Chapter 8
Silviculture of Temperate Mixed Forests from South America

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Abstract Temperate mixed forests of South America extend mostly from 33°S to 55°S latitude and between the Pacific Ocean and the Patagonian Steppe east of the Andes Mountains. West of the Andes in Chile, in a high precipitation regime, the most diverse and large forest types develop. These forests simplify in composition and structure toward the south due to reductions in temperature and in a more pronounced manner east of the Andes, in Argentina, because of an abrupt reduction of the precipitations. Descriptions of the main temperate mixed forest types of Chile and Argentina are presented, focusing on ecologic issues and management proposals. For Chile, we address in this chapter secondary and old-growth forests of the evergreen forest type and secondary forest dominated by *Nothofagus* spp. For

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Argentina, we discuss the case of mixed *Nothofagus* spp. forests in the old-growth phase and of *N. dombeyi* and *Austrocedrus chilensis* mixed forests in the transition from the mesic to the xeric zone. There is a strong ecological and silvicultural base knowledge for the sustainable management of these mixed forests. However, with a few exceptions, its broad application is a pendant matter in both countries.

8.1 Introduction

In South America, temperate forests occur between 33°S and 55°S latitude, at the southernmost tip of the continent (Fig. 8.1). They represent a biogeographic isolated forest island, surrounded by different physionomic and taxonomic types of vegetation (Armesto et al. 1997). The composition and distribution of these forests are regulated by environmental longitudinal and latitudinal gradients. The strong W-E precipitation gradient is mostly due to the Coastal Mountain range in Chile and the Andes Mountain range between Chile and Argentina, both acting as obstacles for the humid winds coming from the Pacific Ocean. The climate is characterized for its moderate to low temperatures that decrease with latitude. Precipitation increases progressively from north to south, being below 300 mm year^{-1} in the so-called Mediterranean region in Chile, above 35°S, and 3000–5000 mm year^{-1} on the western slopes of the Coastal and Andes Mountains south of 38°S, where humid air masses come from the Pacific Ocean. East of the Coastal Mountains in the intermediate depression (40°S), the precipitation diminishes to 2000 mm year^{-1}. On the rain shadow of the Andes, 50 km east from them, precipitation drops dramatically down to around 500 mm year^{-1} in the ecotonal area between the forest

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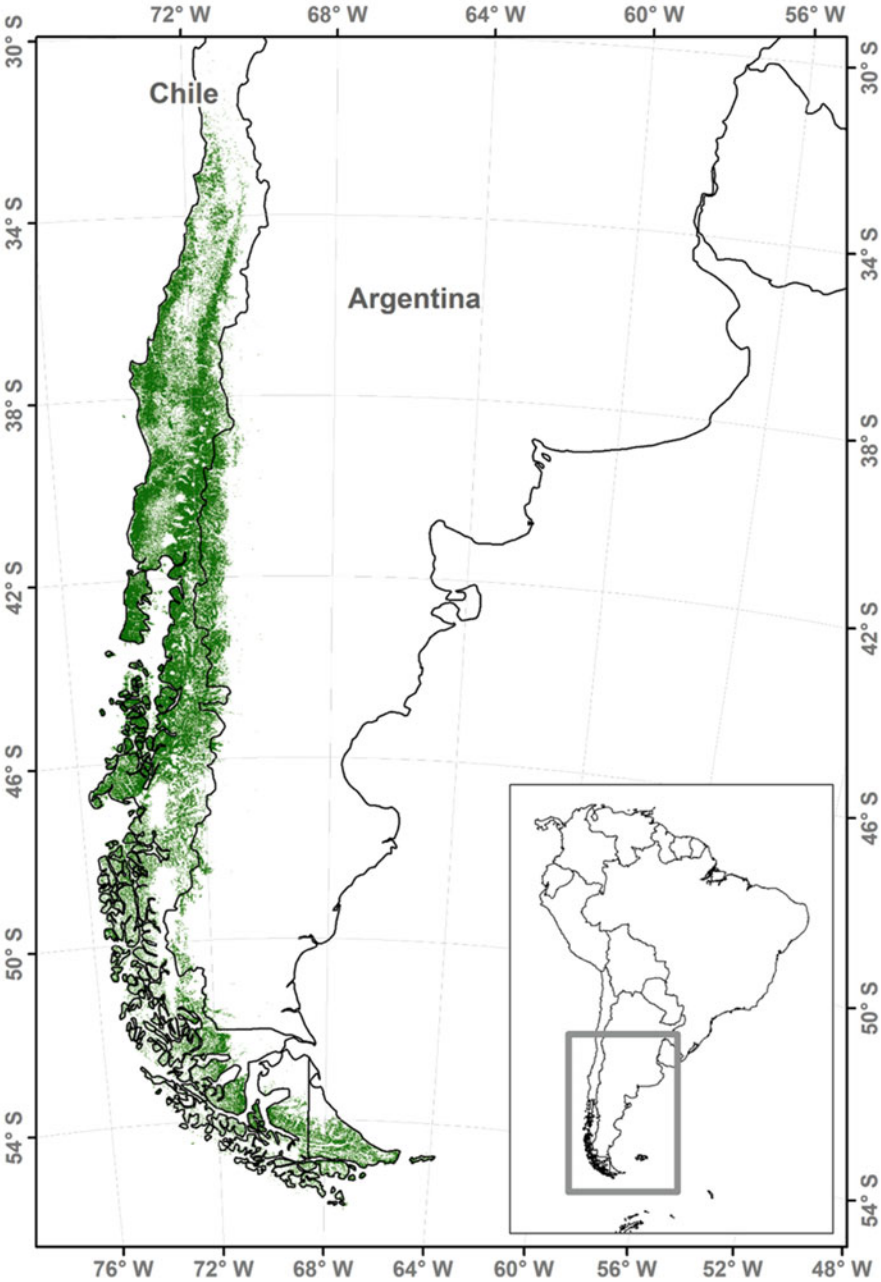

Fig. 8.1 Map of temperate forest of South America from Chile and Argentina. (Extracted from Hansen et al. 2013)

and the steppe and faster east continue to decrease in the Patagonian steppe. Most of this ecotone territory is located within the Argentinean borders, but farther south part of it falls within Chilean territory. These precipitation differences result in the occurrence of mixed and pure forests with high diversity of species, mainly west of the Andes in Chile, north of 47°S. Toward the south, forest composition and structure become simpler, mainly east of the Andes, in North Patagonia, Argentina (Veblen and Alaback 1995). Glaciers have modeled the landscape, and most soils are volcanic, originated from recent andesitic volcanic ashes.

Several forest types are found in the region. West of the Andes, in Chile, between 33°S and 37°S, there is the Mediterranean sclerophyll forest, and between 37°25′S and 43°20′S, it is found a temperate rain forests called Valdivian. Between 43°20′S and 47°30′S, there is the Nord Patagonian rain forest, and further south the Magellanic rain forest occurs (Veblen and Alaback 1995). At relatively high elevations along the whole region, pure *Nothofagus pumilio* subalpine forests are present, and low *N. antarctica* forests occur on a variety of sites, mainly on those poorly drained, cold valley bottoms and the ecotone. East of the Andes, in Argentina, along the strong precipitation gradient between 37°30′S and 55°S, the Patagonian Andes or subantarctic *Nothofagus* forests are found. They are mainly pure stands of *Nothofagus* spp., dry forests, and woodlands, limiting with grasslands and bushes of the Patagonian steppe (Veblen et al. 1996).

Different natural disturbances, such as volcanism, earthquakes, landslides, snow avalanches (in Chile), and wildfires, massive bamboo flowering, and windstorms (in Chile and Argentina), have modeled these forest ecosystems (González et al. 2014). However, the distribution and current structure of the forest types have been strongly affected by anthropogenic fires since the middle 1800s, mainly during the European settlement, because fire was used as a tool to transform forests into agricultural and cattle-raising land (Willis 1914; Otero 2006). During the last century, part of the forest regenerated naturally as secondary (Lara et al. 2003; Veblen et al. 2003). In Magallanes and Tierra del Fuego (47–55°S), wind blowdown is the main disturbance (Rebertus et al. 1997).

Forests are more mixed west of the Andes, in Chile. The most diverse species community forests occur in the dry north, between 37 and 38°S (Bannister et al. 2012), but the evergreen forest, located between 38°S and 47°S, holds the greatest tree species richness (Donoso et al. 1998; Donoso 2015). Half of the 13.6 million ha of Chilean native forests are mixed. The largest broadleaf pure forest types are *Nothofagus pumilio* and *Nothofagus betuloides* (despite the ecotone both species grow together). The conifer forests are *Fitzroya cupressoides*, *Araucaria araucana*, *Pilgerodendron uviferum*, and *Austrocedrus chilensis*, although they form mixed stands on certain sites. Among the Chilean 6.84 M ha of mixed forests, the main types are evergreen (4.13 M), *Nothofagus obliqua-N. nervosa-N. dombeyi* (1.47 M), *N. dombeyi-N. nervosa-Laureliopsis philippiana* (0.56 M), Mediterranean sclerophyll (0.47 M), and *N. obliqua-N. glauca* (0.21 M) (CONAF 2013).

East of the Andes, in Argentina, 95% of the 3.29 M ha of temperate forests are pure (CIEFAP-MAyDS 2016). The *N. pumilio* and *N. antarctica* forests stand out from the rest because they occur along the whole latitudinal range (37–55°S). Up north, *A. araucana* coniferous forest occurs at medium latitudes, *N. dombeyi* grows on mesic sites, and the *Austrocedrus chilensis* forest occurs on mesic as well as on xeric environments. These three species grow in monospecific as well as in two-species stands, with low participation of one of them (<20% of the canopy cover), covering 427,000 ha (CIEFAP-MAyDS 2016). Mixed forests add up to 284,000 ha, and they are defined as those composed by two or more species, given that none of them provides more than 80% of the canopy cover (Bravo-Oviedo et al. 2014). Evergreen and mixed *Nothofagus* stands are basically mixed ingression forests coming from the western side of the Andes were they prosper. There are also mixed post-fire woodlands of forest sprouting species like *N. antarctica*, *Lomatia hirsuta*, *Schinus patagonicus*, and *Maytenus boaria*, which are seral stages of the high *A. chilensis* and/or *N. dombeyi* forests (Veblen et al. 1996; Kitzberger 2012; Rusch et al. 2016). There is also mixed forest of *A. araucana-N. pumilio* and other in small areas with other tree species combinations, such as *A. araucana-N. antarctica* and *A. chilensis-N. obliqua*. The composition of the mixed stands located among the pure depends mainly on the type of disturbance that originated the stand, climatic conditions during the establishment period and species growth rates within the niche (Kitzberger 2012; González et al. 2014).

In Chile, most adult forests are mixed, as well as 3 M ha of secondary forests, and thus mixed stand silviculture should be the essential tool to apply (Donoso et al. 1993b, c; Lusk and Ortega 2003). Secondary forests can be managed focusing on one, two, or several strata, which imply getting involved into uneven-age management or multiage silviculture (Nyland 2003; Donoso 2013). Encouraging mixed forest silviculture is crucial for ecosystem conservation, and since these forests are highly productive, social and economic benefits can be expected as well (Donoso 2015).

In Argentina, silviculture has been developed mainly for the dominant species of each forest type (Bava 1999; Loguercio 1997; Loguercio et al. 2018; Martinez Pastur et al. 2013; Peri et al. 2016), with the exception of the mixed *Nothofagus nervosa-N. obliqua-N. dombeyi* forest type at Lanín National Park, at 40°S, (González Peñalba et al. 2016; Sola et al. 2015). However, east of the Andes, mixed forest management should be given more attention considering that since environmental resources are limited, forests are more susceptible to climate change effects, which render stand adaptation and resilience as two main subjects.

Hereafter, the state of the art of the silvics of four mixed forest types of the region is presented, two of them for the rain forest, west of the Andes, and the other two for mesic-xeric sites, east of that range. On the rain forest, old-growth evergreen stands are proposed to manage it as multiaged, and secondary forests have been managed as even-age with one or two strata. On a mixed *Nothofagus* forest, tending cuttings have been applied at the stem exclusion stage (sensu Oliver and Larson 1996), in stands with and without shade-tolerant species in the understory. On the eastern side of the Andes, on even-aged mixed *Nothofagus* forests, a shelterwood system has been applied, and at last pure *A. chilensis* stands with the presence of *N. dombeyi* regeneration are being converted into a mixed *N. dombeyi-A. chilensis* forests.

8.2 Evergreen Forests

8.2.1 Distribution and Ecology

The so-called evergreen forest type (EFT) is the largest in Chile (4.3 million ha; www.sit.conaf.cl). The EFT is comprised of a great variety of community types having two common characteristics: (1) the dominance of a variable number of evergreen species, including some Podocarpaceae conifers, and (2) their occurrence under a climate of high pluvial precipitations throughout the year (Donoso 2015). It is present from 38° to 47°S in Chile, mostly concentrated in the Coastal Cordillera, the western slope of the Andean Cordillera, and the Island of Chiloe (Fig. 8.1), where forests have the potential for management, but also in the northern portion of the archipelago. They grow below 1000 m a.s.l. in the northernmost latitudes and at elevations of less than 300 m in the southernmost latitudes. The ample geographical range where this forest type develops implies a variation in temperature and precipitation from north to south, in addition to many variations in site fertility. Andean forests are affected by large-scale disturbances (landslides, fires due to volcanic eruptions, etc.), while forest dynamics in the Coastal range is shaped by small-scale disturbances (e.g., windthrow and canopy gaps) (Veblen 1985; Veblen et al. 1981). Soils in the Andes are of medium to high fertility, while in the Coastal range they are of poor fertility (CIREN 2001), but better at lower elevations (Donoso and Nyland 2005).

