Optimal harvest cycle on *Nothofagus* forests including carbon storage in Southern America: an application to Chilean subsidies in temperate forests

Abstract

Different countries may have passed through their forest transitions from net native forest loss to net exotic plantation expansion. More investment in global and national forest monitoring is needed to provide better support to increase sustainable forest management and reduce forest loss, particularly in native forests. These slow-growing forests could get involved in the voluntary carbon markets. In this sense, some international and national initiatives based on subsidies could play a keystone role in the native forest conservation, mainly in small private lands.

This approach aims to identify the optimal harvest cycle of *Nothofagus* forest type based on integral harvesting management (timber resources, natural regeneration and carbon storage) and three scenarios (lack of subsidies and two different national subsidies). The most suitable carbon storage models were Schumacher-Hall, Naslund and one specific model. The coefficient of determination was higher than 0.95 for these three models. If only timber harvesting was considered, the optimal harvest cycles was established between 59 and 62 years according to the presence or lack the national subsidies. However, when forest management and carbon storage were considered, the optimal harvest cycle increases three years. Therefore, the effect of this new alternative can be also observed in net present value and internal rate of return. This integral forest management could be an attractive approach for small private owners and for the global warning mitigation according to the ratified international agreements.

Key-words: bioeconomic model, net present value, interest rate of return, *Nothofagus dombeyi*, *Nothofagus alpina*

1. Introduction

The main cause of climate change is the anthropogenic increase in greenhouse gas concentrations in the earth's atmosphere. The international response to climate change began with the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. Kyoto Protocol emphasizes the forestry sector as one of the main elements to climate change mitigation (Bulkeley, 2013). Other international and ratified agreement (the United Nations Conference on Sustainable Development - or Rio+20) has demonstrated that climate change is not only theoretical concept. In this sense, this Conference recognizes the need to prevent the world's average temperature from rising by more than 2ºC, following the guidelines established by the international scientific community (Ambrósio et al, 2017).

In spite of 31 percent of the carbon is stored in the biomass and 69 percent in the soil, forests play an essential role in the global carbon cycle though the elementary photosynthesis (IPCC, 2007). We only consider the carbon storage of the vegetation, but further studies will study carbon soil storage. Kyoto Protocol (articles 3.3 and 3.4) promotes a huge range of alternatives for increasing carbon storage through forest management (Krause, 2015). An important aspect of sustainable forest management is to assess the impact of forest operations on ecosystem services (Bravo et al., 2015). The estimation of carbon stock requires a destructive sampling to identify live biomass from different species and sizes (Montero et al., 2005). Due to time difficulties and the cost of destructive fuel inventories, allometric equations have been constructed to estimate biomass from traditional forest inventory variables (Agudo et al., 2007; Molina et al., 2014). The diameter at breast height is the most commonly used variable for biomass models (Návar, 2009; Ruíz-Peinado et al., 2012; Del Río et al., 2017), in spite of the insertion of tree height can improve the model fit significantly (Ruíz-Peinado et al., 2011).

A forest management should integrate timber resources and environmental services for the suitable management of slow-growing species (Ruíz-Peinado et al., 2016). In this sense, *Nothofagus* forests can play an important role for the global warning in the southern America based on its area and timber resources market. Most of the sustainable *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus alpina* (Poepp. & Endl.) Oerst forest belongs to small private landowners. For these owners, the profitability of their forests demands a fast return of any investment. According to Chilean law (Law Nº 20,283, article 3), it is necessary "the development of scientific and technical studies to support the established alternative, methods of regeneration,...". The identification of the optimal harvest cycle is an issue from an integral point of view that integrates timber resources and carbon storage (Díaz-Balteiro and Rodríguez, 2006; Knoke et al., 2012).

Bio-economic models could be a useful tool for the consideration of environmental services into traditional forest management (Bravo et al., 2008; Knoke and Seifert, 2008). Carbon storage could have implications that modify the making-decisions for timber resources (Díaz-Balteiro and Romero, 2003). Most of the studies (Stainback and Alavalapati, 2002, 2005; Caparros et al., 2003) have shown economic advantages in relation to the increase of harvest cycle when carbon storage is incorporated. There are a lot of studies of fast-growing species in the southern America (Van Kooten, 2000; Cubbage et al., 2007) that stated the profitable alternatives for an integral forest management. However, a low level of information is available for native forests in the southern America due to its lower profitability and the need of some subsidies. In this sense, the aim of this study is the identification and comparison of the optimal harvest cycle of one *Nothofagus* forest type based on both the timber harvesting management and the integral harvesting management (timber resources and carbon storage). The net present value and the interest rate of return will be used for economic analysis using Faustmann's model. For each forest management alternative, three scenarios were considered based on the lack of national subsidies and the consideration of two different subsidies.

2. Material and methods

2.1. Study area

The study area is located in the easternmost edge of IX Region, in south-central Chile (Figure 1). The Malleco National Reserve belongs to the Araucarias Biosphere Reserve (RBA) which is considered among the most threatened areas of the Chile (Molina et al., 2017). The Malleco Reserve is the oldest natural protected area of Chile (and also in Latin America), which dates back to 1907). Annual precipitation ranges between 2,000 and 4,000 mm; most of it falling during the winter season. It is characterized by a wet climate with daytime summer temperature above 28ºC conductive to fire ignition and propagation.

Figure 1 around here

Malleco Reserve covers 16,625 ha of alternating four of the twelve forest types found in Chile: *Austrocedrus chilensis* (D. Don) Pic. Ser. et Bizz.; *Nothofagus obliqua* (Mirb.) Oerst - *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus alpina* (Poepp. & Endl.) Oerst; *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus alpina* (Poepp. & Endl.) Oerst - *Laureliopsis philippiana* (Looser) Schodde; and *Araucaria araucana* (Molina) K. Koch. Deciduous forests occupy about 87% of the total of the Reserve. There are some forest types must be reserved for preservation and conservation according to the current Chilean legislation. In this sense, the study area is limited to the productive sectors of the Reserve corresponding to 64% of the total land of the Reserve (10,693.4 ha). *N. dombeyi* and *N. alpina* were selected by this carbon storage approach according to its representativeness in the study area.

2.2. Carbon storage in tree stem and roots

Carbon storage was obtained based on every six-years field inventory to assess dynamic carbon storage. The forest inventory was carried out in square plots of 1,225 m^2 using the stratified random sampling method. The inventory amounted 23 stands and 115 sampling units (5 sampling plot for each stand) located across the different north-south transects. The distance between plot centers was established at 70 m in order to avoid overlapping. The sampling intensity should have been higher to reduce estimation error due to the heterogeneity of these multi-aged forests, but it is necessary to take into account the field inventory difficulties (forest cover, slope and penetrability) and the associated costs and limited budget.

The data sampling collected tree mensuration variables in order to identify carbon storage incorporating the most commonly used variables such as diameter at breast height (DBH), tree height (H), health condition, crown shape and crown cover. All of the strata (regeneration, suppressed trees, intermediate trees, co-dominant tree and dominant tree) of stands were inventoried according to its importance in the final harvest model. As an example, diameter at breast height ranged from 2 cm to 2 m. Tree volume was estimated for *N. dombeyi* and *N. alpina* based on specific allometric equations for the study area (Table 1). Tree carbon storage was estimated using destructive sampling of 60 trees (30 trees of *N. dombeyi* and 30 trees of *N. alpina*) that cover the entire range of *Nothofagus* species in the study area according to selection cutting or selective logging management.

Tree carbon storage (Cs) was estimated based on the tree volume (V) using models for IX Region of Chile (Drake et al., 2003), the wood density (WD) of each species and the amount of carbon in biomass (C) (Equation 1). WD is obtained using a 72-hour drying process in an oven set at 110ºC. Finally, C was identified in the laboratory using 92 biomass samples (4 samples for each studied stand).

$$Cs = V * WD * C \qquad (1)$$

Once tree carbon storage was estimated using filed destructive sampling, the most commonly allometric equations (Spurr, Honer, Schumacher-Hall, Prodan et al., Meyer, Burkhart, Naslund and Stoat) were tested to the studied species (Table 2). The model selection was based on the coefficient of determination (defined as the square correlation between measured and estimated values) and the standard error of the estimate. We selected only allometric equations with parameters significant at the 0.05 level, coefficient of determination higher than 95% and standard error of estimate lower than 0.3. We also incorporated an additional hypothesis or specific model that was also fitted according to the collected dataset. Analysis of variance (ANOVA) was used to determinate if significant differences ($p < 0.05$) existed in carbon storage between *N. dombeyi* and *N. alpina*. SPSS© software was used in all analyses. If significant differences have not detected, one allometric equation could be performed to increase sampling size. Our allometric model was fitted using a forward stepwise method. With Principal Component Analysis (PCA), the number of variables can be systematic reduced to a smaller and conceptually more coherent set of variables.

