Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Pacific Northwest Research Station | General Technical Report PNW-GTR-1027 | March 2025

Managing Second-growth Forests in Southeast Alaska for Deer Habitat, Timber, and Carbon Sequestration—Informing Multiobjective Forest Planning

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Abstract

Labarre, Clémence; Nicholls, David; Tóth, Sándor F. 2025. Managing second-growth timber in southeast Alaska for deer habitat and carbon sequestration—informing multiobjective forest planning. Gen. Tech. Rep. PNW-GTR-1027. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 25 p. https://doi.org/10.2737/pnw-gtr-1027.

The Tongass National Forest has a rich history of serving its inhabitants for thousands of years, providing a variety of ecosystem services. Often, there are competing interests for the limited forest resources that provide the ecosystem services most in demand. In this study, we laid the groundwork for assessing three leading ecosystem services—timber, carbon sequestration, and wildlife habitat (specifically deer habitat). We examined in detail the tradeoffs among these ecosystem services and how stakeholders will use them. We projected the future needs and ecosystem services likely to be in demand, including forest carbon sequestration. We also considered present-day issues, such as the development of wood products infrastructure, and a viable second-growth timber utilization industry.

Today there are diverse stakeholder groups in Alaska, including conservation organizations, Alaska Native corporations, forest-dependent communities, Native villages, and U.S. Department of Agriculture, Forest Service land managers. We found that stakeholders agreed upon a select number of ecosystem services that were most important, and there were feasible ways to minimize tradeoffs among these services with proper planning and management. Some considerations included distance from deer forage to old growth, scheduling of precommercial thinning activities, optimizing road layouts to facilitate mill access, and timing of second-growth timber harvests to maximize yield.

In this study, we reviewed the current state of knowledge of the relations among second-growth timber management, subsistence deer habitat, and carbon sequestration to inform our proposed multiobjective forest planning model. We briefly described the model itself. We also reported our preliminary research findings on an illustrative pilot study in the Thorne Bay area, Prince of Wales Island.

KEYWORDS:

Alaska
Ecosystem services
Timber
Tongass National Forest
Wildlife habitat
Young-growth

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Introduction

Background and Context

The Tongass National Forest in southeast Alaska represents one of the largest intact old-growth temperate rainforests in the world, storing a total of 2 to 3 Pg of carbon, or 8 percent of the total forest carbon in the conterminous United States (Leighty et al. 2006). Large patches of intact, productive old-growth remain in the Tongass National Forest, covering about 2.1 million ha. There are also about 295 000 ha of young-growth forest in southeast Alaska. This includes 170 000 ha on the Tongass National Forest, 18 000 ha on Alaska state lands, and 107 000 ha on Alaska Native corporation lands (Crotteau et al. 2020). Many of these stands were initiated following harvests to supply the two regional pulpmills, (which closed in the 1990s), and will soon be reaching merchantable size. At close to 7 million ha, the Tongass National Forest is a diverse forest, offering an array of ecosystem services to its nearly 75,000 regional population.

The wood products infrastructure in southeast Alaska is relatively limited, with few production-scale sawmills. Much of this activity has centered on Prince of Wales Island, which contains more than 4023 km of roads. Although productive old-growth forests have been reduced by more than 40 percent in recent decades (USDA FS 2018), much of this has been exported in round log form rather than being sawn at local sawmills. This shortage of sawmills has hampered the development of a fully functioning industry, where transportation networks and critical infrastructure can be shared, and synergies between producers can be developed. Those mills that have persisted often include a small portion of larger diameter logs in their raw material mix. However, this is now changing. Extensive timber harvests for pulpmills and by Alaska Native corporations over the past 60 years have created large areas of young-growth stands, which are now reaching merchantable age. Silvicultural treatments, including precommercial thinnings, and optimal harvest levels, along with other operational decisions, will have a large impact on the quantity and value of timber as well as the extent and quality of other ecosystem services provided by these stands. Thus, sustainable second-growth harvests could become a key component to the ongoing survival of a wood products industry in southeast Alaska as well as encourage sawmill innovation to adapt to the size and quality of this resource. This could include developing new markets for new products as well as retooling current sawmills to efficiently process smaller diameter material.

In this study, we considered key ecosystem services managed by the Tongass National Forest Thorne Bay Ranger District in southeast Alaska (fig. 1). We explored how to quantify the tradeoffs between carbon sequestration and other ecosystem services, notably harvested timber volume and wildlife habitat. In particular, deer habitat can be strongly influenced by harvesting practices and silvicultural prescriptions, which in turn influence both cover and forage. We considered these tradeoffs in a largely qualitative assessment; however, we also introduced the quantitative methods based on the principles of Pareto optimization. Pareto optimization is an area of multiple-criteria decision making that is concerned with mathematical optimization problems involving more than one objective function to be optimized simultaneously.

Here, we evaluated each point of a three-dimensional surface representing a management plan that offers a specific level of forage habitat available for deer (hectares), harvested timber volume (cubic meters), and carbon stored (megagrams) over a planning horizon of 70 years.

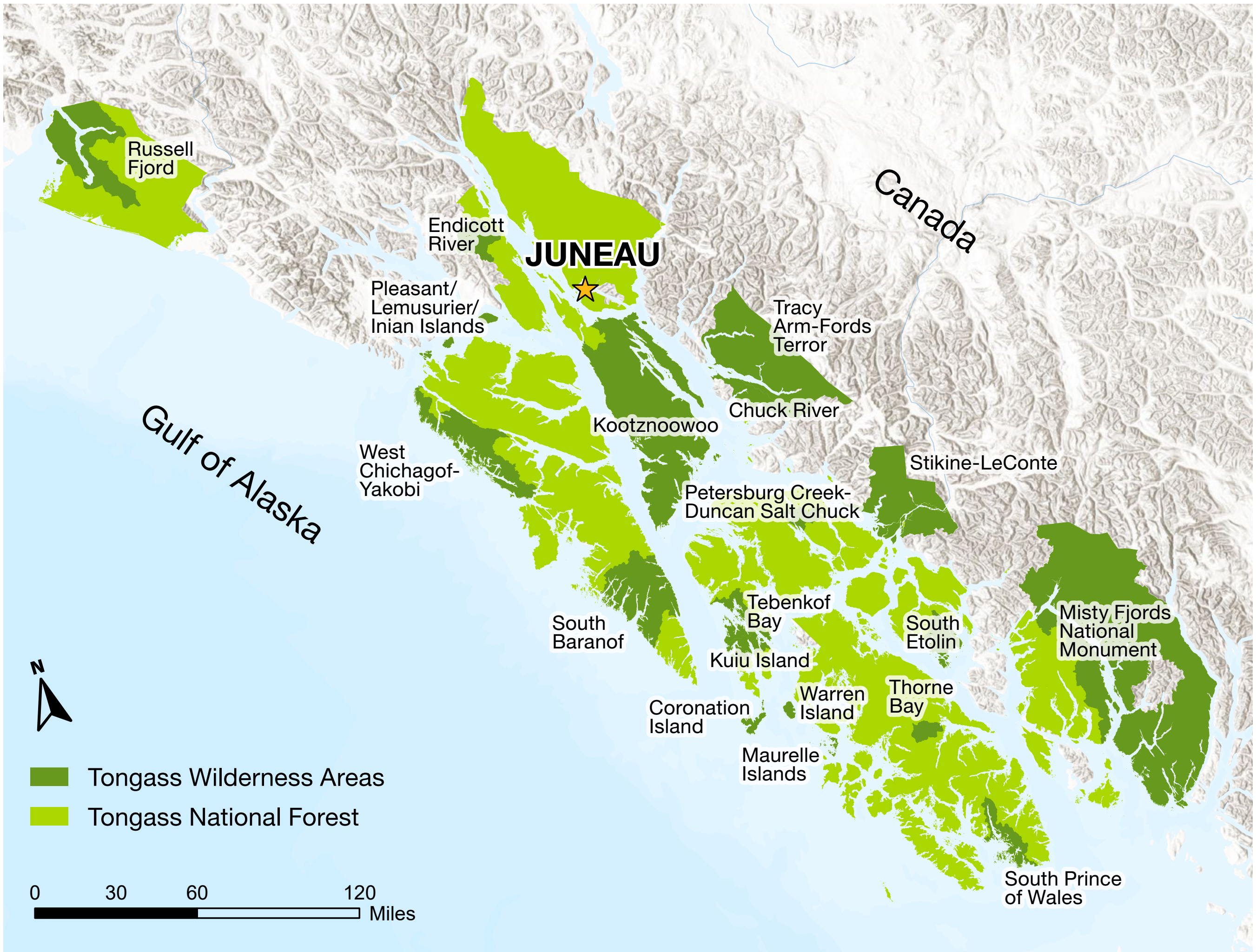

Figure 1—Map of the Tongass National Forest in southeast Alaska showing the extent of Forest Service lands.

