Forest Ecology and Management 432 (2019) 686–693

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Development of 26-year-old mixed forests following different regeneration cutting treatments in Andean temperate rainforests of south-central Chile

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ARTICLE INFO

Keywords:
Forest secondary succession
Even-aged regeneration cuttings
Evergreen temperate forests
Clearcutting
Strip clearcutting
Reserve shelterwood cutting

ABSTRACT

Tree regeneration following even-aged silvicultural methods in the evergreen forest type (EFT) has been scarcely studied in Chile, although this is the largest forest type in a region of highly productive native forests. In 1981/1982 a total of nine 1.44-ha experimental units with old-growth forests of the EFT were subjected to block clearcutting (BCC), strip clearcutting (SCC) and reserve shelterwood cutting (RSC) methods (three replicates in each case) in the Andes range in south-central Chile (41°35′S–72°35′W). The resulting second-growth forest stands following these cuttings were evaluated in terms of composition, density, basal area, mean diameter and height after four and 26 years (432 4 m^2 plots in 1986, and 78 100 m^2 plots in 2008). Four years after cutting, there were > one million tree seedlings per hectare in more than 10 species. In all experimental units one shade-tolerant species (*Amomyrtus luma*), one midtolerant species (*Eucryphia cordifolia*) and two very shade-intolerant species (*Embothrium coccineum* and *Weinmannia trichosperma*) comprised between 69 and 74% of the total density. The SCC favored a greater relative dominance of all the more shade-tolerant species, and the BCC treatment was more favorable for pioneer species (in addition to *E. coccineum* and *W. trichosperma* also *Drimys winteri*, *Caldcluvia paniculata* and *Nothofagus nitida*). At age 26, the short-lived *E. coccineum* dominated in all treatments, and its major coexisting species in terms of tree density were the midtolerants *D. winteri*, *Eucryphia cordifolia* and *N. nitida*, and the shade-tolerants *Laureliopsis philippiana* and *A. luma*. However, the BCC significantly favored the development of *N. nitida* and *D. winteri* (three times more basal area than in the other treatments), which might be explained by increasing soil moisture that occurs in this region following this type of disturbances. While these treatments did not show significant differences in mean diameters and dominant height, the BCC and SCC treatments allowed denser, diverse and well-stocked second-growth forests compared to the RSC method, illustrating the differences between truly even-aged and two-aged silvicultural methods upon these variables. Overall, these forests show a high resilience, rapid reorganization and high productivity following the application of even-aged silvicultural methods.

1. Introduction

Natural large-scale disturbances, land-use changes, or forest regeneration cuttings have favored the development of extensive areas of forests dominated by a single age class, i.e. even-aged forests (Oliver and Larson, 1996; Veblen et al., 1996; Nyland, 2007). The development of even-aged forests in temperate regions has received considerable attention among forest ecologists and silviculturists (e.g., Bormann & Likens, 1979; Oliver, 1980, 1981; Peet and Christensen, 1987; Nyland et al., 2000). Numerous studies have analyzed regeneration and development of even-aged stands following different silvicultural methods or regeneration cuttings that completely or partially remove the forest cover (Kelty, 1987; Walters and Nyland, 1989; Martin and Hornbeck, 1990; McClure and Lee, 1993; Ray et al., 1999; Nyland et al., 2000). These studies show a common temporal pattern in the composition of tree species, initially consisting predominantly (but not exclusively) of early successional shade-intolerant species with a fast initial growth, progressing towards mixed stratified stands containing late-

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https://doi.org/10.1016/j.foreco.2018.10.004
Received 17 September 2018; Accepted 1 October 2018

successional species (Bormann and Likens, 1979; Oliver, 1980, 1981; Smith and Ashton, 1993; Wang and Nyland, 1996; Liptzin and Ashton, 1999; Allison et al., 2003). When secondary succession follows a large-scale disturbance of an established forest, it is expected that the new community will follow the initial floristic model of succession, including pioneer, seral and climax species (Barbour et al., 1987). Also after the implementation of even-aged silvicultural methods, a combination of species of different shade tolerances may simultaneously establish on the site, i.e. shade-tolerant or shade mid-tolerant (hereafter "midtolerant") species establish alongside shade-intolerant species (e.g., Marquis, 1967; Matthews, 1989; Allison et al., 2003; Yamasaki et al., 2014).

