United States Department of Agriculture

Forest Management – Research Partnerships:

Proceedings of the 2019 National Silviculture Workshop

Forest Service Northern Research Station General Technical Report P-193 May 2020

Abstract

Since its inception in 1973, the National Silviculture Workshop (NSW) has brought together forest managers and researchers from across the USDA Forest Service, and more recently our university and other partners, to provide a forum for information sharing and science advancements in silviculture. The 2019 NSW focused specifically on this partnership with the theme "Forest Management-Research Partnerships" in Bemidji, MN. With nearly 300 participants, this proceedings and that of the Journal of Forestry special section (Volume 118, Issue 3), highlight some of the best outcomes of our history of working together, as well as its challenges, and opportunities for the future. The objectives of the workshop included 1) providing a forum to showcase successful partnerships and shared stewardship between forest managers and researchers, 2) enhancing these relationships within the Agency and with our external partners to meet shared goals and objectives, 3) building on the Forest Service strategic objectives for improving the conditions of forests through innovative silviculture and active forest management, and 4) identifying emerging forest management needs to guide future research investment. This report includes of 22 papers (including two from 2017 NSW) and 6 panel-discussion summaries. The report also includes two papers from the 2017 NSW, "Silviculture: The Foundation for Restoration, Resilience, and Climate Adaptation" held in Flagstaff, AZ.

Acknowledgments

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Cover Photo

A field tour during the National Silviculture Workshop at the 70-year-old Level of Growing Stock Experiment on the Cutfoot Experimental Forest. Photo by Nisha van Hees, USDA Forest Service.

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Review Procedures

A single-blind review process was used in reviewing manuscripts submitted for publication. Each manuscript was peer-reviewed by at least two professionals. Reviews were returned to authors to revise their manuscripts. Upon acceptance by the assigned editor, revised manuscripts were forwarded to the U.S. Forest Service, Northern Research Station for final editing and publishing. The workshop Editorial Committee returned some of the manuscripts to the authors as being more suitable for other outlets.

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Sharing the Load to Develop Young-Growth Silviculture for Forage and Biodiversity in Southeast Alaska

Justin S. Crotteau, Michael H. McClellan, Toni L. De Santo, Sheila R. Spores, and Jeffrey C. Barnard[1]

ABSTRACT.—Approximately 170,000 ha have been logged on the Tongass National Forest since the early 20th century, resulting in a vast network of young, and even-aged Sitka spruce–western hemlock stands. Many of these stands are in a stem exclusion phase, with dense overstories that competitively shade out understories. In 2001, a USDA Forest Service planning committee convened to develop multiple resource treatments to examine the effects of precommercial thinning, resulting in a collaborative, long-term project to improve knowledge and catalyze the Tongass-Wide Young Growth Studies (TWYGS) project. This project was designed collaboratively, implemented by partners across the Tongass, and monitored via the Forest Service's Pacific Northwest Research Station. Of the four TWYGS experiments, one has been measured three times in 16 years since treatment. We examine forest development following three levels of precommercial thinning in 15- to 25-year-old stands: unthinned, 4.3 m spacing, and 5.5 m spacing. Results from 5, 10, and 16 years highlight key differences in understory cover and forage biomass between thinned and unthinned treatments. We identify tradeoffs between overstory and understory development following treatment, which will have impacts on future management planning. TWYGS is a hallmark of management-research collaboration, and provides much needed insight into young-growth silviculture throughout the temperate rainforest.

INTRODUCTION

Large-scale commercial logging in southeast Alaska began in the 1950s employing clearcutting as the predominant regeneration method. Stand development following clearcutting in southeast Alaska coastal rainforests typically includes natural regeneration of western hemlock (*Tsuga heterophylla* Raf. Sarg.) and Sitka spruce (*Picea sitchensis* Bong. Carr.) (Alaback 1982a, Deal et al. 1991) and rapid growth of *in situ* red alder (*Alnus rubra* Bong.) and shrubs (Alaback 1980, Robuck 1975). This phase of stand development, referred to as stand initiation (Oliver and Larson 1996), generally lasts for 15 to 25 years, depending on site quality. Within 10 years of clearcutting, newly established conifers begin to overtop the shrubs, and crown closure may be complete by 25 years (Harris and Farr 1974), leading to the stem exclusion phase of stand development. Stem exclusion occurs most rapidly on productive sites and may not occur for decades on in low-productivity sites. During the stem exclusion phase there is a nearly complete elimination of vascular understory vegetation (Alaback 1980, 1982b, 1984; Tappeiner and Alaback 1989). A century after harvest, the understory vegetation begins to re-establish but does not become well developed until the stand reaches 120 to 150 years of age as patch dynamics motivated by individual tree death opens the stand in the understory reinitiation phase (Alaback 1982b, 1984; Oliver and Larson 1996; Tappeiner and

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Alaback 1989). But until this phase of stand development, even-aged conifer stands in the stem exclusion phase after clearcutting are often recognized as having broadly negative consequences for wildlife and fish (Dellasala et al. 1996; Hanley 1993; Meehan et al. 1984; Schoen et al. 1981, 1988; Thedinga et al. 1989; Wallmo and Schoen 1980), particularly where dense, homogeneous canopy cover causes the loss of understory plants. Where even-aged stands form variable and patchy canopies, or in low-productivity areas, heterogeneous overstory cover and resource availability may promote or extend understory cover. Young-growth forests (i.e., second-growth, third-growth, etc.; forests developing following clearcutting old growth) present a challenge to forest managers attempting to maintain or improve understory plant communities for wildlife habitat while enhancing wood production.

There are about 295,000 ha of young-growth forest in southeast Alaska: 170,000 ha on the Tongass National Forest (NF), 18,000 ha on Alaska state lands, and 107,000 ha on Alaska Native corporation lands. Many young-growth stands are now entering or are well into the stem exclusion phase. Management strategies are needed for minimizing the length or the impact of this phase of stand development (i.e., near or total absence of understory vegetation), whether this be a change in rotation length, regeneration method, or intermediate treatments. Successful silvicultural treatments will either delay the onset or hasten the end of the stem exclusion phase, mitigating its effect by increasing light transmission through the overstory canopy.

From the 1970s to the 1980s, while the pulp industry was strong and active management was primarily focused on maximizing timber yield, forest managers typically prescribed precommercial thinnings to 2.4 to 3.0 m spacing, often at 15 to 25 years old. Throughout the 1990s, silviculturists on the Tongass NF increased spacing standards to 4.3 to 4.9 m and tried several alternatives to standard precommercial thinning: variable spacing, wide spacing (5.5 m or more), gaps and thickets, retention of hardwoods, etc. These operational treatments rarely followed the principles of experimental design and lacked appropriate controls, replication, and random assignment of treatments necessary to quantify consequences. Districts worked independently and there was no forest-wide coordination of testing. Follow-up monitoring, analysis, or reporting of these trials was done in only a few cases. It became apparent that a purely operational approach employing administrative studies or demonstration case studies would not yield credible evaluation of silvicultural options suitable to guide future management.

Nevertheless, the most useful long-term empirical evaluation of silvicultural options requires their application at a scale appropriate to routine forest management—i.e., tens of hectares, rather than the fractions of a hectare typical of research plots. Thus, managers and research ecologists collaborated to employ an adaptive management approach to evaluating young-growth silvicultural treatments. Adaptive management is one of several approaches to reduce uncertainty in difficult management environments (Peterson et al. 2003). Redford et al. (2018) paraphrase the early development of adaptive management ideas by Walter and Holling (1990) as an approach that "seeks to structure learning from actions to improve the likelihood of achieving desired outcomes." The Tongass-Wide Young-Growth Studies (TWYGS) project is an attempt to leverage the unique knowledge, skills, and resources of both managers and researchers to solve important young-growth management questions by employing active adaptive management under a research plot framework.

This paper documents the motivation, design, and establishment of TWYGS; reports findings from 16 years of measurement in the first of the four TWYGS studies to come online; and highlights the science-management partnership that has been integral to the success of such a long-term adaptive management project.