A key aspect of this work was the diverse set of stakeholders on the Tongass National Forest, each having their own priorities and valuations of ecosystem services. Included are community residents, Alaska Native villages, conservation groups, Alaska Native corporations, state of Alaska forest managers, Tongass National Forest managers, game hunters, sawmill owners, and loggers, among others. Many of these stakeholder groups provided input on identifying our research objectives, and they may use our key findings to further their community development, business, and natural resource-use needs.

The specific objective of this study was to identify key ecosystem services in the Tongass National Forest, thereby setting the stage for a more indepth quantitative evaluation. This component would include developing and optimizing a modeling framework for evaluating land management tradeoffs on the Tongass National Forest (including specific case study analyses). In preliminary discussions with numerous potential stakeholders, we identified the most active groups as well as their preferred ecosystem services. To demonstrate the concept, we used the Thorne Bay area of the Tongass National Forest as a pilot study site, which was known to have preferred ecosystem services, including forest carbon sequestration, timber, and wildlife habitat. We provided a description of our proposed multiobjective optimization model, along with a discussion of the results that this model provided for the

Thorne Bay demonstration site. In this study, we used these preliminary optimization results to illustrate the mechanics and the benefits of the approach. We hope to expand the scope of our modeling efforts to include larger portions of the Tongass National Forest. Thus, our initial phase of work set the stage for a more detailed multiobjective optimization study evaluating tradeoffs among ecosystem services as part of strategic forest planning.

Economic Perspectives

The most important economic sectors in southeast Alaska, by employee wages, are government (federal and state), healthcare, fisheries and seafood, and tourism. Although the timber industry was vibrant during the pulpmill era (lasting roughly from the mid-1950s to the mid-1990s), in 2020, it contributed only about 1 percent of the total wages for southeastern Alaska, estimated to be $2.16 billion. However, this relatively modest economic contribution can still be a vital component to some communities' well-being (Huber-Stearns et al. 2020).

The timber industry is entering a transition phase. The Tongass National Forest is moving away from old-growth timber harvest in response to changing social values and the significant volumes of second-growth timber that are reaching merchantable size. Although about 77 percent of sawtimber volume is on National Forest System land, in 2015, 67 percent of the harvest was from private lands, including land that Alaska Native corporations own (Marcille et al. 2021). The Tongass National Forest aims to maintain a viable forest industry via young-growth timber harvest, but young-growth stands originated in the 1950s to 1980s and have not yet reached their maximum rate of growth (Daniels et al. 2016). To facilitate the transition, the Tongass National Forest provides a reliable supply of old-growth timber to the existing industry (11 799 m^3/year) to give time for mills to adapt and for young-growth stands to reach economic maturity (USDA FS 2016).

Well-distributed mills and forest processing infrastructure throughout the Tongass National Forest are critical for economically managing the forest for a range of treatments, including thinning for wildlife habitat, salvage operations, and silvicultural actions for timber production (including precommercial and commercial thinning) (Morris and Daniels 2021). Because of high transportation costs in southeast Alaska, coupled with variable market prices for lumber, these activities might not be economically viable even with flexible mill capacities. However, there is social value in putting forest resources to local use under a regime of consistent and dependable timber sales.

The Southeast Conference (2022), the region's state and federally designated economic development organization, articulated that the first regional timber objective was providing an adequate, economic, and dependable supply of timber from the Tongass National Forest to regional timber operators. They found that one key to successfully achieve this goal is to accumulate enough timber supplies for southeast Alaska sawmills to meet production needs for about 3 years, thus providing a buffer against price and timber supply volatility. A second objective was to stabilize the regional timber industry while increasing the timber volume sold relative to employment (there were 272 timber jobs in 2020 versus 4,200 in 1990) (Southeast Conference 2021). A third objective was to work with the U.S. Department of Agriculture, Forest Service to direct federal contracts toward locally owned businesses.

An overarching objective of the Southeast Conference has been to continue some degree of old-growth harvests until the region's young-growth stands are able to support an economic harvest (Southeast Conference 2022). Alexander et al. (2010) demonstrates that young-growth timber that meets the necessary requirements and is capable of economic harvest is limited to about 71 000 to 118 000 m^3/year. Timber workforce development, including forest harvester crews, stewardship crews, sawmill operation, and biomass energy development, has also been identified as a strong industry need. The main timber purchasers within Thorne Bay Ranger District during 2021 were Viking Lumber Company, the state of Alaska, K & D Lumber, and Icy Straits Lumber & Mill, Inc.

Cultural Uses of Timber Products

Timber and wood products have been an integral part of southeast Alaska culture and history for millennia, and Alaska Native tribes remain a key part of the cultural heritage and history of Prince of Wales Island (note that the contemporary wood products industry is discussed later in this report). To evaluate these connections, Johnson et al. (2021) conducted 58 discussions across 11 southeast Alaska communities. In this work, 75 percent of respondents were Tlingit, Haida, or Tsimshian tribal members. They assessed the significance of wood products to rural communities, Alaska Native cultures, and natural heritage sustainability. Their research highlighted the cultural importance of old-growth, high-quality timber from western redcedar (*Thuja plicata* Donn ex D. Don) and Alaska yellow-cedar (*Callitropsis nootkatensis* (D. Don) Oerst. ex D.P. Little) as well as bark, roots, and nonwood tree components that are used to craft a variety of products.

Culturally important products, such as totem poles, dugout canoes, longhouses, woven hats, and woven baskets, are attributed to spiritual well-being, health, education, tourism, and livelihood services. Because many of these products require mature trees, it is important to consider tradeoffs with even-aged forest management strategies. Young-growth forests are typically managed for fast growth, which does not align with a cornerstone of Alaska Native traditional ecological knowledge for sustaining trees "seven generations into the future" (Johnson et al. 2021). Furthermore, precommercial thinning treatments can increase wood production rates but often at the expense of clear, tight growth rings that are desirable for heritage products, such as totems and dugout canoes. Tribal representatives have advocated management practices that enhance cedar regeneration and growth by engaging local artisans in forest planning so there is a better understanding of what artisans need. Specific practices that have been adopted include delivering specific trees to roads as part of ongoing timber sales, allowing bark removal before harvest, simplifying tree-acquisition permit processes, and setting aside cultural forest groves to sustain trees seven generations into the future. All these activities are expected to create trees suited to Alaska Native cultural needs while allowing high-quality wood production as part of old-growth stand management.

Subsistence Hunting and Fishing

Subsistence harvest activities include hunting, trapping, fishing, and berry gathering (Alaska Department of Environmental Conservation 2007). Subsistence hunting activities target Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) and black bears (*Ursus americanus*). Trapping activities target wolves (*Canis lupus*), river otters (*Lontra canadensis*), martens (*Martes americana*), and American beavers (*Castor canadensis*).

