpy of a combustion reaction can quantify the energy that a fuel produced during the combustion reaction. The enthalpy of combustion is defined by the difference between the enthalpy of the products and the reactions for complete combustion at constant temperature and pressure (Moran et al., 2004), as shown in Equation 2:

$$\bar{h}_c = \sum_P n_p \cdot \bar{h}_p - \sum_R n_r \cdot \bar{h}_r \quad (2)$$

where $\underline{h}_c$ is the combustion enthalpy in MJ/kmol, n_r and n_p are the coefficients of reactions and products, respectively, the reaction equations $\underline{h}_r$ and $\underline{h}_p$ are the enthalpies of reactions and products, respectively, and subscripts P and R represent each product and reaction.

The percentage of carbon, oxygen, nitrogen, hydrogen, and sulfur present in the dry biomass composition are among the variables that define the calorific value of forest biomass (Moka, 2016), as well as H_2O levels present in the initial samples (Quaak et al., 1999). These are the most common compounds present in cellulose, and the levels of O, N, H, S, and humidity present in the dry biomass have a direct effect on the material's calorific value and the theoretical definition of the enthalpy of combustion. Indeed, the higher the moisture level contained in the material per unit of mass, the lower the energy produced during the combustion; thus, the lower the calorific value of the material (Quaak et al., 1999). The calorific values found in the literature for Chilean forest biomass are described in Table 1.

	LCV_0 (MJ/kg)	LCV_{25} (MJ/kg)	LCV_{50} (MJ/kg)
Average	17.7	14.0	11.2
Standard deviation	0.31	0.32	0.27

Table 1. Lower calorific value (LCV) of wood biomass for 0%, 25%, 50% wt moisture content, respectively (Ríos et al., 2013; Altamirano et al., 2015).

The available energy produced by the combustion of a certain mass of biomass can be found by multiplying the lower calorific value per unit of mass by the mass of the combustible to be burned as shown in Equation 3:

$$U_e = LCV_{hum} \cdot m \tag{3}$$

where U_c is the available combustible energy in MJ, LCV stands for the low calorific value of the combustible according to its humidity content in MJ/kg, subscript hum represents the level of humidity contained in the biomass stock in %, and m is the total weight of the biomass stock in kg.

2.7 Literature gaps

There are various methods of biomass potential estimation in the literature. For instance, Goerndt et al. (2019) employed small area estimation techniques based on inventory information, forest attributes and product output data to obtain estimation of the wood biomass supply from specific forest areas in the United States. Bascietto et al. (2020) used the ranked set sampling method based on vegetation dynamics data from satellite remote sensing to estimate the biomass potential across specific land covers in Italy. Chinnici et al. (2015) conducted a comprehensive analysis of biomass availability in Sicily using local statistical data combined with a series of parameters obtained from the literature and direct research. These studies have mainly focused on the technical estimation of gross biomass supply in specific areas without considering their production costs. Other studies by De Wit and Faaij (2010), Delivand et al. (2015), Forsell (2013) and Venturini (2019) proposed integrated assessment methods to evaluate biomass spatial availability and productivity, but as these are mainly based on the least-cost planning, they may not reflect the entire potential.

No research has been found that has undertaken the microeconomic approach to estimate the availability of biomass markets. Determining the marginal cost curves of each operating company in the market by using a microeconomic analysis approach is a more accurate and reliable means to estimate supply curves (Binkley, 1981; Niquidet & Friesen, 2014). As in most of the studies in the literature, the operational analysis approach was used to model the supply curves of natural forest management. This methodology includes the main processes involved in the logistics chain for biomass extraction, which are felling or thinning, stacking, chipping or mulching, and transportation. In addition to the price of standing timber generally paid to the landowner, all these processes have an impact on the evaluation of the final cost of wood biomass, generally per unit of volume.

The contribution of this study to the existing literature relies on two main aspects. First, unlike the aforementioned studies that addressed only the technical availability of biomass supply, we consider not only the yield of woody biomass from the sustainable management of natural forests, but also the costs of extracting them. Second, we use local data to calibrate the simulation model. Estimating local biomass availability is convenient to determine the optimal supply networks of biomass for heat and electricity generation. To make wood biomass an economically viable and sustainable option for energy generation purposes, its point of origin should be geographically close to the end user in order to reduce transportation costs and carbon footprint.

The bibliographic analysis was carried out in order to compile all the parameters and variables that define the operational costs and to obtain the cost function of each of the processes involved in the logistics chain of biomass extraction. According to Rios et al. (2013), the costs involved in forest management are sensitive to local circumstances and specific to each site. In the present study, the cost analysis was restricted to Chilean national data. The following section introduces the proposed model as well as some standards, which can be used to determine and simulate the technical feasibility of wood biomass extraction and operational factors.

3 Methodology

3.1 Simulation model

The woody biomass supply curve defines the amount of woody biomass available at various hypothetical wood prices; i.e., it gathers all the information from the biomass sector needed to model energy wood use. The relational model, which is a database model based on first-order predicate logic, is the most appropriate type of model for this study, as it can represent data as relations or tables. Considering the quantity of data, variables, parameters, constraints, and tools necessary to simulate the economic availability of wood biomass, such a model allows for ordering and systematizing. The flow chart diagram of the proposed model shows the connection links between information sources and analytical processes (see Figure 1).