The EFT has this name because all tree species, mostly hardwoods, are evergreen. These species are listed in Table 8.1, including some life history traits. Long-lived pioneers may reach emergent positions (40–50+ m; Parada et al. 2003) in mature or old-growth forests, such a *Nothofagus dombeyi*, *N. nitida*, *Weinmannia trichosperma*, and *Eucryphia cordifolia*. Canopy species (25–35 m) include two conifers (*Saxegothaea conspicua* and *Podocarpus nubigena*, although also *Podocarpus nubigena* may be found at lower elevations) and *Laureliopsis philippiana*, *Dassyphyllum diacanthoides*, *Drimys winteri*, *Aextoxicon punctatum*, and *Persea lingue*. Lower canopy tree species (<20 m) include mostly those of the Myrtaceae family (*Amomyrtus luma*, *Amomyrtus meli*, *Luma apiculata*, *Myrceugenia planipes*), of the Proteaceae family (*Lomatia ferruginea*, *Lomatia dentata*, *Gevuina avellana*, and *Lomatia hirsute*), and *Caldcluvia paniculata*. Some of the mentioned Proteaceae plus *Embothrium coccineum* can act as pioneers as well, but they are relatively short-lived (Table 8.1). Overall, this forest type can have more than 20 tree species in a single forest stand, but of course, this is highly variable according to site productivity that is determined by geographical location.

Table 8.1 Main tree species of the evergreen forest type and some of their life history traits

Species	Family	Life-span[a]	Tolerance to shade	Soil fertility requirements
Nothofagus dombeyi	Nothofagaceae	Long	Intolerant	Low
Nothofagus nitida	Nothofagaceae	Long	Midtolerant	Low
Weinmannia trichosperma	Cunoniaceae	Long	Intolerant	Low
Eucryphia cordifolia	Cunoniaceae	Long	Midtolerant	Medium
Laureliopsis philippiana	Monimiaceae	Long	Tolerant	High
Dassyphyllum diacanthoides	Compositae	Long	Midtolerant	Medium
Saxegothaea conspicua	Podocarpaceae	Long	Midtolerant	Medium
Podocarpus nubigena	Podocarpaceae	Long	Tolerant	Low
Podocarpus salignus	Podocarpaceae	Long	Midtolerant	High
Drimys winteri	Winteraceae	Medium	Midtolerant	Low
Aextoxicon punctatum	Aextoxicaceae	Long	Tolerant	High
Persea lingue	Lauraceae	Long	Tolerant	High
Amomyrtis luma	Myrtaceae	Long	Tolerant	Medium
Amomyrtus meli	Myrtaceae	Long	Tolerant	Medium
Luma apiculata	Myrtaceae	Medium	Tolerant	Medium
Myrceugenia planipes	Myrtaceae	Medium	Tolerant	Low
Caldcluvia paniculata	Cunoniaceae	Short	Midtolerant	High
Embothrium coccineum	Proteaceae	Short	Intolerant	Low
Lomatia ferruginea	Proteaceae	Short	Midtolerant	High
Lomatia dentata	Proteaceae	Short	Tolerant	Medium
Lomatia hirsute	Proteaceae	Short	Intolerant	Low
Gevuina avellana	Proteaceae	Short	Intolerant	Low

References: Donoso (2015), Lusk et al. (1997), and Gutiérrez and Huth (2012)
[a]Long >200 years, medium 100–200 years, short <100 years

8.2.2 *Silviculture in Secondary Forests*

Even-aged secondary forests are dominant in most regions at low and medium elevations in south-central Chile, where past fires for land conversion to agriculture were common, sometimes combined with selective harvesting (Otero 2006; González et al. 2015), leading to open areas that were invaded by pioneer tree species or by a mixture of tree species. In the ample region of the EFT, it is possible to find a variety of secondary forest, but the most common are those dominated by pioneer species such as *N. dombeyi* or by *D. winteri*, but secondary forests dominated by *W. trichosperma* or by *E. cordifolia* may also occur. However, it is also very common to find secondary forests that are a mixture of species of different shade tolerances that have developed following selective harvesting and fires

Fig. 8.2 Different types of common secondary forests within the EFT. (**a**) *Drimys winteri*; (**b**) *Eucryphia cordifolia*; (**c**) *Nothofagus dombeyi*; (**d**) *Mixed*. (Photographs P Donoso)

(González et al. 2015). Some are shown in Fig. 8.2 and typical diameter frequency distributions represented in Fig. 8.3. Although some of these secondary forests are clearly dominated by pioneer species, all correspond to a mixture of tree species. The degree of species mixture in these secondary forests may also be determined by the successional stage of the forest, with a greater likelihood of increasing mixture in stands in the "understory reinitiation stage," as compared to stands in the "stem exclusion stage" of stand dynamics (sensu Oliver and Larson 1996).

These secondary forests in Chile are now on average between 60 and 100 years (e.g., González et al. 2015), passed the age of fastest growth for individual trees (during the two or three first decades of development in initially dense secondary forests), but are experiencing high productivity rates (as high as 15–20 m^3 ha^{-1} $year^{-1}$ Donoso et al. 1999; Navarro et al. 2011), although on average closer to 8–10 m^3 ha^{-1} $year^{-1}$ (Donoso 2015). One major question is whether mixed-species secondary forests are more productive than their analogue pure species secondary forests, but the additive basal area reported by Lusk and Ortega (2003) for mixed-species *Nothofagus*-dominated secondary forests suggests that additive productivity might also occur in these mixed-species forests. In any case, foresters should manage them accordingly. This however depends on whether the expected silvicultural system is for an even-aged one-stratum forest or for a two-stratum forest (even-aged or two-aged) or converted to an uneven-aged forest. In this section we will provide examples of secondary forests managed as even-aged one- or two-stratum forests, with examples for mixed-species forests and for *D. winteri*-dominated forests in the stem exclusion stage. The case of *N. dombeyi*-dominated forests within the evergreen forest type is also interesting, but since it is given in another section of this chapter, we will not deal with it here.

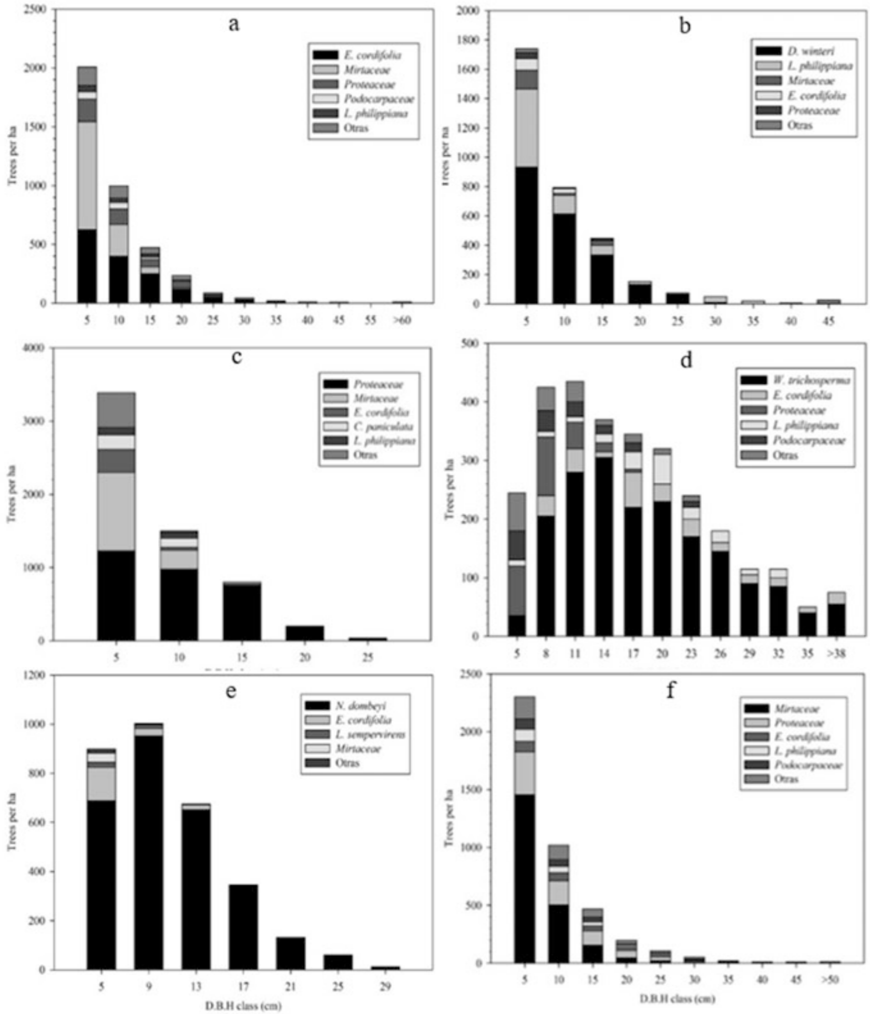

Fig. 8.3 Representation of the diameter frequency distributions of six different mixed-species secondary forests dominated by different species that belong to the EFT. (**a**) *E. cordifolia*; (**b**) *D. winteri*; (**c**) *E. coccineum*; (**d**) *W. trichosperma*; (**e**) *N. dombeyi*; (**f**) Mixed. The lower limit for each diameter class is shown, but notice that they are variable (from 3 to 5 cm). Also the y-axes vary due to the great differences in numbers of trees among some stands

8.2.2.1 Mixed-Species Evergreen Forest

Mixed-species evergreen forest is the result of a mixture of regeneration strategies from propagules in a forest stand, including stump and root sprouts, advanced regeneration, and buried or newly dispersed seeds. As a consequence, these forests have short- and long-lived pioneer species (shade-intolerant and midtolerant), canopy species (midtolerant or shade-tolerant species), and mostly low canopy shade-tolerant species. These forests can include most of the species mentioned in Table 8.1. Here we present two cases, one for forest located at 400 m a.s.l. in the Coastal range at 40°S (Llancahue; Fig. 8.3f) and another at 450 m a.s.l. in the Andes range at 42°S (Correntoso; Fig. 8.3c). The forest in Llancahue is 70 years old (González et al. 2015) and that in Correntoso 26 years old (Schlegel 2014), both in the stem exclusion stage. Both forests have a high proportion of their tree density and basal area concentrated in Proteaceae species (*G. avellana* in Llancahue and *E. coccineum* in Correntoso), in addition to a mixture of midtolerant and shade-tolerant species. In Correntoso *E. coccineum* is going through an accelerating process of mortality and declining diameter growth (6 mm after reaching 10 mm per year at age 10–15, while the remaining tree species have been increasing their growth rates until reaching a plateau of 8 mm during the last years) (Schlegel 2014). While in the Llancahue forest tree species likely have a slow growth rate, there is no evidence of a major mortality of *G. avellana*. Anyhow stand development has been slower in Llancahue, with similar numbers of trees as Correntoso (close to 4000/ha), although a greater basal area (63 vs. 42 m^2 ha^{-1}).

These two cases illustrate that mixed-species secondary forests in the EFT may need early cleaning operations to reduce competition of pioneer species of rapid growth but little potential commercial value, or otherwise an early first thinning that would be mostly precommercial, unless there is a chance to use or sell some firewood. What is important in any case is that tree density must be reduced quite early to allow valuable species to have relatively high diameter rates.

In addition to defining the means to control density and composition in these types of dense and mixed forests, the challenge is to define the intensity and periodicity of future thinnings to reach a desired final mean diameter. To lower tree densities to an average of 400 trees per hectare with a mean diameter close to 35 cm at the time of final harvest, there should be probably three or four thinnings. Density control should be conducted within management zones defined by residual (after thinnings) and maximum (before thinnings) densities estimated through size-density equations or stand density diagrams (Nyland 2002).

In the case of managing only for the canopy-dominant species, for a one-story forest, most favored tree species of high potential commercial value would include some midtolerant or shade-intolerant species (Table 8.1). Therefore, these mixed forests could be managed for two or three major tree species of relatively fast growth rates if density is continuously controlled. In the case of managing for two strata, the second stratum would include mostly midtolerant and shade-tolerant species.

In these examples, following the early density control of non-valuable pioneer species, for the one-stratum management, selected species should be favored by successive crown thinnings. The starting point in these mixed stands with no previous interventions would be usually a relative density above 80% (Schlegel 2014; Donoso et al. 2014b). Considering that mortality is severe above 80% relative density in hardwoods (Nyland 2002) and thinning regimes have to balance good growth rates of individual trees with adequate stockings at the stand level for good volume growth rates, the management zone for these stands could range from 40% to 60% (but see section for *D. winteri* forests).

