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Sustainable Management of Lenga (*Nothofagus pumilio*) Forests Through Group Selection System

Pablo M. López Bernal[1,2,3], Guillermo E. Defossé[1,2,3],
Pamela C. Quinteros[1,2] and José O. Bava[2,3]
[1]Consejo Nacional de Investigaciones Científicas y Técnicas – CONICET
[2]Centro de Investigación y Extensión Forestal Andino Patagónico – CIEFAP
[3]Universidad Nacional de la Patagonia San Juan Bosco – UNPSJB
Argentina

1. Introduction

1.1 Distribution and environmental gradients of lenga forests

Lenga (*Nothofagus pumilio* (Poepp. *et* Endl.) *Krasser*) is a native tree species widely distributed in the Andean forests of Patagonia. In Argentina, lenga forests cover almost the entire length of the sub-Antarctic forests on the eastern slopes of Andean Cordillera, from the 35 º 35 'S latitude parallel in the province of Neuquén to the 55 º S in the province of Tierra del Fuego (Figure 1). This species usually occupies the upper portion of the altitudinal limit of woody vegetation (up to 2000 masl) in its northern distribution area, while it grows near sea level in its southern distribution area in Tierra del Fuego (Donoso Z., 1995, Tortorelli, 2009, Veblen et al., 1977).

Lenga is adapted to grow under a great variety of soils, environmental conditions, and disturbance regimes (Schlatter, 1994). In fact, this species could be found in areas in which average annual precipitation may reach 500 mm year^{-1} (under a Mediterranean type of climate), to others reaching 3,000 mm year^{-1} (under either iso-hygro or Mediterranean type of climates). Lenga is also capable of supporting extreme temperatures, from mean annuals of 3.5 to 4 °C in upper altitudinal areas (Schlatter, 1994) to 7 to 9 °C in milder areas at lower altitudes or also near sea level.

In the northern part of its distribution, lenga grows under a typical Mediterranean climate, with precipitation concentrated during winter and early spring as either rain or snow, followed by a dry and mild period during summer and early fall. Going south, this regime gradually changes to more iso-hydric conditions, being precipitation more evenly distributed along the year. In the northern part of its distribution and up to the 52 º S, however, the amount of annual precipitation is greatly influenced by the barrier that imposes the Andean Cordillera, which creates one of the most spectacular precipitation gradients of the world. There, the western humid winds coming from the South Pacific Ocean discharge most of the precipitation as they go upward to the upper parts of the Andes, passing to the eastern slopes as more dry air masses that rapidly lose their humidity content. This makes that upper mountain ranges near the border with Chile may receive 5000 mm of precipitation per year, while in less than 50 to 80 km toward the Patagonian steppe, precipitation sharply diminishes to ca 500 mm annually (Barros et al., 1983, Jobbágy et al., 1995, Veblen et al., 1977). To the South of the 52 and up to the 55 º S parallel in the island of Tierra del Fuego, a regular rainfall pattern occurs, with rainfall evenly distributed throughout the year (Burgos, 1985);

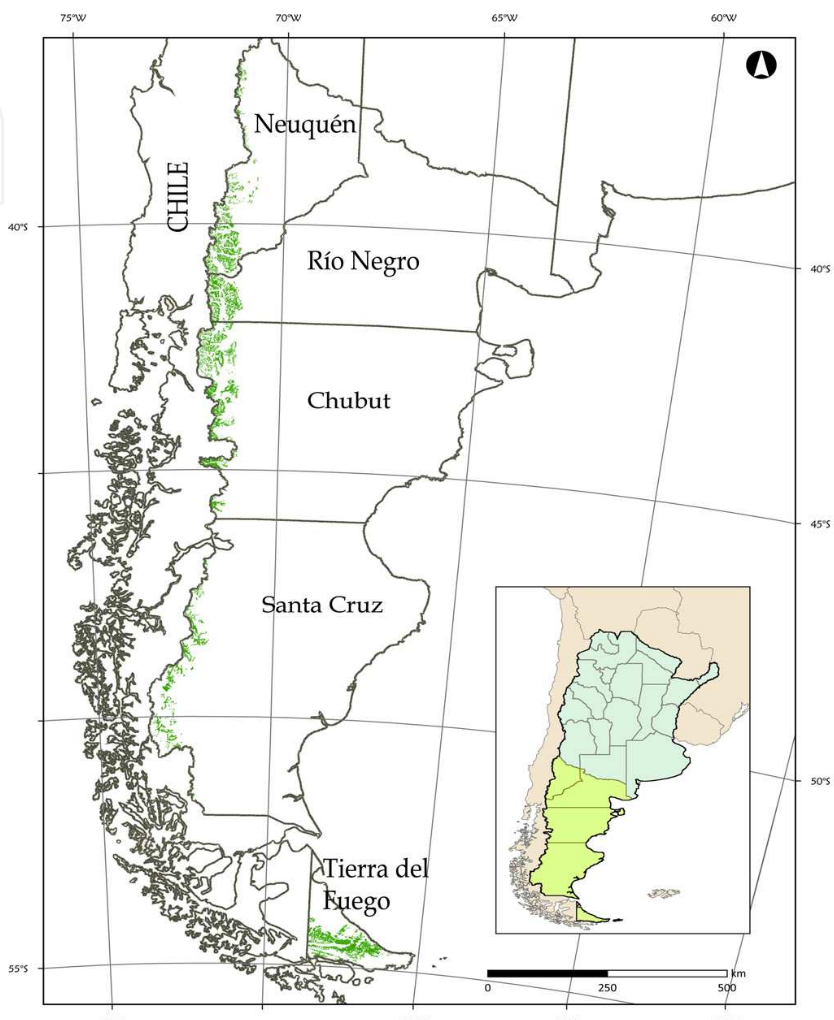

Fig. 1. Distribution of *N. pumilio* forests (green shading) in Argentinean Patagonia.

1.2 Disturbance regime

Throughout its wide distribution area, lenga stands are clearly distinguishable from other component of the Andean forests, being composed of simple monospecific structures with narrow ecotones (Donoso Z., 1995). However, given the different environments in which it develops, lenga presents different structures and regenerative dynamics, mainly associated with the frequency, magnitude and severity of disturbances such as windstorms, fires, avalanches, landslides, or the falling of senescent trees (Donoso Z., 1995, Veblen et al., 1996). As a consequence of these disturbances, lenga stands may present either even or uneven-aged structures, both situations representing extremes in a range of different possible structures. At the southern end of lenga distribution in Tierra del Fuego, tree falls usually occur due to wind storms, and this result in even-aged young structures (Rebertus et al., 1997). Furthermore, the same wind storms that cause large falls may also lead to formation of small gaps in the forest canopy. Uneven-aged structures are usually originated in mature forests located in favorable sites at low altitudes having low frequencies of catastrophic disturbances or human interventions. In these areas, the falling out of senescent trees may promote the opening of gaps or patches of about 0.1 ha (Bava, 1999, Veblen & Donoso Z., 1987) in which regeneration begins. These patches generally possess favorable undergrowth conditions which allow the formation of small clumps of saplings. The result of this process is a multi-aged and multi-strata forest, even when the formation of these gaps may be an episodic phenomenon (Rebertus & Veblen, 1993).