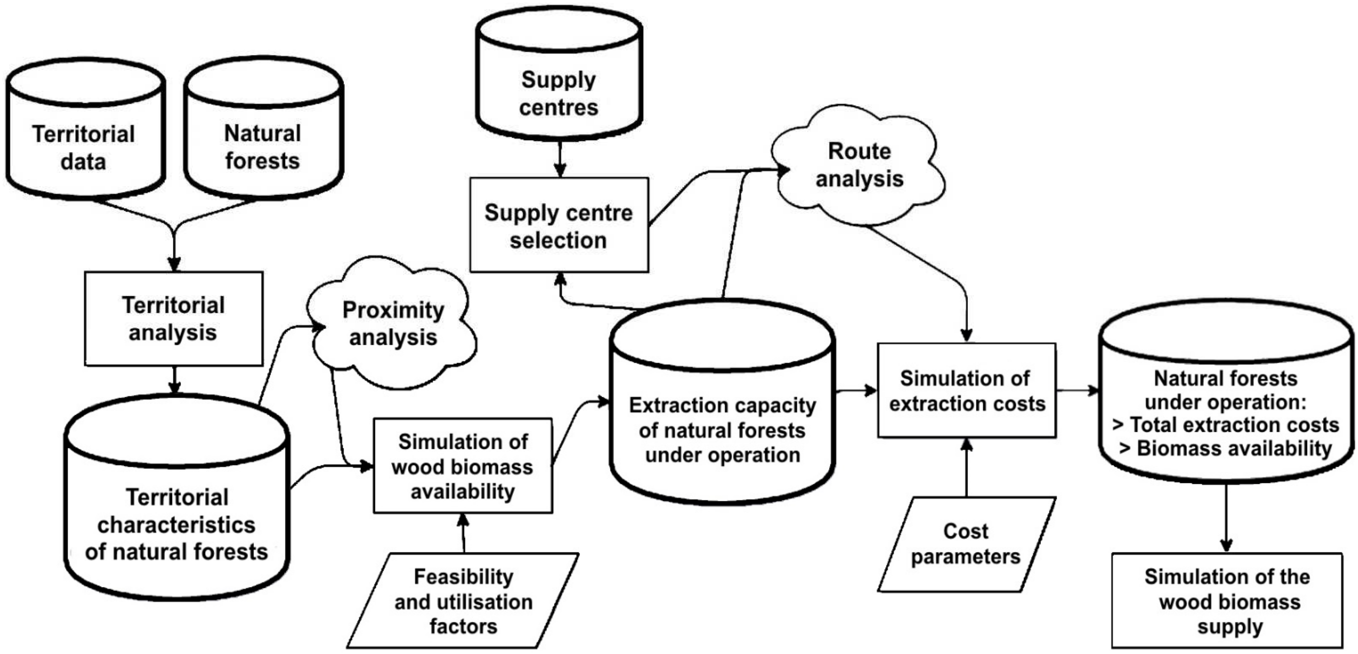

Figure 1. Schematic diagram of the proposed computation model

A territorial analysis, as well as a proximity and route analysis, were required in order to simulate the availability of wood biomass and the related costs of extraction. This step focused on gathering the values of the main model variables. The territorial analysis was carried out using a free and open source geographic information system (GIS) application called QGIS 3.6 software developed by the QGIS Development Team (QGIS Development Team, 2016). The proximity and route analysis were done thanks to Google Maps Directions API (Google Web Services, 2016), which can be used to calculate directions between locations for several modes of transportation. The use of QGIS and Google Maps Directions API were essential for obtaining territorial information for the study.

The data processing of the variables obtained through QGIS and Google Maps Directions API was done using Microsoft Excel spreadsheets. The choice of the supply centre and the management of the Google Maps Directions API was made through scripts written in the Python language program. The simulations of costs, extraction capacity, and economic offerings were done using Microsoft Excel, using the information obtained in the territorial and route analysis previously done with QGIS, Python, and Google Maps Directions API.

3.2 Definition of the model

Simulating the supply curve of wood biomass from the sustainable management of natural forests necessarily involves modelling the relation between cost and availability from all producers, in order to obtain the unit cost of extraction and the available capacity for each supplier. Each of the processes involved in the proposed model is described in the following sections.

3.2.1 *Territorial analysis*

Territorial parameters such as the location, the land area, the territorial extension, the land's slope, and the quantity of wood biomass per hectare of all natural forests were obtained with the QGIS Software. The slope is the main parameter responsible for the levels of automation and the use of machinery and personnel in the forestry work (Cabrera et al., 2011), and it is an essential parameter of the cost model for the evaluation of operational expenses from the management of forest biomass. The QGIS software was used to obtain the average and median slope, and the slope's standard deviation for each forest in question.