It could be expected that future diameter growth in these managed forests should be around 0.5 mm per year (Schlegel 2014; Navarro et al. 2017), although they may be lower if there is no early control of tree density. To reach an expected mean diameter of 35 cm for the rotation age, the time remaining would be approximately 30–50 years if the residual mean diameter following thinning was 12–20 cm. In the Llancahue forest, the first thinning rendered an average of 70–80 m of firewood (US $ 20 per meter), so that these were commercial thinnings (Donoso et al. 2014b). This may not occur in the Correntoso forest with smaller trees. The second thinning should render firewood in any case, but also some small sawlogs. A third and probably a fourth thinning would be likely needed to reduce densities to 300–500 trees per ha. A final shelterwood cut should be used to favor regeneration of this group of midtolerant tree species (maintain a tree cover that prevents regeneration of the pioneer Proteaceae species) and should be conducted to harvest large proportions of veneer timber.

A two-stratum management would require a mixed thinning method, with a reduced density of the upper canopy layer that would allow more light to penetrate to the second strata. In this case, the idea would that once the upper layer reaches the expected 35 cm in mean diameter, not all trees should be harvested following an even-aged silvicultural method, but some 50 trees per hectare should be left standing to continue providing some partial shade to the more shade-tolerant species. This would then be similar to a delayed shelterwood method (Nyland 2002). The final cut should then be conducted when trees in the second strata reach the expected final diameter. If final diameter for this stratum is 35 cm, most likely the trees in the upper stratum will have diameters close to 50 cm. This two-stratum management then would likely make a more efficient use of the site, with a mixture of species of different tolerances, growth rates, phenology, and likely rooting pattern species (requirements for mixed-species silviculture; Kelty et al. 1992). In addition, this management scheme would probably be more economically attractive, with greater volumes harvested in trees of greater value due to their larger diameters, but this has yet to be estimated. These analyses could recommend different threshold diameters, but schemes with trees providing timber for veneer may generate a larger profit (Navarro et al. 2010).

8.2.2.2 *Drimys winteri*-Dominated Secondary Forests

Secondary forests dominated by *D. winteri* have a catastrophic mode of regeneration (clearcuts, fires, abandoned prairies) and start as highly dense even-aged communities. They usually grow on gentle slopes and even flat terrains, at elevations below 400 m a.s.l, under oceanic influences that moderate temperatures. They grow throughout and ample region from north to south (600 km; 39–43°S) and east to west (100 km from the coast to the lower Andean slopes in Chile), which illustrates the ecological plasticity of the species. Across this geographic distribution, different levels of productivity can be found for secondary forests dominated by *D. winteri*, which coupled with diverse restrictions for silviculture determine the options for defining management objectives. Also different degrees of mixtures can be found in forest stands dominated by *D. winteri*, adding another consideration for defining the prospects of management of these forests.

The best forest sites are found with increasing latitude, and particularly in the coastal zone between 41° and 44°S, and the poorest in the extreme zones of the distribution of these forests between 38 and 39°S and between 43 and 44°S, where soil moisture is lower and temperature oscillations are higher (Navarro et al. 1997).

For those forests where the main production objective is high-quality timber, and the secondary objective is the provision of services, it is possible to propose either even- or uneven-aged silvicultural systems. The high-quality timber of several accompanying species of *D. winteri* in these mixed forests, such as *E. cordifolia*, *N. nitida*, *L. philippiana*, *S. conspicua*, and *P. nubigena*, provides these alternative silvicultural systems. One-stratum even-aged management could consider only *D. winteri* and *N. nitida*, which share the main canopy in these even-aged forests (Donoso et al. 2007), while two-stratum or uneven-aged management could include most of these species, although *L. philippiana* is the one that has shown the highest regeneration abundance under the dominant tree canopies of either unmanaged (Soto and Donoso 2006) or managed (Navarro et al. 2010).

For the current state of *D. winteri*-dominated secondary forests (pole size and small sawtimber size), for more productive sites, it is needed to apply thinnings as the most important silvicultural activity, due to the high mortality rates that unmanaged forest area is experiencing (Navarro et al. 1997). In this regard, the suggested management zone for these forests is between 30% and 45% relative densities and three to four thinnings to reach stands with mostly veneer and large sawlog timber. This would happen at an age of at least 80 years with a final number of 400–500 pro hectare for a final harvest with a mean diameter of 40 cm. Density control can be guided with size-density relationships (Donoso et al. 2007) or stand density diagrams (Navarro et al. 2011) developed for these forests.

8.2.3 Uneven-Aged Silviculture in Mature and Old-Growth Forests

Little experience exists in Chile in regard to uneven-aged silviculture. This is surprising considering that there are 4.8 million hectares of mixed old-growth forests between the Maule (36°S) and the Aysén (47°S) regions in Chile (www.sit.conaf.cl). These old-growth forests are in different states of conservation, but likely most accessible ones are partially or severely high-graded. Donoso (2002) studied the potential for uneven-aged silviculture in old-growth forests of the EFT and basically proposed the convenience to use this silvicultural approach in these forests considering the dominance of midtolerant and shade-tolerant species and the multilayered and multiaged structure of these forests. He proposed residual basal areas of 35–50 m^2 ha^{-1} and final basal areas of 55–50 m^2 ha^{-1} before a new entry to the stands (mature harvest diameter at 70–80 cm). Later he implemented selection cuttings with residual basal areas of 40 and 60 m^2 ha^{-1} with the hypothesis that the ones with lower residual densities would better favor the regeneration of *E. cordifolia*, one of the most valuable species in these forests. Schnabel et al. (2017) evaluated the early effects of these cuttings upon structure and composition of these forests and concluded that these cuttings maintained most of the attributes of old-growth forest range, but especially the height range, which were reduced in their higher limits mostly in the lower density cuttings. While regeneration has not been evaluated yet, it seems to be developing well for all most important species (e.g., *D. winteri*, *Podocarpus saligna*, *A. punctatum*, *L. philippiana*) but *E. cordifolia* suffers a lot of browsing from domestic cattle (personal observation PJ Donoso). These species have low diameter growth rates when unmanaged (from 1 to 4 mm $year^{-1}$), but it is expected that they should at least double their growth rates. If that was the case, Donoso and Pilquinao (2013) estimated that cutting cycles for these forests with residual densities of 40 m^2 ha^{-1}, final densities of 55 m^2 ha^{-1}, and mature harvest diameters of 70–80 cm should be of 14–15 years, instead of 5 years that the current law for "selective" harvesting allows in Chile.

8.3 "A Close-to-Nature" Management Concept for Second-Growth Mixed Nothofagus Forests in South-Central Chile

8.3.1 Distribution and Ecology

Among natural forests, second-growth mixed *Nothofagus* forests dominated by *N. obliqua*, *N. alpina*, and *N. dombeyi* of south-central Chile are important for timber production because of their high wood quality and their accessible location in the most productive sites of south-central Chile (Salas et al. 2016). The current distribution of these forests is mainly the result of natural succession after intensive harvesting or abandonment of agricultural land.

The first silvicultural regulation for second-growth *Nothofagus* forest management was introduced by the Chilean National Forest Corporation (CONAF) in 1993 and was based on minimum stocking requirements for thinning. In the following decades, several stocking diagrams were developed, following Gingrich (1967), to support thinning operations. They generally lead to a simplified forest structure (Gezan et al. 2007; Müller-Using et al. 2012). The present contribution is thought to be a complement to these numerical tools, proposing a "close-to-nature" silvicultural concept based on the actual knowledge of the natural dynamics of *Nothofagus* species.

South-central Chile is frequently object of catastrophic natural disturbances such as earthquakes, volcanism, and strong storms, among others. After the occurrence of a disturbance, ecological succession begins with the establishment of pioneer species (Veblen et al. 1980). In the absence of catastrophic disturbances, the natural succession tends toward very diverse forests composed of shade-tolerant species (Brun 1975; Burschel et al. 1976). The secondary forests described here may either be pure or mixed in various proportions of the deciduous *N. obliqua* and *N. alpina* and the evergreen *N. dombeyi*. Depending on the successional stage, other evergreen broadleaf species are generally present in these forest stands, including *Eucryphia cordifolia*, *Laurelia sempervirens*, *Laureliopsis philippiana*, *Persea lingue*, and *Aextoxicum punctatum* (Grosse and Quiroz 1999; Grosse et al. 2006; Elgueta 2013). As a component of old-growth evergreen rain forests, these species have been regarded as commercially valuable, but in the actual state of secondary forests, they rarely are considered as an object of silvicultural interest, because their lower growth rates in the initial states are under the dominant *Nothofagus* stratum.

Assessment of Area, Species, Composition, and Structural Parameters

To characterize the second-growth forests, in 2011 the Chilean Forest Research Institute (Instituto Forestal, INFOR) collected data based on a regional forest inventory design. The area included was the extension covered by mixed second-growth stands of *N. obliqua*, *N. alpina*, and *N. dombeyi* between 36° and 40°33′S (Bio Bio, Araucanía and Los Ríos Region), representing a total area of 989,960 ha. The forest inventory was based on a systematic sampling grid of 1 km by 1 km. This grid size considered the fragmentation of the resource in coastal areas and the Central Valley. Each node of the grid within the polygons defined as second-growth forests of *N. obliqua*, *N. alpina*, and *N. dombeyi* presented a potential sampling point. For the final sample, a random selection resulted in 200 sampling units. Each cluster contained three 500 m^2 circular plots (Müller-Using et al. 2012; Bahamondez and Thomson 2016).

Using the data gathered in the forest inventory, we generated estimates of mean tree density, mean basal area, gross and net volume, and quadratic mean diameter (QMD) (Table 8.2).

In addition to the general descriptors, the samples were classified according to their structure in order to identify the most frequent situations and to propose silvicultural models for them. For this purpose, the 200 samples of the inventory were analyzed. The main factor for this analysis was the composition of the species

Table 8.2 Mean tree density, basal area gross, and net volume and QMD in second-growth *Nothofagus*-dominated forest stands between 36° and 40°33′S, south-central Chile

Variables	Mean	Precision (%)
Tree density (N ha^{-1})	582	8.74
QMD (cm)	23	7.77
Basal area (m^2 ha^{-1})	24	7.77
Gross volume (m^3 ha^{-1})	212	8.18
Net volume (m^3 ha^{-1})	149	9.87

Table 8.3 Composition and structure of the sampled second-growth *Nothofagus*-dominated forests

Stand structure	Description	Frequency of total sample plots (%)
A. Second-growth *Nothofagus* with low or null participation of shade-tolerant species		
A.1 Second-growth *N. obliqua* and/or *N. alpina*	>90% *N. obliqua* and/or *N. alpine*	52
A.2 Second-growth *N. dombeyi*	>50% *N. dombeyi* with other *Nothofagus* and/or tolerant species	11
B. Second-growth *N. obliqua* and/or *N. alpina* with tolerant species in different developmental stages		
B.1 Dominant strata of *Nothofagus* and well-developed secondary strata of evergreen, shade-tolerant species	50–90% *N. obliqua* or *N. alpina* with shade-tolerants in the same third of the diameter range	14
B.2 Dominant strata of *Nothofagus* with participation of evergreen shade-tolerant species beginning to form secondary strata	>50% *N. obliqua* or *N. alpina* with shade-tolerant species in the third lower diameter range. At least 1000 individuals per hectare	12
Other mixtures	<30% *N. obliqua* or *N. alpina*, <50% *N. dombeyi* or *Nothofagus* but none of the other mixtures	11

and the relation between the state of succession of the (one or several) main and the secondary species. The classification obeyed the following rules: a stand was defined as deciduous *Nothofagus* forest with low or null evergreen species, when the basal area of *N. obliqua* and/or *N. alpina* was equal to or greater than 90% of the total basal area. Due to the very similar dynamics and wood properties, for this silvicultural proposal, we didn't differentiate between these two species, so stands included in this category may be monospecific or a mixture of both. In forest with more than the indicated participation of evergreen non-*Nothofagus* species, the diameter range of the sample plot was divided in three equal size classes, and the structure was defined based on whether shade-tolerant species shared the same diameter range as *Nothofagus* species or not. For the evergreen *N. dombeyi*, the applied criterion was another because of the different morphology of their crowns. Here we classified as *N. dombeyi*-dominated forest, when the basal area was equal to or greater than 50%. In case of a minor participation of *N. dombeyi* or less than 30% for *N. obliqua* and *N. alpine*, the plots were classified as other mixtures. The results of this classification process are shown in Table 8.3.

8.3.2 From Forest Dynamics to Silviculture

Uebelhör (1984) developed a successional model for *Nothofagus*-dominated forests in south-central Chile. He has based this on the hypothesis that the development of these forests in the Andean foothills in the province of Valdivia is a very slow process due to the frequency of disturbances, which is why the final stage dominated by shade-tolerant species is not very common. Windthrow, where individual trees, groups of trees, or whole areas fall, is considered the most frequent cause for the regeneration of shade midtolerant (hereafter "midtolerant") and shade-intolerant (hereafter "intolerant") pioneer species. Although Uebelhör (1984) considers that Veblen and Ashton (1978) and Veblen et al. (1989) overestimate the frequency and scope of geological disturbances such as earthquakes and volcanic eruptions, he vastly agrees with them and other authors on the dynamics of *Nothofagus* forests (Donoso 1993).