Twenty-five trees of the destructive field inventory had their root system excavated to establish root biomass and carbon content. An excavator was used to remove the stump.

The excavation was undertaken carefully, with roots exposed using hoes and spades and the stump lifted out by the excavator. All roots were removed from the stump. Root system was divided in three fractions: coarse roots (> 5 cm), medium roots (2-5 cm) and fine roots (< 2 cm). The root samples were washed separating soil particles from the roots. Once all the roots were collected, the moisture content for each fraction was estimated in order to represent root biomass as dry matter content. Each sample underwent a 72-hour drying process in an oven set at 110ºC. Litter was also taken into account in the total carbon storage. Finally, total carbon storage was obtained as the sum of carbon pools associated to stem and root strata.

2.3. Identification of optimal harvesting strategies

Different authors are concerned with optimal solutions to the forest management problem when future utilities are undiscounted (Samuelson, 1976; Mitra and Wan, 1986; Caparros et al., 2003; Meade et al., 2008; Brazee, 2017). The generalized Faustmann model (1849) identifies the present value of the income stream for forest rotation according to the maximising Faustmann's equation. To maximize the value of the land, it needs to maximize the present value of profits from growing an infinite number of timber crops. The optimal harvest age is defined as the time rate of change of forest value is equal to interest on the value of the forest plus the interest on the value of the land (Mitra and Wan, 1986). In this sense, the optimal harvest age is reached when the time rate of change of its value is equal to the interest rate modified by land rent. Other economic factors could be included in the Faustmann model, such as annual and production costs.

The generalized Faustmann formula could accommodate land-use changes by permitting different types of resources such as timber and carbon storage for different harvest periods. Net present value (NPV) is determined by calculating the costs (negative cash flows) and benefits (positive cash flows) for each period of an investment. Forest planning was established in 100 years with decades periods. After the cash flow for each period is calculated, NPV of each one is achieved by discounting its future value at a periodic rate of return. The rate of return is the profit on an investment over a period of time, expressed as a proportion of the original investment. While a higher current interest rate lowers the optimal harvest age, whereas a higher future interest rate raises the optimal harvest age (Brazee, 2007). NPV in Faustmann model (Equation 2) is expressed as the difference between the present value of cash inflows and the present value of cash outflows over a harvest rotation age:

$$NPV = \left[P(t)e^{-rt} + \sum\nolimits_{\forall I} C_I e^{-rI} - K - Hr^{-1}(1 - e^{-rt}) - \sum\nolimits_{\forall s} C_s e^{-rs}\right](1 - e^{-rt})^{-1} \qquad (2)$$

where P(t) are the profits of timber resources (logging, sapwood and pulpwood according to Appendix I) from the sale of each harvest cycle or "t" year, C_I are the profits of carbon storage based on the carbon price (Appendix I), r is the interest rate, K is the costs of afforestation (Appendix I), H is the harvesting operation costs (Appendix I), C_S is the management and maintenance costs (Appendix I), and s are the years when forest cuttings are carried out.

Theoretically, equation 2 can be solved with the forward recursive solution method. However, such a solution would involve infinite numbers of timber prices, timber volumes, annual incomes or expenses, regeneration costs and interest rates, thus making it impractical. It embodies all the optimal harvest age decisions for future timber crops that give rise to this specific value. In this sense, solving for the optimal harvest age empirically would involve the insertion of a specific value of NPV into equation 2 to solve for optimal harvest age. It is important to understand the economic meaning of reaching the optimal harvest age because it affords the opportunity to determine stepwise year by year the harvest decision by comparing the marginal benefit with the marginal cost of waiting. When the left-hand side of equation 2 is greater than the right-hand side, one should wait another year. Conversely, the stand should be harvested.

Faustmann model allows us to identify the optimal harvest cycle of *Nothofagus* species. However, the original model does not include the subsidies that are contemplated and promoted by Chilean Law (Decree Law 701 "Forest Encouragement" and Law Nº 20,283 "Native Forest recovery and encouragement"). We used Díaz-Balteiro approach (1995), which considered subsidies contemplated in the Royal Decree 378/93 in Spain (Equation 3):

$$\mathrm{NPV} = \left[P(t)e^{-rt} + \sum_{\forall I} C_I e^{-rI} + K_1 + K_2 r^{-1}\left(e^{-r} - e^{rn_1}\right) + K_2\, r^{-1}\left(e^{-r} - e^{-rn_2}\right) - K - Gr^{-1}\left(1 - e^{-ir}\right) - \sum_{\forall s} C_s e^{-rs}\right]\left(1 - e^{-ir}\right)^{-1} \qquad (3)$$

where K_1 is the afforestation bonus with native species, K_2 is the bonus for native forest management, n_1 is the number of years with forest management bonus, K_3 is the bonus for biodiversity conservation and n_2 is the number of years with annual subsidies for biodiversity conservation.

We recommender the use of Capital Asset Pricing Model (CAPM) to select the interest rate in future applications to other species and/or other countries. CAPM is a model to estimate the expected return of an asset based on the systematic risk of the asset return (Copeland et al., 2005; Navarro et al., 2010). Theoretically, the CAPM is expressed as:

$$r = R_f + \beta\, [E(R_m) - R_f] \qquad (4)$$

where r is the interest rate of forest sector, R_f is the risk-free return, β is the systematic risk of forest sector and $E(R_m)-R_f$ is the excess market return. The risk-free return, the systematic risk and the excess market return were estimated according to private investments in forest sector.

The internal rate of return is the interest rate that makes the NPV of all cash flows from a project equal to zero. The internal rate of return is an indicator of the profitability of an investment. The appropriate minimum rate should be an internal rate of return which exceeds the cost of capital, and as a consequence, it would have a positive NPV. The internal rate of return was calculated for each management scenario based on a minimum harvest age of 52 years, an administration cost of 39 € /ha*year and interest rates between 8% and 16%.

We considered timber and carbon storage targets for the economic assessment of the optimal harvest cycle,. The number of harvest cycles or selection loggings is infinite with a tree cutting intensity of 20-35% of the basal area leading to a multi-aged forest with continuous regeneration. This approach takes into account the harvest cutting cycles and regeneration condition showing the best management alternative after the first harvest cycle. A minimum harvest cycle of 20 years was established according to regeneration dynamics, growing stock and the costs of periodical cuttings. We simulated the increase of diameter at breast height, tree height, tree volume, basal area and timber stock for the regeneration and suppressed strata. Harvest operations were also incorporated in order to calculate the cutting profits in relation to timber quantity and quality. Optimal harvest cycle was identified using the Root Mean Square (RMS) based on timber and carbon storage profits.

The costs and profits associated with native forests management were calculated according to an economic analysis of public and private datasets. Economic costs and profits have been updated to 2017 (Appendix I). Planting, management and harvesting costs are based on natural regeneration and official prices (Decree Law 701). This legal framework also identifies the management actions to be considered in a native forest management plan. The subsidies were considered (Equation 3) in two ways: Decree Law 701 and Law Nº 20,283. In this sense, our approach considered three economic scenarios in order to identify optimal harvest cycle:

- Scenario A: *Nothofagus* forest without any national subsidy
- Scenario B: *Nothofagus* forest with a national subsidy based on Decree Law 701
- Scenario C: *Nothofagus* forest with a national subsidy based on Law Nº 20,283

3. Results

3.1. Carbon storage in tree stem and roots

While wood density was estimated at 450(±4.7) kg/m^3 for *Nothofagus* species*,* the amount of carbon in the stem reached at 45.28(±1.3)%. Although eight models were tested to estimate carbon storage, only three models (Schumacher-Hall, Naslund and specific models) were selected according to its higher coefficient of determination and its lower standard error of the estimate (Table 3). It was possible to explain more than 80% of the total variance of the carbon storage according to only two components. In this sense, diameter at breast height (DBH) and tree height (H) were the most important components. There were no significant differences (ANOVA test) between *N. dombeyi* and *N. alpina* with similar DBH and H when looking at the carbon storage.