Commercial and sport fishing harvests include a variety of salmon species, halibut, cod, crab, shrimp, and clams. In addition, herring roe harvests are a culturally important activity for Alaska Native populations. Thus, there are potential tradeoffs among the different types of fishing interests, including commercial, sport, and subsistence fishing.

Identifying Ecosystem Services and the Study Area

We identified leading ecosystem services and stakeholders on the Tongass National Forest through several steps. First, we conducted a literature review of past research on the Tongass National Forest, including fields of silviculture, wildlife management and habitat, young-growth timber, and ecosystem carbon dynamics. We then conducted a series of in-person interviews with key stakeholder groups in Sitka, Klawock, and Juneau, Alaska. From these interviews, we identified the most important ecosystem services of interest—second-growth timber management, wildlife habitat (deer), and forest carbon sequestration—as well as management challenges and opportunities.

We also identified supporting elements that would be needed to provide for these ecosystem services. For example, second-growth timber requires adequate road networks, harvesting infrastructure, and at least one local sawmill. Deer habitat is dynamic and highly dependent on the forest successional stage; thus, it requires several forest age classes. Forest carbon is also dynamic and requires knowledge of belowground and aboveground biomass as well as standing live and dead timber.

Next, we identified an appropriate study area within the Tongass National Forest that was representative of these three ecosystem services. We considered a region characterized by second-growth stands that were approaching merchantable size, within the reach of an existing road network, near at least one year-round sawmill, and accessible by nearby communities. Given all these criteria, we decided on the Thorne Bay, Alaska, region on Prince of Wales Island (fig. 1). Finally, we formulated a multiobjective optimization approach, identifying 120 management units. As part of this spatial analysis, we evaluated geographic information system (GIS) layers to determine road systems, transportation distances, potential harvest and precommercial thinning sites, and locations of local sawmills. In addition, we identified units that were projected to be effective deer habitat sites. In this study, we applied our proposed multiobjective optimization model to the Thorne Bay pilot study site to demonstrate the benefits of the model.

The following sections provide an overview of the three ecosystem services—timber, deer habitat, and carbon sequestration; a brief introduction to our model framework; and a summary of the preliminary findings that our model has provided for the Thorne Bay area.

Sawmill Industry

As recent as 2000, 20 active sawmills operated across the Tongass National Forest; the greatest concentration of sawmills was on Prince of Wales Island. During 2019, four sawmills (18 percent) remained active, and thirteen sawmills (59 percent) were no longer in production (table 1). Five sawmills (23 percent) were idle during calendar year 2019 (Morris and Daniels 2021). Because of numerous factors, including local employment availability, processing equipment limitations, macroeconomic conditions, and timber supplies, sawmills were working at just 15 percent of their capacity rate (table 2). Thus, many sawmills have unused infrastructure as well as inconsistent log supplies.

In 2019, most (78 percent) processed material was sent to destinations in the continental United States, followed by international exports to the Pacific Rim (Crone 2007), with less material being exported to Canada. This raises the question of how to support local economies through greater lumber processing, drying, finishing, and other processes requiring local labor. The timber industry in southeast Alaska is at a competitive disadvantage compared to the Pacific Northwest because Alaska has higher wages, higher transportation

Table 1—Active and idle sawmills in southeast Alaska, 2019

Sawmill	Location	Equipment description and capabilities	Status as of 2019	Employees
				NUMBER
Viking Lumber Company	Craig	Conventional carriage, bandsaw headrig, resaws, edgers, trim saw, log debarker and merchandiser	Active	38
Icy Straits Lumber & Milling Company	Hoonah	Portable sawmill, horizontal band resaw, log debarker, dry kiln, planer, moulder	Active	10
Western Gold Cedar Products	Thorne Bay	Shake and shingle mill, carriage mill, chain-fed scragg added in 2018	Active	2
Falls Creek Forest Products	Petersburg	Portable circle sawmill, trim saw, log and lumber decks, dry kiln, moulder	Active	2
D & L Woodworks	Hoonah	Portable circle sawmill	Idle	1
Thuja Plicata Lumber	Thorne Bay	Portable circle sawmills, carriage mill with circle saw headrig, shake mill, shingle mill	Idle	1–2
The Mill	Petersburg	Two portable circle sawmills	Idle	1
Alaska Specialty Woods	Craig	Portable circle sawmill, dry kiln, planer, moulder	Idle	0
Thorne Bay Wood Products	Thorne Bay	Portable circle sawmill, trim saw, log and lumber decks, dry kiln, planer, moulder	Idle	0

Note: There were 22 sawmills in the sample.
Source: Morris and Daniels (2021).

Table 2—Annual sawmill survey results, 2000 through 2019, volume in cubic meters

Year	Active sawmills	Employees	Installed sawmill capacity	Estimated sawmill production	Sawmill capacity utilization
	NUMBER		CUBIC METERS		PERCENT
2019	4	50	320	36	11
2018	7	52	255	36	14
2017	8	51	268	37	14
2016	9	58	268	42	16
2015	9	51	268	44	16
2014	10	54	282	44	16
2013	10	60	284	42	15
2012	10	58	284	33	12
2011	10	56	378	27	7
2010	10	64	368	37	10
2009	11	58	588	32	5
2008	11	94	666	56	8
2007	14	158	690	75	11
2006	11	123	836	76	9
2005	12	136	849	82	10
2004	13	148	874	73	8
2003	13	155	873	76	9
2002	11	160	1071	94	9
2001	—	—	—	—	—
2000	19	321	1184	206	17

— = no data.

costs, and less-efficient capital (Robertson and Brooks 2001). One justification for the continued sale of timber from the Tongass National Forest is to sustain employment in the region (Knoder 2002). Daniels et al. (2016) estimated that a volume of 707 cubic meters (25,000 cubic feet) was harvested in 2015; 78 percent of this volume was exported, 17 percent went to sawmills, 3 percent was used as fuelwood, and less than 1 percent was used for log home manufacture.

Funding of forest management activities to foster socioeconomic benefits for Prince of Wales communities is an ongoing challenge in an era of generally decreasing funding and budget cuts. These activities include road building, silvicultural prescriptions (for example, precommercial and commercial thinning), wildlife habitat management, salmon habitat restoration, and management for carbon markets. In addition, diversification of wood products and local markets would be beneficial because there is an active firewood collection community on Prince of Wales Island, providing cordwood for several school wood-energy systems. However, use of locally produced lumber is generally lacking except for limited use of dimension lumber for construction projects (Morris and Daniels 2021).

Forest Management to Enhance Deer Habitat

The core forest ecosystem components for suitable deer habitat include water, understory forage, shelter, and cover (Nelson et al. 2008). However, it is important to recognize that, while timber and carbon are both commodities (with potentially broad geographic reaches), deer habitat is a proxy for deer harvest rates (having local effects). As such, it is conceivable that forest thinning treatments would not change deer harvest rates significantly; however, this would depend on variables, such as degree of thinning, age classes thinned, initial stand conditions regarding habitat and foliage abundance, and the degree to which post-thinning conditions were conducive for deer habitat.

The understory dynamics needed to provide a balance of these services are related to forest successional stages, ranging from stand initiation to old growth (discussed below). A wide range of understory vegetation can become available to deer during early stand development, including huckleberry and blueberry shrubs (*Vaccinium* L. spp.); salmonberry (*Rubus spectabilis* Pursh); half-shrubs, such as bunchberry dogwood (*Cornus canadensis* L.); and several herbaceous forbs (Farmer and Kirchhoff 2007). Under shady conditions, most of these forage species are evergreen, providing much-needed winter nutrition (Nelson et al. 2008). Deer forage is dynamic in that it is abundant after clearcutting but then quickly loses vigor as overstory trees reduce sunlight. Forage quality may be higher in shaded habitats than clearcuts because of greater availability of succulent leaves, higher crude protein, and lower tannin astringency, which affects protein digestion. Shrubs and forbs growing in shade often retain leaves throughout much of the winter, whereas leaves of plants growing in full sunlight usually senesce in early autumn.