In relation to its tolerance to shadow, lenga has been classified as either "purely heliophilous" (Mutarelli & Orfila, 1971), "semi-heliophilous" (Tortorelli, 2009), "medium tolerant" (Rusch, 1992) to "semi-tolerant" (Donoso Z., 1987). These controversial or even opposite classifications are probably due to the different habitats these descriptions came from. It has been well established that for many species, proper development may depend on the limiting resources a given environment may have (Choler et al., 2001) so the radiating needs of lenga regeneration may significantly vary depending on a set of other environmental factors (Rusch, 1992).

In sites with high rainfall levels (i.e. South of Tierra del Fuego and West of Chubut province), lenga regeneration is established even after major disturbances affecting up to hundreds or even thousands of hectares (Rebertus et al., 1997, Veblen et al., 1996). The same occurs in forests affected by intensive forest harvesting (Gea Izquierdo et al., 2004, Mutarelli & Orfila, 1971, Rebertus & Veblen, 1993, Rosenfeld et al., 2006). By contrast, in sites with water deficit during the summer, as in the northern sector of lenga distribution in Río Negro, Neuquén and Chubut provinces, regeneration cannot be established with low canopy coverage (Bava & Puig, 1992). In these areas, regeneration establishment is strongly influenced by water availability and usually occurs in small gaps caused by falling trees (Rusch, 1992).

Recent studies have analyzed the effects of micro-environmental factors on the establishment and growth of lenga seedlings in natural gaps. These studies showed that in the driest sites of lenga distribution, the shade generated by individuals from the edge of the gaps and the presence of coarse woody debris, produce a facilitator effect on seedling establishment (Heinemann & Kitzberger, 2006, Heinemann et al., 2000). Seedling survival in these xeric sites have been positively related to water availability, while in mesic sites survival seems to be controlled by both water availability and light (Heinemann & Kitzberger, 2006, Heinemann et al., 2000).

2. History of productive use of *N. pumilio* forests in Argentinean Patagonia

Most of lenga productive forests in Argentinean Patagonia, owned by either private or state sectors, started to be exploited at the beginning of the XXth century, but did not reach significant levels of harvest until mid-century, with the emergence of large sawmills that used almost exclusively high quality timber. Since then, the closing down of these large sawmills and the gradual installation of small and medium sawmills generated changes in harvesting techniques, extraction rates, and final products. These changes were usually marked by the lack of effective control policies by the state administration, which lead to the absence of sustainable management practices. Furthermore and to worsen this situation, these forests have been traditionally used as summer pastures for cattle, which in many cases has caused the degradation of the understory, with long delays in, and even preclusion of, regenerative processes.

The objective of this chapter was to analyze the evolution of productive schemes of lenga forests along their history of use, which will help us understand the overlap of strains on this resource, impacts on their conservation status, and the difficulties that currently have the implementation of sustainable management systems. For this purpose, we got information derived from published analyses, statistical records of the Forest Administration, analyses of historical harvesting, and of the impacts of livestock on forest regeneration. This information is presented for two contrasting situations, located one in the northern lenga distribution area in Chubut province and the other in its southern distribution area in Tierra del Fuego.

2.1 Pre-industrial

The original inhabitants of continental Patagonia were mostly nomadic Indian tribes that depended largely on the guanaco (*Lama guanicoe Muller*) for their livelihood. These tribes used ecotone and steppe areas of and did not settled in the Andean forests, although there are some examples of communities who lived associated with *Araucaria araucana (Molina) K. Koch* forests in northern Patagonia. Lenga forests, located at higher altitudes, were only occasionally used as firewood in the journeys crossing the Andes (Musters Chaworth, 1871). In Tierra del Fuego, unlike continental Patagonia, guanaco used lenga forests as part of its habitat, perhaps due to the absence of its natural predator, the puma (*Puma concolor* Linnaeus). Some Indian tribes lived much of the year in these interior forests, while others were established on the shores of the Beagle Channel, all surrounded by lenga forests. In this region, the use of lenga for small constructions and canoes, although in small scale, has been reported (Bridges, 2000). The major effect of indigenous peoples on Patagonian forests has been the recurrent employment of fire, either for hunting purposes or used as a communications signal (Kitzberger & Veblen, 1999).

During white settlement, cracked poles, rustic tables, or shingles, were widely used products from lenga forests, but undoubtedly, fire was the most devastating factor affecting them. In the Argentine sector of Tierra del Fuego, an estimated 20,000 ha were burnt in the early twentieth century. Contemporarily and in an attempt to open land for sheep raising, pioneers in the Chilean Patagonia initiated what could now be called catastrophic fires, burning large portions of lenga woodlands (2.8 million ha, Fajardo & McIntire, 2010), reducing their original area by a half (Otero Durán, 2006). In the rest of its distribution area, thousands of hectares were also burnt, although reliable data are not available (Willis, 1914). The recovering of lenga forests after those fires depended on a multiplicity of factors, among which the availability of safe sites (*sensu* Harper, 1977) for seed germination and seedling establishment, and the grazing pressure exerted on the burned sites played a crucial role. The outcomes in former lenga forests were then open fields to raise sheep or the slow recovery of lenga forests. After that beginning and in the mid 40´s, factors such as the strengthening of national protected areas, the decline of sheep production and the displacement of rural populations modified this process of impoverishment or forest clearance, at least at regional level. Though, the lenga forests that were formerly used as summer ranges for sheep gradually changed to cattle grazing areas. It is interesting to note that the introduction of cattle ranching in the area has a vague origin, as the early explorers (Musters Chaworth, 1871), cite the existence of wild cattle in the forests of the region already in 1870, possibly coming from Valdivia, Chile (settled around 1600), or escaped from the cattle drives that native communities transported from Argentina to Chile.

2.2 The beginnings of industrial use: High grading

The first forest industries installed in the early twentieth century, either for medium or small sawmills, or for wood veneer production, were characterized by softly logging, cutting only healthy, medium-sized trees. Stem rots, caused mostly by fungi of the genera *Postia* and *Piptoporus*, is a very common phenomenon that affects lenga trees, being very important in old age trees. This determined that in virgin forests, only a small proportion of trees contained good quality timber. For that reason and in general, forest workers used to cut down only trees in good health status, medium-sized (40 - 50 cm DBH), which generally did not exceed 10% of forest trees in a stand. This type of "soft logging" was locally known as "floreo" (high grading).

2.3 Forest management plans

The first Argentine Forest Law was put in force in 1948. While the concept of forest management, as a synonym of timber production, was prevalent in that law, it included articles about protection of soil, water and biodiversity. Although it mandated for the implementation of Forest management plans, its principles and regulations were applied sparingly. As a result, logging continued in public forests in an unplanned way. In the mid 50´s of the XXth century, the first forest management plans were designed and applied by Croat forest engineers, who arrived to Argentina after the World War II. These plans represented a breakthrough for the understanding of lenga forests, but had little practical effects on forest management due to the weaknesses of the Administrative forestry services of the Patagonian provinces.

By the 80's, the practice of giving access to cut lumber in public or private forests depended on the approval of forest management plans by the provincial forest service, practice that became usual. However, these were just cutting plans, without long term planning horizon and being controlled at different levels of implementation.

Silvicultural aspects were changing over time with the evolution of knowledge about forests dynamics, from the early experiences on shelterwood systems in Chile (Cruz M. & Schmidt, 2007), clear-cut in Argentina (Mutarelli & Orfila, 1971), to the currently used alternatives, ranging from a group selection system (Bava & López Bernal, 2005) up to a variation of shelterwood systems with dispersal and-or aggregate retention (Martínez Pastur et al., 2009).