3.2.2 *Proximity and distance analysis*

The distance between a forest and the nearest accessible road was calculated using Equation 4. The Earth's radius, assumed to be 6,378 km, was used to emulate the surface of the Earth and to obtain a viable approximation of the distance between two points along the Earth's surface (Weisstein, 2016). For such calculations, it was necessary to use WGS84 coordinates in radians from the EPSG:3785 code of both locations. The location of the nearest road to each forest was found using Google Maps Directions API.

$$d\big((\sigma_1,\lambda_1);(\sigma_2,\lambda_2)\big) = R \cdot Arc[cos\,cos\,(\sigma_1) \cdot cos\,cos\,(\sigma_2) \cdot cos\,cos\,|\lambda_1 - \lambda_2| + sin\,sin\,(\sigma_1)\ \cdot sin\,sin\,(\sigma_2)\ ] \qquad (4)$$

where $d((\sigma_1,\lambda_1);(\sigma_2,\lambda_2))$ is the minimum distance between two points through the Earth, R is the Earth's radius (km), σ_i is the latitude of the point i (radians), and λ_i stands for the longitude of the point i (radians).

3.2.3 *Biomass availability modelling*

The operational feasibility analysis provided an assessment of each forest's characteristics to determine if they met all the conditions required for operation. Based on recommendations and conclusions from Ríos et al. (2013), the maximum admissible slope for wood biomass extraction in this study was fixed to 45% (i.e., equivalent to 24.23 degrees). Moreover, the maximum admissible distance to the nearest transportation route was set to 5 km. It is worth noting that the available wood biomass defined in the study refers to material that was considered as waste by the timber industry and could not be used for the production of boards, plywood, furniture, etc., due to its composition, size, or appearance.

Three scenarios were analysed in the study. First, we considered a reduced production capacity, which applied a utilisation factor of 50% (i.e., half of the wood biomass available in the forest was harvested). Such a scenario is representative of adverse ecological conditions in natural forests when producers are forced to restrict the thinning process in order to protect natural forests. The second and third scenarios consider a utilisation factor of 75% and 90%, respectively, of the available wood biomass present in the locations in question. The second scenario reflects an average production activity, while the third scenario supposes a maximum production, including the extraction of a significant volume of waste from thinning.

3.2.4 Supply centres selection

Taking into account that wood biomass is used predominantly as a fuel source in Chile, the electricity production substations of the SIC (Central Interconnected System) national grid, as well as the existing biomass plants were considered as potential supply centres. The model selected the substation or plant that was closest to the centre of mass of the forests in the region, province, or commune analysed. The centre of mass and the forest position were determined using QGIS, and the nearest substation or biomass power station to the centre of mass was selected by taking the shortest land surface distance. The calculation of the centre of mass was done using the following equations 5 and 6:

$$CM_j lat = \frac{\sum lat_{B_i} \cdot V_i}{\sum V_i} \quad (5)$$

$$CM_j long = \frac{\sum long_{B_i} \cdot V_i}{\sum V_i} \quad (6)$$

Where $CM_j lat$ is the latitude of the centre of mass associated with the supply centre CO_j, $CM_j long$ is the longitude of the centre of mass associated with the supply centre CO_j, lat_{Bi} is the latitude of the forest B_i associated with CO_j, $long_{Bi}$ is the latitude of the forest B_i associated with CO_j, and V_i is the volume of wood biomass available from the forest B_i in tons.

3.2.5 Thinning or harvesting cost modelling

The first stage to simulate in the logistics chain was thinning. This cost component was modelled as follows:

$$C_{CO}(B_i) = c_{co,i} \cdot V_i \quad (7)$$

where $C_{CO}(B_i)$ is the total cost of thinning or harvesting in the forest B_i in US\$, $c_{co,i}$ is the cost of thinning or harvesting per unit of weight in the forest B_i in US\$/ton, and V_i is the volume of wood biomass available in the forest B_i in tons.

The average slope of the forest adjusts the cost per unit of weight linearly, as shown in Equation 8. This adjustment was made to reflect the changes in the technology and the productive factors that should be implemented as the complexity of the biomass extraction increases.

$$c_{co,i} = c_{co,i,min} \cdot \left(1 + \frac{slope(B_i)}{slope_{max}}\right) \quad (8)$$

where $c_{co,i,min}$ is the minimum cost per unit of weight of thinning or harvesting in the forest B_i in US\$/ton, the $slope(B_i)$ is the maximum value between the average slope and the mean slope of the forest B_i in degrees, and the $slope_{max}$ represents the maximum admissible slope equal to 24.23 degrees, thus discarding forests with higher slopes.

Equation 8 was modelled based on the survey developed by the Ríos et al. (2013), which determined that the harvesting cost of wood biomass with 50% wt moisture content ranges between 6.67 US\$/ton and 13.35 US\$/ton. It also considered the slope of the forests as the main variable that defines the operational conditions of the harvest. For this reason, the forests with a slope of 0° were designated with the minimum extraction cost, while those with the maximum acceptable slope were designated with the maximum cost.