Precommercial thinning can be used to extend the period of abundant forage (Hanley et al. 2013). Eventually, a stem-exclusion phase dominates, with little understory vegetation available. Older, mature stands offer primarily shelter for deer, but they must be located close enough to areas offering forage so that deer can easily access both areas. Forest managers will often perform precommercial thinning to increase tree growth while also reducing canopy closure (which in turn increases deer forage). Thus, silvicultural treatments can be designed to accelerate both tree growth and deer forage development, thereby simultaneously creating value for both ecosystem services.

Stand Development Stages

The following sections provide a timeline from stand initiation to old-growth establishment from a perspective of deer habitat for stands dominated by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carrière) on Prince of Wales Island.

STAND INITIATION—The stand-initiation stage (8 to 10 years old) is characterized by rapid tree growth, high browse production, and poor snow intercept. Tree densities can range from 1,500 to 10,000 trees per hectare, and crown ratios (the proportion of total tree length supporting live foliage) are often 75 to 100 percent. Seedling or sapling size trees in this stage are often less than 12.7-cm diameter at breast height (d.b.h.).

STEM EXCLUSION—During the stem-exclusion stage (15 to 25 years old), dense canopy cover limits sunlight to the forest floor, and understory plant abundance can decline, or they could even vanish, within about 35 years, unless thinning treatments are conducted. On stands having low productivity and for naturally regenerated stands, the stem-exclusion stage might be delayed (Zaborske et al. 2002). For 25 to 30 years after logging, the biomass volume of young-growth understory during snow-free months in clearcuts exceeds that of old-growth forests; however, this resource tends to present less digestible protein for ungulates (Nelson et al. 2008). A variety of silvicultural treatments can be used to enhance both deer forage and movement corridors, including reducing or abating slash in treated stands and creating travel corridors within thinning treatments in the absence of existing routes, terrain features, or other habitat connectivity drivers. The thinning window is about 15 to 30 years postharvest in medium- to high-productivity stands so that the precommercial thinning costs can be offset by end-of-rotation harvests to the greatest degree (Nelson 2008). Alaback (2010) suggests a 12- to 15-year planning horizon for precommercial thinning effects on understory vegetation, with target residual densities of 548 to 748 trees per hectare.

Prince of Wales Island forests are characterized by large areas of stem-exclusion, second-growth forest that has accumulated over the past 50 to 60 years after harvest. Stand canopy cover typically ranges from 75 to 100 percent with low crown ratios. In addition, these stands have the following characteristics:

- 15 to 30 years—pole-size trees ranging from 12.7- to 23-cm d.b.h.
- 30 to 45 years—pole-size trees ranging from 15- to 30-cm d.b.h.
- 45 to 55 years—growth of 6 m^3 per hectare per year on highly productive sites
- 55 or more years—merchantable volume class, can produce commercial timber

Given this projection of age classes and diameters, it is anticipated that 14 million ha will be commercially viable by the mid-2030s (USDA FS 2018).

UNDERSTORY REINITIATION—In the understory-reinitiation stage (120 to 150 years old), overstory tree mortality helps create open area for understory trees. Precommerical thinning has been shown to accelerate understory reinitiation for periods of up to 100 years (Nelson et al. 2008). Deal (2001) found that the heterogeneous stand structures that develop after partial cutting are similar to old-growth stands versus uniform young-growth stands that develop after stand-replacing disturbances. Also in this age class, silviculture systems using partial cutting could provide a sustainable timber resource, including more valuable spruce trees, while also maintaining structural diversity and old-growth characteristics (Deal et al. 2002, 2009).

Several other treatments could be used as stands reach commercial size, including the following (Aboudara 2022):[1]

- Variable-density thinning—to support long-term deer habitat and promote succession toward the old-growth development stage
- Ridgeline canopy retention—to facilitate deer movement during severe winters to minimize distance between habitat and forage
- Gap thinning on flatter slopes—to reduce deer predation
- Habitat thinning, with slash remaining onsite—to provide nutrients for undergrowth vegetation (and in conjunction with some trees being girdled for canopy light control)

OLD GROWTH—During the old-growth stage (more than 150 years old), large trees dominate with stem densities approaching 500 trees per hectare (Nelson et al. 2008). The old-growth structure suitable for deer habitat relies on a gap-phase dynamic, where small-scale blow downs (typically less than 1 ha in size) occur in the forest canopy, allowing sunlight to reach the soil and the understory plants (USDA FS 2018). This leads to the creation of fine-grained, uneven-aged forest structures that are characteristic of old-growth stands (Nelson et al. 2008).

Precommercial Thinning to Enhance Deer Habitat

Several silvicultural practices have proven effective in enhancing deer habitat in southeast Alaska. Although precommercial thinning is often employed, other strategies have also been used. For example, combining light thinning with girdling, pruning limbs, or planting red alder (*Alnus rubra* Bong.) could replace typical precommercial thinning, while reducing slash (Hanley et al. 2013). Slash greater than 1.9 m high can impede deer movement and may persist 5 to 15 years after treatment depending on the age of the thinned stand (Farmer et al. 2006; Hanley et al. 2006, 2013).

Pruning limbs from trees left during precommercial thinning provides increased side-lighting that helps sustain positive understory responses and benefits wildlife (Altman and Hagar 2007; Hanley et al. 2006, 2013). Pruning also leads to more understory forage with less canopy loss and diminished effects from loss of snow interception and slash. The species of tree also has an influence on quality of forage and habitat. The presence of red alder promotes a more structurally diverse forest canopy, retains understory forage longer, improves nitrogen fixation, and enhances growth of understory plants (Deal 2007, Deal et al. 2017, Hanley and Barnard 1998, Hanley et al. 2006, Nelson et al. 2008, Tarrant and Trappe 1971). Red alder often persists for more than 40 years, but the duration of its effect on delaying stem exclusion is unknown. For winter forage, western red cedar and Alaska yellow-cedar should be favored as retention trees over those with lesser forage value, such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock, and Sitka spruce (Nelson et al. 2008).

Timber harvest strategies that mimic gap-phase forest dynamics have the most potential for retaining habitat for deer through all successional stages, at least in the northern

[1] **Aboudara, Q. 2022.** Personal communication. Natural resource coordinator, SHAANSEET, 501 Main Street, Craig, AK 99921, qaboudara@shaanseet.com.

one-third of the Coastal Rainforest Ecoregion that ranges from northern California to coastal Alaska, as far north as Prince William Sound. Deal (2001) showed that partial cutting (less than 50 percent basal area of the stand and removal of fewer than 30 trees per hectare) can be employed to maintain many of the understory attributes of unharvested stands of western hemlock and Sitka spruce.

In thinning-from-below treatments, smaller diameter stems are removed, leaving larger trees. This treatment can also be applied to allow for the creation of small canopy openings. These openings should range in diameter from 0.3 to 1 times the height of mature trees in the stand, with an average opening diameter of 0.5 times the mature tree height (Dawson et al. 2007). Avoidance of timber harvests that create fragmentation and edge on flat terrain may help prevent high rates of predation on sensitive species, for example, predation on marbled murrelets (*Brachyramphus marmoratus*) by Steller's jays (*Cyanocitta stelleri*) and common ravens (*Corvus corax*) (Farmer et al. 2006). Nelson et al. (2008) recommend customizing small forest openings for summer range (less than 20 ha) and for winter range (1 to 3 ha).

Deer Habitat Range Considerations

Black-tailed deer inhabit the Coastal Rainforest Ecoregion, an extensive area that includes much of the west coast. Nelson et al. (2008) summarize habitat guidelines for black-tailed deer in the Pacific Northwest, which serve as a proxy for the Sitka spruce and western hemlock forests of southeast Alaska. In related research, Suring (2011) found that migrators may travel 4.8 to 9.6 km, mostly during winter and during rutting periods. Schoen and Kirchhoff (1990) reported that winter home ranges can vary in size from 42 to 302 ha, with an average area of 122 ha. Dasmann and Taber (1956) found that deer can have such strong fidelity to traditional home ranges that they will starve to death rather than travel a few kilometers to access abundant forage. Thus, deer in southeast Alaska appear to have specific geographic habitat requirements.