2.4 Cattle

As already mentioned, the first activity developed in Patagonian was sheep ranching. Near the Andes, the usual ranching scheme was a system that alternated winter grazing (locally called invernadas) in low areas with summer grazing areas at higher altitudes in the forest (called veranadas). There are plenty of examples of this system in mountain areas around the world. In the mid-twentieth century, with increasing population established in the area, cattle raising was becoming important, with the same production scheme.

In lenga forest ecosystems of Patagonia, herbivory causes severe impacts, because this species is palatable to both wild (camelidae, deer and leporidae), and domestic livestock, and heavy grazing can prevent forest regeneration (Veblen et al., 1996). In Argentina, lenga forests suitable for timber production are mainly concentrated in the provinces of Chubut and Tierra del Fuego. Lenga forests in the province of Chubut are also a very important part of traditional cattle management, which similarly to what formerly occurred with sheep, alternates winter fields in the steppe with summer fields at the mountains (York et al., 2004).

Therefore, 19 % of the forests suitable for timber production are potentially degraded by cattle grazing (Bava et al., 2006). In Tierra del Fuego, by contrast, is the wild guanaco (*L. guanicoe*) which has a negative impact on regeneration. This impact has been reported especially in forests located northwards of Fagnano Lake and in the Chilean side of the Isla Grande de Tierra del Fuego (Cavieres & Fajardo, 2005).

It is possible to distinguish between direct and indirect effects on forest regeneration caused by large herbivores. The direct consumption of seedlings keeps the lenga regeneration stunted (Perera et al., 2004) and multi-stemmed (Bava & Rechene, 2004). The consumption of other species may cause a decrease in the diversity of the understory. The transport of seeds through feces allows the introduction of exotic species (Bava & Puig, 1992). Immersed in lenga forests is frequent to find meadows, locally called "mallines" in the province of Chubut or "vegas" in Tierra del Fuego. These meadows are highly valued by farmers because of their high productivity in forage species. Due to the existence of meadows near the forests, and the little vegetation cover that characterizes the undergrowth of lenga (Lencinas et al., 2008), an intensive use of resources and a great impact on regeneration and understory forest areas close to the meadows has been reported (Quinteros, unpublished data). The changes that livestock generated in the understory, such as increased coverage of grazing tolerant species, mainly exotic, constitutes an indirect effect on the development of lenga regeneration, because the high grass coverage competes for water resources with lenga seedlings, affecting their growth and development (Quinteros, unpublished data).

3. Group selection system in *N. pumilio* forests

3.1 General concepts

The selective silvicultural systems are characterized by generating uneven-aged stands where regeneration layer strongly interacts with the mature forest, and this interaction could either be favorable or unfavorable for seedlings or saplings of different species (Daniel et al., 1979). With this method, individual trees are removed (or small groups of them), opening small gaps that can be used by tolerant species. Harvesting procedures require frequent partial cuts, where the harvest interval is called “Cutting Cycle” and there is not a rotation age where all production is harvested, as in the even-aged methods (Daniel et al., 1979).

In the Group Selection System (GSS), harvested trees are pooled in small groups (typically up to 10 mature trees), thus creating gaps in the canopy larger than the individual selection cuttings, which are better suited to the requirements of semi-tolerant species, as is the case of lenga (Bava & Rechene, 2004). It also provides some advantages of even-aged stands, as the saplings grow in conditions of intra-cohort competition. This competition favors the production of better shaped stems, while the harvest is partially concentrated, reducing its costs and minimizing the damages from falling trees (Daniel et al., 1979).

Under this scheme, some decisions that have to be taken are (Davis & Johnson, 1987):

- Cutting cycle: time between harvest entries on each stand.
- Reserve growing stock level: residual volume or basal area (BA) immediately after harvest.
- Group, patch or gap size: defined in function of objective species requirements.

The historical origin of this type of management helps gauge its applicability and scope in different productive forest systems. Uneven-aged forest management had its origins in Central Europe, where since the twelfth century exist harvest protocols regulating the forest extraction, by limiting the numbers of individuals or the volume to be harvested (Becking, 1995). However, the real practice was a selective extraction of the best stems (high-grading) without control policies that would ensure the regeneration and future productive potential of the forest, affecting negatively the productive quality of large areas. For this reason, between the fifteenth and eighteenth centuries this type of logging was progressively sidelined (Puettman et al., 2009), and new forest practices, such as clear-cutting, emerged (Becking, 1995). In the early nineteenth century, an alternative selection system was formalized for various regions of Europe, where clear-cuts were banned and where the landowners of small forest stands were especially interested in the high frequency of harvesting (short cutting cycles) thus maintaining a continuous cash flow (Puettman et al., 2009).

As mentioned in the previous section, the historical context of lenga forests in Patagonia, and particularly in the north of its distribution, is in some ways comparable to the origins of the implementation of selective cuts. The predominance of small and medium producers, the low productivity of these forests and the low control capacity of state agencies has meant that in most cases the harvest have been a high-grading, often of low intensity. Thus the GSS, where harvesting is simultaneous with other silvicultural tasks (such as thinning or regeneration release) on the one hand represents an economically feasible objective for local producers, and on the other a simplification of the control tasks posed by the state.

Moreover, the prolonged rotation periods needed for lenga forests and the brief history of the implementation of these schemes in Patagonia prevents direct observation of long-term management examples. Given this situation, models of conservation and sustainable management based on emulation of natural disturbance regimes are very attractive for developing sustainable management practices (Perera et al., 2004).

From this view, various management systems have been proposed through intense felling as clear-cuts or shelter-wood cuttings (Arce et al., 1998, Martínez Pastur et al., 2009); with the intention of imitating mass disturbances that naturally occur, especially in southern Patagonia. However in Chubut province, the rainfall regime with wet winters and prolonged dry periods in summer, prevents the proper regeneration establishment in large areas subject to direct sunlight (Rusch, 1992). For this reason, an adaptation of Group Selection System (1997) is currently proposed for these sites, imitating the predominant disturbance of gap dynamics (Bava, 1999, Veblen & Donoso, 1987, Veblen et al., 1981, Veblen et al., 1980). This promotes the establishment of regeneration patches formed by felling from one to six trees (Antequera et al., 1999, López Bernal et al., 2003).

3.2 Adaptation of GSS to *N. pumilio* forests

3.2.1 Definition of canopy gap

The minimum unit for the application of different treatments in a group selection system is the "forest patch" or "canopy gap". However, the definition of canopy gap or its size is often unclear. On one hand, there are different definitions of the “canopy gap limit” and on the other, there are various ways to simplify its form. Additionally, there are several field methods for gap size measurement. López Bernal et al. (2010) compared different ways of this three issues, specifically:

i. Gap limit definitions: there are two main schools of thought defining this parameter. One is proposed by Brokaw (1982), who defined the gap as a "hole" in the forest that extends across all levels to an average height of two meters above the ground, and whose boundaries are defined as vertical walls. The space calculated by this method is usually called the "canopy gap" (Figure 2). However, this method has been criticized because it underestimates the area affected by the gap (Popma et al., 1988). The other definition was proposed by Runkle (1981), based on the concept of an "expanded gap" whose limits extend to the base of the bordering trees. Runkle argued that this method has the advantage of including the area where light availability is directly and indirectly influenced by the gap.

ii. Calculation methods: regardless of the gap type (i.e. the definition of its limits), there are several methods to calculate or estimate the surface area of a gap. These methods mainly differ in the degree of form simplification, i.e. how well they capture boundary irregularities, moving from ellipses to polygons, octagons or hexadecagons, either with straight sides or with sections of an ellipse (Brokaw, 1982, Green, 1996, Lima, 2005, Runkle, 1981, Zhu et al., 2009).