3.2.6 *Stacking cost modelling*

This model component is calculated using Equation 9 as follows:

$$C_{AC}(B_i) = c_{ac,i} \cdot V_i \tag{9}$$

where $C_{AC}(B_i)$ is the total cost of stacking in the forest B_i in US$, $c_{ac,i}$ is the stacking cost per unit of weight in B_i in US$/ton, and V_i is the volume of wood biomass available in tons.

Through a series of surveys done on forest operators, Bertran and Morales (2008) determined that the cost of stacking was 2.49 US$ per ton of biomass consumed.

3.2.7 *Chipping cost modelling*

This model component was calculated using Equation 10 as follows:

$$C_{AST}(B_i) = c_{ast,i} \cdot V_i \tag{10}$$

where $C_{AST}(B_i)$ is the total cost of chipping in B_i in US$, and $c_{ast,i}$ is the cost of chipping per unit of weight associated with B_i in US$/ton.

In the literature, the cost of chipping or mulching was usually standardised at a fixed value per ton for the whole industry. Bertran and Morales (2008) have set the unit cost for chipping at 7.07 US$/ton, based on the survey done on forest operators by the Non-Conventional Renewable Energy Project in Chile.

3.2.8 *Transportation cost modelling*

Other researchers have considered transportation as the most important cost variable of the entire logistics chain of wood biomass extraction from forests (Perez-Verdin et al., 2017). The proposed model used the Google Maps Directions API in order to determine logistically and economically viable routes of transportation. This tool provides information on transportation costs for optimum routes between two geographically referenced positions as a function of travel time, distance, and itinerary. The cost associated with the transport of wood biomass per supplier was calculated using Equation 11:

$$C_{TR,ij}(B_i; CO_j) = C_t \cdot dVial(B_i; CO_j) \cdot V_i \tag{11}$$

where $C_{TR,ij}(B_i;CO_j)$ is the total cost of transport from the forest B_i to the supply centre CO_j in US$, C_t is the cost per unit of weight of transport in US$/km/ton, $dVial(B_i;CO_j)$ is the optimum road distance between the forest B_i and the supply centre CO_j in km, and V_i the volume of wood biomass available in B_i in tons.

According to Bertran and Morales (2008), the cost per unit of weight of transport C_t can be assumed to be 0.145 US$/km/ton, while the optimum road distance between the forest and the supply centre dVial ($B_i;CO_j$) was determined using the Google Maps Directions API.

3.2.9 *Cost of standing timber modelling*

At present, no public or private actor has taken advantage of wood biomass production from natural forests, nor has anyone ensured that these conditions will be pursed over time. For this reason, the proposed model considered a unit cost of extracted biomass as an addition to other supply chain costs. This extra cost reflects the payment to the landowners for standing timber and the sustainable management of natural forests. The price of standing timber generally paid to the landowners was calculated as follows:

$$C_{MP}(B_i) = c_{mp,i} \cdot V_i \quad (12)$$

where $C_{MP}(B_i)$ is the total cost of standing timber in the forest B_i in US$, and $c_{mp,i}$ is the cost per unit of weight of standing timber associated to B_i in US$/ton.

Rios et al. (2013) estimated that the unit cost of standing timber $C_{mp,i}$ ranged between 4.45 and 7.12 US$/ton in a survey, where the variance was determined individually from expected margins. In this study, it was estimated that the average value for $C_{mp,i}$ was 5.78 US$/ton.

3.2.10 Total cost per forest

The total cost of wood biomass production for each forest, noted $CMUP_i(B_i;CO_j)$, represents the total cost of each process involved in the extraction from a forest to provide one ton of wood biomass at the supply centre. This total cost was calculated using Equation 13:

$$CMUP_i(B_i; CO_j) = \frac{C_{CO}(B_i)+C_{AC}(B_i)+C_{AST}(B_i)+C_{TR,ij}(B_i)+C_{MP}(B_i)}{V_i} \quad (13)$$

The total cost of wood biomass production for each forest was used to create supply curves. By arranging the forests in increasing order of total cost with their respective production volumes allows simulating the marginal cost curve of the biomass market for any supply centre.

3.2.11 Supply curves modelling

The supply curves were distributed according to the increasing order of costs of the different supply centres, which showed the availability ratio and the cost behaviour for the biomass theoretically available in the analysed region. It is worth noting that the behaviour of extraction costs and technical availability was different for each forest, due to the non-uniformity of the natural forests that were analysed, thus leading to variations in the supply curve.

4 Results

In this study, the proposed model was applied to the 7th Region of Chile, which presents a total area of natural forest of 581,515 ha (i.e. almost 20% of the total Region land area) (CONAF, 2014).Three types of scenarios were analysed using utilisation factors (f) of 50%, 75%, and 90% to represent the minimum, expected, and maximum extraction supply, respectively. The results indicated that the simulated availability of wood biomass with 50% wt moisture content in the first scenario (f = 50%) was 354,010 tons/year. The second scenario (f = 75%) indicated the availability of 531,015 tons/year of wood biomass with 50% wt moisture content. In the third scenario (f = 90%), the market supply curve suggested a result of 637,218 tons/year of 50% wt moisture content biomass. Figure 2 shows the three market supply curves according to the level of production for each scenario. The difference in marginal extraction costs was mostly influenced by the utilisation factor causing a decrease or increase in the extraction costs for the same level of production. Similarities can be observed in the shape of the three curves, thus highlighting the impact of the degree of extraction on the final product cost.