The field inventory showed average values of 1,118 trees/ha, 559.79 m^3/ha and 80.90 m^2/ha (Table 4). The stem carbon storage was significant higher in Schumacher-Hall and specific models (more than 130 t/ha) when compared with Naslund model (more than 110 t/ha) (Table 4). *N. dombeyi* and *N. alpina* reached at 68.69% of the stem carbon storage per unit area according to the specific model (Figure 2). More than 85%

of the trees were categorized in the three smallest diameter categories (< 35 cm), and as a consequence, these diameter categories ranged from 30.24% (Naslund) to 65.66% (specific model) of the total stem storage.

Figure 2 around here

The average roots biomass and litter biomass were 33.04 t/ha and 8.48 t/ha, respectively (Table 5). There were no significant differences (ANOVA test) among root biomass fractions. In this sense, fine roots biomass was 10.72 t/ha, which accounted for 32% of total root biomass. The carbon storage in roots indicated a root-shoot ratio of 0.098 for these *Nothofagus* stands based on the specific model. In addition, litter biomass was 3.96 t/ha, approximately a ratio of 0.029 relative to carbon biomass in tree stems. The carbon content in medium and coarse roots was significantly higher than in fine roots (Table 5). Statistically the average carbon content was similar for fine roots and litter (ANOVA test).

3.2. Identification of optimal harvest cycle without forest management and carbon storage

The studied forest type has shown an average growth of 0.65 cm/year of diameter and 0.63 cm/year of height without any forest management (Gezan, 2009). Different interest rates and cutting rotations were identified to calculate NPV by Equation 3 (Table 6). Finally, the interest rate was estimated at 10% under Capital Asset Pricing Model (Equation 4) in a similar way than other Chilean forestry studies (Navarro et al., 2010). Total volume ranged from 996.10 m^3/ha to 1,116.71 m^3/ha and timber extraction ranged from 298.83 m^3/ha to 334.8 m^3/ha according to the subsidies presence. Net present value in scenarios with subsidies (scenarios B and C) was higher than in scenario A (an increase between 36.82% and 37.02%) (Table 7). The internal rate of return ranged from 12% (scenario A) to 14% (scenarios B and C). The optimal harvest cycle was established between 59 years (scenario A) and 62 years (scenarios B and C) (Table 7). There were no significant differences between scenario B and scenario C in relation to the internal rate of return and the optimal harvest cycle.

3.3. Identification of optimal harvest cycle with forest management and carbon storage

In a similar way to the forest management without carbon storage consideration, different interest rates and cutting rotations were identified to calculate NPV by Equation 3 under an integral forest management (timber resources and carbon storage) (Table 8). The interest rate was estimated at 10% under Capital Asset Pricing Model (Equation 4). In this case, timber volume ranged from 1,164.95 m^3/ha to 1,217.24 m^3/ha and timber extraction was between 349.17 m^3/ha and 365.17 m^3/ha. The lowest net value present was obtained by scenario A (Table 9). An increase between 12.18% (scenario C) and 33.41% (scenario B) was performed by net present value. The internal rate of return ranged from 14% (scenario A) to 16% (scenarios B and C).. The optimal harvest cycle was established between 62 years (scenario A) and 64 years (scenario B) according to forest management and carbon storage (Table 9).

4. Discussion

The selected trees are representative from a wide age range of *N. dombeyi and N. alpina* stands commonly found in the “Malleco National Reserve”. Carbon storage is a difficult variable to measure due to the need of tree cutting. These difficulties lead to the search of indirect models predicted from common forest inventory variables for estimating biomass and carbon content (Ritson and Sochaki, 2003; Návar 2009). Diameter at breast height is the most common variable in biomass studies showing reliable relationships (Agudo et al., 2007; Návar 2009; Ruiz Peinado et al., 2011, 2012; Del Río et al., 2017). The inclusion of tree height provides more suitable carbon storage results. Our model suggested a strong dependence of carbon storage on diameter at breast height and tree height. Inclusion of other variables well correlated with crown characteristics did not improve model fit significantly. The test of goodness-of-fit recommended the use of Schumacher-Hall, Naslund and the specific models (Table 3). Schumacher-Hall was also considered the most suitable model by other carbon storage studies (Marques da Silva et al., 2009; Moreno et al., 2011). All of these models allow us to simulate carbon stocks under different thinning intensities (Bravo et al., 2008, 2015; Ruiz Peinado et al., 2016) based on the simplicity required by the forest managers.

Above-ground vegetation plays an essential role in relation to carbon storage (Moreno et al., 2011; Thomas and Martin, 2012). Carbon stem storage was estimated between 113.05 t/ha and 137.15 t/ha for this *Nothofagus* forest type. Tree stem showed an elevated percentage of the total carbon storage (between 89.36% and 91.06%) when stem and root strata were considered. In this sense, field sampling should be design to achieve the objectives pursued according to the available budget. According to our field sampling, wood density was estimated at 450(±4.7) kg/m^3 likewise correspondingly by other *Nothofagus* studies (Medina et al., 2015). The carbon content of tree stem (45.28%) and tree roots (43.82%) was similar to a global synthesis research (Ma et al., 2018).

A stand could promote higher carbon stocks than others under different alternatives of forest management (Navar, 2009; Bravo et al., 2008, 2015; Ruiz-Peinado et al., 2016). The assessment of private owners' harvesting behavior, risk preferences and subjective judgments reveals strong indications of the difficulties for private owners to make rational decisions when faced with economic uncertainty (Andersson and Gong, 2010). The primary reason for selling wood fuel was that the harvesting operation cleared the ground of debris (Bohlin and Roos, 2002). Direct economic risks such as price and cost changes are seen by private owners as much more important than indirect economic risks such as biological damages and fire risk (Lönnstedt and Svensson, 2002). Although forest management in this forest type is a profitable activity according to the financial return from timber products, it depends on the distance to the markets and the availability and quality of the road network (Donoso and Lara, 1999). Old-grown stands and remnant forest parches are complicated to forest management according to the costs of periodical cuttings, planting and pruning. In these vulnerable areas, subsidies could be necessary to promote an Internal Rate of Return (IRR) over 10% (Donoso and Lara, 1999). An IRR higher than 13% shows a profitable forest management (Cubbage et al., 2007) in spite of the elevated costs associated to selective loggings and selective cuttings. These IRR values are explained by the increase of native wood price and the decrease of harvesting costs (Cubbage et al., 2014).

Forest management planning has led to the production of timber resources in a sustainable way. As society's demands for natural ecosystems have been modified, tools traditionally used in forest management and forestry planning have proved insufficient (Di Salvatore et al., 2013). The consideration of environmental services requires bioeconomic and multivariable models (Díaz-Balteiro and Romero, 2003; Díaz-Balteiro and Rodríguez, 2006). Our bioeconomic model has always promoted forest natural regeneration so as to guarantee its successful development. Carbon storage was also included to support forest managers in defining optimal harvest cycle based on timber resources (maximum NVP) and environmental resources (natural regeneration and carbon storage). This approach provides attractive results integrating tangible assets

(NPV) and environmental services to forest multifunctionality target. Therefore, an integral forest management reaches higher profits than traditional management based on our economic analysis. As an example, the IRR increases an 2% between the integral forest management and the traditional forest management (Tables 5 and 6). This fact is related to the NPV increase according to sawn timber volume and carbon storage.

On the one hand, this approach has identified an optimal harvest cycle ranging from 59 years (scenario A) to 62 years (scenario B and C) without carbon storage profits. NPV differences varied from 238.7 €/ha (scenario B) to 240 €/ha (scenario C) between the lack of subsidies and the presence of them. NPV differences between Decree Law 701 and Law Nº 20,283 are minimal (1.3 €/ha). On the other hand, the optimal harvest cycle ranged from 62 years (scenario A) to 64 years (scenario B) with carbon storage profits. In this case, the differences between the scenario B and the scenario C are higher in regard to NPV and the number of years (189.6 €/ha). It is noted that there is an increase between one and three years in the optimal harvest cycle according to an integral forest management. In relation to NPV, the increase ranged from 12.78% (scenario C) to 34.32% (scenario B). It would be more profitable if this forest type was managed from an earlier age. Our optimal harvest cycles showed differences in relation to southern European studies where optimal harvest cycles ranged from 49 years for *Populus* spp. to 68-70 years for *Pinus* spp. (Díaz and Romero, 1995). These differences are associated to environmental conditions and annual forest growth between Southern America and Southern European.