The relative dominance of species with different shade tolerances is highly dependent on the type and intensity of the cut and resulting environmental conditions, ecological characteristics of the local species, and the characteristics of the forest at the time of cut, especially in relation to the type and quantity of advance regeneration and propagule availability (Hibbs, 1983; Swanson et al., 2011). In the cases of strip clearcutting or shelterwood cutting either the adjacent forest (in strips) or the residual overstory (shelterwood) provide some shelter on the cut area, which maintains greater rates of soil moisture and nutrients in the soil compared with clearcuttings (Keenan and Kimmins, 1993). These differences (light, moisture, nutrients) may eventually affect differential patterns of regeneration and growth of seedlings (Matthews, 1989; Hornbeck et al., 1987). These conditions complement with the sprouting capacity of many hardwoods, which further favors regeneration of more shade-tolerant species (Del Tredici, 2001; Swanson et al., 2011).

Among temperate rainforests of Chile, the evergreen forest type is the largest, growing throughout the Coastal and Andean ranges, and is characterized by its multispecific composition dominated by broadleaf evergreen species. In the Andes this forest type is pervasive from 40°–47° S Lat. (Donoso, 2015), and large-scale natural disturbances are common, including earthquakes and associated mass movements, volcanisms and associated fires and landslides, and also massive windthrows (Veblen and Ashton, 1978). These stand-replacing disturbances generate even-aged stands (Veblen et al., 1981), which are originally dominated by pioneer tree species and gradually more shade-tolerant species start to occupy lower strata, a process highly affected by gap dynamics (Veblen, 1985). The frequency of large-scale disturbances is shorter than the longevity of pioneer tree species, and that allows these species to remain as dominant or emergent trees in these Andean forests (Veblen and Ashton, 1978). Among pioneers, *Nothofagus* tree species play a relevant role, especially *N. dombeyi* (Mirb.) Oerst. (shade-intolerant) and south of 40°S *N. nitida* (Phil.) Krasser (midtolerant; Donoso and Soto, 2016). Other pioneer species include the shade-intolerants *Weinmannia trichosperma* Cav., and *Embothrium coccineum* J.R. Forst. & G. Forst., and the midtolerants *Eucryphia cordifolia* Cav. and *Drimys winteri* J.R. Forst. & G. Forst. Both *D. winteri* and *N. nitida* have a competitive advantage in poorly-drained soils or soils with permanent high moisture content (Donoso, 1989a, 2015; Donoso et al., 2007).

In spite of the global importance of the evergreen forest type in Chile (its large extent, valuable hardwood species, and complexity), there are few studies on their silviculture. The Chilean forest law allows the application of the shelterwood and "selective" silvicultural methods since 1979, but later it introduced, through specific regulations, the authorization to use strip clearcuttings (Donoso et al., 1998). Of all these options, through legal or illegal harvests, forest owners mostly high-grade their forests through selective cuttings, which in either case harvest the best and leave the worst (Donoso, 2013). There are no reports of the effects of regeneration cuttings for even-aged forests in the Evergreen Forest Type, except for the one by Donoso (1989b), who reported the regeneration of more than a million tree seedlings (≥3 cm in height) four years after the implementation of block clearcutting (BCC), strip clearcutting (SCC) and shelterwood cutting, where residual trees have never been cut later, so it became a reserve shelterwood cutting (RSC).