BACKGROUND AND OBJECTIVES

Past research has investigated the effectiveness of several silvicultural treatments on preventing or minimizing the stem exclusion phase of stand development. These include thinning, pruning, and enriching deciduous species composition in conifer stands. Because ecological processes in forests can differ markedly from region to region, we examined forestry literature from the Pacific Northwest, coastal British Columbia, and southeast Alaska.

Thinning in Conifer Stands

Precommercial thinning became common practice on the Tongass NF in the late 1970s, where it has since been applied to approximately 81,000 ha of young-growth stands in the forest. Traditionally, thinning has been used to reallocate resources and increase growth on selected crop trees and maximize timber outputs, but other possible benefits include delaying the onset of the stem exclusion phase, increasing understory plant diversity, and improving wildlife habitat (Nyland 2016). Attempts to re-establish understory herbs and shrubs through thinning young-growth conifer stands have had mixed success. For example, Deal and Farr (1994) found that thinning of young even-aged stands promoted tree growth but did not extend herbaceous production, and that wide spacing resulted in the establishment of a new cohort of western hemlock regeneration. On the other hand, Cole et al. (2010) found that precommercial thinning intensity had no effect on understories; rather, all thinning intensities (750, 500, 370, and 250 trees ha^{-1} in 16 to 18 year old stands) resulted in a 7-year pulse (the duration of the study) in understory vegetation production beyond the productive pretreatment conditions.

As part of the Forest Service Alaska region's second-growth management program (SGMP), five demonstration sites in southeast Alaska were commercially thinned in 1984–1985. The purpose of the study was to evaluate the ability of commercial thinning to enhance wood production, understory vegetation, and quality forage for Sitka black-tailed deer (*Odocoileus hemionus sitkensis*). Three separate thinning treatments were applied: (1) uniform individual tree selection (ITS), not to be confused with "selection" regeneration harvests or thinning methods; (2) strip + ITS, 7.6-m strips with 100 percent removal and matrix thinned to 6.1- to 7.6-m spacing, and (3) strip, alternating 6.1-m cut and leave strips. Thirteen to 14 years after treatment, strip and strip + ITS treatments had the greatest total understory biomass, but biomass was dominated by conifer regeneration (Zaborske et al. 2002). The ITS treatment had less understory biomass per hectare, but over half the biomass was in shrubs, ferns, and forbs which had greater nutritional value for deer. Estimates of deer-forage availability showed that the ITS treatment, which was the most conventional approach of the three treatments, created better forage resources for deer than did the other treatments, and that summer forage availability was similar to the values estimated for old-growth forest (Zaborske et al. 2002).

Other research has identified the effect of gap-making on understory development. Although not technically thinning, creating gaps in a stand is an intermediate treatment intended to improve its value to wildlife. Harris and Barnard (2017) found that understory biomass was eight times greater in gaps (150-m^2 to 430-m^2 openings) than in untreated skips, 23 years after treatment. Although gaps commonly recruit abundant western hemlock regeneration (Alaback, unpublished[2]; Harris and Barnard 2017), these studies suggest that small gaps or patchiness within stands prolong localized but enduring understory vegetation pools useful for deer forage.

[2] Unpublished report. Alaback, P.B. 2010. An evaluation of canopy gaps in restoring wildlife habitat in second growth forests of southeastern Alaska. 15 p. On file at the USDA Forest Service Pacific Northwest Research Station – Juneau Forestry Sciences Laboratory.

Pruning Conifers

In the early 1990s, five field trials were established in southeast Alaska to monitor the response of western hemlock and Sitka spruce to thinning and pruning (Petruncio 1994). Followup monitoring showed that developing high-quality clear wood in Sitka spruce was doubtful owing to the development of epicormic branches on pruned tree boles (Deal et al. 2003). Although pruning may not fully achieve wood-quality objectives, it may have added value for habitat objectives. Recent field observations of Petruncio's (1994) experiments suggest that thinning plus pruning was more effective than thinning alone in promoting understory diversity and abundance. Understory response was not measured immediately before and after thinning and pruning, so we can draw only limited inferences from it, but it is reasonable to conclude that pruning increased understory vigor by admitting sidelight from the low solar angles common to these northern latitudes.

Mixed Red Alder-Conifer Stands

Recent studies of mixed-conifer and red alder stands have indicated that alternative pathways to the stem exclusion phase (i.e., loss of understory vegetation) are possible following clearcutting in southeast Alaska (Hanley 2005). Logging practices used after 1970 aimed to reduce site impacts, and consisted of high-lead log yarding in which trees are carried through the air and soil disturbance is minimized. Following this type of logging, dense, uniform conifer stands develop to the exclusion of understory plants. Pre-1970 methods of logging resulted in considerable soil disturbance which made excellent seed beds for red alder to colonize (Ruth and Harris 1979). In contrast to the dense, uniform conifer stands following high-lead logging, alder-conifer mixed young-growth stands have a species-rich and highly productive understory with biomass quantity similar to that found in old-growth stands, with species composition tending toward devil's club (*Oplopanax horridus* (Sm.) Miq.), salmonberry (*Rubus spectabilis* Pursh), red elderberry (*Sambucus racemosa* L. var. *racemosa*), and ferns (Deal 1997, Hanley and Barnard 1998, Hanley and Hoel 1996, Hanley et al. 2006). This species-rich understory persists for as long as 45 years after logging with heavy forest floor scarification. Understory species richness was highest in stands with 18 to 51 percent alder and lowest in pure conifer or pure alder stands (Deal et al. 2004).

Management of Young-Growth Forests to Improve Wildlife Habitat

The response of birds to thinning of young-growth stands is highly variable and dependent upon foraging and nesting requirements particular to each species (Weikel and Hayes 1997, 1999). Although some species of birds increase in abundance following thinning, others have declined, and others have shown no measurable change (Adam et al. 1996, Dellasalla et al. 1996, Hagar et al. 1996, Hayes et al. 1997, Weikel and Hayes 1997). Many studies comparing thinned and unthinned stands have correlated differences in bird abundance with tree density, but have not documented other changes in vegetation resulting as a byproduct of thinning (i.e., understory vegetation, presence of snags, presence of hardwoods) that may be important to birds for nesting or foraging. Dellasalla et al. (1996) identified an increase in two species, dark-eyed Juncos (*Junco hyemalis*) and hermit thrushes (*Catharus guttatus*), to the percentage of forb cover, a habitat feature found to be higher in thinned than unthinned stands. Hagar et al. (1996) found that warbling vireos (*Vireo gilvus*) responded not only to thinning but also to associated habitat features such as tree species composition, cover of certain understory plants, and density of hardwoods.

The importance of hardwoods to birds breeding in coniferous forests of the Pacific Northwest and southeastern Alaska is not clear, but several studies suggest that mixed forest stands are higher quality habitat than pure conifer stands. Low bird diversity (southeast Alaska; Kessler and Kogut 1985) and abundance (British Columbia; Schwab 1979) have been found in dense young-growth conifer stands. Both bird abundance and diversity are positively associated with the density of deciduous trees in young-growth forests (Gilbert and Allwine 1991, Huff and Raley 1991, McComb 1994). The simple stand structure and sparse understory below dense young-growth canopies may limit the number of nest sites available to birds, and reduce nest concealment, a feature associated with successful nesting for some open-cup nesting species (reviewed by Kelly 1993, Martin 1993). Deciduous vegetation in coniferous stands is an important component for successful nesting in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantations in British Columbia (Easton and Martin 2002). Nesting density was higher in mixed than coniferous young-growth stands in southeast Alaska, where five species, including two cavity nesters, were found using red alder as a nesting substrate. Multiple studies suggest red alder is an important foraging substrate (De Santo, in preparation[3]; Gilbert and Allwine 1991; McComb 1994) and is preferred over conifers by some forest birds (Weikel and Hayes 1999). Furthermore, insect biomass is sometimes greater in deciduous vegetation (Allan et al. 2003, Stiles 1980, Willson and Comet 1996, Wipfli 1997), providing a necessary food source for insectivorous wildlife (e.g., birds, bats, small mammals).