It is worth noting that the potential of biomass extraction was different for each forest, and the utilisation factor represented a certain amount of biomass available for extraction without disturbing the forest's natural ecosystem. In the analysis below, results are shown considering the second scenario (f = 75%) as the base-case scenario, since it was the most representative and probable case and reflected the conditions of the sustainable management of natural forest biomass extraction.

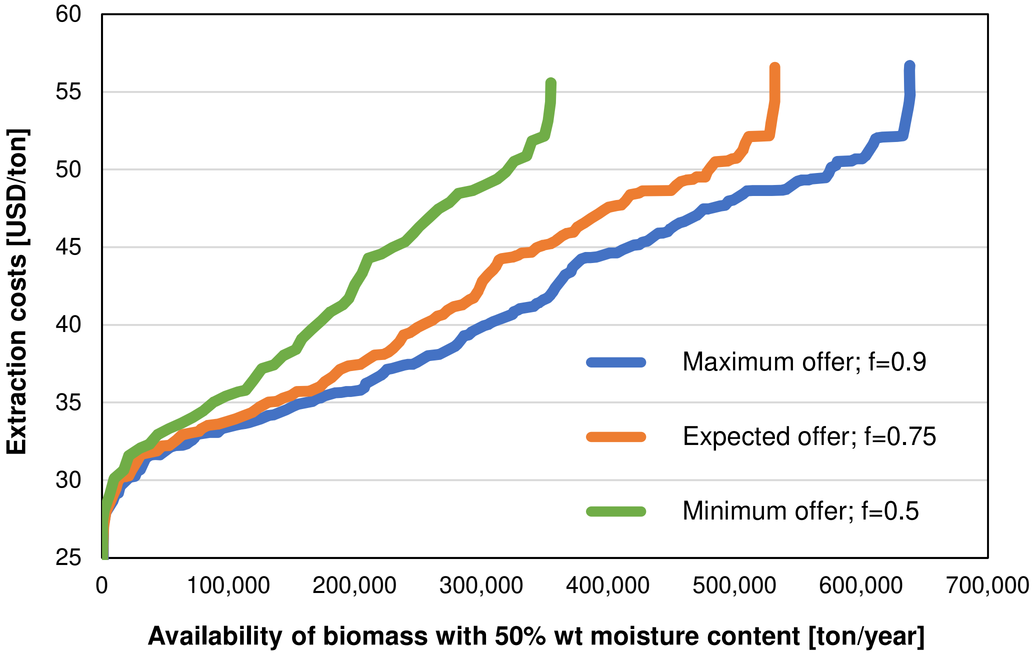

Figure 2. Market supply curves of wood biomass in the 7th Region.

The supply centre chosen by the model is located at the coordinates 35°68'61"12 South and 71°37'72"19 East. Figure 3 shows the simulated marginal total cost for the expected scenario (f = 75%) and the average total cost that all suppliers would charge to deliver the first tons of wood biomass. The results showed that the average total cost had a moderate increase in comparison with the supply curve. Such increase in average cost was about 6.1% for each additional 100,000 tons/year, which suggested an increase of 26.7% of the average cost per ton for the expansion of the production rate from 100,000 to 500,000 tons/year. Since the average cost represented the average production cost of all the suppliers, any buyer who requires a certain order of biomass volume should pay at least the average cost per ton.