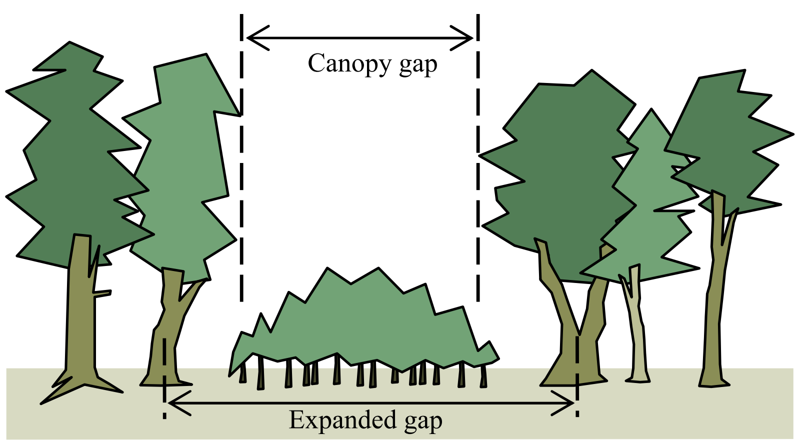

Fig. 2. Canopy and expanded gap scheme.

iii. Field Methods: Finally, different methods, such as measuring directions and distances from gap center or the triangles method (Lima, 2005), may be applied to measure the variables needed to calculate gap size. These methods may be more or less effective depending on the characteristics (such as understory density and height) of the forest being studied. The optimal field method must also be evaluated in terms of its simplicity of operation, time requirement, necessary tools, etc.

The three issues listed above are all based on the conception of a gap as a surface. The relationship between gap diameter and canopy height has also been used as a reference parameter in some studies (Albanesi et al., 2008, Minckler & Woerheide, 1965, Runkle, 1985), especially where gap creation has been used as a management activity. Canopy height is a parameter with a direct influence on the amount of received radiation. Therefore, the addition of canopy height in any calculation may lead to a significant improvement in the accuracy of gap size estimation.

López Bernal et al. (2010) concluded that the Polygonal Expanded Gap Diameter / dominant canopy Height ratio (from now on D/H) is an expeditious method to characterize gap size. This method not only allows the estimation of the incident radiation, but also the comparison of gaps of different stands and even of different species (Albanesi et al., 2008, OMNR, 2004). The method also incorporates dominant canopy height, which improves gap characterization at different sites. A range for this variable for lenga forests is between 14 and 30 m, and makes D/H an adaptable parameter. The strong correlation between D/H and incident radiation makes this parameter a good radiation predictor for gaps in a broad range of gap sizes and with canopies of different heights, and represents a useful tool, both to define silvicultural guidelines and to carry out forest ecological studies.

3.2.2 Tree marking guidelines

The main strategy proposed by Bava and Lopez Bernal (2005, 2006) for marking in virgin or high graded forests, focuses on trees from which it is currently possible to gain good quality logs, or on young healthy trees showing high timber potential. If these trees exceeded the minimum diameter at the breast height (DBH) of 35 cm (or 40 cm if they had smooth bark), they are felled in order to open or expand the gap, but if they not exceed that diameter, their growth is favored by cutting or girdling competitor trees. Thus, the procedure identifies almost homogeneous small patches within the stand, and depending on their structure, the decision between this three alternatives is made:
Gap opening: Operation for the opening of a gap by felling healthy mature trees and girdling old rotten ones, where a small regeneration patch must grow successfully.
Gap release: Operation oriented to release seedlings patches in old gaps by cutting old over-matures neighbor trees.
Thinning: Release of young healthy saplings or poles (15-30 cm DBH), by cutting competitors trees, mostly from the same cohort.
These general rules can become more specific, taking into account the rainfall level (Figure 3):

Mesic sites (Rainfall > 1100 mm/year)

Stage 0: Patch of mature trees.
i. In a patch composed of mature trees, new gaps with D/H between 1.5 -2 have to be open. We expect that after a rotation of 35 years, the regeneration here will be at least 5 m height.
Stage 1: Gap with seedlings less than 1 m height.
ii. If the available light is not enough for a successful growth, we enlarge the gap up to H/D 2. That allows maximizing the height growth up to 25-30 cm/year.
Stage 2: Gap with seedlings higher than 1 m.
iii. In this case, it is possible that the regeneration losses his form and vigor because of inappropriate light conditions, and the opening of a new gap as in situation 0 is needed. In the other case, with the regeneration in good condition, we enlarge the gap up to D/H = 2. In that case we expected height growth rates similar to that mentioned in situation 1.
iv. If the gap is colonized by seedlings with good growth, there is the possibility that some dominant seedlings with bad form are preventing the proper development of the rest; in this case they should be removed by cutting or girdling.
Stage 3: gap with saplings.
v. In this situation the gaps limits are unclear and it is possible to recognize the good quality saplings or poles with the potential to reach commercial sizes (DBH > 40 cm). They have to be released from their main competitors.

Xeric sites (Rainfall < 1100 mm/year)

Stage 0: Patch of mature trees.
vi. In this situation, where individuals from the canopy have reached an age and size that made them suitable for harvesting, new gaps should be open with D / H between 0.8