Investigations suggest that some small mammals, such as shrew-moles (*Neurotrichus gibbsii*) and Trowbridge's shrews (*Sorex trowbridgii*), are more abundant in red alder stands than in conifer stands in Oregon (Gomez 1992). In southeast Alaska, Hanley (1996) found no significant differences between mixed red alder-conifer and nearby old-growth stands (primarily composed of conifers) in the abundance or growth rate of common shrews (*S. cinereus streatori*), deermice (*Peromyscus keeni*), or long-tailed voles (*Microtus longicaudus litoralis*), suggesting that habitat quality for these species in even-aged mixed stands may be equal to that of old-growth forests. Shrub cover in young-growth stands is positively associated with the abundances of some small mammals of the Olympic Peninsula (*Sorex trowbridgii*, *Clethrionomys gapperi*, *Neurotrichus gibbsii*, *Peromyscus oreas*, *P. maniculatus*; Carey and Johnson [1995]) and in the Oregon Coast Range (Townsend's chipmunks, *Tamias townsendii*; Hayes et al. [1995]).

Food value of understory vegetation for Sitka black-tailed deer depends on plant species composition and biomass (Hanley et al. 2012). Understory deer forage value was greater in alder and mixed alder-conifer stands than pure conifer stands (Hanley and Barnard 1998). In another study, both shrub and herbaceous production were positively correlated with red alder basal area in young-growth stands, which in turn was highly correlated with food resources for deer in summer but not in winter (Hanley et al. 2006). Understory species composition is very important for deer, with blueberry (*Vaccinium* spp.) shrubs and evergreen forbs most important in winter. Evergreen forbs (e.g., bunchberry dogwood [*Cornus canadensis* L.], five-leaved bramble [*Rubus pedatus* Sm.], fernleaf goldthread [*Coptis aspleniifolia* Salisb.], and threeleaf foamflower [*Tiarella trifoliata* L.]) are especially difficult to manage for because they are shaded by both overstory trees and understory shrubs. Thus, the temporal dynamics of stand development are an important consideration in silvicultural treatment design (Hanley 2005).

[3] De Santo, T. Manuscript in preparation. Passerine use of coniferous and mixed second-growth forests in southeast Alaska. Manuscript in preparation. On file at the USDA Forest Service Pacific Northwest Research Station – Juneau Forestry Sciences Laboratory.

Study Objectives

The TWYGS adaptive management project was designed to explore differences among silvicultural treatments of young-growth forests to meet multi-resource objectives. These studies assess the ability of intermediate silvicultural treatments to provide for wood production, wildlife habitat, and subsistence resources. The primary research objectives are to evaluate the response of vascular understory plants and overstory trees to several silvicultural practices—thinning (both by conventional means and by girdling), pruning, planting of red alder, and treatment of thinning slash. These studies are intended to last a minimum of 20 years in order to adequately assess the dynamic vegetation responses to silvicultural treatment.

The experimental treatments are intended to meet four general objectives:

1. Develop a more diverse vertical and horizontal forest structure than is found in unmanaged young-growth stands.
2. Reduce the length of time spent in the stem exclusion phase of stand development by delaying its onset or hastening the transition to understory re-initiation phase.
3. Increase (compared to no action) and maintain understory plant species richness, abundance, and productivity, especially key forages for Sitka black-tailed deer.
4. Maintain or improve wood production with sufficient quantity and quality to yield commercial products.

TWYGS includes four experiments, described in depth in the following section (Table 1):

1. A test of mixed hardwood-conifer stands, created by planting red alder at low and moderate densities in 0- to 5-year-old stands. This age range should allow for the successful planting and establishment of red alder, a shade-intolerant species.
2. A test of moderate and heavy precommercial thinning in 15- to 25-year-old stands. This is the normal age range for precommercial thinning in southeast Alaska.
3. A test of moderately heavy precommercial thinning combined with two pruning treatments, in 25- to 35-year-old stands. This is the typical age for pruning in southeast Alaska.
4. A test comparing girdling and conventional precommercial thinning, with and without slash treatment, in stands over 35 years old. This treatment examines stands beyond the typical age range for precommercial thinning (though not yet large enough for commercial products), but was representative of the many older, productive, young-growth stands within the beach fringe, where timber harvesting is currently restricted on the Tongass NF.

Table 1.—Replicates and areas by TWYGS experiment. Experiment 1 is a test of mixed hardwood/conifer stands, created by planting red alder at low and moderate densities, Experiment 2 is a test of moderate and heavy pre-commercial thinning, Experiment 3 is a test of moderately heavy pre-commercial thinning combined with two pruning treatments, and Experiment 4 is a test a comparing girdling and pre-commercial thinning with slash treatment.

Experiment	Age range (years at treatment)	Blocks (remaining)[a]	Total area (ha)	Average area (ha) per unit	Year treated
1	0-5	23 (23)	359	15.6	2003
2	15-25	20 (18)	712	35.6	2002
3	25-35	19 (13)	718	37.8	2002-3
4	35+	17 (17)	211	12.4	2006

[a1]Values in parentheses refer to the number of blocks still in the study as of 2019.

PROJECT ESTABLISHMENT

Experimental Design, Site Selection, and Layout

Each of the four experiments used a randomized complete block design, with 17 to 23 blocks established throughout the Tongass NF (excluding Yakutat Ranger District) from 2002 to 2006 (Fig. 1). In most cases the experimental blocks were laid out within a single harvest unit, which was divided into three to five experimental units, depending on the number of treatments in the experiment (Fig. 2). In some blocks, the experimental units were created from adjacent harvest units to increase experimental unit sizes.

Young stands needed to meet several criteria to be included in this study. All harvest units had a site index of at least 22.9 m (50-yr basis; Farr 1984) and were located at elevations lower than 365 m above mean sea level. Most units had a southerly aspect so they would be in deer winter range. Within-unit site productivity, stand density, and stand composition were required to be relatively uniform. Units were not previously thinned or weeded.