Where snowfall is deep (more than 0.6 m), deer typically select productive, coarse-canopy, old-growth forests on southerly aspects below 250 m elevation during winter (Schoen and Kirchhoff 1990). In these stands, the forest canopy intercepts snow while allowing sunlight to reach the forest floor, which enhances understory vegetation. In areas with less snowfall and during snow-free months, deer are less geographically restricted to habitat selection.

Shanley et al. (2021) compared light detection and ranging (LiDAR) approach mapping with the Forest Service's Forage Resource Evaluation System for Habitat and Tongass Interagency Deer Winter Habitat Suitability Index habitat models to improve the understanding of deer habitat dynamics on a managed forest landscape. The authors found that the maximum elevation of habitat that deer use is about 460 m. They also prioritized habitat selection parameters, showing that deer select the following:

- Elevations below 250 m, with only a small percentage of deer remaining at higher elevations during winter
- Southerly aspects and moderate slopes less than 10 degrees
- Understory cover of less than 10 percent
- Edge habitat less than about 500 m from areas of taller trees, often close to roads, suggesting selection for road-side forage; shorter distances to openings are selected because light penetrates to the forest floor along edges and increases forage productivity while still providing deer with cover

Winter habitat selection for Sitka black-tailed deer in southeast Alaska has been investigated using LiDAR-based models (Schoen and Kirchhoff 1990) and Random Forest machine learning techniques (Shanley et al. 2021). Shanley et al. (2021) found that about 103 000 ha of regenerating clearcuts on the Tongass National Forest could return to productive wildlife habitats as seen before the pulpmill era. Since Forest Service restoration stewardship contracts cost close to $1,200 per hectare, this would require an estimated $124 million to treat all stands. Thus, a prioritization process is needed to ensure that the most important areas are treated first (Shanley et al. 2021). This is one of the reasons we proposed a formal mathematical optimization as our method of choice.

Winter Habitat Connectivity

In heavily logged areas, deer habitat can be improved if tree lines are maintained from low-elevation, old-growth forest corridors to higher elevations where snow accumulation depths exceed 0.6 m (Kirchhoff 1994). Nelson et al. (2008) also noted the importance of low-elevation, old-growth stands; they found that deep snow prevented deer from accessing interior forest habitat. In cases where this old-growth forest connectivity cannot be met, management actions that provide adequate wildlife habitat with younger trees (more than 50 years old, and able to intercept snow) should be considered. Elevation, length of corridor, tree heights, adjacent landscapes, and windthrow susceptibility should all be considered when designing corridors to enhance natural movement (USDA FS 2016). Perra and Brinkmann (2021) summarized some of the key tradeoffs between deer habitat and understory development, forest management, and hunting success. In general, intensively thinned or clearcut stands as well as seedling stands accumulate more snow because there is almost no snow interception by taller trees (Bennetsen 2020). Hunters generally prefer clearcuts because of greater visibility and are less amenable to hunting in stands with unmanaged slash or in dense smaller diameter stands found in the stem-exclusion stage (Brinkman et al. 2009).

Deer Habitat in Thorne Bay Area

The Prince of Wales Landscape Level Analysis Project promotes preserving deer habitat, maintaining sustainable wolf populations, and meeting estimated human deer harvest demands (USDA FS 2018). It recommends that deer habitat support up to seven deer/km^2 in biogeographic provinces where deer are the primary prey of wolves. The project plan also assesses the likelihood of deer population persistence by comparing key habitat metrics from the current habitat to pre-large-scale logging habitat (and observing changes occurring during this timeframe of roughly 60 years).

In the Thorne Bay area, there is a need to map critical deer winter range, deer summer range, riparian areas, proposed timber sales, and proposed and existing road networks. All these factors can influence the function, location, patch size, and diversity of forest deer habitat. Thus, a current challenge among managers is translating the already existing, yet incomplete data into dynamic systems that would consider actions to control or regulate these services.

Sitka black-tailed deer are important ecological indicators of resource management in rain forests of southeastern Alaska for several reasons:

- They have relatively large migratory home ranges that require management of landscapes rather than isolated patches of habitat.

- They need productive and nutritious food supplies year-around, making them largely dependent on old-growth forests and a variety of habitats that differ seasonally and in response to snow.
- They are an important game species in the subsistence economy of rural residents.
- They are related in the food-chain to predator populations and berry-picking activities. Alaska blueberries (*Vaccinium ovalifolium* Sm.) can serve as a deer habitat indicator in young-growth stands (Alaback 2010).

The Forest Service identified management objectives of maintaining lower elevation, productive old-growth forested habitats; improving wildlife habitat in young-growth stands; and reducing road densities and fragmentation that negatively affect wildlife species (USDA FS 2018). Deer habitat could be improved through forest treatments that (1) increase forage quality, (2) increase forage abundance and availability, and (3) improve accessibility.

We assumed that the presence of overmature stands (more than 120 years old) in a home range distance (200 m) from forage habitat would facilitate access to the food area while providing thermal cover.

The multiobjective optimization framework that we proposed in the present study attempts to incorporate the above requirements explicitly. Our proposed model allowed for a comprehensive look at the dynamics of deer habitat at the landscape level in response to various silvicultural options. We postulated that maximizing the area of deer habitat would serve as a good proxy for improving the subsistence economy of local residents by providing more access to game hunting and berry picking. Both foraging deer and berry shrubs share a preference for early-successional forest habitat.

Forest Carbon

There is a broad range of international scientific literature on forest ecosystem carbon dynamics. These carbon flows are influenced by a number of factors, including silvicultural prescriptions and levels of forest harvest (Harris 2020, Leighty et al. 2006), wildfire events and wildfire risk (Law and Waring 2015), climate change (Moomaw et al. 2019), and international trade (Kastner et al. 2011). The Tongass National Forest is a rich carbon reserve, storing more forest carbon than any other national forest in the United States (Roos et al. 2011). However, the estimated loss of Tongass National Forest ecosystem carbon during the 20th century is estimated to have been between 6.4 and 17.2 Tg (Leighty et al. 2006). More recently, the average aboveground carbon density in the Tongass National Forest was estimated to be 190 Mg per hectare in live trees, snags, and logs across 3.9 million ha of forest land (Barrett 2014).

Whether tradeoffs exist between forest carbon retention and wood products production or deer habitat management is an open question, and our proposed model was designed to evaluate this question quantitatively. Leighty et al. (2006) found that estimated carbon fluxes were sensitive to both the projected rate of carbon accumulation (primarily in second-growth forests) and the amount of carbon left in standing biomass after harvest. Both timber production and carbon sequestration have been evaluated through joint production approaches (Olschewski and Benítez 2010) and stochastic evaluations of market prices (Petrasek et al. 2015). These studies generally found that the choice of carbon pricing behavior model affects rotation length. Petrasek et al. (2015) suggested that accounting for carbon stored in the forest and in wood products as well as avoiding emissions via the use of wood might be significant income contributions for forest owners. One shortcoming of these studies is the focus on stand-level management as opposed to watershed- or landscape-level management, which would involve a broader range of risk factors.

Rue-Johns et al. (2021) assessed the effects of silvicultural treatments on understory growth and carbon sequestration, evaluating four age classes: 0 to 5 years, 15 to 25 years, 25 to 35 years, and 35 years and older. The authors relied on data from the Tongass-Wide Young-Growth Studies and the Prince of Wales Commercial Thinning Study on Prince of Wales Island. They found that total stand carbon did not increase with the addition of understory carbon to overstory carbon; however, patterns of carbon allocation during stand development had implications for overall stand nutrient cycles and future patterns of carbon sequestration. Their cover-to-understory biomass regression provided insights on understory dynamics, wildlife habitat, and total stand carbon. They also found that thinning treatments resulted in significantly greater total understory biomass versus the untreated controls.