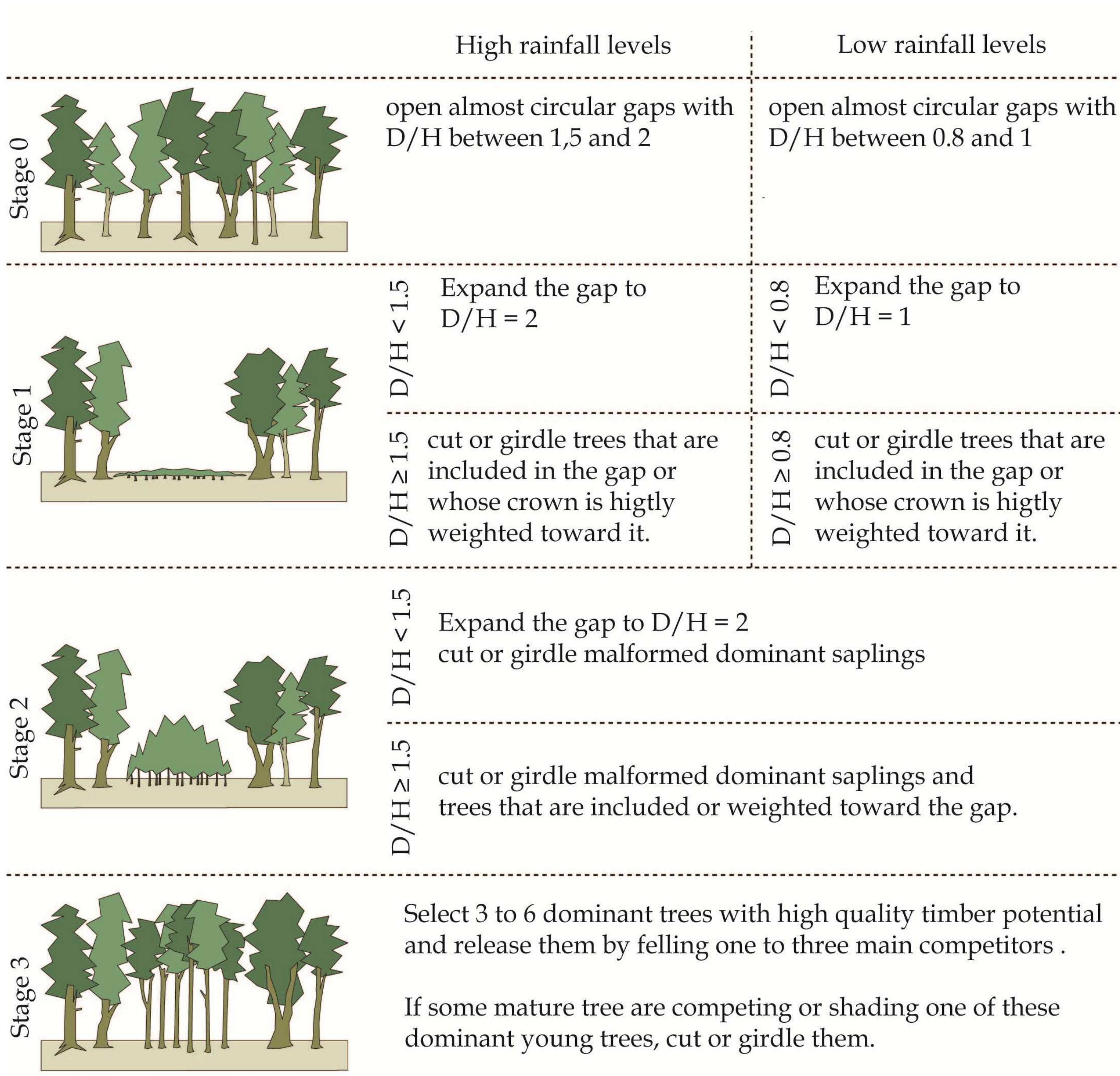

Fig. 3. Schematic representation of the marking procedure.

and 1. Situations where seedlings are already present should be preferred. Thus it is expected that after a short cycle of about 35 years regeneration has reached a height of about 3 m.

Stage 1: gap with seedlings less than 1 m height.

vii. Given this situation, it is recommended to take no action unless you notice the presence of an isolated adult tree stocked in the gap (not as border tree), which should be girdled.

Stage 2: gap with seedlings higher than 1 m.

viii. If the gap has a size from D/H < 1, it should be expanded to reach D/H = 1.5 to 2. The height growth in this condition will reach 15-20 cm/year.

ix. If the gap is colonized by seedlings with good growth, it is the possible that dominant seedlings with bad form are preventing the proper development of the rest; in this case they should be girdled.

Stage 3: gap with saplings.

x. In these cases the gap limits are unclear and individuals have reached a size that allows us to identify those with potential to reach the appropriate size for harvesting (e.g. DBH greater than or equal to 40 cm). They should be released from its major competitors to maximize their growth.

There are three key issues for the success of group selection system in lenga forests. First, regeneration must be installed and growing properly in the gap as to reach their final height with a good stem form. Second, the lateral crown growth of trees bordering the gap must not interfere with the proper development of saplings. Finally, the remaining volume stock after each intervention must maintain its stability until the next harvest. Here we review these three issues, focusing on the aspects that should be taken into account in the definition of guidelines for forest management of lenga by group selection system.

3.3 Regeneration requirements

3.3.1 Regeneration establishment

Several studies in the northern area of distribution of lenga (xeric sites) have concluded that the establishment of the regeneration of this species is strongly dependent on the availability of water during the growing season. In the drier sites located to the east, regeneration is only installed on microsites that, because of being shadier or because of the protection of course woody debris, remain wetter in summer (Heinemann & Kitzberger, 2006, Heinemann et al., 2000, Rusch, 1992). Thus, the position within the gap is a decisive factor for the recruitment of regeneration in drier sites, whereas in moist sites the position does not influence seedling survival. The same authors found that the initial growth of seedlings in the driest sites was greater in the shady parts of the gap, while in wetter sites the initial growth was higher in the center, concluding that moisture and light availability are the limiting factors for recruitment and early growth for sites with lower and higher levels of precipitation, respectively.

Thus, on the sites without drought stress during the summer, as in the western sector of the distribution of lenga in the province of Chubut, larger gaps will be more adequate, in which the interaction between the canopy and the regeneration is lower. By contrast, in sites with a high hydric deficit during the growing season, located east of the distribution of this species, the facilitating effects in microsites protected from direct sunlight and with lower evapotranspiration by the canopy, outweigh the effect of competition for other resources. As a result, smaller gaps will present the highest values of recruitment.

3.3.2 Saplings growth

Having established the regeneration, the requirements for their development change as the seedlings grow in height and their roots explore the soil profile (Callaway & Pugnaire, 2007). Figure 4 shows the values of mean annual increments in height (MAIh) for every level of precipitation and gap size. These values were estimated by a mixed ANCOVA model, in which sapling height was included as a co-variable (López Bernal, unpublished data). During the first 20 years since the gap opening, in the sites with higher levels of precipitation, the dominant seedlings located in the central sector of the gap showed higher growth in larger gaps ($p = 0.03$ and $p = 0.045$ for 0-10 and 10-20 years respectively). By contrast, in sites with lower average annual rainfall, there is a tendency for smaller gaps to show higher height growth, especially during the first 10 years.

Summarizing, we can infer that during the first 20 years since the opening of the gaps, the growth of regeneration is determined by light availability in moist sites and water availability in dry sites, with average values of about 22 cm/year and 15 cm/year, respectively, showing a decrease in the differences due to rainfall with the gap age.

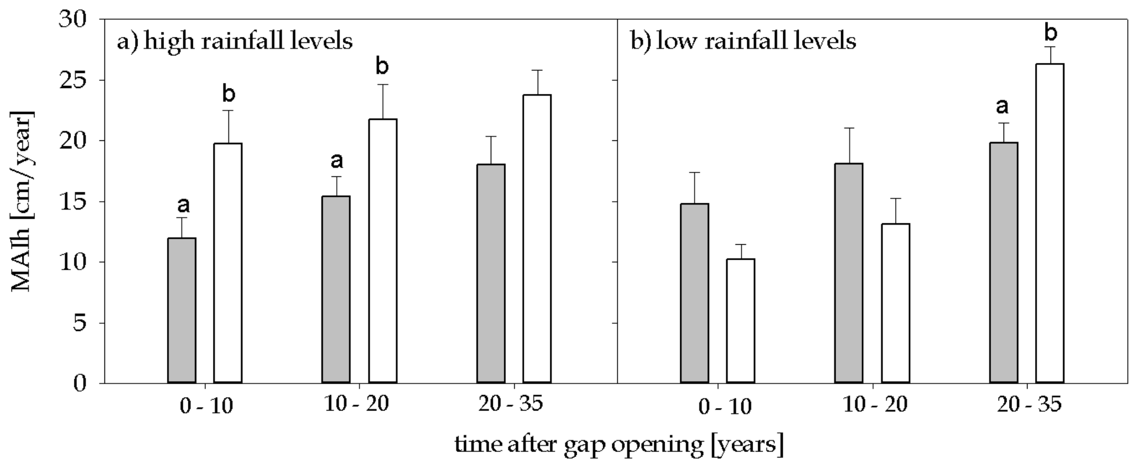

Fig. 4. Mean annual increase in height (MAIh) for each precipitation level and gap size class (small gaps = gray bars, large gaps = white bars) along a 35 years cutting cycle. Different symbols indicates significantly different means (Fisher's posthoc test, α = 0.05).