Although the model dynamics for *Nothofagus*-dominated forests proposed from Uebelhör (1984) (Fig. 8.4) is a simplification of a complex successional process, we consider that it is adequate and useful as a tool for close-to-nature management of second-growth mixed stands. It integrates the main theories on natural dynamics for these forests and indicates the consecutive stages of succession from the colonization of open areas to a potential final stage, also considering that disturbances might occur, causing a regression to a preceding stage. It can be observed that from the early developmental stages until the final stage, the participation of evergreen species (shade-tolerant and midtolerant) increases. Conversely, the presence of shade-intolerant or midtolerant *Nothofagus* species decreases.

Because of its lineal flow chart design, it is easy to locate the situation of a specific forest, turning it into a very useful management tool (Cabello 2005; Donoso and Lara 1998; Grosse 2009). As a near-to-nature concept, it should maintain biodiversity, genetic variability, and productive potential (Pro Silva 2012). Our proposal intends to represent the different successional stages. Trying to combine high growth rates and good quality timber production with increasing biodiversity, through the presence of shade-tolerant and midtolerant species, the accent is placed on mixed stands with a high participation of *N. obliqua*, *N. dombeyi*, and/or *N. alpina*, representing phase 4 in Uebelhör's dynamic model (Figs. 8.4 and 8.5). This combination also diminishes the risk of plagues and diseases due to a more complex vertical structure of the forest acting as a natural barrier to flying insect, such as the coleoptera *Holopterus chilensis*, which can seriously affect the most valuable trees (Cabrera 1997; Baldini and Pancel 2002). Furthermore, in comparison with pure *Nothofagus* stands, mixed stands prevent the establishment and expansion of bamboo (*Chusquea* spp.), which in turn hinders further regeneration (Veblen and Donoso 1987). It is important to mention that these indirect advantages are not the only reasons to include the shade-tolerant and midtolerant species, as they also provide high-quality wood.

Considering forest dynamics and the current structure of Chilean forests, we propose three silvicultural management models, one for each structural situation identified in the inventory results. These are (A) an even-aged management model for *Nothofagus* stands without evergreen species, (B1) management in two strata for mixed stands with high participation of *Nothofagus* species, and (B2) a uneven-aged continuous cover management for forests with low participation of *Nothofagus*

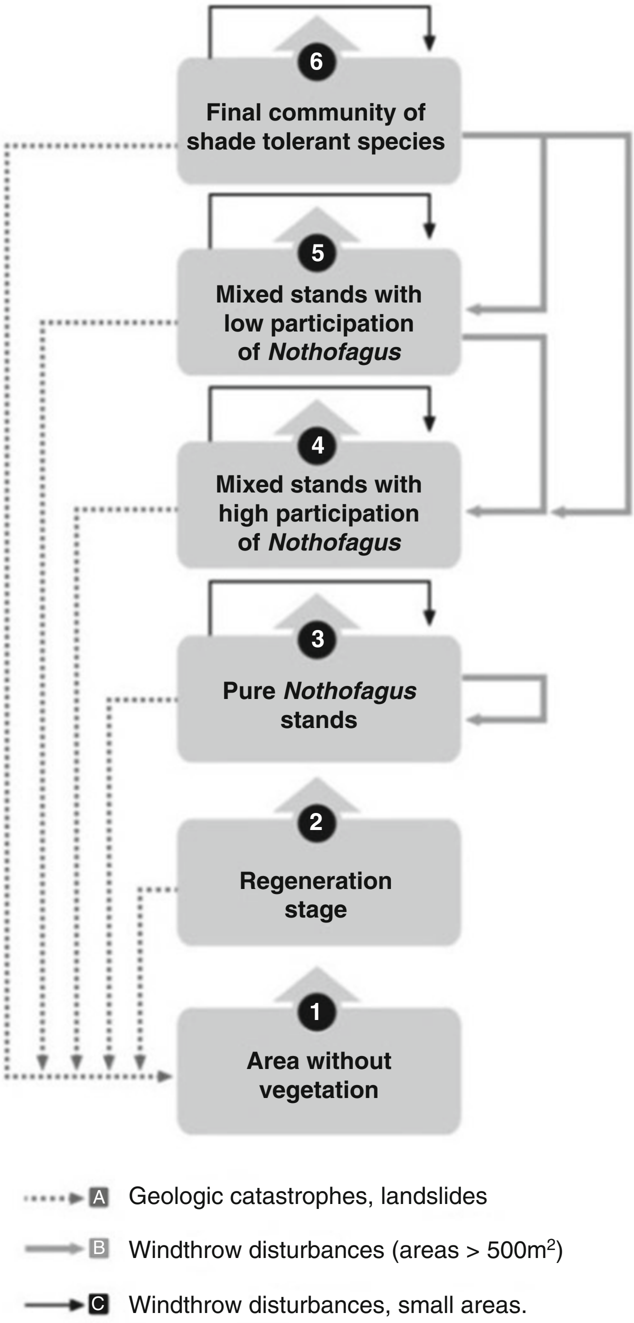

Fig. 8.4 Successional pattern of *Nothofagus* forests in south-central Chile (Uebelhör 1984)

Fig. 8.5 *Nothofagus obliqua* stand with temperate evergreen species in the second strata

species, based on a group selection system. For each situation, we defined recommendations concerning the main silvicultural objectives, reference densities for thinnings, and regeneration methods. This information is described for three case studies below and summarized in Table 8.4.

8.3.3 Case Studies

In order to illustrate this management concept, we selected three examples of characteristic stands, one for each structure type, and explain the silvicultural treatment for each of them (Figs. 8.6, 8.7, and 8.8).

The first stand diagram (Fig. 8.6) shows a nearly pure *N. obliqua* stand. The successional stage corresponds to stage 3 of Uebelhör's model, where we often find a mixture of *N. obliqua* and *N. alpina*. The management objective is sawtimber under a relatively simple management model, as there is only one tree stratum. The rotation age, reaching diameters of 45 cm, extends to 60–80 years, where two or three thinnings will be necessary to maintain the basal area at 30% of maximum tree density. In this range, the increment in value is highest (Lara et al. 2000; Steuer 2008). At final harvest the standing volume in such a management model may be 404 m^3 ha^{-1} with an average annual growth of 10.1 m^3 ha^{-1} (Donoso et al. 1993b). A transition toward mixed forests with dominant *Nothofagus* (successional stage 4) can be planned for the next rotation, incorporating shade-tolerant species in the natural regeneration process.

Table 8.4 Silvicultural management concept for *Nothofagus*-dominated second-growth forests in south-central Chile

Structure type	Future structure according to the successional stages from Uebelhör (1984)	Proposed management system	Objectives and management recommendations
A. Second-growth *Nothofagus* with low or null participation of shade-tolerant species	Stage 3, only *Nothofagus*	Even-aged method	*Nothofagus* timber production. Reference basal areas 30% relative density for *N. obliqua*, *N. alpina*, and 40% for *N. dombeyi* according the density management diagram developed by the Chilean Forest Research Institute (Müller-Using et al. 2012). Regeneration can be established by small clear-cuts of at least 0.1 ha (Grosse et al. 1996; Reyes et al. 2014). Rotation length between 60 and 80 years
B. Second-growth *N. obliqua* and/or *N. alpina* with tolerant species in different development stages	Stage 4–5, mixed stands with participation of *Nothofagus*	1. Two-aged method	Timber production from *Nothofagus* with high heartwood proportion and other valuable shade-tolerant evergreen species. Relative density for management about 35%. Long rotation system, 125 years. Regeneration in gaps, regeneration of *Nothofagus* species must be established artificially
	Stage 4 mixed stands with low participation of *Nothofagus*	2. Uneven-aged method	Saw-wood production from *Nothofagus* with high heartwood proportion and other valuable shade-tolerant evergreen species. The concept of relative density does not apply for this uneven-aged continuous cover management system. Regeneration occurs in small gaps

In mixed *Nothofagus* forests with evergreen species, the developmental stage of the evergreen stratum can be evaluated according to its advance in relation to the *Nothofagus* stratum. If there is a dominant *Nothofagus* stratum with small tree

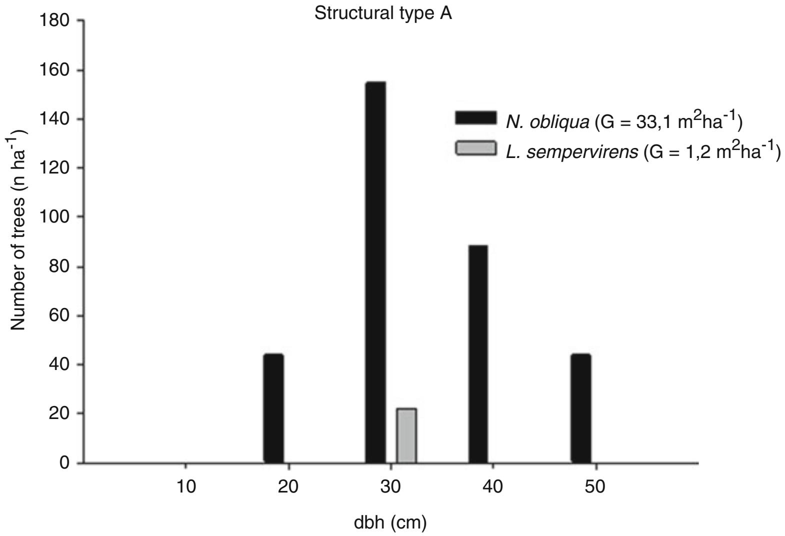

Fig. 8.6 Diameter structure for a nearly pure *Nothofagus* stand (type A). (Data from the Chilean National Forest Inventory)

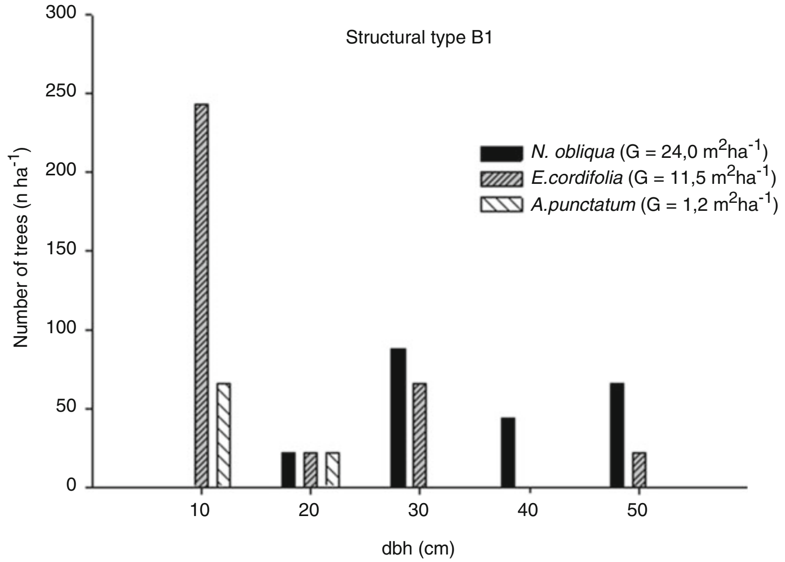

Fig. 8.7 Diameter structure for a mixed stand with a dominant stratum of *Nothofagus* and second stratum of shade-tolerant evergreen species (type B1). (Data from the Chilean National Forest Inventory)

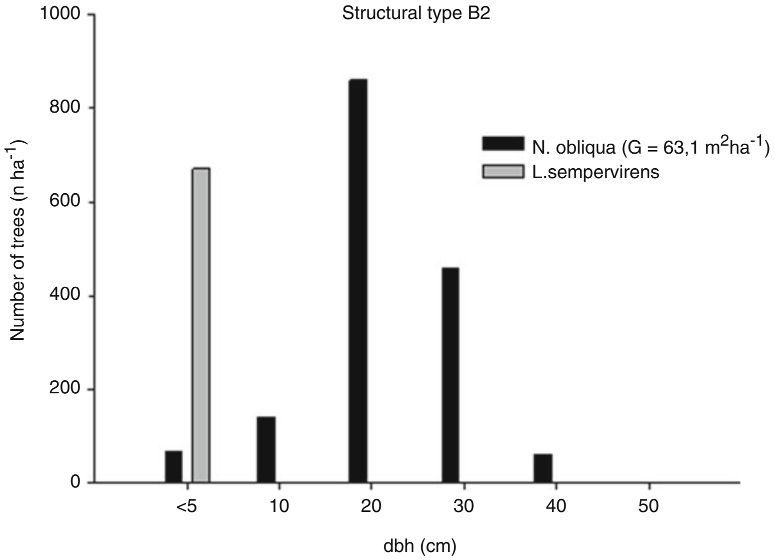

Fig. 8.8 Diameter structure for a mixed stand with a dominant stratum of *Nothofagus* and a very young second stratum of evergreen and shade-tolerant species (type B2). (Data from the Chile-an National Forest Inventory)

diameters and a complete second stratum of evergreen species, filling the spaces between the stems of the first stratum (type B1, Fig. 8.7), a two-stratum management model is recommended. This model is orientated toward "Mixed forest with high participation of *Nothofagus*" (Uebelhör's successional stage 4).