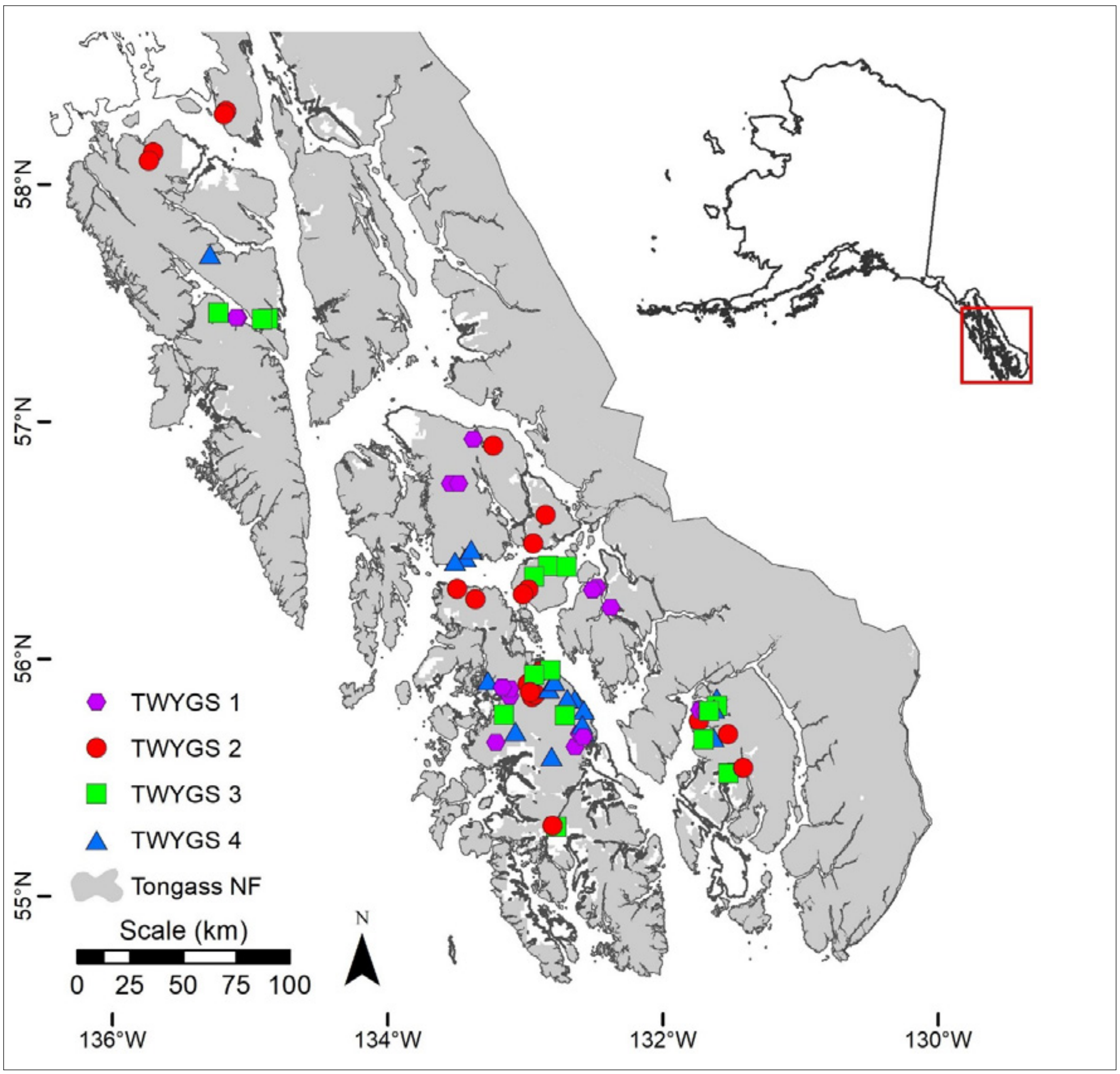

Figure 1.—Tongass National Forest, with installation locations from each of the four experiments in the Tongass-Wide Young-Growth Studies (TWYGS).

Experimental units were delineated to minimize edge effects, and 30- to 46-m untreated buffers were left between experimental units. When possible, buffers coincided with untreated stream buffers. To conduct the studies at an operational scale and to incorporate typical levels of within-stand heterogeneity, the desired minimum size of the experimental units was set at 4 ha. The total area per block and the average experimental unit area varied widely among the four experiments (Table 1). Treatments were randomly assigned to experimental units (Fig 2).

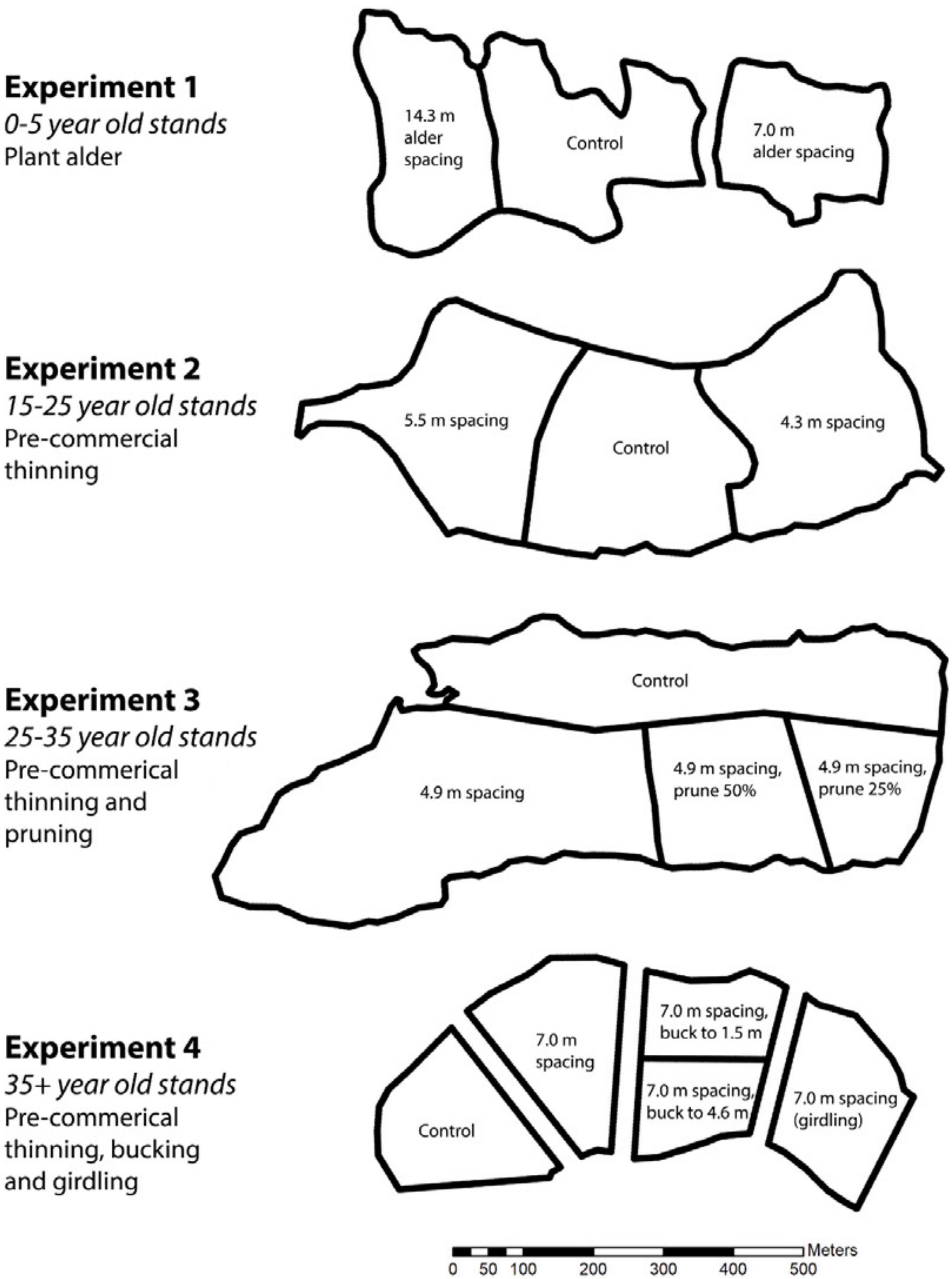

Figure 2.—Conceptual diagram of treatments within installations for each of the four Tongass-Wide Young-Growth Studies experiments.

Experiment 1: Planting red alder in 0- to 5-year-old conifer stands

Three treatments were included in Experiment 1:

1. A control, where no red alder were planted.
2. Red alder planted at low density (49 trees per hectare, 14.3-m spacing).
3. Red alder planted at moderate density (198 trees per hectare, 7.0-m spacing).

Complete sets of treatments were replicated in 23 blocks. The red alder planting stock was grown from seed collected in southeast Alaska, producing bare-root 1-0 seedlings, 30 to 61 cm tall. Contractors planted alder in the spring and summer of 2003. Seedlings were planted in a 0.1-m^2 scarified area of mineral or mixed organic and mineral soil, at least 1.5 m from any conifer that would compete with it within 5 years.

Experiment 2: Precommercial thinning of 15- to 25-year-old conifer stands

Three treatments were included in Experiment 2:

1. A control, where no thinning was done.
2. Moderate precommercial thinning to 548 conifers per ha (4.3-m spacing), allowing for a spacing variation of plus or minus 50 percent (2.1 to 6.4 m).
3. Heavy precommercial thinning to 333 conifers per ha (5.5-m spacing), allowing for a spacing variation of plus or minus 50 percent (2.7 to 8.2 m).

Complete sets of treatments were replicated in 20 blocks. Red alder was not removed, but western hemlock and Sitka spruce were removed with equal preference. Red cedar (*Thuja plicata* Donn ex. D. Don) and Alaska yellow cedar (*Callitropsis nootkatensis* (D. Don) Oerst. ex D.P. Little) presence are variable across the forest, so preference for these species (hereafter, cedar) was considered at the site level. Where cedar was common, it was treated as other conifers and considered for removal; in areas where cedar was uncommon, it was retained. Retained conifers were selected based on height, form, vigor, and freedom from disease. Thinning was performed by chainsaw. A 3.0- to 6.1-m buffer was retained on either side of streams and an effort was made to avoid depositing slash into streams.