The integral management (NPV and carbon storage) without subsidies would be only profitable with a high value of the carbon fixation. However, the carbon dioxide market is very irregular and unstable based on supply, demand and international environmental agreements (www.sendeco2.com). In this sense, one effective way to promote carbon storage in forest planning could be the guarantee of the price of timber at the end of the harvest cycle. In other words, a longer harvest cycle is favored by an additional subsidy based on the price of timber sales. This additional subsidy does not need to be very high, given the three-years difference between optimal harvest cycles.

The mitigation and adaptation of global warming needs to incorporate carbon storage into forest management (Bulkeley, 2013; Krause, 2015). Bioeconomic model increases the flexibility of this methodology enabling an extrapolation to other territories and other scales. The inputs used, such as carbon price, interest rate, timber volume, timber price and subsidies, are easy for forest managers to obtain because they are traditionally available from agencies and governments. Although fast-growing species are much more profitable than native forests (Cubbage et al., 2007, 2014), these former forests could achieve the profitability threshold under some alternatives of forest management. However, subsidies for native forest management could get better rates of return than the forest management for timber production in order to hold the land. According to our findings, the integral forest management of *Nothofagus* forests is more suitable in terms of ecological and economic benefits than the traditional forest management. These findings could lead to national reforestation policies in order to transform some abandoned private lands to native secondary forests.

5. Conclusions

Native forest management is an attractive investment because of both the timber resources and the environmental services. In this sense, some countries promote subsidies which provide an improvement in the net present value and the internal rate of return. It is important to bear in mind that if *Nothofagus dombeyi - Nothofagus alpina* forests area managed, the internal rate return will be higher according to its optimal harvest age.

Nowadays, forest policies imply to the obligation to reforest with slow-growing species in very areas of southern America. In spite of these policies means that the internal rate of return is low in comparison with fast-growing species, the economic balance could be positive when it includes environmental services like carbon storage. Traditional timber management does not ensure optimal harvest cycle according to our results. It is necessary to increase three years the harvest cycle in order to reach maximum net present value, and as a consequence, higher profits to private landowners. Therefore, an economic improvement was identified by the consideration of an integral forest management with the maximization of timber resources, carbon storage and natural regeneration condition.

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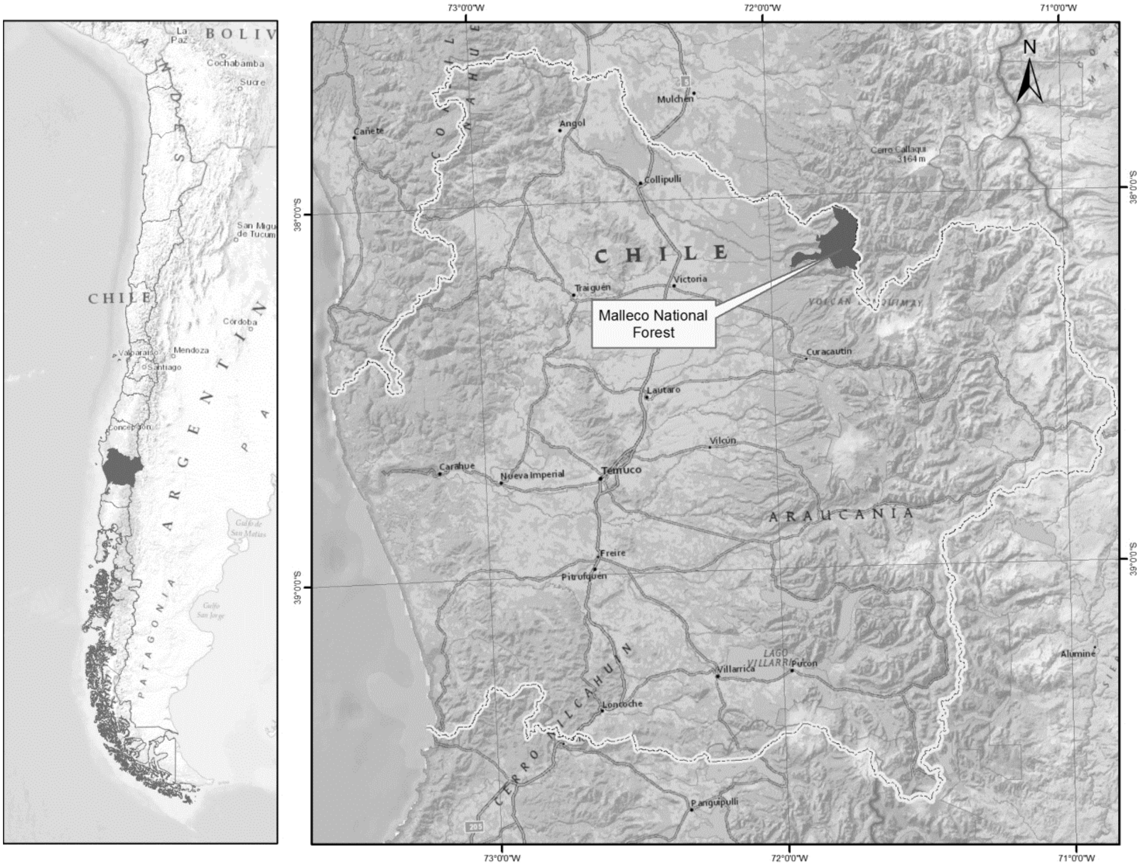
Figure captions

Figure 1. Study area location

Figure 2. Carbon storage on above-ground *Nothofagus* forests according to each species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Concepción
ARGENTINA
Golfo de San Matías
Golfo San Jorge
PATAGONIA
73°0'0"W
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N
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Angol
Cañete
Cerro Callaqui 3164 m
Collipulli
CHILE
Victoria
Traiguén
Malleco National Forest
VOLCÁN TOLHUACA
Curacautín
Lautaro
Vilcún
Carahue
Nueva Imperial
Temuco
ARAUCANÍA
Freire
Pitrufquén
Aluminé
LAGO VILLARRICA
Villarrica
Pucón
Loncoche
CERRO NILCAHUIN
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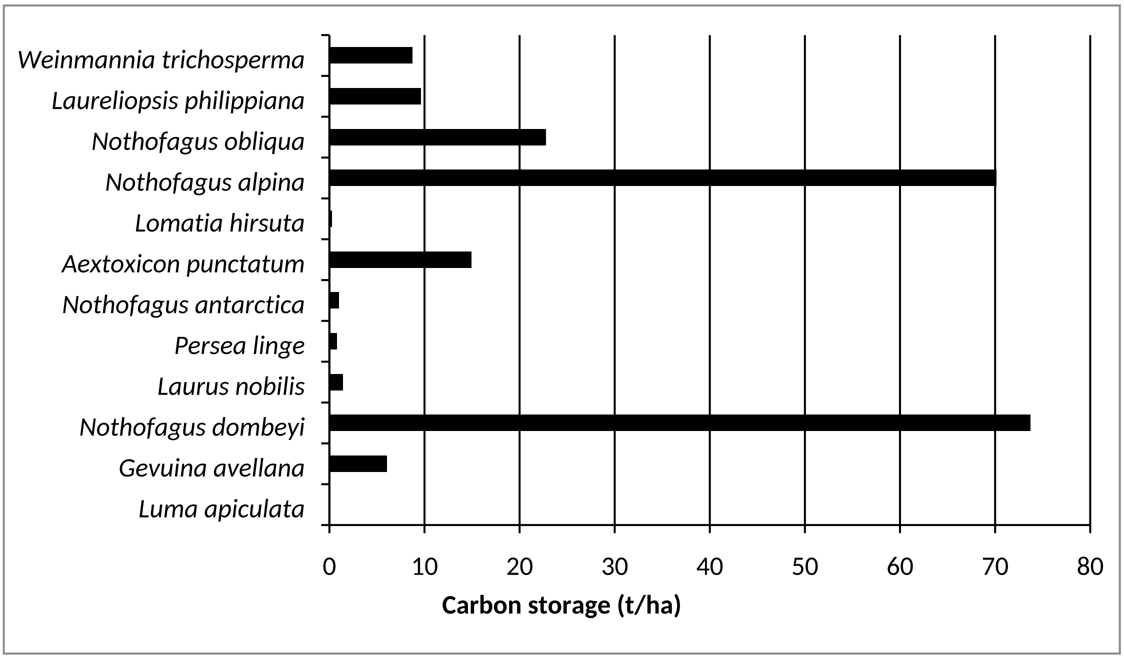
Weinmannia trichosperma
Laureliopsis philippiana
Nothofagus obliqua
Nothofagus alpina
Lomatia hirsuta
Aextoxicon punctatum
Nothofagus antarctica
Persea linge
Laurus nobilis
Nothofagus dombeyi
Gevuina avellana
Luma apiculata
0
10
20
30
40
50
60
70
80
Carbon storage (t/ha)