D'Amore et al. (2015) modeled the impacts of thinning treatments on carbon accretion in young-growth forest stands. They suggested that unthinned treatments would be preferable for short-term carbon sequestration. However, other ecologically beneficial results, such as wildlife habitat conservation, may override the effects of thinning strategies on carbon sequestration. Their model can be used to calculate regional carbon loss accounting for silvicultural management. They calibrated their carbon accretion model with different thinning management intensities occurring on 20-year-old stands; however, it can be adapted for thinning operations on stands between 25 and 40 years of age as well. Additionally, they applied decay functions to residues that are left after treatment and to long-term products such as sawtimber (i.e., lumber). A key distinction between our proposed multiobjective optimization approach and the methods in previous work mentioned above is that our method is a comprehensive, landscape-level modeling of carbon dynamics (as opposed to stand-level modeling) in response to silvicultural treatments or the lack thereof. What might be an optimal carbon strategy at the stand level might not be optimal at the watershed or landscape levels. Moreover, our model is capable of quantifying the tradeoffs that might exist among managing for deer habitat, wood products, and carbon.

Existing Tongass National Forest Carbon Mapping

Forest carbon within the Tongass National Forest can vary greatly depending on region, age class of timber, and whether aboveground carbon or total ecosystem carbon is considered. Crotteau et al. (2022) evaluated live tree carbon across all Prince of Wales Island stands and found that live tree carbon ranged from 265 to 498 Mg per hectare. Others estimated forest carbon in Alaska at 30-m resolution with both high and low estimates (Data Basin 2019a). The carbon estimates were built from more than 1,000 Forest Service Forest Inventory and Analysis (FIA) ground measurements and interpolated using machine learning (Random Forest) with topographic, disturbance, and other covariates. High and low estimates were based on the ratio of aboveground carbon to total biomass carbon (Leighty et al. 2006). Soil carbon in southeast Alaska and the Tongass National Forest has also been estimated (Data Basin 2019b). Leighty et al. (2006) also showed how existing GIS attributes were used to delineate polygon areas expected to contain differing carbon density. After removing areas with no carbon from consideration, they delineated soil categories based on Alexander et al. (1990). The actual delineation of polygon types by soil category was left out for aboveground carbon density calculations to reduce the number of polygons.

Economic Value of Forest Carbon

Forests in Alaska, which account for about 17 percent of all Forest Service lands, are a major carbon sink (Roos et al. 2011). If carbon credit markets were developed in Alaska, a cap-and-trade system for forest carbon could provide a management incentive for carbon sequestration in the forms of afforestation, reforestation, and reduced deforestation. Although this could become a revenue stream for forest landowners, to be effective, the income gained would need to be high to offset the high operating costs in Alaska (Roos et al. 2011). In coastal Alaska, where natural fire is rare and carbon credits management does not interfere with the primary disturbance processes, the main disadvantage of carbon credit protocols, if implemented, could be diminished opportunities for forest products or other ecosystem services (AK DNR 2020).

Methods: Multiobjective Spatial Optimization

Many forest ecosystem services are important to stakeholders on the Tongass National Forest. In the present modeling exercise, for demonstration purposes, we focused on the interplay between the level, timing, and location of timber harvests; deer habitat criteria (both forage and cover); forest carbon retention; and sawmill location. We provided a nonmathematical description of the proposed model as well as a discussion of its results when implemented on our pilot study site near Thorne Bay, Alaska.

Multicriteria Optimization Model Structure

We cast our multicriteria management problem in the Tongass National Forest as a multi-objective linear integer program. Mathematical programs, including the one presented here, comprise a set of functions that represent desired management objectives, such as maximizing carbon sequestration, harvested timber volume flow, or area of accessible forage habitat (forage habitat within accessible distance from cover habitat), and a set of inequalities that represent the constraints, within which decision makers can pursue these objectives. The use of decision variables connects both sets of mathematical objects. In our proposed models, these variables are optimized to achieve the stated objective functions while satisfying all given constraints.

In contrast to common linear programs, where the variable domains are continuous, decision variables in integer programs are discrete, either binary or integer. In our model, we used binary variables to represent thinning or harvesting decisions that are discrete in nature (whether to apply precommercial thinning to a certain stand in a certain future planning period or not). These were yes-or-no decisions, hence, the binary (a.k.a., Boolean) declaration of these variable domains. However, we also used continuous variables to capture sums of volumes or areas that result from binary assignment of values to the decision variables. Although these accounting variables are not decision variables per se, the resulting mathematical program is technically a mixed integer linear program. It is linear because we were able to model all the key relations in the Tongass National Forest management system with purely linear mathematical constructs. This linearity in structure has a great computational advantage when it comes to solving real management problems of practical size (in terms of the number of management units, alternative treatment options, and planning periods) on the Tongass National Forest. Optimization models that comprise tens of thousands of units, many treatment options for each unit, and many time periods are much harder to solve than those that comprise only hundreds of units, fewer treatment options, and fewer time periods.

An important characteristic of the optimization model that we proposed was that it had more than one objective function. We wanted to capture all the management objectives that arose from the decision problem as separate functions of the decision variables whose values our program was designed to optimize. In our Tongass National Forest demonstration, there were only three functions representing the objectives of maximizing harvested timber volume, maximizing carbon sequestration, and minimizing the area of accessible forage habitat over a 70-year long planning horizon. The primary implication of having more than one objective function is that unique, singular solutions do not exist if any of the objectives conflict with one another. What this conflict means in practical terms is that if we optimized the program for only one of the three objective functions, such as carbon sequestration, then we would get a different solution than if we optimized the program for another objective, such as timber volume. Under competing objectives, multiple solutions (i.e., 70-year management plans) exist depending on what preferential weights the decision maker places on them. In this study, we attempted to identify all or most alternative management plans that are Pareto optimal under all possible combinations of weights. Pareto optimality here refers to management plans, none of which can be improved for one objective without compromising another objective. This restricted set of alternative plans is uniquely important to decision makers because all other management plans can be shown to be dominated by at least one objective. Thus, our goal was to identify or approximate this unique set of Pareto-optimal forest management plans for the Thorne Bay demonstration site.

Planning Horizon, Planning Periods, Spatial Scale, and Decision Variables

Based on our stakeholders' recommendations, we chose to use a 70-year planning horizon separated into fourteen 5-year planning periods. These choices defined the temporal scale and resolution of the management plan that we wished to optimize. As for spatial scale, we chose an area of 1287 ha near Thorne Bay composed of 121 management units (stands), with an average size of 10.33 ha each. We defined the decision variables for each of these 121 management units and 14 planning periods based on whether a unit should be precommercially thinned or not and whether it should be harvested or not.

Objective Functions

The first objective maximized the minimum area of forest habitat over the 14 planning periods, where both thermal insulation/shelter and sufficiently developed forage were projected to be present for deer. Thus, the model identified which of the 14 planning periods was projected to have the least habitat and then optimally rescheduled precommercial thinning and harvest activities to increase this minimum area to the extent possible. The management units that had access to sufficient forage and cover (shelter) habitat in each planning period were determined in the constraint structure of the model, which is explained in the next section. The second objective maximized the discounted sum of harvest volumes from all 121 management units over the 14 planning periods. A 3 percent social discount rate was applied to harvest volumes at the midpoints of each of these planning periods when the projected volume was scheduled to be extracted to account for the potential risk of losing timber to natural disturbances, such as windstorms or disease. The third objective maximized the projected total of carbon stored in all 121 management units over the course of the management plan.