Experiment 3: Precommercial thinning and pruning of 25- to 35-year-old conifer stands

Four treatments were included in Experiment 3:

1. A control, where no thinning or pruning was done.
2. Moderately heavy precommercial thinning to 420 conifers per ha (4.9-m spacing), allowing for a spacing variation of plus or minus 50 percent (2.4 to 7.3 m). Stands were thinned but not pruned.
3. Precommercial thinning, as (2) above. In addition, 25 percent of the conifers on an area basis were pruned (106 trees per ha) up to no more than one-half of the total tree height in 2.7 to 5.2-m lifts. Trees selected for pruning were distributed as evenly as possible across the unit while selecting for the largest diameter trees.
4. Precommercial thinning, as (2) above. In addition, 50 percent of the conifers (212 trees per ha) were pruned, as (3) above.

Complete sets of treatments were replicated in 19 blocks. Species retention preferences were the same as Experiment 2. Retained trees were selected based on height, form, vigor, and freedom from disease. Conifers selected for thinning were girdled with a double chainsaw cut if they were greater than 18 cm in diameter; smaller trees were cut down completely by chainsaw. A 3.0- to 6.1-m buffer was retained on either side of streams, and an effort was made to avoid depositing slash into streams.

Experiment 4: Precommercial thinning of conifer stands 35 years old or older

Five treatments were included in Experiment 4:

1. A control, where no thinning or slashing was done.
2. Heavy precommercial thinning to 198 conifers per ha (7.0-m spacing). Thinning was accomplished by conventional methods, i.e., felling the tree with a chainsaw. Thinning slash was not treated.
3. Precommercial thinning, as (2) above. Thinning slash was treated by cutting downed boles into 4.6-m lengths.
4. Precommercial thinning, as (2) above. Thinning slash was treated by cutting downed boles into 1.5-m lengths.
5. Precommercial thinning, as (2) above, but thinning was accomplished by girdling the tree with a chainsaw (not felling). Thinning slash was not treated.

Complete sets of treatments were replicated in 17 blocks. Species retention preferences were the same as Experiment 2 and 3. Retained trees were selected based on height, form, vigor, and freedom from disease. A 3.0- to 6.1-m buffer was retained on either side of streams, and an effort was made to avoid depositing slash into streams.

VEGETATION RESPONSE TO EXPERIMENT 2: 16-YEAR DYNAMICS

Methods

Data collection

A grid of five systematically located, 0.05-ha permanent plots were installed in each experimental unit (see above text). Plots were established at least 25 m from the treatment boundary to reduce edge effects. Overstory and understory data were collected in 2007, 2012, and 2018 (5, 10, and 16 years after treatment, respectively).

We assessed unit overstories by recording status (live or dead), species, and diameter at breast height (d.b.h.; 1.37 m) for all standing trees >2.5 cm d.b.h. within each thinned plot. In most control plots, it was impractical to measure all trees because of high density (>3000 trees ha^{-1}) and a grid of nine, 9-m^2 subplots was established to sample overstory attributes. We measured canopy cover on each plot by taking canopy photos at plot center using a fisheye lens on a Nikon D5000 digital camera; cover was estimated using Gap Light Analyzer (in 2007) (Frazer et al. 1999) or HemiView (2012 and 2018) (Rich et al. 1999). Canopy cover estimates by these two programs are comparable in these young-growth stands (pers. obs., J. Crotteau).

Field crews visually identified and estimated areal cover of each vascular understory species (≤1.3 m tall) in sixty, 1-m^2 quadrats per unit, which were distributed evenly and systematically across permanent plots, at least 6 m from plot centers to avoid trampling. Nonwoody understory biomass (hereafter, just “understory biomass”; kg ha^{-1}) was estimated for these quadrats using cover-to-biomass regressions that we developed. We destructively sampled understory biomass (i.e., dry weight) for each species by clipping and weighing plants across a range of targeted cover values (from 1 to 100 percent cover, by ~10 percent increments).

Biomass samples were located within the treatment units but outside the permanent plots, and only at installations connected to the Prince of Wales road system for access to drying ovens. After oven-drying plant materials at 100 °C for at least 24 hours as weight stabilized, we developed cover-to-biomass regressions for current annual growth of each forage type (i.e., leaves and twigs, not woody growth). Separate regressions were fit for each measurement year because relationships may vary based on environmental factors. For uncommon species that lacked sufficient observations, we used local regression equations (Hanley, unpublished data[4]). Canopy and biomass data were collected from mid-June through mid-August to coincide with peak understory development (per Hanley et al. 2012).

Analytical methods

We calculated stand density (trees ha^{-1}) and stand density index (SDI) (Reineke 1933) for each treatment unit to evaluate the effects of the treatments on the stand structure and understory dynamics. All cover and biomass data were analyzed at the unit level. Understory biomass (kg ha^{-1}) for each species was calculated using cover-to-biomass regressions, then summed by functional class in each unit, where functional classes were ferns, forbs, graminoids, shrubs, and understory trees.

We fit linear mixed-effects models to square-root-transformed understory biomass using lme4 (Bates et al. 2015) and lmerTest (Kuznetsova et al. 2017) in R (R Core Team 2016). We assessed biomass by understory functional class to understand how treatment affects understory structure and functional composition over time. Model fixed-effects included two *a priori* orthogonal contrasts and their interaction with sampling event (three levels: visit 1, 2, and 3 in 2007, 2012, and 2018, respectively). Orthogonal contrasts were defined as the thinning effect, where treatment units were pooled and contrasted with the untreated control, and the thinning intensity effect, where the heavy thinning was contrasted with the moderate-intensity thinning. We established visit 2 (2012) instead of visit 1 as the baseline sampling event to have the model calculate the temporal contrasts we were interested in. We considered this a more efficient statistical means to interpret the changes over time, especially because none of our visits represent an immediately pretreatment or post-treatment "baseline." Installation ("site" or "block") was treated as a random-effect.

Additionally, we calculated the ratio of biomass in thinned units to control units to further evaluate understory response to thinning.

Species composition is an important ecological attribute of understory development. To supplement our analysis of biomass by functional class, we isolated and summarized the species with >10 percent relative cover in each treatment type to evaluate how treatment affects dominant understory species.

We used the Forage Resource Evaluation System for Habitat (FRESH)-Deer model (Hanley et al. 2012) to quantify the habitat value for Sitka black-tailed deer. FRESH-Deer integrates substantial field and laboratory studies of the nutritional characteristics of forages in southeast Alaska and studies of deer metabolic requirements (Hanley et al. 2012). This model calculates "deer days" per hectare, where 1 deer day is defined as the food resources necessary to sustain one adult female deer for 1 day. FRESH-Deer does not consider herbivore-plant interactions, deer population dynamics, or physical accessibility through stands, so the model output should be interpreted as the potential forage at a single point in time. FRESH-deer provides an upper bound on the number of deer a habitat can support with currently available forage

[4] Data on file at the USDA Forest Service Pacific, Northwest Research Station, Juneau Forestry Science Laboratory.

Table 2.—Mean overstory characteristics (and standard error) following treatment in the Tongass-Wide Young-Growth Studies Experiment 2 (TWYGS 2). Stands were precommercially thinned to 4.3-m or 5.5-m spacing in 2002, then measured in 2007, 2012, and 2018. Density and relative density refer to trees with diameter at breast height ≥2.5 cm. Stand density index (SDI) is the metric equivalent (25.4 cm diameter at breast height trees ha^{-1}) of Reineke's (1933) SDI.