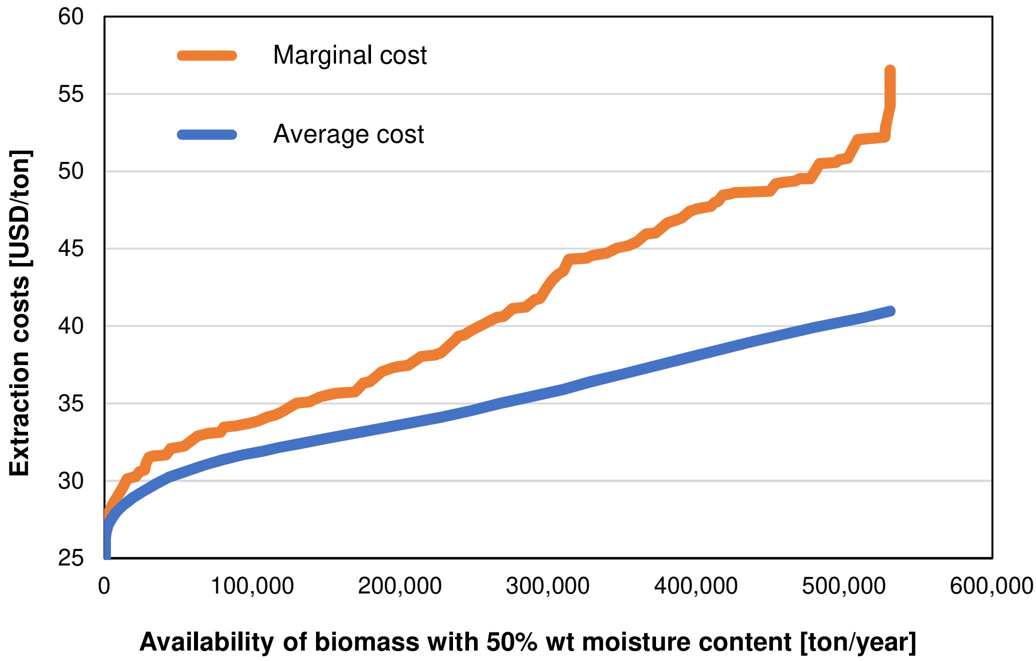

Figure 3. Marginal and average total cost of the wood biomass extracted in the 7th Region

The simulated average cost for the 531,015 tons/year available in the 7th Region was 41 US$/ton. For such a volume of biomass available in that area, the cost of the different production variables is shown in Table 2.

Production variable	Share of total average cost
Thinning / harvesting	25%
Stacking	7%
Chipping	14%
Transportation	38%
Landowner payment	16%

Table 2. Average cost for each variable

The transportation cost was the variable with the greatest weight on the structure cost for wood biomass extraction in the 7th Region of Chile. The dynamics highlighted between the marginal cost (i.e., supply curve) and the marginal distance covered by transport indicated that the transportation variable had the greatest impact on the supply curve.

5 Sensitivity analysis in the simulation of the biomass supply curve

5.1 Impact of the maximum admissible slope

The vast majority of the land surface of the natural forests of the 7th Region under study had slopes within ranges of operation according to legal restrictions of forest management. The exclusion of the operative feasibility included forest surface with an average or median slope higher than 24.23°. In this study, the slope restriction had a small incidence on the availability of biomass, which consisted of only 5.8% of the natural forests in the 7^{th} Region, and equivalent to 6.6% of the total biomass volume available that could not be harvested in the Region.

5.2 Impact of the distance to the nearest road

The distance of the land to the nearest road was the operational feasibility restriction, which had the greatest influence on the availability of biomass. The maximum admissible range of 5 km distance restricted 13.7% of natural forests in the Region and reduced the biomass availability by 20.5%. Table 3 shows the results of the simulated availability of wood biomass based on the distance restriction between the forest area and the nearest transport route. For instance, it can be observed that less than half of the biomass would be available to harvest if the distance restriction would be only 2 km. This highlights the significance of road infrastructures in these forest areas.

Distance to the nearest route (km)	Available biomass (tons/year)
1.00	106,349
2.00	241,293
3.00	381,005
4.00	481,712
5.00	531,015

Table 3. Available biomass as a function of the distance to the nearest route

5.3 Impact of transportation costs

In this study, the cost to transport wood biomass was assumed to be 0.145 US$$\cdot$km$^{-1}\cdot$ton^{-1}. In order to evaluate the influence of transportation costs on the market supply curve, two other scenarios were analysed, where the value of transportation costs was 50% cheaper and 50% more expensive than the cost previously assumed in the simulation, 0.0725 and 0.2175 US$$\cdot$km$^{-1}\cdot$ton^{-1}, respectively.

As a result, it was observed that a 50% increase in transportation costs to 0.2175 US$$\cdot$km$^{-1}\cdot$ton^{-1} caused an increase of 18.3% of the average costs for the total 531,015 tons of available wood biomass in the Region. Similarly, the 50% reduction in transportation cost caused a decrease of 18.3% in the total cost for harvesting and delivering the total available biomass. This showed the direct effects of the transport sub-element on the supply curve.

5.4 Optimisation of the biomass market supply curve for the province of Talca

One of the advantages of the simulation model proposed in this study was the flexibility and level of automation with which it was designed. The method allows for the rapid adjustment of the processes of territorial analysis and routes for any province, commune, region, or country. Although the automation capabilities of the model were high, the model presented a bottleneck in the Google Maps Directions API tool, which allows a maximum of 2,500 requests per day. That is why the supply centres that were analysed had to be chosen selectively, given that each supply centre can require about 2,000 queries. With these limitations in mind, the market supply curves for the province of Talca were analysed by examining five supply centres located in the proximity of Constitución, San Rafael, Panguilemo, Talca, and San Clemente (see Figure 4).