In this model production focuses on a diversity of products, such as timber with high proportion of heartwood of *Nothofagus* species and younger softwood timber of other species. In this management system, two rotations overlap: one is the dominant layer of *Nothofagus*, in which 75% of trees are harvested when they reach a dbh of 45 cm, and the other is shade-tolerant species with the 25% of now large remnant *Nothofagus* stems with a very high valuable heartwood proportion. In the following rotations, this model continues as a system of alternating harvests between a stratum of *Nothofagus* and the stratum of evergreen more shade-tolerant species. In Uebelhör's diagram, this model lies between stages 3 and 5. Regeneration of *Nothofagus* species must be established artificially as only few *Nothofagus* parent trees will remain. This management model considers a higher-density pure *Nothofagus* forests. Average annual increments are estimated in 8.7 m^3 for *Nothofagus* stratum and 5.3 m^3 for evergreen species (data from National Forest Inventory). Because of the additive growth effect (Donoso and Lusk 2007) of the two strata, we recommend to maintain it about 35% of maximum tree density. The expected production goal of this model is approximately 807 m^3 ha^{-1} (Rojas et al. 2010).

In the third situation, evergreen species are beginning to occupy the middle stratum under a dominant *Nothofagus* stratum (type B2). This situation is

Table 8.5 Seedling and sapling density in understory strata and species shade-tolerance

Species	Seedlings (n ha^{-1})	Saplings (n ha^{-1})	Shade-tolerance
E. cordifolia	117	204	Midtolerant
L. sempervirens	468	331	Midtolerant
P. lingue	796	64	Tolerant
D. winteri	70	140	Midtolerant
A. luma	70	267	Tolerant
L. hirsuta	70	127	Intolerant
E. coccineum	468	140	Intolerant
Total	2059	1273	

represented in Fig. 8.8, and complete regeneration data for this stand is given in Table 8.5. For this situation, we included the regeneration data because it is relevant for choosing the adequate management model. As we show in Table 8.5, it is characterized by the succession toward a mixed forest with low participation of *Nothofagus* species.

In this third situation, more time is required to integrate shade-tolerant species into the management, and their presence in the superior strata is a gradual and more individual process. In this condition, it is recommended to pass from even-aged to uneven-aged management. As in the case mentioned before, these stands are in the successional stage: “mixed forests with abundant *Nothofagus*” (Uebelhör’s stage 4). The difference with the previous model is the change toward a permanent production system with evergreen species. Gradually the transition from stage 4 to stage 6 occurs. Data from Donoso and Pilquinao (2013) show for uneven-aged evergreen forests without management a volume range between 415 and 549 m^3 ha^{-1} and increments of 2.4 and 3.0 m^3 $year^{-1}$. This would be significantly higher under management.

8.3.4 Conclusions

Until now, the silvicultural treatments of *Nothofagus* second-growth forests in south-central Chile has been focused mainly on optimizing thinning operations, where the first successional stage after disturbance, with pure *Nothofagus* pioneer species, has been the object. Analyzing the data provided by a regional inventory of this forest resource, we found three different types of tree species mixtures, which can be associated with distinct successional stages of second-growth forests. Doing so, we are able to leave behind a focus that only considers a single option for stand intervention. This perspective provides the opportunity for a more holistic management which defines the prescription on the basis of the natural trend of stand development. This concept conceives longer rotation times with greater development of species diversity, leading to an increasing variety of wood products and environmental benefits, such as higher resilience, more carbon stocking, and greater soil protection.

8.4 Subantarctic Forest of *Nothofagus alpina*, *Nothofagus obliqua*, and *Nothofagus dombeyi* from Argentina: Structure, Dynamics, and Silviculture

8.4.1 Distribution and Ecology

In Argentina, along the eastern foothills of the Andes between 39°29′–40°22′S and 71°15′–71°40′W, and up to 1000 m a.s.l., in areas with annual precipitation of 1000–2000 mm and deep and drained volcanic soils, mixed subantarctic *Nothofagus* forests occur. The deciduous *N. alpina* and *N. obliqua* and the evergreen *N. dombeyi* are the dominated tree species and cover 44,000 ha (CIEFAP-MAyDS 2016). Here, hybridization between *N. alpina* and *N. obliqua* occurs naturally (Gallo et al. 2000). *Nothofagus* are decline monoecious trees showing wind pollination and anemocory, limited seed dispersal, and a 4-year reproductive cycle for the formation of a cohort (Riveros et al. 1995). They exhibit masting, annual seed production estimated in 4900 seeds m^{-2}, and a transitory soil seed bank (Dezzotti et al. 2016). Seeds of *N. dombeyi* are intrinsically lighter (Burschel et al. 1976; Dezzotti et al. 2016) (Table 8.1). Recently fallen seeds are frequently pre- and post-dispersal predated and vain probably due to self-fertilization, and germination increases during most fertile periods (Burschel et al. 1976; Donoso 1993; Donoso et al. 1993a; Bustamante 1996; Figueroa et al. 2004; Dezzotti et al. 2016).

Nothofagus shows interspecific divergences judging from ecological and physiological evidence (Table 8.1). Niche differentiation among species is mainly related to light and manifests early, and it would explain the variability in stand structure within this mixed forest type (Müller-Using and Schlegel 1981; Weinberger and Ramírez 2001; Donoso et al. 2013). *Nothofagus dombeyi* is the most light-demanding, whereas *N. alpina* is the most shade-tolerant tree. In natural forest, *N. alpina* tend to present an asymmetric left-handed size distribution, due to a greater abundance of smaller individuals under the canopy (Donoso et al. 2014a). After selective cuttings, the original balanced composition tends not to be maintained because of the lower competitive ability of *N. alpina* regeneration after the increased radiation of the forest floor (Dezzotti et al. 2004). In plantation, *N. dombeyi* exhibited a better response to larger whereas *N. alpina* to smaller gaps (Grosse 1988; Donoso et al. 2013). The persistence of *N. alpina* in intermediate shade was related to low respiration and light compensation point (Read and Hill 1985) (Table 8.6). In addition, seed weight tended to correlate with tree temperament: heavier seeds exhibit less anemocory, and plants are adapted to shaded habitats under canopy (*N. alpina*), while lighter ones are dispersed by wind at greater distance, and plants develop in sunny areas of gaps (*N. dombeyi*).

Table 8.6 Characteristics of *N. alpina*, *N. obliqua*, and *N. dombeyi*

Characteristic	*N. alpina*	*N. obliqua*	*N. dombeyi*
Subgenus[a]	*Lophozonia*	*Lophozonia*	*Nothofagus*
Range (S latitude)[b]	36°30′–40°30′	32°50′–41°30′	36°30′–47°00′
Leaf type, texture, size (cm^2)[c, d]	de, ca, 6.6	de, ca, 4.7	pe, co, 1.8
Specific leaf area ($cm^2\ g^{-1}$)[e, f]	338–417, 418	228–442, 366	137–316
Foliar area ($cm^2\ ind^{-1}$)[e, h]	100.6, 113.5	78.9, 135.4	64.1, 39.1
Relative foliar area ($cm^2\ g^{-1}$)[e, f]	79–98	54–104	58–134
Seed weight (mg)[h, i, j]	3.8–13.3	6.2–24.4	0.6–4.4
Seed production (seed ind^{-1} $year^{-1}$, seed ha^{-1} $year^{-1}$)[i]	26,900–140	244,700–540	765,000–4220
Sapling stem length/root length[g]	1.2	1.5	1.8
Anemocory[j]	Lower	Intermediate	Higher
Vegetative reproduction	Yes	Yes	No
Chlorophyll (10^{-5} g cm^{-1})[e]	2.7	3.6	4.9
Light compensation point (μmol m^{-1} s^{-1})[e]	9	16	17
Photosynthetic efficiency (μmol m^{-1} s^{-1})[e]	0.027	0.019	0.018
Net photosynthesis max. (μmol m^{-1} s^{-1})[e]	6.0	6.7	6.6
R_{dark} (μmol m^{-1} s^{-1})[d]	0.6	0.9	1.1
Light intensity for germination (min., %)[e]	3.1	2.2	3.9
Cyttaria[j]	*Cs*	*Cs*, *Cb*	*Ch*, *Cj*
Heterobathmia[k]	Yes	Yes	No

[a]Hill and Jordan (1993)
[b]Veblen et al. (1996)
[c]*de* deciduous, *pe* perennial, *ca* cartaceous, *co* coriaceous (Romero 1980)
[d]Müller-Using and Schlegel (1981)
[e]Read and Hill (1985)
[f]Dezzotti (2008)
[g]Donoso and Cabello (1978) and Marchelli and Gallo (1999)
[h]Dezzotti et al. (2016)
[i]Burschel et al. (1976) and Veblen et al. (1996)
[j]Genus of gall-forming parasitic fungi exclusive of *Nothofagus*. *Cs C. spinosae*, *Cb C. berteroi*, *Ch C. hariotti*, *Cj C. johowii* (Humphries et al. 1986)
[k]Genus of Lepidoptera whose larvae are miners of *Nothofagus* (Kristensen and Nielsen 1983)

The dynamics of these subantarctic forests is influenced by the light-demanding, opportunistic character of *Nothofagus* species and their capacity to endure harsher conditions than neighboring tree species, the disturbance regime, and the physical environment that abruptly changes following an E-W direction. In the eastern flanks of the Andes in Argentina, *Nothofagus* rapidly colonizes open sites forming even-aged populations following the synchronous elimination of previous vegetation, caused by the periodical occurrence of large-scale disturbances.

These allogenic impacts are mainly natural and anthropogenic fires. In this initiation stage of succession, *Nothofagus* follows a "catastrophic regeneration mode." During stem exclusion stage, self-thinning drastically reduces density and

Table 8.7 Structure of three unmanaged stands of *N. alpina* (*Na*), *N. obliqua* (*No*), and *N. dombeyi* (*Nd*) in understory reinitiation (*) and old-growth stages (**) from the Lanín Reserve

Site	Variable	Species						Total / *Mean*
		Na	%	*No*	%	*Nd*	%	
Quilanlahue (**)	*D*	–	–	80	42	110	58	190
40°08′ 60″S	*BA*	–	–	13.9	28	35.0	72	48.9
71°28′ 00″W	*V*	–	–	173.8	16	926.1	84	1099.9
750 m a.s.l.	dbh_c	–	–	47.0	–	63.7	–	55.4
	h_{max}	–	–	40.7	–	38.0	–	39.4
	Cc	–		18.1	22	52.8	66	70.9
Yuco (*)	*D*	40	9	380	83	40	9	460
40°08′ 49″S	*BA*	5	9	42.8	73	10.5	18	58.3
71°30′ 19″W	*V*	57.9	7	450.5	57	283.4	36	791.8
844 m a.s.l.	dbh_c	39.8	–	37.8	–	57.8	–	45.1
	h_{max}	34.2	–	34.7	–	37.0	–	35.3
	Cc	11.1	13	68.1	78	8.3	9	87.5
Chachín (**)	*D*	30	30	–	–	70	70	100
40°09′ 50″S	*BA*	19.5	33	–	–	39.2	67	58.7
71°39′ 00″W	*V*	271.1	20	–	–	1071.0	80	1342.1
700 m a.s.l.	dbh_c	91.0	–	–	–	84.4	–	87.7
	h_{max}	35.8	–	–	–	45.0	–	40.4
	Cc	18.1	23	–	–	54.2	70	72.3

D density (ind ha^{-1}), *BA* basal area (m^2 ha^{-1}), *V* volume (m^3 ha^{-1}), dbh_c mean quadratic diameter at breast height (cm), h_{max} maximum tree height (m), *Cc* crown cover (%) (Dezzotti et al. 2016)

increases biomass of trees. In the absence of large-scale disturbances, understory replenishment may start with seedlings in a "gap-phase regeneration mode," when small- (<500 m^2) to medium-sized light gaps (500–2500 m^2) are opened up by the fall of senescent, old-growth individuals after 150–200 years (Veblen et al. 1996) during the understory reinitiation stage.

Although *Nothofagus* is formed by gap-dependant trees, in large openings mortality of immature individuals can be high due to the extreme temperatures of a climate with marked seasonality (Dezzotti et al. 2004; Donoso et al. 2013). As a result of the absence of shade-tolerant trees, neither successional replacement of *Nothofagus* nor change in species composition is likely to occur. In the absence of coarse disturbances, small-scale ones produce environmental heterogeneity that promotes a shifting forest mosaic during the old-growth stage. In this region, mixed *Nothofagus* forests are mainly in the understory reinitiation and old-growth stages, although there are also fewer in the initiation and stem exclusion stages. Old-growth stands are single-cohort with unimodal size frequency distributions, with 40–70 m^2 ha^{-1} basal area and 900–1400 m^3 ha^{-1} volume, and with individuals of >300 years of age, >100 cm dbh, and 30–40 m height (Table 8.7).

Conversely, in the nonseasonal and floristically more diverse areas of the Valdivian district, in coastal and mountainous areas west to the Andes in Chile, *Nothofagus* tends to be successionally replaced by shade-tolerant, broadleaved, and conifer trees during advanced stages of forest development. However, the periodic occurrence of large-scale perturbations interrupts any directional change in community composition and maintains the *Nothofagus*-dominated forests (Veblen et al. 1996).