	Canopy cover (percent)			Density (trees ha^{-1})			Stand density index		
	Control	4.3 m	5.5 m	Control	4.3 m	5.5 m	Control	4.3 m	5.5 m
2007	88 (1.7)	68.4 (3)	61.8 (2.4)	5223 (88)	514 (22)	394 (12)	759 (88)	208 (22)	159 (12)
2012	84.1 (1.8)	72.3 (2.5)	65.7 (2.9)	5638 (111)	560 (25)	452 (18)	1117 (111)	371 (25)	286 (18)
2018	92.2 (1.2)	84.2 (2.7)	83.2 (2)	6282 (225)	818 (34)	929 (28)	1745 (225)	505 (34)	453 (28)

as the limiting factor. These results provide a quantitative forage value to compare between treatment alternatives, and should not be interpreted as an absolute representation of how many deer a stand supports (Hanley et al. 2012).

We used the FRESH-Deer model to calculate deer days for all units in two summer and six winter scenarios. In the summer scenarios, the model uses all available understory biomass but different metabolic requirements, with one assuming a solo female (maintenance) and the other assuming a mother with a fawn (maintenance + lactation). In the winter scenarios, forage nutritional values reflect only the plant biomass that persists through the winter and that remains unburied by snow, and the metabolic requirements are changed to represent deer winter needs. FRESH-deer uses a nonlinear relationship between canopy cover and forest floor snow depth to determine forage availability; we modeled six snowfall scenarios ranging from 0 to 100 cm to demonstrate a range of winter forage conditions based on snowfall. We use "deer forage" as the integration of edible understory biomass and nutritional content, as represented by FRESH deer days ha^{-1}. Treatment effect on deer forage in each scenario was assessed using the mixed-effects modeling procedure described above.

Results

Overstory context

Treated units were thinned to 4.3-m and 5.5-m spacing (549 and 332 trees ha^{-1}, respectively). Five years after treatment (in 2007), treated units were still within 20 percent of target tree densities (Table 2); by 16 years after treatment (in 2018), units increased to 49 percent and 180 percent more trees than initial prescriptions in the 4.3-m and 5.5-m treatments, respectively. Despite the large difference in tree density growth between the 4.3-m and 5.5-m treatments, mean SDI growth from year 5 to 16 was nearly identical (increased by 300). The misalignment between density growth and SDI growth across treatments shows that the 5.5-m treatment was inundated with ingrowth (primarily western hemlock), which was less present in the 4.3-m treatment. Ingrowth also occurred in the control treatment, where the increase in SDI was 3.3 times what we observed in treated units because of the large number of saplings already present. Overall, large changes in tree densities resulted in minor increases to the already high canopy cover in the control. The slight canopy cover differences between 4.3-m and 5.5-m treatments in 2007 disappeared by 2018 owing to growth that increased with treatment intensity, but both treatments still had noticeably more open canopies than the controls in the final measurement.

Understory biomass and composition

Total understory biomass varied by treatment and year (Fig. 3). Biomass in thinned units was approximately 1 metric ton ha^{-1} in 2007, with less in subsequent years, but lowest in 2012 (10 years after treatment; Table 3; $p < 0.001$). Crotteau et al. (2020) identified that annual states of understory biomass in southeast Alaska are sensitive to both exogenous (climatic) and endogenous (stand density) influences, which explains some of the variation along the y-axis in Figure 3. In this analysis, we found that total understory biomass was consistently three to six times greater in the thinned units than the controls ($p < 0.001$). Total biomass varied by thinning treatment intensity (i.e., was greater in 5.5-m than 4.3-m treatment) in 2007, but not in 2012 or 2018 ($p < 0.01$).

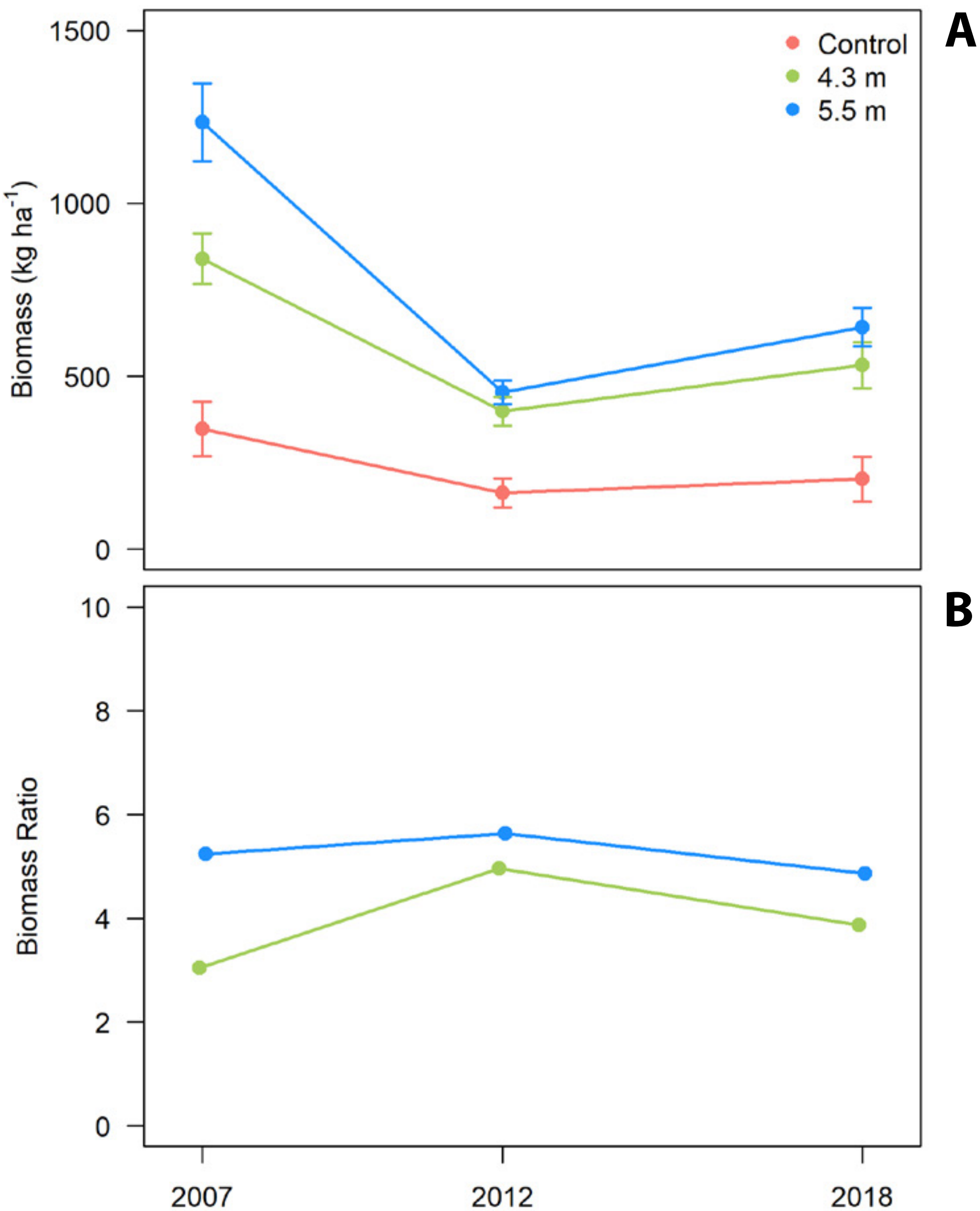

Figure 3.—Total nonwoody understory biomass dynamics in the TWYGS Experiment 2. Stands were precommercially thinned to 4.3-m or 5.5-m in 2002. Fig. 3A shows the total (nonwoody) understory biomass (kg ha^{-1}) from each of three treatments, including the control; Fig. 3B shows the median ratios of biomass in the thinned units relative to the control unit.

Table 3.—Treatment effects on understory biomass by functional class in the Tongass-Wide Young-Growth Studies Experiment 2 (TWYGS 2). Stands were treated in 2002 then measured in 2007 (visit 1), 2012 (visit 2), and 2018 (visit 3). Contrasts were defined as a priori orthogonal linear contrasts within fitted mixed-effects linear models of treatment on square-root transformed understory biomass. Statistical effects are displayed by direction ("+" for positive, "-" for negative) and strength of effect ("+++" = P ≤ 0.01, "++" = 0.01 < P-value ≤ 0.05, "+" = 0.05 < P-value ≤ 0.10, and [blank] for P-value > 0.10).