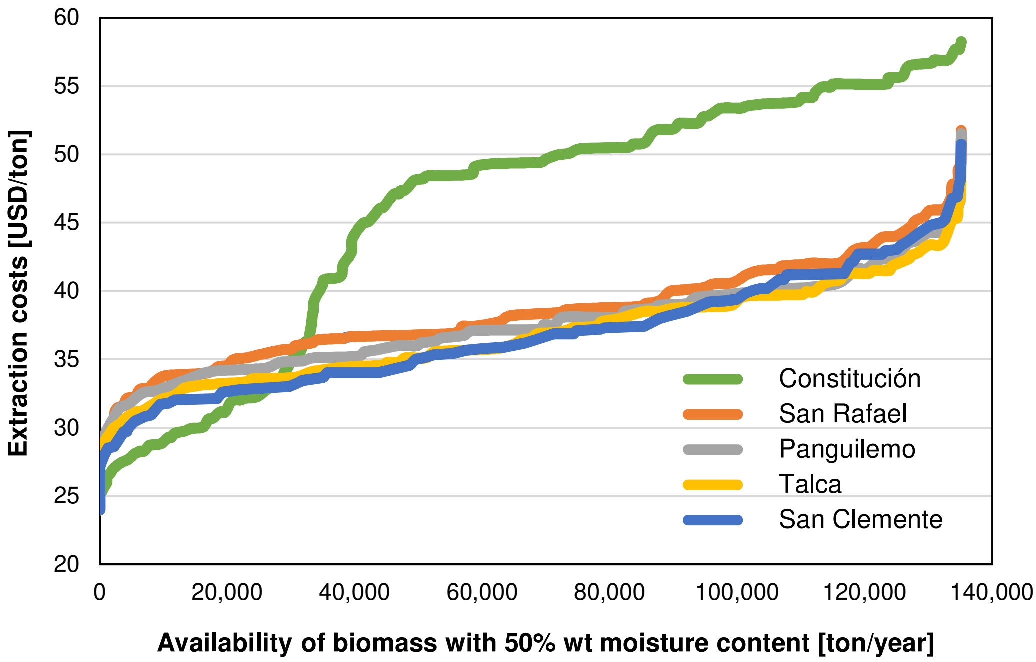

Figure 4. Supply curves for the substations closest to the towns of the Talca province

The simulated supply curves displayed in Figure 4 show that the urban towns of San Rafael, Panguilemo, Talca, and San Clemente have a similar cost structure. This similarity in the cost structure was mainly due to the geographical proximity between each town, which caused the simulation to select similar patterns of optimal routes between the forests and the supply centres. The urban area of Constitución is located further away from the other four towns, which implied a different transportation route than the other supply centres.

Moreover, the results indicated that the urban centre of Constitución presented the most economical extraction costs for the first 38,100 tons/year of biomass available in the province of Talca. On the other hand, the urban centre of San Clemente exhibited the most economical cost conditions for the rest of the biomass available in the province, making it the ideal supply centre for a level of consumption between 38,100 tons/year and 135,126 tons/year.

6 Discussion

The simulated availability of wood biomass with a moisture content of 50% by weight was 531,015 tons/year based on an extraction utilization factor of 75%. Among the factors evaluated in this study, the distance between the land and the nearest road represented the restriction of operational viability with the greatest influence on the calculation of biomass availability in the seventh region of Chile. The calculations made by Gysling et al. (2017) estimated the availability of natural forest biomass with 0% wt moisture content at 815,000 tons/year for the same region addressed in this study, which is equivalent to 1,222,500 tons/year of biomass with 50% wt moisture content.

Overall, Rios et al. (2013) and Gysling et al. (2017) estimated a greater availability of biomass in the region under study because they only focused on the potentially usable biomass and ignored the technical or economic restrictions of the supply chain. The methodology proposed here allows for more realistic estimations, as it considers the operation feasibility and the use of utilization factors, which allow to set limits according to the economic, ecological, and social conditions of forests. It is worth to mention that the discrepancy with the results from the two aforementioned studies could be even larger if more restrictions had been established in the maximum distance between supply centres and the nearest transport routes. For instance, a maximum admissible distance of 1 km would result in a value of biomass availability as low as 106,349 tons/year for the 7^{th} Region of Chile.

The simulated average cost for the 531,015 tons/year in the 7^{th} Region was 41 US$/ton, the cost of transportation being the highest of all, representing 38% of the total cost. The values of extraction costs obtained in the study are similar in range to those presented by other research groups and studies conducted in the country. One of them by Bertran and Morales (2008) obtained an average extraction cost varying from 13.85 US$/ton to 25.64 US$/ton. Another study carried out by Ríos et al. (2013) determined that the marginal costs of biomass extraction from the sustainable management of natural forest range from 45 US$/ton to 120 US$/ton in the 14^{th} Region of Chile. The differences with the results obtained in the present work comes from the fact that the proposed simulation model is more complete, as it takes into account assumptions made for some parameters of the logistics chain and more realistic factors, such as a more conservative rate of extraction, a maximum admissible slope, the distance from the land to the nearest road and the geographical characteristics of the region under study.

It is worth noting that the potential of wood biomass energy depends not only on its availability, but also on the competition between alternative uses of the resource (Berndes et al., 2003). Therefore, more research is needed that focuses on assessing demand-side issues and modelling demand curves (i.e. price) of woody biomass at each supply center. The estimation of both supply and demand curves would allow to have a global market vision. This could be useful in energy policy analysis or in wood energy use models, where the wood supply curve could be directly connected to different scenarios of energy wood demand (Tavoni et al., 2007). The estimation of woody biomass demand curves requires to understand the relationship between product features and price. To do so, Sasatani and Eastin (2018) applied a market-based analysis to estimate the size of the potential market for wood products in each particular location and then assume a market penetration rate to estimate consumer demand and the associated revenue functions of the biomass products.