Moreover, the growth data for gaps between 20 and 35 years old shows that at this stage the saplings grew independently of the availability of water, at least enough to keep differences between the sites with higher and lower levels of precipitation. These observations are consistent with several studies which reported that the balance between facilitation and competition interactions usually tends toward negative values when the "facilitated" individual, approaches the age of maturity (for a comprehensive review of this phenomenon see Callaway & Pugnaire, 2007, pp 240).

3.3.3 Saplings density

Density of seedlings in gaps is often highly variable. During the first years after the creation of gaps, density is strongly determined by the availability of water in the soil, so in places with water deficit during the summer, a greater density is usually observed in the shady gap borders or in microsites caused by the presence of coarse woody debris (Heinemann & Kitzberger, 2006). However, with the subsequent development of the seedlings and the processes of mortality, linked to competence or because of the small disturbances that occur within the gaps (such as total or partial collapse of one of the trees limit), these patterns are lost. For example, it has been observed that in gaps between 20 and 35 years old, significant differences in saplings density between different parts of the gap are not detected (Figure 5, Lopez Bernal et al. Unpublished data). On the other hand, considering only the central part of the gap, there is also great variability, which prevents detect possible influences of gap size or rainfall levels.

3.4 Lateral crown growth of trees bordering the gap

The average closing rate of gaps due to lateral growth of bordering trees is approx. 19 cm/year. This is high enough so that can occur the gap healing before that regeneration can reach the upper stratum (López Bernal et al. unpublished data).

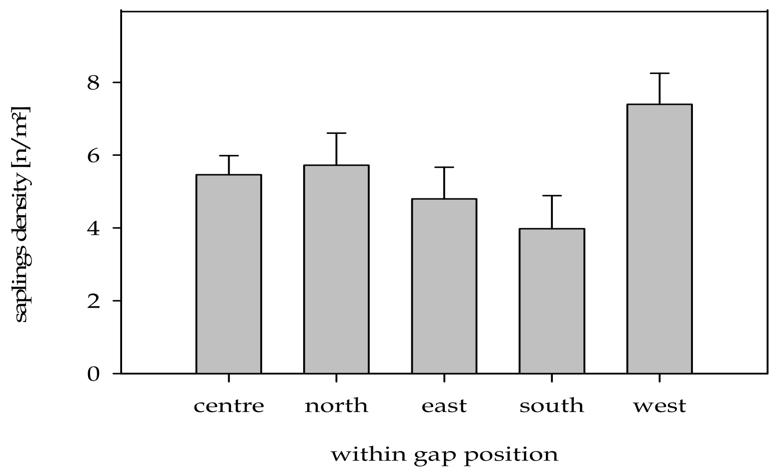

Fig. 5. Average seedling density at different locations within 20-35 years old gaps.

Figure 6 represents the two mechanisms of gap healing (i.e. lateral crown growth of bordering trees and regeneration height growth), indicating the time needed for them to close gaps of different sizes (ordinates). In general, larger gaps require more time for healing by crowns growth and less time for healing by regeneration growth. Thus, the curves representing each mechanism are cut at the point corresponding to the gap size that allows the regeneration to reach the canopy just before the crown growth of bordering trees prevents it. It can also be inferred how long will it take for this to happen (abscissa).

Thus, the ① arrow represents the development of a gap in a humid stand, where it is feasible to open a gap with D/H between 1.5 and 2, favoring the seedlings installation and saplings development until its final height. Moreover, the ② and ③ arrows represent the development of a gap in a xeric stand, where it is necessary to open smaller gaps to ensure seedling establishment, but after a 35 years cutting cycle is necessary to enlarge the gap to prevent the healing by the lateral crown growth of bordering trees.

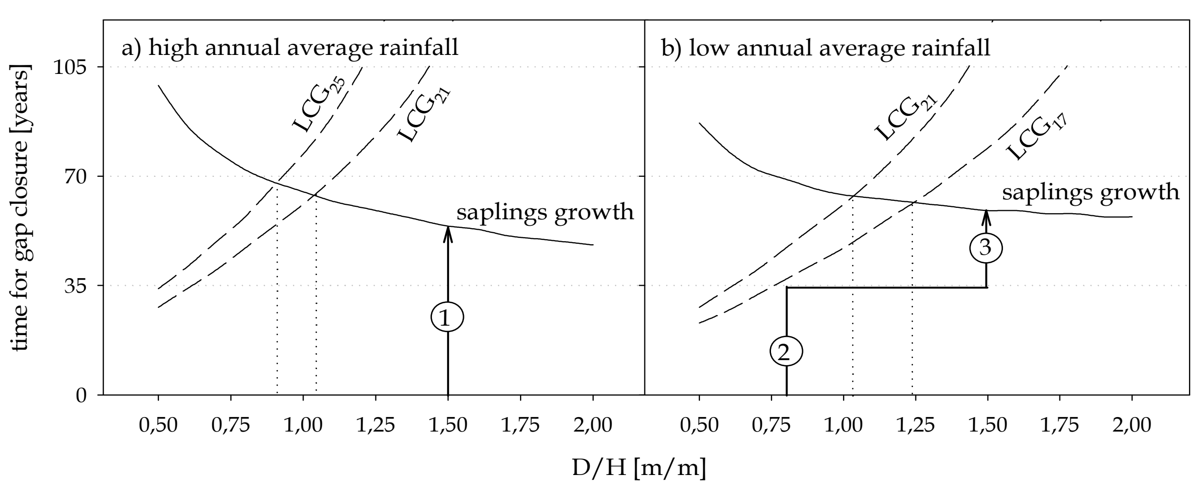

Fig. 6. Necessary time to close gaps of different sizes (D/H) through the height growth of regeneration (solid lines) or the lateral crown growth of the bordering trees (dashed lines) at sites with different dominant height ($LCG_{17,\ 21\ \&\ 25}$). For references of the arrows ①, ② and ③ see above.

3.5 Adaptability of GSS to *N. pumilio* natural dynamics

Managing an uneven-aged forest through selection cuts implies a continuous production of wood, so that the remaining stand becomes very important. The regeneration which is established after each harvest and the remaining young trees with timber potential will be the wood source in the coming rotation cycles, so that they constitute the basis for the system´s sustainability (Antequera et al., 1999). That is why post-harvest mortality is a factor of utmost importance.

The harvested stands are affected in their stability, according to the original structure, topography and the type of intervention (Burschel & Huss, 1997, Smith et al., 1997). This weakening effect leads to the fall of trees after the harvest, phenomenon that can seriously affect the quality of the remnant stand. In Tierra del Fuego the windfalls occur even in virgin forests (Rebertus et al., 1997), which poses a logical doubt on the real possibility of implementing this system.

Bava & López Bernal (unpublished data) found that there is no relationship between the manner in which a tree dies (uproot, break or standing death) and the harvest intensity, site quality or stand structure. However, a higher percentage of uprooted trees were observed. The stems that break down correspond to well-anchored individuals, when the wind burden cannot be transmitted by the trunk to the root and soil (Abetz, 1991), or to trees affected by rots, as frequently happens in lenga forests. The uprooting happens when the wind burden is transmitted to the root but cannot be transmitted to the soil (Abetz, 1991). In lenga forests of Tierra del Fuego this can occur in shallow soil stands, when the root system grows superficially (Bava, 1999).