Contrast	Group mean tested (+)	Group mean tested against (-)	Total	Graminoid	Forb	Fern	Shrub	Tree
Early effect	visit 1	visit 2	+++	+	+++	+++	+++	+++
Late effect	visit 3	visit 2	+++					+++
Overall thinning	Treated (4.3 and 5.5 m)	Control	+++	+++	+++	+++	+++	+++
Overall thinning × early effect	Treated vs. control, in visit 1	Treated vs. control, in visit 2	+++				+++	
Overall thinning × late effect	Treated vs. control, in visit 3	Treated vs. control, in visit 2						++
Thinning intensity	5.5 m	4.3 m		+++				++
Thinning intensity × early effect	5.5 vs. 4.3 m, in visit 1	5.5 vs. 4.3 m, in visit 2	++		++			
Thinning intensity × late effect	5.5 vs. 4.3 m, in visit 3	5.5 vs. 4.3 m, in visit 2				+		

Table 4.—Percentage cover of dominant understory species in the Tongass-Wide Young-Growth Studies Experiment 2 (TWYGS 2). Stands were treated in 2002. "Dominant" refers to species that comprise at least 10 percent of the total understory composition within each treatment (Control, 4.3 m overstory spacing, and 5.5 m overstory spacing) and measurement year (2007, 2012, and 2018).

	Control			4.3 m			5.5 m		
	2007	2012	2018	2007	2012	2018	2007	2012	2018
Cornus canadensis							9.9		
Vaccinium ovalifolium	9.2	4.3		18.6	13.8	23.7	20.6	14.3	21.5
Menziesia ferruginea	5.2		3.7	7.4	7.9	17.3		8.0	16.6
Rubus spectabilis		3.1		12.1	7.6		13.6	10.8	12.2
Vaccinium parvifolium			2.5						
Tsuga heterophylla	4.9								

Understory biomass by plant functional type exhibited only minor variations from the observed total understory biomass trends (Table 3). Just as with total biomass, all functional classes had greater biomass in thinned units than controls ($p < 0.001$), and all classes had more biomass in 2007 than 2012 ($p < 0.05$). Like total biomass, forbs responded positively to treatment intensity in 2007, the positive treatment effect was greater on shrubs in 2007 than 2012, and trees had more biomass in 2018 than 2012 ($p < 0.01$). Unlike the trends we observed in total biomass, however, there were positive thinning intensity effects on graminoid and tree biomass throughout, as well as on ferns in 2018, and 2018 thinning intensity effect on trees was greater than 2012 ($p < 0.05$).

Typical dominant species in thinned units were *Vaccinium ovalifolium*, *Menziesii feruginea*, and *Rubus spectabilis* (Table 4). *V. ovalifolium*, which reached upwards of 20 percent cover by 2018, is an especially important understory plant as it provides both palatable leaves and twigs as well as carbohydrate-rich berries eaten by nearly all local wildlife. Dominant vegetation was very similar across thinned treatments, though the evergreen *Cornus canadensis* comprised a notable portion of the 5.5-m treatment understory in 2007, 5 years following treatment. The control treatment was sometimes characterized by other dominant understory species, such as *V. parvifolium* and *Tsuga heterophylla*, but no dominant species ever had greater than 10 percent cover in any measurement year.

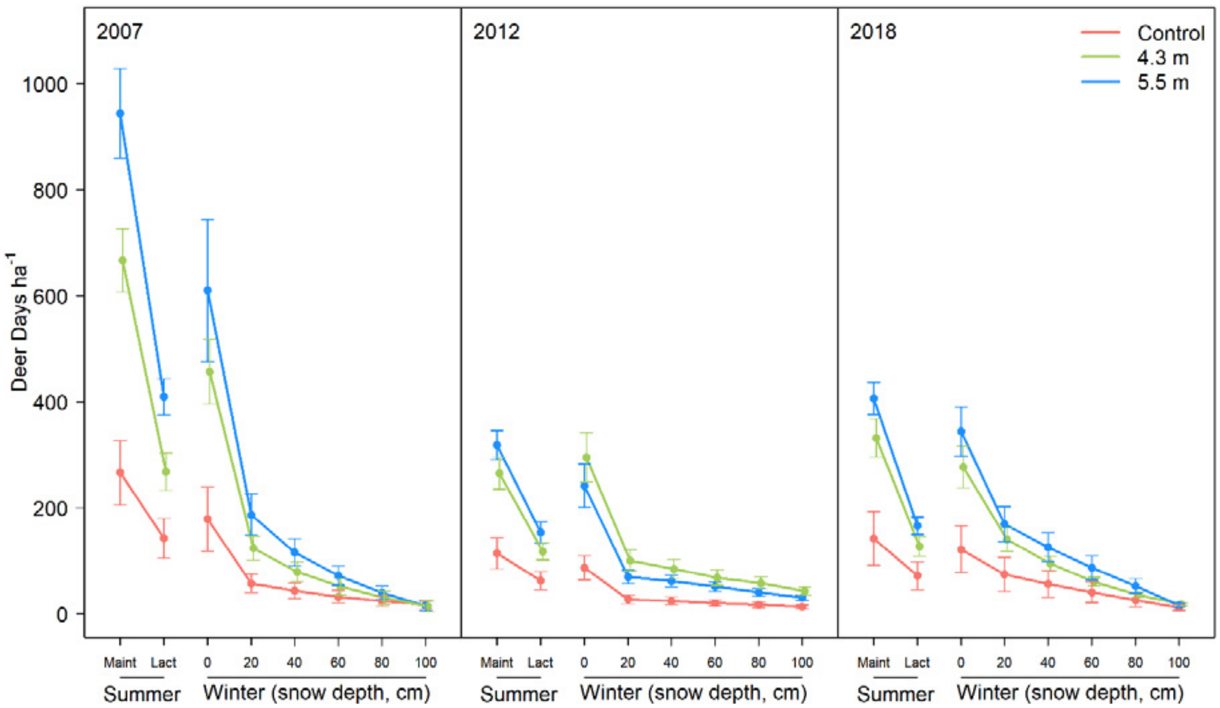

Figure 4.—Deer forage (i.e., deer days ha^{-1}, as defined by Hanley et al.'s (2012) FRESH-deer model) for two summer and six winter scenarios in the Tongass-Wide Young-Growth Studies Experiment 2. Stands were precommercially thinned to 4.3-m and 5.5-m in 2002 then measured in 2007 (visit 1), 2012 (visit 2), and 2018 (visit 3). Summer scenarios include single doe maintenance (Maint), and lactating doe (Lact); winter scenarios include maintenance given snow depths of 0 cm, 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm.

Deer forage

Deer forage exhibited substantial variability across the combinations of treatment, measurement year, and FRESH-deer scenario, ranging from 944.5 deer days ha^{-1} in the 5.5-m treatment in 2007 to only 12.3 deer days ha^{-1} in the control in 2018 (Fig. 4). Deer forage in lactation scenarios was on average 56 percent lower than single fawn maintenance scenarios, according to increased nutritional needs. Additionally, available deer forage declined rapidly with snowfall; 100 cm of snowfall left just 7 percent of winter forage accessible to deer. Yet, available deer forage in thinned units was always significantly greater than the controls ($p \leq 0.001$), except for in the 80- and 100-cm scenarios in 2007 (Table 5). There were some variations in deer forage over time, likely as a result of the climatological factors that caused 2012 plant biomass to be low (i.e., cool temperatures or low precipitation). This resulted in a greater effect of thinning in 2007 than 2012 on summer forage ($p < 0.01$), and greater effect of thinning in 2018 than 2012 for half of the winter scenarios and the summer lactation scenario ($p < 0.05$). Although we observed differences in understory biomass owing to thinning intensity, the deer forage data show no evidence of significant differences between the 5.5-m and 4.3-m thinning treatments (Table 5).