In this study we follow this experiment to evaluate the development of these second-growth forests during the first 26 years after cutting. The working hypotheses were: (1) The relative dominance of tree species according to their shade tolerances is a function of the level of cutting and shelter provided by the silvicultural treatments applied, i.e., shade-intolerant species have a greater importance in the BCC and lower in the RSC, and (2) RSC has a slower stand development as reflected in lower basal areas, tree densities and mean tree diameters. This study then becomes the first to report early-successional patterns (past the Stand Initiation Stage and into the Stem Exclusion Stage of forest stand dynamics (*sensu* Oliver and Larson, 1996)) of tree regeneration following even-aged silvicultural cuttings in temperate rainforests of the Southern Hemisphere.

2. Methods

2.1. Study area and experimental design

The study area is located at the foothills of the Andes mountain range in the Llanquihue Forest Reserve, adjacent to the Alerce Andino National Park, south-central Chile (41°31′S-72°39′ W; Fig. 1). A west-coast maritime climate with a mild temperature range dominates the area, with a rainfall range from 2500 to 3500 mm and slight decreases during summer months (Donoso, 1989b; Schlatter et al., 1995). The average monthly temperature in July (winter) is 7 °C, and 15 °C in January (summer) (Schlatter et al., 1995). Soils are deep and are derived from recent volcanic ash layers with a topography dominated by steep hills (CIREN, 2001; Schlatter et al., 1995). Overall, soils are well-drained (CIREN, 2001), although in places with gentle slopes, the internal drainage is moderate to slow, and on occasions there is temporary water saturation (Donoso, 1989b). Soils contain high amounts of organic matter, and have a sandy-silt texture (CIREN, 2001).

Our study area (≈100 ha) is dominated by old-growth multi-layered forests located between 420 and 550 m a.s.l. (Table 1). Prior to applying the regeneration cuttings, tree density, tree basal area, and understory cover were measured (ICSA, 1983). Basal area was dominanted by *Laureliopsis philippiana* (Looser) Schodde (34%), the Podocarps *Podocarpus nubigena* Lindl. and *Saxegothaea conspicua* Lindl. (27%), *N. nitida* (10%), *D.winteri* (7%), *E. cordifolia* (6%) and *W.trichosperma* (3%). All these are commercial tree species (Donoso, 1989b). Other species (13% of basal area) in the forest included *Dasyphyllum diacanthoides* (Less.) Cabr., *Caldcluvia paniculata* (Cav.) D. Don, *Lomatia ferruginea* (Cav.) R. Br., *E. coccineum*, and species from the *Mirtaceae* family, such as *Amomyrtus luma* (Mol.) Legrand & Kausel and *Myrceugenia planipes* (Hook. et Arn.) Berg. *Nothofagus nitida* was the tallest tree species with a dominant height of 27 m above a main tree canopy with an average height of 22 m and dominated by *W. trichosperma*, *E. cordifolia*, *L. philippiana* and *S. conspicua*. These are common values for forests of this forest type within the region of Valdivian Temperate Rainforests (*sensu* Donoso and Soto, 2016). Regeneration of commercial tree species was dominated by *L. philippiana* and *D. winteri*. Bamboos (*Chusquea quila* Kunth and *Chusquea macrostachya* Phil.) were the dominant species in the understory, and their cover was especially high in higher elevation experimental units (2, 7, 8 and 9). Some silvical characteristics of these species are given in Table 2.

Nine experimental units covered with these old-growth forests received the three different types of even-aged regeneration cuttings mentioned earlier (block clearcutting (BCC), strip clearcutting (SCC) and reserve shelterwood cutting (RSC)), each having three replicates (Fig. 1 and Table 1). No experimental unit had a south aspect; rather they had mostly NE to NW aspects. We do not think that this is a major limitation of the study since the region is characterized by high rainfalls. However, south-facing slopes may be more favorable for *Podocarpaceae* conifers and less favorable for *E. cordifolia* (P. Donoso personal observation). Each experimental unit was harvested in an area of