Table 1. Equations used for estimating tree volume

Species (source)	Volume equation
N.dombeyi (Drake et al., 2003)	$V = 0.00003544*DBH^2*H +0.00015692* DBH^2$
N.alpina (Drake et al., 2003)	$V = 0.0000351*DBH^2*H +0.0002135* DBH^2+0.007392*H -0.08867$

where V is the tree volume (m^3), DBH is the diameter at breast height (cm) and H is the tree height (m)

Table 2. Allometric equations tested to the studied species

Model	Mathematical formulation
Spurr	$V = a_0 + a_1 \cdot DBH^2 \cdot H + \varepsilon$
Honer	$V = \frac{DBH^2 + \varepsilon}{(\alpha 0 + \alpha 1/H)}$
Schumacher & Hall	$V = \alpha 1 - DBH^{\alpha 2} \cdot H^{\alpha 3} + \varepsilon$
Prodan et al	$V = \alpha 0 + \alpha 1 \cdot DBH^2 - H + \alpha 2 \cdot DBH^2 + \varepsilon$
Meyer	$V = \alpha 0 + \alpha 1 \cdot DBH + \alpha 2 - DBH^2 + \alpha 3 \cdot DBH \cdot H + \varepsilon$
Burkhart	$V = \alpha 0 + \alpha 1 \cdot DBH^{\alpha 2} - H^{\alpha 3} + \varepsilon$
Naslund	$V = \alpha 0 + \alpha 1 \cdot DBH^2 + \alpha 2 \cdot DBH^2 \cdot H + a_3 \cdot DBH \cdot H^2 + \alpha 4 - H^2 +$
Stoat	$V = \alpha 0 + \alpha 1 \cdot DBH^2 + \alpha 2 - DBH^3 + \alpha 3 \cdot H + \alpha 4/H + \varepsilon$

* DBH is the diameter at breast height (cm), H is the tree height (m), V is the carbon storage (kg/tree), α_1, $\alpha_{2,}$ $\alpha_{3,}$ α_4 are the estimated parameters and ϵ is the random model error

Table 3. Allometric equations for tree carbon storage obtained by Schumacher-Hall, Naslund and specific models

Model	Carbon storage model	R^2	SEE	SRE
Schumacher-Hall	$CS = e^{-11.1144} DBH^{2.0626} H^{0.863}$	0.984	0.3043	0.288
Naslund	$CS = -0.293306 + 0.000095\, DBH^2 + 0.000007\, DBH^2 H + 0.000076\, DBH\, H^2 + 0.000003\, H^2$	0.952	0.0639	0.064
Specific	$CS = 0.223 + 0.002\, DBH - 0.020\, H + 0.00020\, DBH^2$	0.986	0.2473	0.267

where CS is the carbon storage (kg/tree), DBH is the diameter at breast height (cm), H is the tree height (m), R^2 is the coefficient of determination, SEE is the standard error of the estimate and SRE is the square root of the average error

Table 4. Carbon storage (t/ha) differences based on Schumacher-Hall, Naslund and specific models

DBH (cm)	Density (trees/ha)	Volume (m^3/ha)	Basal area (m^2/ha)	Carbon storage (t/ha) Schumacher-Hall	Carbon storage (t/ha) Naslund	Carbon storage (t/ha) Specific model
15	375	38.55(±2.15)	6.62(±1.97)	9.08(±2.16)	5.69(±2.14)	9.44(±2.06)
25	448	130.98(±3.46)	21.98(±3.28)	17.32(±3.47)	12.84(±3.45)	32.09(±3.37)
35	160	98.49(±3.42)	15.39(±3.23)	14.17(±3.43)	11.71(±3.40)	24.13(±3.33)
45	70	80.05(±4.09)	11.13(±3.91)	14.52(±4.10)	12.64(±4.08)	19.61(±4)
55	42	74.82(±3.06)	9.97(±2.88)	14.15(±3.07)	12.67(±3.05)	18.33(±2.98)
65	10	25.80(±5.62)	3.32(±5.43)	12.70(±5.63)	11.59(±5.61)	6.32(±3.53)
75	0	0.00	0.00	0.00	0.00	0.00
85	4	19.15(±1.33)	2.27(±1.14)	10.31(±1.34)	9.63(±1.32)	4.69(±1.24)
95	1	6.08(±3.36)	0.71(±3.18)	10.19(±3.37)	9.59(±3.35)	1.49(±3.28)
105	2	15.14(±1.47)	1.73(±1.29)	6.19(±1.48)	5.85(±1.46)	3.71(±1.38)
115	1	9.22(±1.36)	1.04(±1.17)	8.20(±1.37)	7.81(±1.34)	2.26(±1.27)
125	2	22.16(±1.82)	2.45(±1.64)	7.29(±1.83)	6.97(±1.80)	5.43(±1.73)
135	3	39.36(±3.24)	4.29(±3.05)	6.29(±3.25)	6.05(±3.23)	9.64(±3.15)
145	0	0.00	0.00	0.00	0.00	0.00
155	0	0.00	0.00	0.00	0.00	0.00
165	0	0.00	0.00	0.00	0.00	0.00
175	0	0.00	0.00	0.00	0.00	0.00
Total	1118	559.79(±48.6)	80.90(±35.5)	130.40(±48.8)^{a*}	113.05(±48.4)^{b*}	137.15(±47.1)^{a*}

where DBH is the diameter at breast height (cm)

*Mean values in a row followed by the same letter are not significantly different ($p<0.05$)

Table 5. Carbon storage per unit area in roots and litter biomass

Component	Biomass (t/ha)	Carbon content(%)	Carbon storage (t/ha)
Coarse roots	11.29(±3.45)^{a}	43.82(±3.15)^{a}	4.68
Medium roots	11.03(±3.14)^{a}	43.42(±3.45)^{a}	4.46
Fine roots	10.72(±5.15)^{a}	37.29(±5.53)^{b}	4.32
Total roots	33.04(±3.14)		13.46
Litter	8.48(±2.99)^{b}	38.17(±4.01)^{b}	3.96

*Mean values in a column followed by the same letter are not significantly different ($p<0.05$)

Table 6. Sensibility analysis of profitability without forest management and carbon storage using production costs and prices of Appendix I

Scenario	Interest rate (%)	First cutting (years)	Second cutting (years)	Optimal harvest cycle (years)	Net present value (€/ha)
A	8	45	+12	57	726.1
	9	45	+13	58	697.3
	10	45	+14	59	648.2
	12	45	+17	62	618.7
	13	45	+17	62	608.2
B	8	45	+15	60	945.7
	9	45	+16	61	912.9
	10	45	+17	62	886.9
	12	45	+18	63	856.3
	13	45	+18	63	801.7
C	8	45	+16	61	932.4
	9	45	+16	61	875.3
	10	45	+17	62	888.2
	12	45	+18	63	851.7
	13	45	+18	63	831.2

Table 7. Net present value and optimal harvest cycle without forest management and carbon storage according to the three considered scenarios: without any subsidies, (scenario A), with national subsidy based on Decree Law 701 (scenario B) and with national subsidy based on Law Nº 20,283 (scenario C).

Scenario	Timber volume (m^3/ha)	Timber extraction (m^3/ha)	Interest rate* (%)	Net present value (€/ha)	Internal Rate of Return (%)	Optimal harvest cycle (years)
A	996.10	298.83	10	648.2	12	59
B	1116.71	334.80	10	886.9	14	62
C	1073.79	334.78	10	888.2	14	62

*The interest rate was calculated based on Capital Asset Pricing Model

Table 8. Sensibility analysis of profitability with forest management and carbon storage using production costs and prices of Appendix I

Scenario	Interest rate (%)	First cutting (years)	Second cutting (years)	Optimal harvest cycle (years)	Net present value (€/ha)
A	8	45	16	61	904.6
	9	45	16	61	900.0
	10	45	17	62	892.9
	12	45	17	62	851.3
	13	45	17	62	847.6
B	8	45	16	61	1234.9
	9	45	16	61	1203.7
	10	45	19	64	1191.3
	12	45	19	64	1022.2
	13	45	19	64	997.7
C	8	45	17	62	1136.4
	9	45	17	62	1101.5
	10	45	18	63	1001.7
	12	45	18	63	984.3
	13	45	18	63	976.1

Table 9. Net present value and optimal harvest cycle with forest management and carbon storage according to the three considered scenarios: without any subsidies, (scenario A), with national subsidy based on Decree Law 701 (scenario B) and with national subsidy based on Law Nº 20,283 (scenario C).