Discussion

This study reveals long-term understory dynamics following treatments designed to simultaneously develop timber and deer forage, and notably demonstrates the long-lasting, biologically significant benefits of thinning on understory development. Our 16-year analysis of TWYGS Experiment 2, precommercial thinning in 15- to 25-year-old stands, revealed that understories behaved dynamically following treatment, but generally followed a predictable pattern, and differences between treatments were relatively stable over time. Overall,

Table 5.—Treatment effects on deer forage for two summer and six winter scenarios in the Tongass-Wide Young-Growth Studies Experiment 2 (TWYGS 2). Stands were treated in 2002 then measured in 2007 (visit 1), 2012 (visit 2), and 2018 (visit 3). Contrasts were defined as a priori orthogonal linear contrasts within fitted mixed-effects linear models of treatment on deer forage (i.e., deer days ha^{-1}, as defined by the FRESH-deer model (Hanley et al. 2012). Statistical effects are displayed by direction ("+" for positive, "-" for negative) and strength of effect ("+++" = P ≤ 0.01, "++" = 0.01 < P-value ≤ 0.05, "+" = 0.05 < P-value ≤ 0.10, and [blank] for P-value > 0.10).

			Summer		Winter					
Contrast	Group mean tested (+)	Group mean tested against (-)	Maintenance	Lactation	No Snow	20cm	40cm	60cm	80cm	100cm
Early effect	visit 1	visit 2		+++	+++	+++			---	---
Late effect	visit 3	visit 2	++			+++	+++			---
Overall thinning	Treated (4.3 and 5.5 m)	Control	+++	+++	+++	+++	+++	+++	+++	+++
Overall thinning × early effect	Treated vs. control, in visit 1	Treated vs. control, in visit 2	+++	++					--	---
Overall thinning × late effect	Treated vs. control, in visit 3	Treated vs. control, in visit 2		+		++	+		+	
Thinning intensity	5.5 m	4.3 m								
Thinning intensity × early effect	5.5 vs. 4.3 m, in visit 1	5.5 vs. 4.3 m, in visit 2								
Thinning intensity × late effect	5.5 vs. 4.3 m, in visit 3	5.5 vs. 4.3 m, in visit 2								

understory biomass and deer forage decreased with time since thinning, with some variation likely owing to regional climatological drivers (Anderson et al. 1969, Crotteau et al. 2020). This decrease was expected because overstories have become denser as crowns expand upward and outward, and resources once available to the understory were increasingly used up by the more dominant overstory (Alaback, 1982a, Oliver and Larson 1996). Understory biomass in the untreated control was an order of magnitude less than expected for this stand age range given Alaback's research (1982a), which included woody understory biomass, but was similar to nonwoody biomass in untreated 38- to 42-year-old mixed alder-conifer stands in southeast Alaska (Hanley et al. 2006). As the canopy continues to close with overstory growth, we expect the understory in untreated controls to be further excluded in the next decade according to the competitive stand development trends identified by these studies.

The principal research question in this study was, what is the effect of thinning on the forest understory, and how long does that effect last? Our analysis revealed that thinning (1) increased understory biomass three to six times more in thinned than unthinned treatments; (2) changed species composition (higher cover by *V. ovalifolium*, especially); and (3) increased forage available to Sitka black-tailed deer (except for in the 80- and 100-cm snowfall scenarios at the first visit, 2007). Although 5-year results for this study were published, it was unclear if these trends would continue over the next decade (Hanley et al. 2013). In 16- to 17- year-old stands that were treated on nearby tribal land, Cole et al. (2010) found that post-thinning understory production exceeded baseline conditions for 7 years, after which understory biomass in thinned stands was still significantly greater than in unthinned stands. This study extended the findings from Hanley et al. (2013) and Cole et al. (2010), providing evidence for the longevity of precommercial thinning to produce and maintain understory biomass. We found that the proportion of biomass in thinned versus unthinned units has been stable across all three measurements. In this respect, treatment effectiveness has not diminished in 16 years. However, understory biomass composition is very important for biodiversity and forage mixing. Key understory species for deer forage include *Coptis aspleniifolia*, *Cornus canadensis*, *Rubus pedatus*, *Tiarella trifoliata*, and *Vaccinium ovalifolium*. Of these species, only

C. canadensis and *V. ovalifolium* attained at least 10 percent of total species composition, the former only breaching this threshold early in the 5.5-m treatment and the latter notably more abundant in the thinned units. FRESH-deer integrated cover with composition for deer forage. Although species assemblages within each of the TWYGS stands were far more complex than the simple dominant species listed in Table 4, our model analysis of forage suggested that assessment by dominant species was sufficient to identify the key differences amongst the treatments: namely, that there was much greater cover of one or two very important deer forage species in thinned treatments than unthinned treatments. Thus, abundance of *V. ovalifolium*, especially, may be a reliable indicator of deer forage habitat suitability in these young-growth stands.

This study also sought to examine whether residual tree spacing has an appreciable impact on understory vegetation. We identified some limited differences in understory between 4.3-m and 5.5-m spacing, and they changed with time. The 5.5-m spacing treatment had greater graminoid and tree biomass throughout the measurements, but by 16 years also had greater fern biomass. Yet, shrubs dominated composition in both treatments, which led to the lack of significant difference in deer forage between thinning treatments. It is not surprising that we found no significant difference in deer forage between active thinning treatments given the similar spacing prescriptions. Post-treatment overstories in these treatments were strikingly similar compared to the control—9.8 percent (4.3-m treatment) and 7.5 percent (5.5-m treatment) of control tree density (overstory trees ha^{-1}) in 2007. Other studies have similarly found minor thinning variations do not make as much of a difference as thinning itself, or stand age at treatment (Cole et al. 2010, Zhang et al. 2013). One of the management implications for this finding is that the wider 5.5-m spacing is not recommended for future treatment, as it is more expensive to implement, detrimental to timber quality because it promotes larger knots and more juvenile wood, and produces no detectable benefits to deer forage. The 4.3-m spacing accomplishes as much understory benefit for reduced investment and greater yield.

SCIENCE-MANAGEMENT PARTNERSHIP

Long-term silvicultural experiments like this require committed collaboration between managers and scientists. The multi-decade TWYGS partnership between the Tongass NF and the Pacific Northwest Research Station enabled stakeholder-driven problem identification, rigorous experimental design, regular monitoring and upkeep, scientific analysis, and an open channel for communication of results and future needs. The longevity of the program grew, in part, from the research-management partnership. This co-production model of science supports land management decisions and brings together specialists with complementary skills to answer questions neither could answer alone, ultimately producing knowledge critical for complex land management decisionmaking (Enquist et al. 2017).

The TWYGS partnership was established as a vehicle for adaptive forest management to examine a dominant uncertainty facing the Tongass NF, namely, balancing multiple uses in developing young-growth forests. The partnership acknowledges differing skills and interests between personnel in research and management, uniting them to examine long-term questions of interest to both parties. As the partners monitor and learn from varied young-growth strategies, the growing body of knowledge will facilitate adjustments to future silvicultural prescriptions to yield both timber and wildlife habitat, while contributing to the broader knowledge of coastal rainforest dynamics. The focus on a dominant uncertainty—a difficult science and management conundrum—is a key element of adaptive management, which includes the iterative cycle that begins with assessing the uncertainty, designing a treatment focused on the specifics of that uncertainty, implementing an experimental design, monitoring outcomes, evaluating results, adjusting management treatments, and repeating (Nyberg 1999). In fact, the personal observations from the TWYGS experiments recently contributed to significant land management decisions. Managers on the Tongass NF used evidence from TWYGS to adjust precommercial treatments in at least three ways. First, Experiment 3 suggested that pruning may be valuable for both wildlife and wood quality, so pruning has been implemented more rigorously in subsequent treatments. Second, the implementation of Experiment 4 revealed that slash treatment (i.e., bucking felled trees to be left on site) was too expensive to put into practice. And third, many trees girdled in Experiment 4 quickly snapped at the girdle point because of the double-cut chainsaw technique used. Managers continue to prescribe girdling, but now specify a technique that shaves off the bark rather than cuts into the wood to improve snag stability. As the TWYGS experiments mature, we expect the research-management partnership will continue to provide practical insights that refine forest practices according to the adaptive management cycle on the Tongass NF.

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