Constraints

The first set of constraints simply defined the rules for allocating silvicultural treatments to the management units. Each management unit could only be precommercially thinned or harvested once during the planning horizon. In addition, a minimum harvest volume constraint was added to control how early a unit could be harvested. If the projected volume for that unit did not exceed the minimum threshold, the unit was ineligible for harvest. Similarly, units were not eligible for precommercial thins once they reached 40 years of age. A second set of constraints controlled the extent to which harvest volumes and areas thinned could fluctuate from one 5-year planning period to the next. In particular, harvest volumes could only go up or down by a maximum of 25 percent from one planning period to the next. Similarly, the total area of scheduled thins could not increase or decrease by more than 35 percent from one planning period to the next. The function of these constraints was to avoid abrupt changes in timber production or associated workloads.

To control when a management unit could be considered accessible forage habitat, we first required that only units that had been precommercially thinned in the previous 10 to 15 years were eligible. This reflected that harvested stands could return to an early-successional stage habitat favorable for understory development only 10 to 15 years after they were cut. Secondly, we required that a sufficient area of mature stands of 120 years of age or older were present within an accessible distance from the forage area. This requirement was necessary because deer need accessible thermal cover or shelter away from the foraging area for the latter to be effective. Using the model described above, we ran multiobjective integer programming software to find Pareto-optimal forest management plan alternatives.

Results and Discussion

The Pareto-optimal forest management plans that resulted from our multicriteria analysis described in the previous section are presented in figure 2. Each black dot on the Pareto front represents a forest management plan that is mapped as Cartesian coordinates based on its three projected objective function achievements. The concentration of dots (management plans) in the lowermost corner of the front indicates solutions that maximize both timber volume and area of accessible forage habitat. In contrast, solutions that maximize carbon sequestration (in the uppermost corner of the front) correspond with the lowest achievements in terms of timber and area of accessible forage habitat. This means that if a stakeholder wanted to increase carbon sequestration, they would have to gradually reduce both timber harvest and area of accessible forage habitat. However, area of accessible forage habitat provisions are less sensitive to the maximization of carbon sequestration than to the maximization of timber harvest volumes.

We selected the four management plans, labeled as solutions 1 through 4 on the Pareto front, to contrast the projected objective achievements with regards to area of accessible forage habitat, carbon sequestration, and harvest volume, should these plans be implemented. We selected these management plans after considering the suite of ecosystem services available to stakeholders in southeast Alaska, following preliminary outreach that identified key natural resource needs. For example, fish habitat, recreation, and berry shrub habitat were also considered in the initial screening process, but we removed them because our scope was limited to fewer ecosystem services and their resulting management plans.

We believe that these contrasts, or tradeoffs, illustrate the benefits of our modeling approach because they show, in quantitative terms, the scope as well as the limitations of

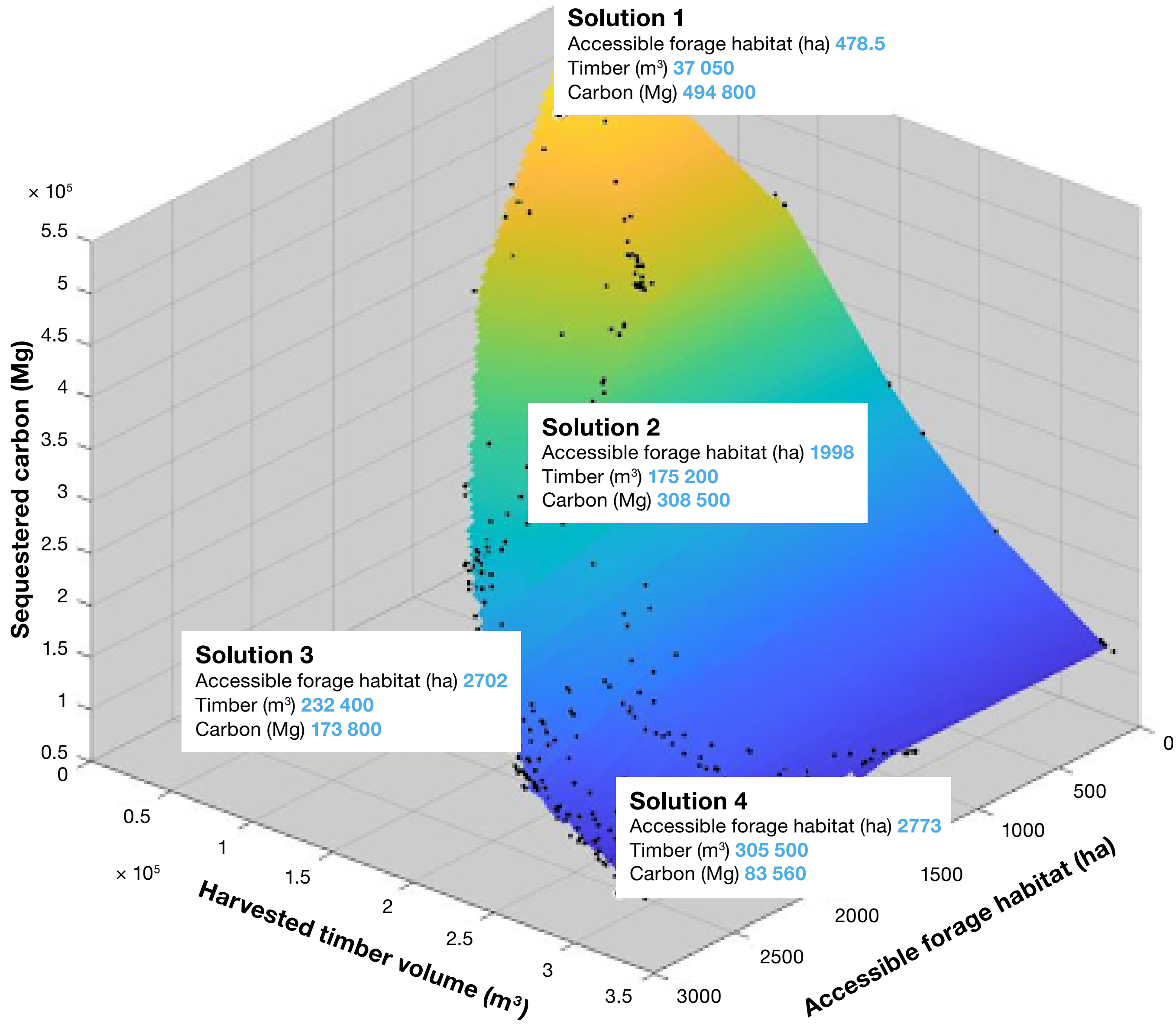

Figure 2—Pareto-optimal forest management plans for the vicinity of Thorne Bay, Alaska. Each point of the three-dimensional surface, called the Pareto or efficient front, represents a forest management plan that offers a specific amount of each of the three ecosystem services that we modeled: area of accessible forage habitat (forage habitat within accessible distance from cover habitat), harvested timber volume, and carbon stored over the planning horizon (70 years). Four of the management plans are highlighted: solutions 1 through 4. The corresponding labels for each of these solutions list the area of accessible forage habitat, harvest volume, and sequestered carbon that are projected to result from each of the plans if implemented.

the joint provisions of these three ecosystem services at the Thorne Bay area in Alaska. We wish to emphasize that the choice of these four solutions does not represent our team's or the stakeholders' preferred alternatives. We simply chose them so that the associated tradeoffs would contrast enough to show that our multiobjective optimization method can be useful to others, and our discussion focuses on these four solutions.