Scenario	Timber volume (m^3/ha)	Timber extraction (m^3/ha)	Interest rate* (%)	Net present value (€/ha)	Internal Rate of Return (%)	Optimal harvest cycle (years)
A	1,164.95	349.48	10	892.94	14	62
B	1,217.24	365.17	10	1,191.32	16	64
C	1,191.49	357.44	10	1,001.72	16	63

*The interest rate was calculated based on Capital Asset Pricing Model

Appendix I. Production costs and prices used in the Faustmann model

Production costs	Cost (€/ha)
Harvesting operations	545 €/ha
Plantation	602 €/ha
Plants (1,300 plants/hectare)	401 €/ha
Site preparation and clearing	250 €/ha
Weed management	71 €/ha
Forest management planning	113 €/ha
Path maintenance	82 €/ha
Culverts	17 €/ha
Annual costs (maintenance)	45 €/ha
Profits (prices)	
Logging	1.2 €/inch
Sapwood	20 €/m^3
Pulpwood	16 €/m^3
Afforestation bonus with native species	841 €/ha
Bonus for native forest management and biodiversity conservation	801 €/ha
Bonus for biodiversity conservation	521 €/ha
Carbon ton price (www.sendeco2, average price of 2017)*	21.4 €/t

* It is calculated as the product between the CO_2 ton price (5.83 €/t) and 3.67 (carbon molecular weight in relation to CO_2 molecular weight).

Optimal harvest cycle on *Nothofagus* forests including carbon storage in Southern America: an application to Chilean subsidies in temperate forests

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Optimal harvest cycle on *Nothofagus* forests including carbon storage in Southern America: an application to Chilean subsidies in temperate forests

Abstract

Different countries may have passed through their forest transitions from net native forest loss to net exotic plantation expansion. More investment in global and national forest monitoring is needed to provide better support to increase sustainable forest management and reduce forest loss, particularly in native forests. These slow-growing forests could get involved in the voluntary carbon markets. In this sense, some international and national initiatives based on subsidies could play an keystone role in the native forest conservation, mainly in small private lands.

This approach aims to identify the optimal harvest cycle of *Nothofagus* forest type based on integral harvesting management (timber resources, natural regeneration and carbon storage) and three scenarios (lack of subsidies and two different real subsidies). The most suitable carbon storage models were Schumacher-Hall, Naslund and the specific model. The coefficient of determination was higher than 0.95 for these three cases. If only timber harvesting was considered, the optimal harvest cycle was established between 57 and 59 years according to the presence or lack the state subsidies. However, when forest management and carbon storage were considered, the optimal harvest cycle increases three years. Therefore, the effect of this new alternative can be also observed in net present value and internal rate of return. This integral forest management could be an interesting approach for small private owners and for the global warning mitigation according to the ratified international agreements.

Key-words: bioeconomic model, net present value, interest rate of return, *Nothofagus dombeyi*, *Nothofagus alpina*

1. Introduction

The main cause of climate change is the anthropogenic increase in greenhouse gas concentrations in the earth's atmosphere. The international response to climate change began with the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. Kyoto Protocol emphasizes the forestry sector as one of the main element to climate change mitigation (Bulkeley, 2013). Other international and ratified agreement (the United Nations Conference on Sustainable Development - or Rio+20) has demonstrated that climate change is not only theoretical concept. In this sense, this Conference recognizes the need to prevent the world's average temperature from rising by more than 2ºC, following the guidelines established by the international scientific community (Ambrósio et al, 2017).

In spite of 31 percent of the carbon is stored in the biomass and 69 percent in the soil, forests play an essential role in the global carbon cycle though the elementary photosynthesis (IPCC, 2001). We only consider the carbon storage of the vegetation but further studies will study carbon soil storage. Kyoto Protocol (articles 3.3 and 3.4) promotes a huge range of alternatives for increasing carbon storage through forest management (Krause, 2015). An important aspect of sustainable forest management is to assess the impact of forest operations on ecosystem services (Bravo et al., 2015). The estimation of carbon stock requires a destructive sampling to identify live biomass from different species and sizes (Montero et al., 2005). Due to time difficulties and the cost of destructive fuel inventories, allometric equations have been constructed to estimate biomass from traditional forest inventory variables (Agudo et al., 2007; Molina et al., 2014). The diameter at breast height is the most commonly used variable for biomass models (Návar, 2009; Ruíz-Peinado et al., 2012), in spite of the insertion of tree height can improve model fit significantly (Ruíz-Peinado et al., 2011).

A forest management should integrate timber resources and environmental services for the suitable management of slow-growing species (Ruíz-Peinado et al., 2016). In this sense, *Nothofagus* forests can play an important role for the global warning in the southern America based on its area and timber resources market. Most of the sustainable *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus alpina* (Poepp. & Endl.) Oerst forest belongs to small private landowners. For these owners, the profitability of their forests demands a fast return of any investment. According to Chilean law (Law Nº 20,283, article 3), it is necessary "the development of scientific and technical studies to support the established alternative, methods of regeneration,...". The identification of the optimal harvest cycle is an required issue from an integral point of view that integrates timber resources and carbon storage (Díaz-Balteiro and Rodríguez, 2006; Knoke et al., 2012).

Bio-economic models could be a useful tool for the consideration of environmental services into traditional forest management (Bravo et al., 2008; Knoke and Seifert, 2008). Carbon storage could have implications that modify the making-decisions for timber resources (Díaz-Balteiro and Romero, 2003). Most of the studies (Alouze, 2001; Stainback and Alavalapati, 2002, 2005; Caparros et al., 2003) have shown economic advantages in relation to the increase of harvest cycle when carbon storage is incorporated. There are a lot of studies of fast-growing species in the southern America (Van Kooten, 2000; Cubbage et al., 2007) that stated the profitable alternatives for an integral forest management. However, a low level of information is available for native forests in the southern America due to its lower profitability and the need of some subsidies. In this sense, the aim of this study is the identification and comparison of the optimal harvest cycle of one *Nothofagus* forest type based on timber harvesting management and integral harvesting management (timber resources and carbon storage). Net present value and interest rate of return will be the basic indicators for economic analysis using Faustmann's model. For each forest management alternative, three scenarios were considered based on the consideration of two different subsidies and the lack of state subsidies.

2. Material and methods

2.1. Study area

The study area is located in the easternmost edge of IX Region, in south-central Chile (Figure 1). The Malleco National Reserve belongs to the Araucarias Biosphere Reserve (RBA) which is considered among the most threatened areas of the Chile (Locatelli, 1999). The Malleco Reserve is the oldest natural protected area of Chile (and also in Latin America), which dates back to 1907). Annual precipitation in the study area ranges between 2,000 and 4,000 mm; most of it falling during the winter season. It is characterized by a wet climate with daytime summer temperature above 28ºC conductive to fire ignition and propagation.

Figure 1 around here

Malleco Reserve covers 16,625 ha of alternating four of the twelve forest types found in Chile: *Austrocedrus chilensis* (D. Don) Pic. Ser. et Bizz.; *Nothofagus obliqua* (Mirb.) Oerst - *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus alpina* (Poepp. & Endl.) Oerst; *Nothofagus dombeyi* (Mirb.) Oerst - *Nothofagus alpina* (Poepp. & Endl.) Oerst - *Laureliopsis philippiana* (Looser) Schodde; and *Araucaria araucana* (Molina) K. Koch. Deciduous forests occupy about 87% of the total of the Reserve (Locatelli, 1999). There are some forest types must be reserved for preservation and conservation according to the current Chilean legislation.

In this sense, the study area is limited to the productive sectors of the Reserve corresponding to 64% of the total land of the Reserve (10,693.4 ha). *N. dombeyi* and *N. alpina* were selected by this carbon storage approach according to its representativeness in the study area.