The post-harvest mortality is not significantly related with the percentage of extracted BA. However, when we compare between different stand structures, we note that uneven-aged forests presented minor damage to the even-aged, while the bi-stratified stands presented intermediate damages (Figure 7, ANOVA $p = 0.014$). These differences may have their origin in phenomena observed at two separate scales: in a stand-scale, uneven-aged forests present a more gradual decline of wind speed from the forest canopy up to the understory, allowing a better adaptation mechanics of trees to wind and giving more stability to the whole (Gardiner, 1995). On the other hand, at the individual-level, Wood (Wood, 1995) observed that the tree develops stems only with the resistance needed to support regular wind intensities, growing adaptively. In this way, the increased heterogeneity of uneven-aged stands would provide more opportunities for development of more resistant individuals, which remain after the harvest, and that play a very important role in the stand stability (Burschel & Huss, 1997, Mattheck et al., 1995, Smith et al., 1997). The structural alterations produced by the harvest causes greater exposure of individuals to wind, but in a different way for each one, and would depend on other factors besides the size of the gaps, the h/d value, the felling damages, and homogeneity of the remnant forest.

We have mentioned the importance of the forest stability for sustainability in a selection cuts system, where the productive potential for future interventions is represented by individuals which remain after harvest. In this sense, the results indicate that the post-harvest losses are a limiting factor for the implementation of this system, and which would only be advisable by uneven-aged forests. Moreover, the system success also depends on the conscientiously choosing of the trees to cut, and to carry out the harvest operations carefully. If these conditions are present, the group selection system would be a viable alternative, which would maintain the forest cover, with a cutting cycle of approximately 35 years and extracting a timber volume equivalent to the historical average.

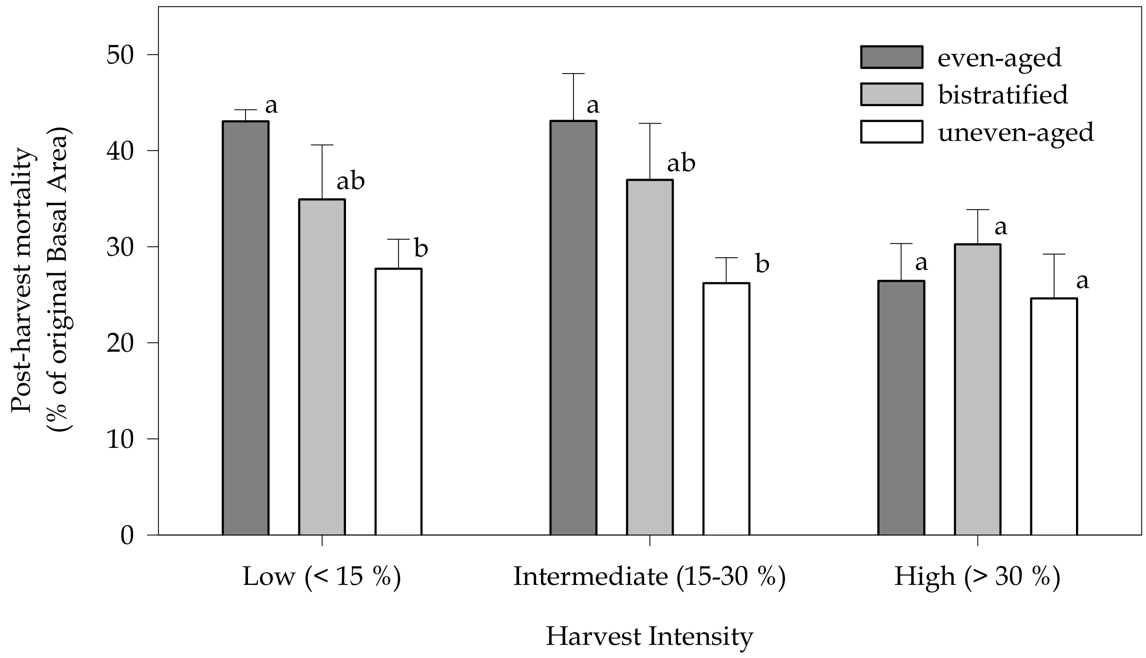

Fig. 7. Post-harvest mortality by harvest intensity and original stand structure. Different symbols indicate significantly different means (Tuckey's posthoc test, α = 0.05).

3.6 Case study

In this section we present the main results of three trials located in the province of Tierra del Fuego where group selection cut were applied (Bava & López Bernal, 2006). These were implemented in uneven-aged stands with trees from at least three generations and where it was possible to identify the natural process of gap dynamics.

The tree marking was made in November 2003 and the harvest in February 2004, which consisted of felling and bucking of complete stem. During the tree marking, DBH, height and average sawing bole diameter of all marked trees was recorded. At the same time, it was recorded if the tree was felling to open a new gap, to release existing regeneration, or to optimize the growth of young trees. The felling, skid trails opening and bole extraction were carried out in the same campaign. In all three essays harvest tasks were performed by the same team, using directional felling techniques for tree felling and a skidder for bole extraction.

After the tree marking, a forest inventory was carried out in each of the three trials. Measurements were performed in 300 m² circular plots spread over a 50 m x 50 m grid, representing a sampling intensity of 1.2 %. In each plot, the DBH of all individuals over 10 cm was measured, recording their sawing potential (indicating the length and medium diameter of the logging portion of the bole), and if it had been marked, whether for felling or girdling.

All three trials represented intermediate quality sites, located on gentle slopes and possessing uneven-aged structures. The trial 1 had about 360 tree per ha, a BA of 44 m²/ha and a high proportion of overmature trees (DBH over 60 cm) with a low sawing quality. Essay 2 had 430 trees per ha, a BA of 49 m²/ha and presents a high proportion of trees with a DBH between 40 and 60 cm. Essay 3 had 498 trees per ha, a BA of 52 m²/ha with a high proportion of trees with DBH between 30 and 50 cm (Figure 8).

Timber stock differences between trials derived in great differences on tree marking. The marking intensity, expressed as a percentage of the original AB, was considerably higher in trial 3 than in trial 1 and 2, proportionally to the differences in timber stock. Moreover, differences in the stand structures generated varying amounts of felled and girdled trees (Table 1).