Chusquea culeou (E. Desv. Poaceae) is the most frequent and abundant component in the understory and clearings of different size and origin in this mixed forest (Veblen et al. 1996). Colonization and early development of *Nothofagus* are impaired by its massive proliferation and by the thickness of the litter that develops beneath the main canopy that constitutes an unsuitable seedbed (Burschel et al. 1976). It shows a vegetative phase of between 14 and 50 years, after which it flowers and dies in a gregarious and synchronous mode (Lusk 2001). This process dramatically changed rapidly light, temperature, soil organic matter, nutrient cycling, and granivorous demography (Giordano et al. 2009; Austin and Marchesini 2012). After flowering and massive senescence of *C. culeou*, *Nothofagus* would occupy sites through seed, regrowth, or advance regeneration. However, its ability to compete with *C. culeou* is reduced because of a lower seed production and seedling emergence, growth, and survival (Dezzotti et al. 2016).

8.4.2 Stand Growth and Productivity

Dominant height-age curves for *Nothofagus* species were available as productivity and quality site indicators, which were adjusted using the model of von Bertalanffy-Richards. According to this model, the three *Nothofagus* species exhibited an anamorphic pattern of growth of dominant height for the different classes of site quality. *Nothofagus dombeyi* exhibits the largest growth in dominant height; however, the three species attains 40 m at 100–110 years in the best quality sites (Attis Beltrán et al. 2018) (Fig. 8.9). Diameter growth models indicate differences in tree

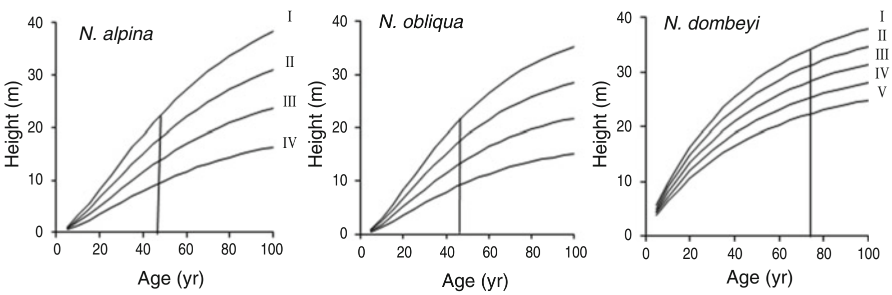

Fig. 8.9 Dominant height-age curves of Nothofagus within the Lanín Reserve based on site index at a respective reference age (ra) at dbh. For *N. alpina* and *N. obliqua*, ra = 45 year and site class *I*, 19; *II*, 19–15; *III*, 14.9–11; and *IV*, <11 m. For *N. dombeyi*, ra = 75 year, *I*, >33; *II*, 33–30; *III*, 29.9–27; *IV*, 26.9–24; and *V*, <24 m (Attis Beltrán et al. 2018)

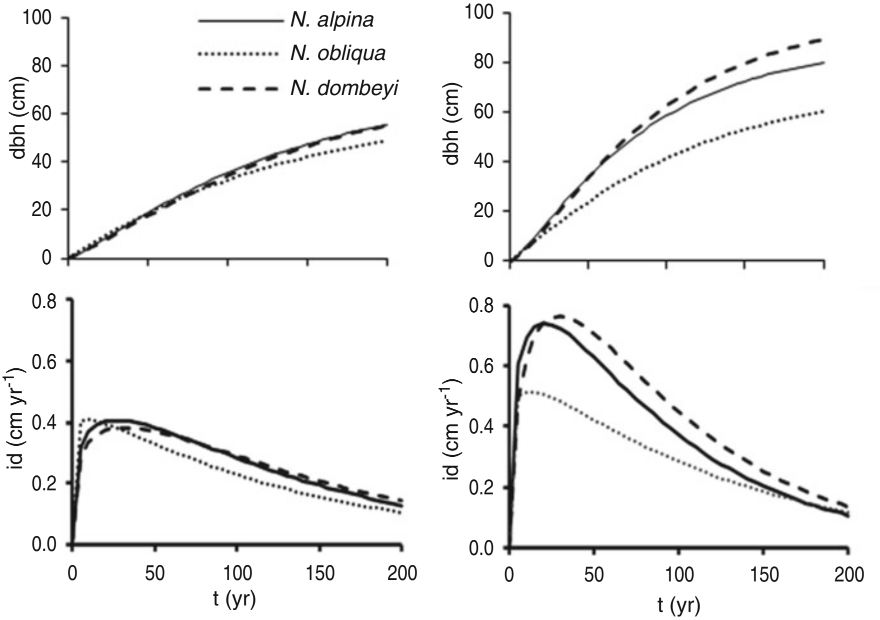

Fig. 8.10 Diameter at breast height (dbh) and current diameter increment (id) along time for *N. alpina*, *N. obliqua*, and *N. dombeyi* of the intermediate (left) and dominant and codominant strata (right) based on growth models (Attis Beltrán et al. 2018)

performance related to species and social strata (sensu Smith et al. 1996). For the dominant, codominant, and intermediate stratum, *N. dombeyi* shows the largest values of maximum asymptotic diameter, and *N. obliqua* exhibits the smallest. For the dominant and codominant stratum, *N. dombeyi* and *N. alpina* exhibit the largest absolute and maximum diameter growth, whereas for the intermediate stratum, the three species show a similar increment (Attis Beltrán et al. 2018) (Fig. 8.10).

8.4.3 Forest Management and Silviculture

In the Lanín National Park (39°7′–40°40′S, 71°42′–71°12′W), current legislation permits forest management as a strategic conservation policy, but strictly in zones categorized as reserve (195,010 ha, 47.3% of the area). Here, selective cuttings started at the beginning of the twentieth century and attained the largest extension and intensity during 1940–1960. This earlier activity was characterized by lack of planning, diffuse silvicultural prescriptions, weak governmental control, and short period licences. Felling was particularly directed to *N. alpina* and *N. obliqua* trees of commercial size. At present, the low proportion of large trees of both species in mixed stands and the numerous unmanaged stands dominated by *N. dombeyi*

Table 8.8 Prescribed remaining cover of shelterwood method in relation to cutting types and development stages applied to *Nothofagus* stands from the Lanín Reserve

Stages	Cutting type	Stage	Remaining cover	
			Crown (%)	Basal area (m^2 ha)
Regeneration	Preparatory	3, 4	70–80	30–35
	Establishment		40–50	25–30
	Secondary		30–40	15–25
	Removal		15–20	10–15
Conduction	Thinning	1, 2	80–90	15–30

1, stand initiation; 2, stem exclusion; 3, understory reinitiation; 4, old-growth

evidence this practice. However, the natural and anthropogenic fires that have occurred during the late nineteenth century also determine population structures (Veblen et al. 2003).

Sustainable management started in the late 1980s, and at present, there are about 1000 ha destined to obtain wood and firewood from trees and bamboo canes from *C. culeou*. Management units are located in Chachín, Nonthué, Yuco, and Quilanlahue, at 700–1050 m a.s.l. Considering species temperament, stand dynamics, and dominant mature structures, silviculture is carried out largely by the shelterwood system, which promotes establishment and growth of natural regeneration (Smith et al. 1996). The removal of the old stand is made in a series of cuttings that extends over a relatively short period of the rotation, usually one-fifth of the cutting period estimated in around 100 years, by means of which the establishment of one cohort of advance regeneration is encouraged (Table 8.8). Dominant, healthy, well-formed, and stable older trees, with the potential of further grow, are retained for variable periods. This is carried out to preserve a source of seeds until immature plants are established and help these plants to keep partly shaded and protected against freezing in winter and desiccation in summer. In addition, these trees are reserved for soil and drainage protection and aesthetic purposes. Reserved trees exhibit superior characteristics that in future interventions provide timber of greater relative value.

Standing, dead or dying, and fallen trees are kept in the forest site to preserve the structural complexity and promote the maintenance of the biological and functional diversity. Because a source of seeds is retained, this system allows implementing cuttings and then awaiting a good seed period.

Preparatory cuttings are implemented to strengthen the vigor of trees destined to be left in subsequent stages. Establishment cuttings should be implemented 20–30 years after preparatory cutting, with the aim to open up enough vacant growing space in a single operation to allow establishment of a new cohort under the protection of remaining adult trees (Table 8.8, Figs. 8.11, 8.12, and 8.13). This treatment involves the largest area within forest management plans. After 2–3 years of this last intervention, secondary cuttings are carried out in order to homogenize the spatial distribution of open areas for regeneration. Establishment cuttings are applied to gradually uncovering the new crop and making the best use of the

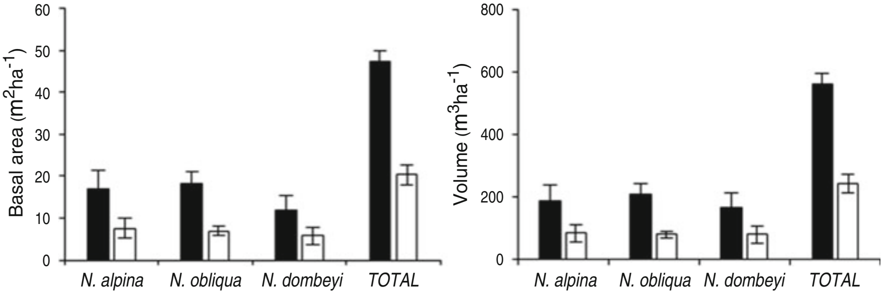

Fig. 8.11 Pre- (black bar) and harvest (white bar) basal area (left) and volume (right) for *N. alpina*, *N. obliqua*, and *N. dombeyi* in Yuco after preparatory and establishment cuttings. Vertical bars indicate the standard error of the mean ($n = 19$) (González Peñalba et al. 2016)

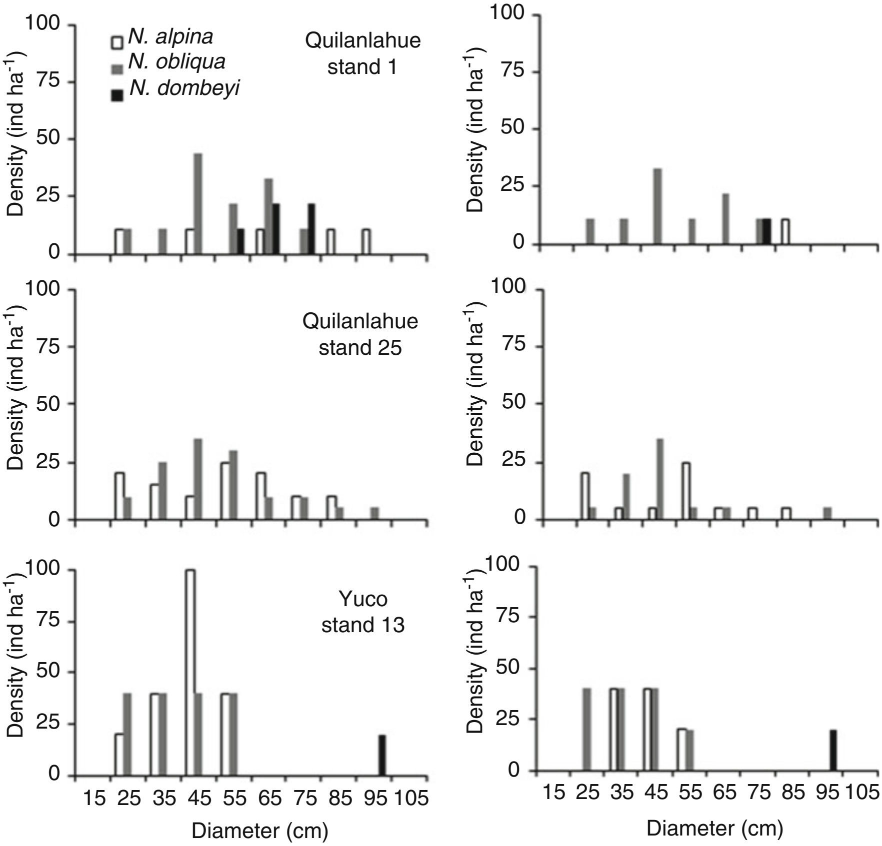

Fig. 8.12 Diameter at breast height frequency distribution of *N. alpina*, *N. obliqua*, and *N. dombeyi* before (left) and after (right) establishment cuttings in three stands within the Lanín Reserve (González Peñalba et al. 2016)

Fig. 8.13 Old-growth stands of *N. alpina*, *N. obliqua*, and *N. dombeyi* in Yuco showing adult and juvenile trees after 5 (left) and 15 years (right) of establishment cuttings

potential of remaining old trees to increase in value. Removal cuttings represent the last intervention of the regeneration period. However, this stage was not applied yet given that this period, estimated to be 25–30 years and involving a density of 2500 saplings ha^{-1} of height $\geq$2 m, was not fully attained. Rotation is estimated in 120–140 years; however, this age could be reduced to less than 100 years during future cohort management, based on research made in other regions (Lara et al. 1998). Conduction treatments as thinning are only carried out at experimental level, given the shortage of stands overpassing the initiation and stem exclusion stages (see *Thinning*).

8.4.3.1 Monitoring

Since 1988, continuous monitoring of management is made in circular and rectangular permanent sampling plots of 500–2700 m^2 each, located between 71°38′–71°26′W and 40°07′–40°10′S (González Peñalba et al. 2016). In these plots, composition, abundance, size, and growth of adult trees and natural regeneration and abundance of *N. obliqua* and *N. alpina* stump sprouts are evaluated every 5 years. The monitoring system consists of (i) 22 plots in stands under understory reinitiation and old-growth and subjected to establishment cuts, in which there were also installed subplots for evaluation of regeneration, and (ii) 8 plots in stands under initiation, in which part of them were subjected to crown thinning of the upper canopy, in order to release reserved trees from competition for future harvesting. In the lower stratum, small trees are not felled because they do not affect large trees and favor bole formation without lateral branches. The rest of the plots is unthinned and acts as control.