2.2. Carbon storage in tree stem

Tree volume was obtained based on every six years field inventories to assess dynamic carbon storage. The forest inventory was carried out in square plots of 1,225 m^2 using the stratified random sampling method. The inventory amounted 23 stands and 115 sampling units (5 sampling plot for each stand) located across the different north-south transects. The distance between plot centers was established at 70 m in order to avoid overlapping. The sampling intensity should have been higher to reduce estimation error due to the heterogeneity of these multi-aged forests, but it is necessary to take into account the field inventory difficulties (forest cover, slope and penetrability) and the associated costs and limited budget.

The data sampling collected tree mensuration variables in order to identify carbon storage incorporating the most commonly used variables such as diameter at breast height (DBH), tree height, health condition, crown shape and crown cover. All of the strata (regeneration, suppressed trees, intermediate trees, co-dominant tree and dominant tree) of stands were inventoried according to its importance in the final harvest model. As an example, diameter at breast height ranged from 2 cm to 2 m. Tree volume was estimated for *N. dombeyi* and *N. alpina* based on specific allometric equations for the study area (Table 1). Carbon storage was estimated using destructive sampling of 60 trees (30 trees of *N. dombeyi* and 30 trees of *N. alpina*) that cover the entire range of

Nothofagus species in the study area according to selection cutting or selective logging management.

Carbon storage (CS) in tree stem was estimated based on the tree volume, the wood density (WD) and the amount of carbon in biomass (C) (Equation 1). WD is obtained using a 72-hour drying process in a oven set at 110ºC. Finally, C was identified in laboratory using 92 biomass samples (4 samples for each studied stand).

$$CS = V * WD * C \qquad (1)$$

Once carbon storage was estimated using filed destructive sampling, the most commonly allometric equations (Spurr, Honer, Schumacher-Hall, Prodan et al., Meyer, Burkhart, Naslund and Stoat) were tested to the studied species (Table 2). The model selection was based on the coefficient of determination (defined as the square correlation between measured and estimated values) and the standard error of the estimate. We incorporated an additional hypothesis or specific model that was also fitted according to the collected dataset. Analysis of variance (ANOVA) was used to determinate if significant differences ($p < 0.05$) existed in carbon storage between *N. dombeyi* and *N. alpina*. SPSS© software was used in all analyses. If significant differences have not detected, one allometric equation could be performed to increase sampling size. Our alometric model was fitted using a forward stepwise method. With Principal Component Analysis (PCA), the number of variables can be systematic reduced to a smaller and conceptually more coherent set of variables.

Finally, carbon storage of all species per unit area was estimated using tree volume models for IX Region of Chile (Drake et al., 2003), wood density of each species according to other Chilean studies (Hernández and Pinilla, 2010) and an average amount of carbon in biomass. Although carbon amount varies between 35% to 65%

percent of dry weight, 50% is often takes as a default value of carbon in biomass (Lowe y Raes, 2000).

2.3. Identification of optimal harvesting strategies

Different authors are concerned with optimal solutions to the forest management problem when future utilities are undiscounted (Samuelson, 1976; Mitra and Wan, 1986; Caparros et al., 2003; Meade et al., 2008; Brazee, 2017). The generalized Faustmann model (1849) identifies the present value of the income stream for forest rotation according to the maximising Faustmann's equation. The optimal harvest age is defined as the time rate of change of forest value is equal to interest on the value of the forest plus the interest on the value of the land. In this sense, the optimal harvest age is reached when the time rate of change of its value is equal to the interest rate modified by land rent. Other economic factors could be included in the Faustmann model, such as equivalent annual costs, subsidies and revenues. Net present value (NVP) in Faustmann model (Equation 2) is the different between the present value of cash inflows and the present value of cash outflows over a harvest rotation age.

$$NPV = \left[I(t)e^{-it} + \sum_{\forall 1} C_I e^{-iI} - K - Gi^{-1}(1-e^{-it}) - \sum_{\forall S} Y_s e^{-is} \right] \left(1-e^{-it}\right)^{-1} \qquad (2)$$

where I(t) is the income that is obtained by selective logging from the sale of each harvest cycle or "t" year, C_I is the selective logging profits, K is the costs of afforestation, G is the operating costs, Y_S is the cutting and maintenance costs, and s_1, s_2,... are the years when forest cuttings are carried out. Forest planning was established in 100 years (10 periods of 10 years).

Faustmann model allows us to identify the optimal harvest cycle of *Nothofagus* species. However, the original model does not include the subsidies that are contemplated and promoted by Chilean Law (Decree Law 701 "Forest Encouragement" and Law Nº 20,283 "Native Forest recovery and encouragement"). We used Díaz-Balteiro approach (1995), which considered subsidies contemplated in the Royal Decree 378/93 in Spain (Equation 3):

$$NPV=$$

$$\left[I(t)e^{-it} + \sum_{\forall I} C_I e^{-iI} + P_m i^{-1}(e^{-i} - e^{-in_1}) + P_c i^{-1}(e^{-i} - e^{-in_2}) + K_I - K - Gi^{-1}(1 - e^{-it}) - \sum_{\forall s} Y_s e^{-is} \right](1 - e^{-it})^{-1} \tag{3}$$

For the economic assessment of the optimal harvest cycle, we considered timber and carbon storage objectives. The number of harvest cycles or selection loggings is infinite with a tree cutting intensity of 20-35% of the basal area leading to a multi-aged forest with continuous regeneration. This approach takes into account the harvest cutting cycles and regeneration condition showing the best management alternative after the first harvest cycle. A minimum harvest cycle of 20 years was established according to regeneration dynamics, growing stock and the costs of silvicultural treatments. We simulated the increase of diameter at breast height, tree height, tree volume, basal area and timber stock for the regeneration and suppressed strata. Harvest operations were also incorporated in order to calculate the cutting profits in relation to timber quantity and quality. Optimal harvest cycle was identified using the Root Mean Square (RMS) based on timber and carbon storage profits.

The costs and profits associated with native forests management were calculated according to an economic analysis of public and private datasets. Economic costs and profits have been updated to 2017 (Appendix I). Planting, management and harvesting costs are based on natural regeneration and official prices (Decree Law 701). This legal framework also identifies the management actions to be considered in a native forest management plan. The subsidies were considered (Equation 3) in two ways: Decree Law 701 and Law Nº 20,283. In this sense, our approach considered three economic scenarios in order to identify optimal harvest cycle:

- Scenario A: *Nothofagus* management without any state subsidy
- Scenario B: *Nothofagus* management with state subsidy based on Decree Law 701
- Scenario C: *Nothofagus* management with state subsidy based on Law Nº 20,283

3. Results

3.1. Carbon storage in tree stem

While wood density was estimated at 450(±4.7) kg/m^3 for *N. dombeyi* and *N. alpina,* the amount of carbon in stem reached at 45.28(±1.3). On the other hand, there were no significant differences (ANOVA test) between *N. dombeyi* and *N. alpina* when looking at carbon storage. Although eight models were tested, only three models (Schumacher-Hall, Naslund and specific model) were selected according to its higher coefficient of determination and its lower standard error of the estimate. We selected only allometric equations with parameters significant at the 0.05 level, coefficient of determination higher than 95% and standard error of estimate lower than 0.3 (Table 3). It was possible to explain more than 80% of the total variance of the carbon storage according to only two components. In this sense, diameter at breast height and tree height were the most important components.

The field inventory showed a mean of 1,118 trees per hectare, of more than 559.79 m^3 per hectare and of more than 80.90 m^2/ha (Table 4). 87.92% of the trees were categorized in the three smallest diameter categories (< 35 cm). Carbon storage was significant higher in “Schumacher-Hall and specific model” (more than 130 t/ha) when compared with “Naslund” (more than 110 t/ha) (Table 4). The three smallest diameter categories (< 35 cm) ranged from 30.24% (Naslund) to 65.66% (specific model) of the total carbon storage. The analysis of the carbon storage for each inventoried species reached to the 68.69% of the total carbon storage per hectare for *N. dombeyi* and *N. alpina* (Figure 3).

3.2. Identification of optimal harvest cycle without forest management and carbon storage

The studied forest type has shown an average growth of 0.65 cm/year of diameter and 0.63 cm/year of height under without any silvicultural management (Gezan, 2009). Total volume ranged from 957.79 m^3/ha to 1073.79 m^3/ha and timber extraction ranged from 287.34 m^3/ha to 322.14 m^3/ha according to the subsidies presence. While the interest rate was fixed at 10% for the three scenarios (Navarro et al., 2010), the Internal Rate of Return ranged from 12% (scenario A) to 14% (scenario B and C). Net present value was higher in scenarios with subsidies than in scenarios without subsidies (26.93% of increase). The optimal harvest cycle was established between 57 years (scenario A) and 59 years (scenario B and C) (Table 5). There were no significant differences between scenario B and scenario C.