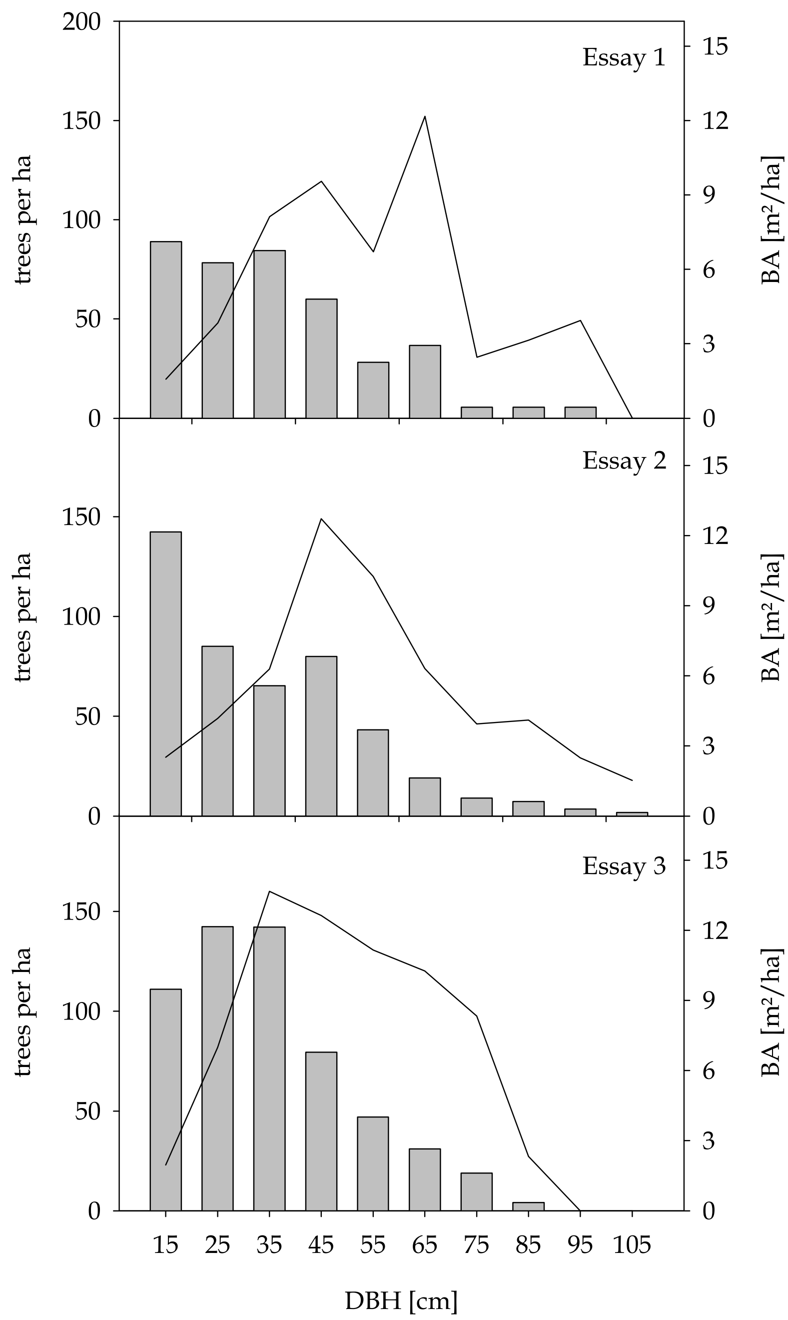

Fig. 8. Diametric frequency distribution for each trial.

The number and size of gaps or patches that were intervened were also different. In the first two trials, which showed similar productions, about 11 gaps per ha were opened by felling or girdling between 2.5 and 3 trees. In trial 3, with a much higher timber production, the number of opened gaps was also bigger, mainly due to a high proportion of patches with young trees (DBH between 20 and 40 cm), while the number of trees per gap increased to 3.4 (Table 2). Moreover, the proportion of gaps or patches with *gap opening*, *gap release* or *patch thinning* interventions differ between essays, pointing out differences in the original stand structures.

Although the three trials were conducted in similar structures, there were significant differences (up to 100%) in the amount of lumber in each. This was reflected in the number of gaps per hectare, but not in their size. The trial with highest harvest intensity (28% of BA) produced twice as sawtimber than the other two, mainly due to felling tending to release young pole trees. This is different from harvests in Chubut province, where the largest volume portion comes from gap opening cuts (Berón et al., 2003).

	Trees (N/ha)			Basal area (m²/ha)		
Essay	felling	girdling	Total	felling	girdling	Total
1	28.0 (87%)	4.0 (13%)	32.0	4.8 (96%)	0.2 (4%)	5.0
2	24.4 (86%)	3.8 (14%)	28.2	4.6 (85%)	0.8 (15%)	5.4
3	58.5 (75%)	19.1 (25%)	77.6	11.8 (81%)	2.8 (19%)	14.6
Mean	37.0 (81%)	9.0 (19%)	45.9	7.1 (86%)	1.3 (14%)	8.3

Table 2. Number and proportion of trees and AB marked in each essay, distinguishing between felling and girdling.

Intervention objective	Essay 1	Essay 2	Essay 3	Mean
Gap opening (N/ha)	2,0	7,6	7,3	6,7
Gap release (N/ha)	1,3	0,4	5,2	2,7
Patch thinning (N/ha)	7,3	3,2	10,2	6,9
Total gaps / patches per ha	10,7	11,2	22,8	16,4
Felled trees per gap	2,6	2,2	2,6	2,5
Girdled trees per gap	0,4	0,3	0,8	0,7
Total	3,0	2,5	3,4	3,1

Table 3. Number of interventions for gap opening, gap release or patch thinning per ha, and number of marked trees per gap in each essay.

According to the remnant structures after harvesting, all three trials are able to recover the volume of extracted timber. However, the best choices to implement a group selection system are stands like in trial 3, i.e. a forest with uneven-aged structure and with a high proportion of trees with DBH between 30 and 50 cm. These structures allow a higher proportion of "gap release" and "patch thinning" interventions, which generates a bigger timber harvest in the first cycle, leaving a high number of young trees in optimal growth conditions. The harvest intensity of this trial is very similar to the historical average for Tierra del Fuego province, at about 27% of BA (Bava & López Bernal, 2004), while is much higher than the historical mean for the province of Chubut, of about 15% (Berón, et al., 2003).

4. Conclusion

The Group Selection System is a valid alternative management system for lenga forests of Argentinean Patagonia. This system emulates one of the most common natural dynamic processes in these forests and provides optimal conditions for regeneration establishment and further development. It is especially recommended for sites with medium to low rainfall levels, where the frequency of large-scale disturbances is low and where the forest presents a natural uneven-aged structure. In Argentina, these situations mainly occur in Chubut province and in the northern part of the lenga distribution in Tierra del Fuego province, where there are already experiences with this type of management.

Moreover, the GSS is compatible with the local production system, dominated by small and medium producers, without financial or technological capacity to afford the costs of intensive harvesting or long-term silvicultural investments. The GSS is adapted to these systems by splitting the turnover age in shorter cutting cycles, giving a more flexible cash flow to these systems, and by allowing that in a single intervention, different silvicultural practices can be carried out. This last point is also an advantage for state control agencies by allowing them to condition the timber extraction to the implementation of other practices that do not generate immediate benefits, such as thinning or regeneration release.

Finally, to ensure the sustainability of forests managed by the GSS, there are at least two aspects that should be especially considered. The first one is that the forester must make his proper interpretation of the natural forest dynamics to decide whether it is feasible or not the implementation this system. The second one implies that to maintain the productive potential for future interventions, logging activities should be conducted with special attention to the remaining forest, using low-impact harvesting technologies.

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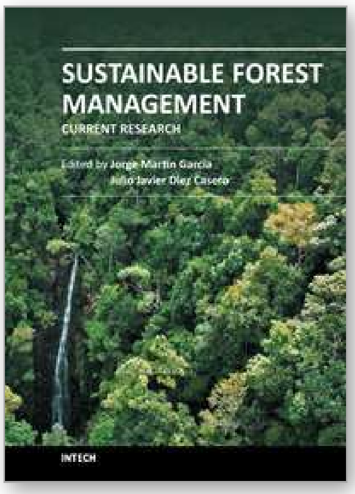

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Sustainable forest management (SFM) is not a new concept. However, its popularity has increased in the last few decades because of public concern about the dramatic decrease in forest resources. The implementation of SFM is generally achieved using criteria and indicators (C&I) and several countries have established their own sets of C&I. This book summarises some of the recent research carried out to test the current indicators, to search for new indicators and to develop new decision-making tools. The book collects original research studies on carbon and forest resources, forest health, biodiversity and productive, protective and socioeconomic functions. These studies should shed light on the current research carried out to provide forest managers with useful tools for choosing between different management strategies or improving indicators of SFM.

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821