8.4.3.2 Growth and Production After Cutting

Considering silvicultural prescriptions (Table 8.3), in particular in the Yuco management area, 20.3 m^2 ha^{-1} of basal area (42.9% of pre-harvest) and 242.2 m^3 ha^{-1}

of volume (43.1%) were extracted. The contribution of each species in volume was 34.5% for *N. alpina*, 32.8% for *N. obliqua*, and 32.7% for *N. dombeyi* (Fig. 8.13). Within all management areas, after 10 years of cuttings, remnant trees exhibited a current diameter growth of 0.35 cm year^{-1} (SE = 0.04) and volume growth of 7.4 m^3 ha^{-1} year^{-1} (SE = 0.78), equivalent to 1.6% year^{-1} (SE = 0.12, n = 6) (González Peñalba et al. 2016).

8.4.3.3 Stump Sprouts

Although the main objective of shelterwood is to promote natural regeneration from seed, *N. obliqua* and *N. alpina* present vegetative reproduction too. In stands under shelterwood cut, the amount and conservation status of *N. obliqua* and *N. alpina* sprouts were recorded after 5 and 10 years of tree cutting. High proportion of stumps with live but poorly preserved sprouts, probably given progressive loss of vigor and mortality due to competition, would indicate a mean of four shoot stump after 15–25 years. Extensive sprout management should be applied to reach this value and anticipate the process of natural mortality. The size and growth of the dominant stumps (5.3 cm dbh, 5.9 m height) achieved height growth of 0.36 m year^{-1}.

8.4.3.4 Natural Regeneration

Before silvicultural intervention, mature stands have null or very low abundance of advance regeneration given the light-demanding temperament of all tree species and the large canopy cover that normally exceeds 80%. Shortly after establishment cuttings, colonization of a new tree cohort starts; however, at a given moment, age of the regeneration phase is variable because of the occurrence of 2–3 years of good seed production. Regeneration height of 2 m is reached after 10–15 years. In the Lanín Reserve, natural regeneration is a process in progress given that establishment cuttings were carried out less than 25 years ago. Current mean density of seedling (height $<$2 m) and saplings ($\geq$2 m) was estimated in 4963 and 5735 ind. ha^{-1}, respectively. The response of *Nothofagus* to felling was highly positive taking into account abundance, conservation status, and growth of tree recruitment, whose values largely exceeded prescriptions. However, domestic cattle must be excluded, and the thick litter layer of *C. culeou* should be weakened in regeneration areas (González Peñalba et al. 2016). The genetic effect of management on these young plants was evaluated, comparing species composition between upper and lower canopy and microsatellite markers. After 20 years of establishment cuttings, the original balanced composition of the adult component was not maintained in the regeneration; contrarily, no impact was detected in the gene pool at species level (Sola et al. 2016). However, monitoring is carried out continuously to record eventual changes on composition and structure of tree population related to species temperament, physical setting, and silviculture, in the context of adaptive management.

8.4.3.5 Thinning

The response to commercial crown thinning was only experimentally evaluated in stands overpassing the initiation stage, with mean tree ages between 43 and 57 years. This conduction treatment reduced the mean quadratic diameter by 7.7% and stand volume by 31.5%. After 10–15 years, dominant and codominant trees for the thinned stand exhibited diameter growth equal to 0.42 cm $year^{-1}$ and current volume growth equal to 13.0 m^3 ha^{-1} $year^{-1}$, while for the untreated stand, values were 0.25 cm $year^{-1}$ and 6.7 m^3 ha^{-1} $year^{-1}$, respectively. This preliminary trail showed that thinning implementation is recommended because it allows a significant increase in productivity and decrease in rotation age and is easy to apply as long as the individuals for releasing are clearly identified, provide poles and firewood with economic value, and can be implemented even if it is not the optimal moment. It is also recommended a precommercial thinning when stands attain 20–30 years.

8.5 *Nothofagus dombeyi-Austrocedrus chilensis* Forests

8.5.1 Distribution

Mixed forests of *Nothofagus dombeyi* and *Austrocedrus chilensis* are located east of the Andes, between 40 and 43°S, and occupy 32,800 ha (CIEFAP-MAyDS 2016) (Figs. 8.1 and 8.14). While *A. chilensis* grows on mesic and xeric sites, *N. dombeyi* only grows on mesic sites, with precipitation over 900 mm $year^{-1}$. Besides, where the precipitation is more than 1000 mm $year^{-1}$, there are woodlands and other forests that, naturally or through management, could be converted into mixed *N. dombeyi-A. chilensis* forests (Veblen and Lorenz 1987; Dezzotti 1996; Veblen et al. 2003).

These are:

Fig. 8.14 Landscape from *N. dombeyi-A. chilensis* forests with dead trees due *mal del ciprés* disease (left) and stand structure of them with regeneration of both species (right). (Photographs H. Gonda and M. Caselli, respectively)

(i) Pure *N. dombeyi* or *A. chilensis* with few individuals of the other species, covering 21,500 ha (CIEFAP-MAyDS 2016).
(ii) Post-fire mixed woodlands of *N. antarctica*, *Lomatia hirsuta*, *Schinus patagonicus*, and *Maytenus boaria*, which are seral stages toward high pure or mixed *N. dombeyi* or *A. chilensis* forests (Kitzberger 2012; Rusch et al. 2016). They extended northern from 43°S and occupy 52,000 ha (CIEFAP-MAyDS 2016).
(iii) Forests dominated by *A. chilensis* on mesic sites (precipitation over 1000 mm year^{-1}), covering around 32.800 ha, are being partially affected by a disease called *mal del ciprés*; this disease is caused by *Phytophthora austrocedrae* (Greslebin et al. 2007) and produces gradual defoliation and mortality (Rajchenberg and Cwielong 1993; La Manna et al. 2008) (Fig. 8.14). In national parks, 40% of the total area of *A. chilensis* forests is affected by the disease (Núñez et al. 2014).

Natural invasion of *N. dombeyi* observed in diseased stands represents the opportunity to convert stands and manage them as mixed forests (Loguercio 1997; Amoroso et al. 2012).

8.5.2 Structure and Dynamic

Pure and mixed *N. dombeyi*-*A. chilensis* forests are post-fire forests (Veblen and Lorenz 1987; Veblen et al. 1996). The stands have one or two age classes, being the oldest species that have been protected from wildfires in refuges and then first recolonized the sites. *A. chilensis* is dioecious so the regeneration depends on the presence on female seed plants. The structure is often stratified into two stories (Veblen and Lorenz 1987; Dezzotti 1996), due to the different height growth rate of the species (Fig. 8.15). *N. dombeyi* grows faster early in life and reaches maximum heights first, while *A. chilensis* present a long-term lineal growth (Fig. 8.16). On the overstory of best sites, *N. dombeyi* can reach 40 m in height, while *A. chilensis* individuals in general do not exceed 30 m (on the best sites), even when they have established themselves earlier (Veblen and Lorenz 1987; Loguercio 1997) (Fig. 8.16 and Table 8.9).

Since *N. dombeyi* is not a shade-tolerant species, natural regeneration in dense stands is absent. *A. chilensis* is a little more shade-tolerant than *N. dombeyi*, so suppressed seedlings can survive for many years in the understory. However *N. dombeyi's* mortality of seedlings is mainly caused by water deficit due to competition rather than the lack of light (Caselli et al. in press). On humid sites, *N. dombeyi* regenerates in canopy gaps of 200 to over 2000 m^2 produced by treefalls (Veblen 1989). On drier sites, where it is combined with *A. chilensis*, it regenerates in canopy gaps of 400–600 m^2 (Veblen et al. 1996). On xeric sites, the regeneration *of N. dombeyi* in the gaps can be affected by extreme drought events, particularly in rocky soils with steep slopes (Suárez and Kitzberger 2008, 2010). *A. chilensis* can

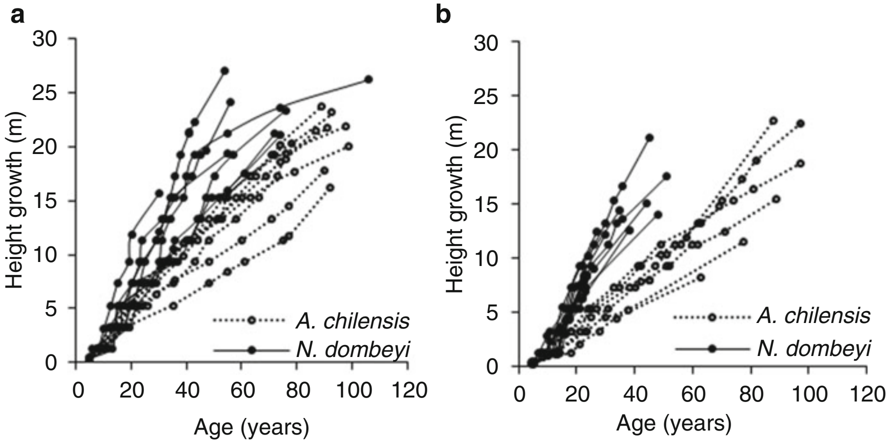

Fig. 8.15 Height growth of dominant and codominant trees (**a**) and intermediate and suppressed trees (**b**) of several mixed stands of *N. dombeyi* and *A. chilensis* located between 41°34′ and 42°00′

regenerate in smaller gaps (Fig. 8.14) and tend to be more drought resistant (Suárez and Kitzberger 2008, 2010). Pioneer species from the initial seral stage (*L. hirsuta*, *S. patagonicus*, and *A. maqui*) appear as dispersal remnants in those stands.

8.5.3 Natural Conversion of A. chilensis *Stands with "Mal de Ciprés" to Mixed* A. chilensis-N. dombeyi *Stands*

The release of growing space caused by the *A. chilensis* disease promotes natural regeneration (Loguercio 1997; Amoroso and Larson 2010). When mortality caused by the disease is not so high, the regeneration of *A. chilensis* predominates. But when mortality caused by the disease is higher and there are *N. dombeyi* seed trees nearby, the regeneration of this species dominates (Amoroso and Larson 2010; Amoroso et al. 2012). In the regeneration establishment phase (up to 4–5 m height), height increment of *N. dombeyi* and *A. chilensis* varies between 20 and 55 cm year^{-1} and 10–35 cm year^{-1}, respectively, depending on the canopy cover (Caselli, unpublished data). During the stem exclusion stage, *N. dombeyi* (Fig. 8.16) also achieves higher growth diameter. This is the case for all diameter classes, reaching maximum values of 8–12 mm year^{-1} and 4–7 mm year^{-1} for *N. dombeyi* and *A. chilensis*, respectively (Fig. 8.17).

The height and diameter growth result in a higher volume growth of *N. dombeyi* and an additive effect on the growth of the mixed stands (Loguercio 1997). On a given site, between age 60 and 80, mixed *N. dombeyi*-*A. chilensis* stands reach

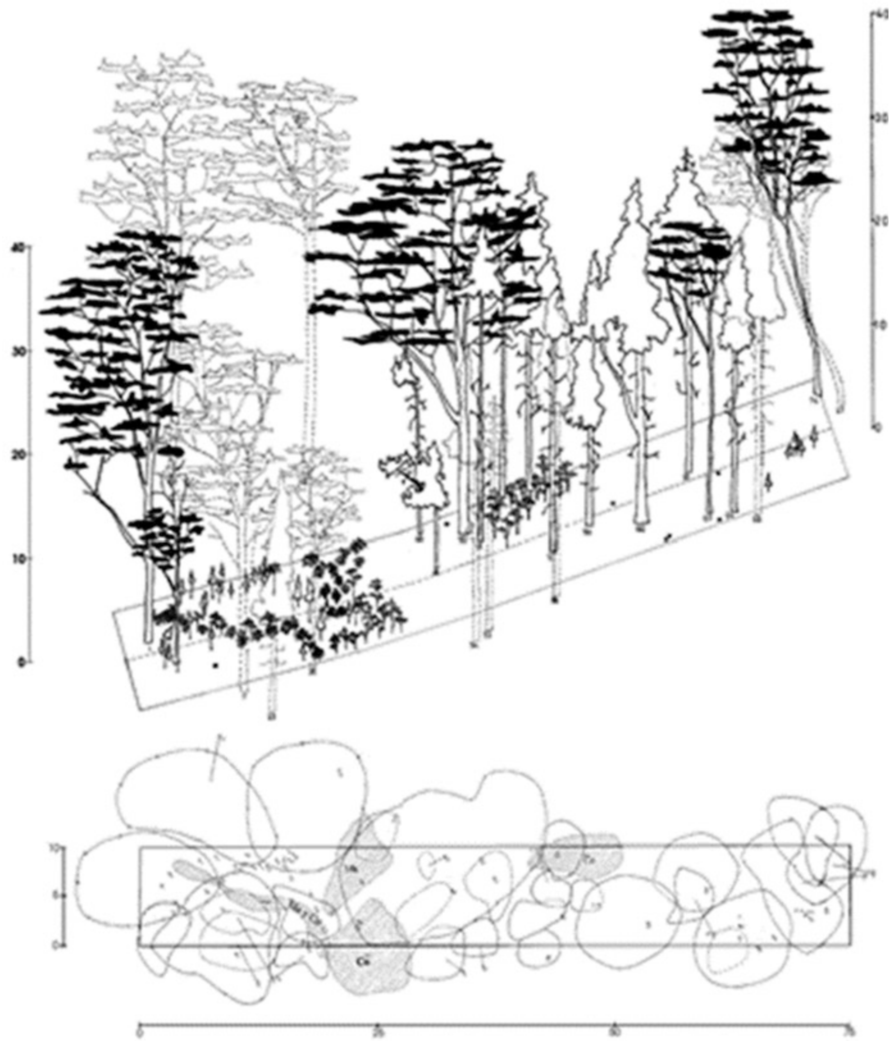

Fig. 8.16 Mixed stand profile of *N. dombeyi-A. chilensis* without interventions near Mascardi Lake, Nahuel Huapi National Park, Rio Negro Province, Argentina. Co, regeneration of *N. dombeyi*: Ma, *M. boaria*. Distances are in meters. Dosimetric parameters in Table 8.9

higher increments (8 and 13 m^3 ha^{-1} $year^{-1}$) than pure *A. chilensis* stands (4.8 and 7.5 m^3 ha^{-1} $year^{-1}$) (Table 8.10). In a mixed stand at "Loma del Medio-Rio Azul" Forest District (41°58′S–71°38′S), *N. dombeyi* trees sum 42% of the volume but contribute with 73% of the current volume increment (Loguercio 1997). Other stands showed the same trend (Table 8.10).