3.3. Identification of optimal harvest cycle with forest management and carbon storage

Total volume ranged from 1,131.79 m^3/ha to 1,181.79 m^3/ha and timber extraction ranged from 339.54 m^3/ha to 354.54 m^3/ha according to the scenario. The Internal Rate of Return ranged from 14% (scenario A) to 16% (scenario B and C). The lowest net value present was obtained by scenario A. Net present value was 15.91% higher in scenario B than in scenario C. The optimal harvest cycle according to forest management and carbon storage was established between 60 years (scenario A) and 62 years (scenario B) under an interest rate of 10% (Table 6).

4. Discussion

The selected trees are representative from a wider range of age of *N. dombeyi and N. alpina* stands commonly found in the "Malleco National Reserve". The wood density and the amount of carbon in biomass are the most difficult variable to measure due to the need of tree cutting. These difficulties lead to the search of allometric equations predicted from common forest inventory variables for estimating stem biomass and effects of different silvicultural treatments (Ritson and Sochaki, 2003; Návar 2009; Bravo et al., 2015; Ruiz Peinado et al., 2016). We recommended the use of allometric equations according to the goodness-of-fit obtained for Schumacher-Hall, Naslund and specific model (Table 3) and the simplicity required by the forest managers.

Diameter at breast height is the most common variable in biomass studies showing reliable relationships (Agudo et al., 2007; Bravo et al., 2008; Návar 2009; Ruiz Peinado et al., 2011, 2012). The inclusion of tree height provides more suitable carbon storage results. Significant differences were found between Schumacher-Hall (Marques da Silva et al., 2009) and specific models and Naslund model (Gezan, 2009). The more accurate way to estimate carbon storage is to develop regression models for its estimation from common stand inventory data. Our model suggested a strong dependence of stem carbon storage on diameter at breast height and tree height. Inclusion of other variables well correlated with tree size did not improve model fit significantly as those variables were already highly correlated to canopy cover and the competition in the neighbourhood.

Aboveground vegetation is the most important stratum in relation to carbon storage (Löwe and Raes, 2000). In regard to this importance, field sampling should be design to achieve the objectives pursued according to available budget. Therefore, our approach only considers carbon stem storage because its elevated contribution in relation to the rest parts of the tree (branches, leaves and roots). Wood density was estimated at 450(±4.7) kg/m^3 for *N. dombeyi* and *N. alpina* likewise correspondingly by other Chilean studies (Hernández and Pinilla, 2010). The amount of carbon (45.28%) is similar to other reference values in Mediterranean Basin studies (Löwe and Raes, 2000; Agudo et al., 2007).

Some stands of the same species can promote higher carbon stocks than others based on tree and forest characteristics and forest management (Navar, 2009; Ruiz-Peinado et al., 2016). The examination of private owners' harvesting behaviour, risk preferences and subjective judgments reveals strong indications of the difficulties for private owners to make rational decisions when faced with uncertainties (Andersson and Gong, 2010). The primary reason for selling wood fuel was that the harvesting operation cleared the ground of debris (Bohlin and Roos, 2002). Additionally, direct economic risks such as price and cost changes are seen by private owners as much more important than indirect economic risks such as biological damage and other incomes generated by forests (Lönnstedt and Svensson, 2002).

Although forest management in the study forest type is a profitable activity according to financial return from timber products, it depends on the distance to the markets and the availability and quality of the road network (Donoso and Lara, 1999). In this sense, in old-grown stands and remnant forest parches are complicated to forest management according to the costs of periodical cuttings, planting and pruning. In these vulnerable areas, subsidies could be necessary to promote an Internal Rate of Return (IRR) over

10% (Donoso and Lara, 1999). An IRR higher than 13% shows a profitable forest management (Cubbage et al., 2007) in spite of the elevated costs associated to selective loggings. These IRR values are explained by the increase of native wood price and the decrease of harvesting costs (Table 3).

Traditional forest planning has led to the production of timber resources in a sustainable way. As society's demands for forest ecosystems have been modified, tools traditionally used in forest management and forestry planning have proved insufficient (Di Salvatore et al., 2013). The consideration of environmental services requires bioeconomic and multivariable models (Díaz-Balteiro and Romero, 2003; Díaz-Balteiro and Rodríguez, 2006). Assessing functional features of forests with our approach allows us to get information on forest multifunctionality to support forest planners in defining optimal harvest cycle based on timber resources (maximum NVP), and environmental resources (natural regeneration and carbon storage). This paper provides attractive results integrating target assets (NPV) and environmental services to forest management. According to the economic analysis, an integral management reaches higher incomes than traditional management. As an example the IRR increases an 4% between integral management and traditional management (Tables 5 and 6). This fact is in relation to the NPV increase according to sawn timber volume and carbon storage.

Our bioeconomic model has always promoted forest natural regeneration so as to guarantee its successful development. In this sense, this approach has identified an optimal harvest cycle ranging from 57 (scenario A) to 59 years (scenario B and C) without forest management and without carbon storage income. NPV differences varied from 199.7 €/ha (scenario B) to 200 €/ha (scenario C) between non-state grants and subsidies. NPV differences between Decree Law 701 and Law Nº 20,283 are minimal (0.3 €/ha). On the other hand, the optimal harvest cycle ranged from 60 (scenario A) to

62 years (scenario B) with forest management and with carbon storage income. In this case, the differences between scenario B and scenario C are higher in relation to NPV and number of years. It is noted that there is a increase of three years in the optimal harvest cycle according to an integral forest management. In relation to NPV, the increase ranged from 11.43% (scenario C) to 25.55% (scenario B). It would more profitable if this forest type is managed from an earlier age. Our optimal harvest cycles showed differences in relation to southern European studies where optimal harvest cycles ranged from 49 years for *Populus* spp. to 68-70 years for *Pinus* spp. (Díaz and Romero, 1995). These differences are associated to environmental conditions and annual forest growth between southern America and southern European.

Carbon stem storage was estimated between 113.05 t/ha and 137.15 t/ha for the study forest type. In spite of the high amount of carbon is in the stem, future studies should analyze the aboveground storage including the three strata of the vegetation: stem, canopy and root. The integral management (NPV and carbon storage) without subsidies would be only profitable with a high value of the carbon fixation. However, the carbon dioxide market is very irregular and unstable based on supply, demand and international environmental agreements (Barrio et al., 2007). In this sense, one effective way to promote carbon storage in forest planning could be the guarantee of the price of timber at the end of the harvest cycle. In other words, a longer harvest cycle is favored by an additional subsidy based on the sale price of timber. The additional subsidy does not need to be very high, given the three years difference between optimal harvest cycles.

The mitigation and adaptation of global warming need to incorporate carbon storage into forest management (Bulkeley, 2013; Krause, 2015). Bioeconomic model increases the flexibility of this methodology enabling an extrapolation to other territories and other scales. The inputs used, such as carbon price, interest rate, timber volume, timber price and subsidies, are easy for forest managers to obtain because they are traditionally available from agencies and governments. According to our findings, integral forest management of this forest type is more suitable in terms of ecological and economic than traditional tangible assets management. These findings could lead to reforestation policies in order to transform some abandoned private lands to native secondary forests. Nevertheless, native harvesting is much less profitable than fast-growing species like *Eucalyptus globulus* Labill. (Cubbage et al., 2007). However, subsidies for native forest management could get reasonable financial return based on an integral management of those stands offered better rates of return than only holding the land.

5. Conclusions

Native forest management is an attractive investment because of both the timber resources and the environmental services. In this sense, some countries promote subsidies which provide an improvement in the net present value and internal rate of return. It is important to bear in mind that if *Nothofagus dombeyi - Nothofagus alpina* forests area managed, the internal rate return will be higher according to its optimal harvest age.

Nowadays, forest policies implies to the obligation to reforest with slow-growing species in very areas of southern America. Despite of these policies means that the internal rate of return is low in comparison with fast-growing species, the economic balance is positive when it includes environmental services like carbon storage. Traditional timber management does not ensure optimal harvest cycle according to our results. It is necessary to increase three years the harvest cycle in order to reach maximum net present value, and as a consequence, higher profits to private owners.

Therefore, an economic improvement was identified by the consideration of an integral forest management with the maximization of timber resources, carbon storage and natural regeneration condition.

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