Availability and economic factors are essential data for policy strategies seeking to promote the use of the wood energy resource. However, sustainability indicators resulting from the use of wood biomass must also be carefully considered. Indeed, bioenergy production faces challenges such as land availability, water scarcity, biodiversity concerns, and land degradation (Dooley and Kartha 2018, IPBES 2019, Shukla et al. 2019), which have often not been included in potential estimates (Offermann et al. 2011). Furthermore, environmental impact of large-scale bioenergy deployment is being increasingly criticized (Creutzig et al. 2015). Recently, the Socio-Economic Council, an independent advisory board of the Dutch government, reported that the Netherlands should phase out the use of biomass, as the resource is seen too scarce to be used for heat and power production (SEC, 2020). If wood biomass is essential to achieve national and international targets on renewable energy and carbon emission reduction, it must be produced locally from sustainably managed forests.

Air pollution remains the main issue regarding the use of wood biomass in some locations, such as in central-southern Chile (Jorquera et al. 2018), where biomass is the main source of energy for heating and cooking purposes. The fine and coarse particulate matter (i.e. $PM_{2.5}$ and PM_{10} respectively) that is emitted as a result of wood combustion, can remain suspended in the air for certain periods of time (Villalobos et al. 2017) and can cause serious health issues including heart attacks, respiratory disease, and premature death (Landrigan et al. 2018, Yang et al. 2017). In this sense, increasing the efficiency of the biomass stove is seen as a viable option in the short term to reduce PM emissions. Also, the implementation of improved stoves can improve the efficiency of biomass use and achieve significant fuelwood savings (Cutz et al. 2016). However, in the long term, it is necessary to expand the range of technological options for the generation of renewable and clean energy, for example, through the implementation of efficient and cleaner combustion plants that transform woody biomass into sustainable power and heat energy carriers. The benefits of externalities, such as lower fuel consumption and better public health indicators justify the investment in more efficient biomass technologies.

7 Conclusions

This study presents a methodology that can simulate the economic potential of wood biomass from the sustainable management of natural forests in the 7th Region of Chile. The proposed model can adapt to the main variable parameters, thus allowing the investigation on the effects of various key parameters for forest management on the simulated wood biomass supply. However, given that the information on the operating costs and technical availability of Chile's natural forests production is unknown, the procedure to estimate the total available supply and its costs was more complex. Compared to other national research, the present study provides a more realistic calculation model. The parametric analysis reveals that the maximum admissible distance to the nearest transport route and the transportation costs are the two variables that have the most influence on the wood biomass supply and cost. It was found that maximum admissible distance to the nearest transport route is a key factor in the decline or the expansion of the wood biomass supply from the sustainable management of natural forests. This factor reveals that natural forests in the 7th Region of Chile are mostly at considerable distances from existing access roads, and this could restrict the availability of the resource according to operational impediments not contemplated in this study. The sensitivity analysis of the maximum admissible distance to the nearest transport route shows that the wood biomass supply would be reduced by almost 80%, from 531,015 tons/year to 106,349 tons/year in the scenario where the maximum admissible distance to the nearest road would be limited to 1 km instead of 5 km. The second most important parameter influencing the wood biomass supply is the economical variable of the transportation cost, which presented the greatest variance and impact on the total biomass extraction cost, besides affecting the pattern and extension of operating costs. The transportation cost explains 38% of the average extraction costs for the total biomass available in the 7th Region, and a variation of ± 50% of the transportation cost translates into a variation of ± 18.3% on the average extraction costs for the available 531,015 tons/year in the 7th Region of Chile. For this amount of annual wood biomass production from the sustainable management of natural forests of the studied region, the simulation estimates an average extraction cost of 40.97 US$/ton.

Although the model introduced in the present study was used to evaluate the availability of wood biomass and its related extraction costs for the 7th Region of Chile, it has the flexibility to be tested with multiple scenarios. It can be used to identify wood biomass availability and cost characteristics for any commune, province, region, or country in more exhaustive analyses, as the proposed model permits to utilise such parameters depending on specific characteristics of the area to be analysed. Essentially, the purpose of this simulation tool is to serve the assessment process of new biomass resource identification, allowing decision-makers to increase the potential of sustainable and cost-effective woody biomass, while reducing greenhouse gas emissions and dependence on fossil fuels for heat and electricity generation.

Future investigations include (1) the improvement of the cost function, since the integration of a greater number of parameters and variables may achieve a more precise evaluation of operational feasibility and extraction costs for each specific natural forest, and (2) the modelling of the consumer demand curves, in order to have a more global vision of the wood biomass market for future planning implementation.

8 Acknowledgment

The authors would like to acknowledge the student Pablo Esteban Larraguibel for his support. The authors gratefully acknowledge the research support provided by CEDEUS (CONICYT/FONDAP 15110020), by SERC-Chile (CONICYT/FONDAP 15110019) and by the UAI Earth Research Centre.

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