Table 8.9 Stands structural parameters of *N. dombeyi-A. chilensis* mixed forests without cuts, near Mascardi (Fig. 8.16) and Guillelmo lakes (41°20′56″S, 71°30′54″ and 41°22′47″S y 71°29′14″, respectively)

	Mascardi lake						Guillelmo lake					
Specie	Age (years)	Hd (m)	Nha^{-1}	QMD(cm)	BA (m^2 ha^{-1})	Vol. (m^3 ha^{-1})	Age (years)	Hd (m)	N ha^{-1}	QMD (cm)	BA (m^2 ha^{-1})	Vol. (m^3 ha^{-1})
N. dombeyi	76	33.3	277	45.4	44.9	747.6	49	23.6	433	35.4	42.6	525.4
A. chilensis	101	23.7	138	42.1	19.2	195.9	94	21.6	520	21.2	18.4	150.8
L. hirsuta	–	–	79	12.0	0.9	–	–		–	–	–	–
S. patagonicus	–	–	27	9.7	0.2	–	–	–	127	7.1	0.5	–
D. juncea	–	–	–	–	–	–	–	–	120	13.8	1.8	–
Total	–	–	415	39.8	64.3	943.5	–	–	1200	25.9	63.3	676.2

Age average age, *Hd* dominant height, *N ha*$^{-1}$ trees per ha, *QMD* cuadratic mean diameter, *BA* basal area, *Vol* total volume

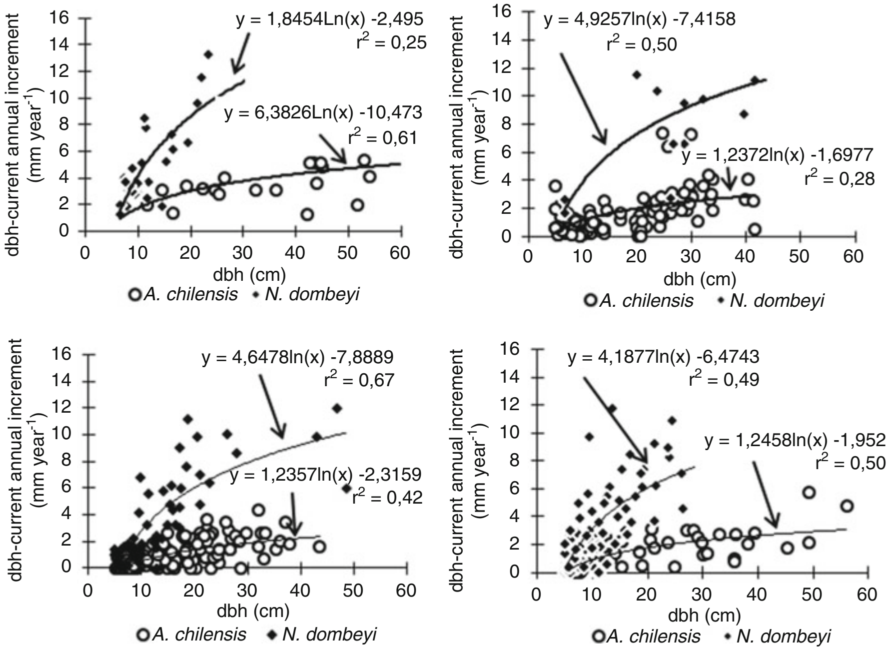

Fig. 8.17 Diameter increment of *N. dombeyi* and *A. chilensis* in four mixed permanent plots (41°58′S–71°38′S) (Loguercio 1997)

8.5.4 Toward an Adaptive Forest Management for the Mixed Forest

Management of *A. chilensis* forests depends on the presence of *mal de ciprés* disease, disturbance to which must be adapted. Although recommended sanitation cuttings (harvest of dead and severely defoliated trees) had been carried out for the last 20–30 years, they have proved to be not effective to halt the expansion of the disease. In response to that, improvement and salvage cuttings and measures to promote natural regeneration have been proposed (Loguercio 1997; Loguercio et al. 2018). Improvement cuttings consist in harvesting badly formed trees to improve stand quality. Salvage cuttings involve the removal of dead trees. Partially defoliated trees can live for many years (even decades too) and must not be removed. Salvage cuttings can produce as much as 3–4 m^3 ha^{-1} $year^{-1}$, with 3–5-year cutting cycles; volume growth of remnant trees was similar to mortality volume (Loguercio 1997). Female sick individuals that remain in the stand are important as they provide seed for natural regeneration. The establishment of natural regeneration in open stands is facilitated by maintaining some understory vegetation because it provides a favorable microclimate. As a result of this management, stand structure tends to become gradually multiaged. The intensity and frequency of cuttings are subjected to the evolution of the mortality.

Table 8.10 Structure parameters of pure and mixed *A. chilensis (Ach)* and *N. dombeyi* (*Nd*) stands at "Loma del Medio-Rio Azul" forest (41°58′S–71°38′S). (Loguercio 1997)

Specie	Age (years)	Hd (m)	N ha^{-1}	BA (m^2 ha^{-1})	QMD (cm)	Vol. (m^3 ha^{-1}) (%)	Curr. Incr. (m^3 ha^{-1} $year^{-1}$)
Pure stands							
Ach	60	21.8	350	18.6	26.0	351	7.3
Ach	65	19.2	1157	37.0	20.2	247	4.8
Ach	83	15.2	2341	41.9	15.1	238	2.6
Mixed stands							
Ach	n.d	23.8	200	27.0	41.5	244 (84)	3.6 (53)
Nd	n.d	14.8	440	6.5	13.7	45 (16)	4.0 (47)
Total			640	33.5	25.8	289	7.6
Ach	n.d.	20.4	850	39.3	18.3	290 (69)	1.3 (14)
Nd	n.d.	21.3	120	11.4	34.2	128 (31)	7.7 (86)
Total			960	33.1	21.0	418	9.0
Ach	64	19.1	1200	36.5	19.7	251 (58)	3.4 (27)
Nd	39	23.7	590	16,2	18.7	182 (42)	9.3 (73)
Total			1790	52.7	19.5	433	12.7
Ach	n.d.	23.6	550	37.4	29.4	325 (65)	3.1 (24)
Nd	n.d.	21.2	760	17.5	17.1	177 (35)	9.6 (76)
Total			1280	44.9	20.1	502	12.7

Hd: dominant height; N ha^{-1}: trees per ha; BA: basal area; QMD: quadratic mean diameter; Vol.: total volume; Curr. Incr.: volume current increment

In mixed *N. dombeyi*-*A. chilensis* stands where *mal del ciprés* is present, regeneration of *N. dombeyi* can enhance productivity and produce high-quality timber representing an opportunity to develop a more intensive silviculture (Loguercio 1997; Loguercio et al. 2018). There is not much information about management of mixed *N. dombeyi*-*A. chilensis* affected by *mal del ciprés*, but current knowledge about growth and dynamics of these forests would make it possible to elaborate the first silviculture guidelines. Treatments should consider the conversion of pure disease *A. chilensis* into mixed structures and its subsequent conduction to regulate its composition and density. Since *N. dombeyi* outgrows *A. chilensis* (Tables 8.9 and 8.10, Figs. 8.16 and 8.17), to control composition and growth of mixed stands, it is convenient to keep species in separate groups rather than in a uniform mixture. The area assigned to each species will depend on the management objective. Group selection methods are considered appropriate for the regeneration of *N. dombeyi*, with final gaps of approximately 500–1000 m^2. However, on xeric sites gaps should be open only where advanced regeneration is present, and they should be expanded gradually, in two or three entries, every 5 years. This would also be recommended where the diseased *A. chilensis* trees occur in groups. Established regeneration, that is, when they reach 4–5 m of height, would be achieved in 10–15 years. Then a cleaning cut to favor the best saplings should be applied. Along the stem exclusion stage, two to three thinnings should be carried out before the final cut to be done when DBH reaches 45–50 cm. The nicest *N. dombeyi* trees could eventually be pruned to produce clear timber.

In places within the stands where *A. chilensis* is to be maintained as the main species, the same management guidelines as for pure forests can be applied. To maintain the stand composition, *N. dombeyi* seedlings should be removed before they reach 3–5 m of height, except for a few with very good form and vigor.

When natural regeneration does not prosper, reforestation of one or both species can be carried out. Gaps and stripes, with an area less than 350 m^2, have resulted in high initial survival (>80%) for both species (Pafundi et al. 2014). On mesic sites ($\pm$1000 mm $year^{-1}$), *A. chilensis* and *N. dombeyi* plantations with the presence of diseased *A. chilensis*, canopy cover values between 30% and 75% favor the initial survival of both species. On xeric sites (<700 mm $year^{-1}$), this protection effect is more pronounced.

8.6 Concluding Remarks

Mixed temperate forests of South America are found south of 33°S, most of them west of the Andes Mountains. East of the Andes, mixed forests are small ingressions from the west and transitions between pure forests types of mesic and xeric sites.

Forest management of evergreen forests west of the Andes, with their great variety of species (more than 20 per ha, mostly hardwoods), with different behavior, growth rates, and timber quality, represents the greatest challenge. Some options have been presented for this forest type, considering even- and uneven-aged silvicultural systems. For old-growth forests, uneven-aged silviculture is proposed by means of the selection cutting system oriented to shade-tolerant and midtolerant species with a large life-span. It is estimated that tree growth can be doubled with this management. Nevertheless, the model should be consolidated through its proper implementation and monitoring, in operational management cases.

Secondary mixed forests in Chile also present a great variety of species composition, reproduction forms, and development states that, depending on sites, enable different management models to apply. Management outlines for even- and two-aged forest types with one or two strata and the presence of intolerant, midtolerant and/or shade-tolerant species have been presented. In general the examples indicate the convenience to initiate the reduction of the density at an early age, orienting the management to more valuable species. The decisions to conduct cuttings for the main species are made by means of available density diagrams and density equations.

Mixed secondary forests of *Nothofagus* spp., known in Chile as "renovales," predominate in the stem exclusion phase with ages between 60 and 80 years. There, management decisions are made according to the presence or absence of shade-tolerant and midtolerant species and stand stocking. The management aims to combine the value production of the *Nothofagus* and to favor the development of the midtolerant and shade-tolerant species of the second stratum for its future production. Thinnings are also defined using available management density diagrams.

East of the Andes, in Argentina, mixed *Nothofagus* forests do not present the tolerant and semi-tolerant shade species of the evergreen forest type, due to the humidity threshold. These forests predominate in the old-growth and reinitiation stage. Hence, forest management is done with a shelterwood system. Its successful implementation, with achieved regeneration on approximately 1000 ha along more than 25 years in the reserve area of Lanín National Park, is an outstanding example of effective silvicultural management in the subantarctic forests from Argentina. It has been observed that young *Nothofagus* stands, even though its growth rate is smaller than the most humid zone in Chile, respond to thinnings with an increment in volume, even with 40–60 years of age.

Xeric conditions reduce tree diversity, predominating pure forests. The climatic rigorousness that predisposes the occurrence of stress in the trees due abiotic and biotic damages, including the potential effects of climate change, suggests an approach of adaptive management. For example, the *A. chilensis* forests affected by *P. austrocedri*, where the regeneration of *N. dombeyi* is invading, present the opportunity to convert it to mixed forests. *N. dombeyi* increases the stand productivity, broadening the possibility of a more intensive silviculture, in comparison with the pure and diseased *A. chilensis* forests. Due to the greatest growth of *N. dombeyi*, its stocking in the stand must be regulated to allow *A. chilensis* to grow successfully.

Overall, there is a considerable knowledge about ecology, dynamics, and silviculture for a sustainable management of mixed temperate forests of South America. However, effective forest management in a large scale is not yet applied, being this the major pending challenge for the forestry sectors of Chile and Argentina.

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