If Thorne Bay stakeholders chose solution 1, projected carbon sequestration would be maximal at 494 800 Mg of carbon over the 70-year planning horizon. On the other hand, projected timber production would be limited to 37 050 m^3 with solution 1, a mere 12 percent of the projected volume for solution 4 (305 500 m^3), 16 percent of the projected volume for solution 3 (232 400 m^3), or 21 percent of the projected volume for solution 2 (175 200 m^3). Moreover, the lowest amount of accessible forage habitat in all fourteen 5-year planning periods would be only 478.5 ha in solution 1. This would be only 17.7 or 17.2 percent of the projected minimum area of accessible forage habitat associated with solutions 3 and 4, respectively, and it would be 24 percent of the projected minimum area of accessible forage habitat for solution 2. Thus, if the stakeholders agreed to shift from solution 1 to solution 2, they could increase both the projected minimum area of accessible forage habitat as well as timber harvest volume by more than fourfold at the price of losing 38 percent of the carbon sequestration potential of solution 1. If the stakeholders were even more willing to forego carbon sequestration and chose solution 3 or 4, they could increase projected area of accessible forage habitat by 5.6 and 5.8 times, respectively, and timber harvest volume by 6.3 and 8.2 times, respectively. In contrast, in solution 3, the projected sequestered carbon would drop to one-third of the projected sequestered carbon for solution 1, and in solution 4, the projected sequestered carbon would drop to 83 percent of the projected sequestered carbon for solution 1. Figure 3 shows the area of harvests, precommercial thinning treatments, and deer habitat (accessible forage and cover) in each of the fourteen 5-year planning periods.

For deer, the area of cover habitat is shown in addition to the area of accessible forage habitat, As discussed earlier, deer must have access to both cover and forage within a certain distance. Because of this, the area of accessible forage habitat can be different from the area of cover habitat in any given period. Deer cannot access all forage habitat from cover habitats, and they cannot access all cover habitat from any forage spot. Deer habitat dynamics in planning periods 13 and 14 in solutions 1 and 2 illustrate this. Because much less harvesting occurs in solutions 1 and 2, a lot more cover habitat will be available by the end of the 70-year planning horizon than in solutions 3 and 4; a larger amount of second-growth forest will reach the cutoff age of 120 years for cover habitat by the 13^{th} planning period because of the initial age-class distribution of the forest. However, limited thinning and harvesting also means that less, early-successional stage forage habitat will be available for deer. In other words, no matter how much mature cover habitat is available for shelter, lack of accessible forage can compromise how much deer habitat (accessible forage and cover) is present on the landscape. These dynamics play out differently in solutions 3 and 4, where more harvesting and thinning are scheduled to occur. This reduces the amount of cover habitat for deer by the end of the planning horizon, but it increases the amount of accessible forage habitat because of added early-successional stage habitat, whose development follows 5 to 10 years after harvests or precommercial thins. If lack of accessible forage habitat is the true bottleneck, as might be the case on Prince of Wales Island, the projected areas of accessible forage habitat rather than cover habitat will drive the effective well-being of deer populations. And this in turn would affect subsistence hunting opportunities for local Tlingit and

Haida Alaska Native communities. If shortage of cover habitat was the bottleneck for deer, the above dynamics would play out in reverse.

To illustrate the spatial dynamics of the tradeoffs described above, we mapped the harvesting and thinning activities for the four solutions. In figure 4, the maps in each panel show the management units in the Thorne Bay area that are scheduled to be harvested or precommercially thinned and those that are projected to reach or be in cover or accessible forage habitat status in the corresponding planning period under each of the four solutions. We specifically chose planning periods 11 through 13 (years 51 through 65) to show contrast among the four solutions both in terms of the areas of thinning and harvesting activities as well as the resulting area of habitat components for deer. Cover habitat is dominant in solution 1, which is a direct result of the limited harvesting and thinning activities that were scheduled in this solution. In the other three solutions (2, 3, and 4), accessible forage habitat becomes increasingly dominant because more thinning and harvesting were scheduled to occur gradually. This gradual shift from little to more management is also reflected in the projected timber volumes as well as sequestered carbon.

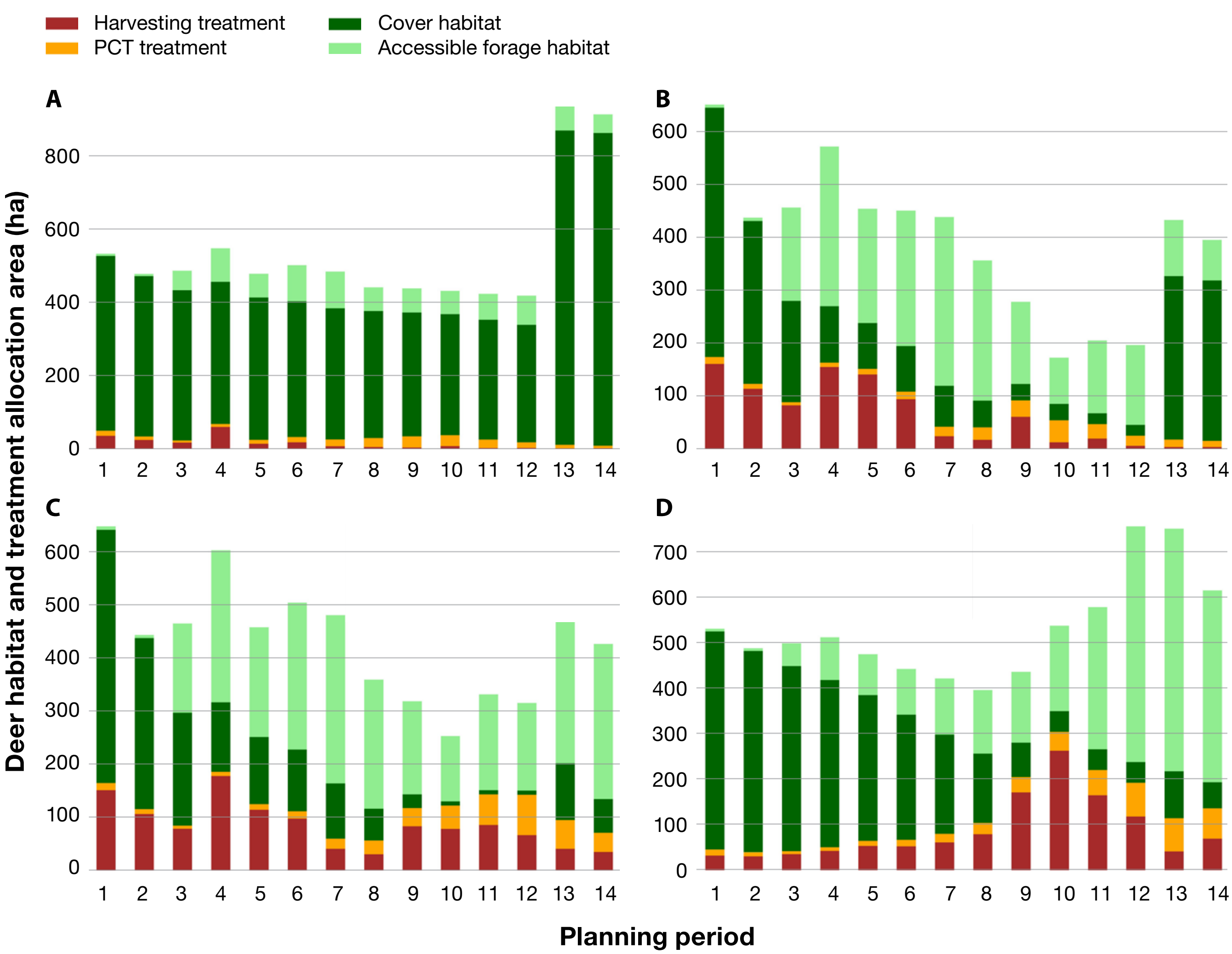

Figure 3—Four modeled solutions for deer habitats and forest treatments (including precommercial thinning [PTC]) of 14 individual 5-year planning periods: (A) solution 1, maximal carbon, because it has more cover habitat (old-growth forest); (B) solution 2, balanced strategy; (C) solution 3, maximal timber and balanced carbon and accessible forage habitat; (D) solution 4, maximal timber and accessible forage habitat. The area of accessible forage habitat can be different from the area of cover habitat in any given period because deer cannot access all forage habitat from cover habitats.

We did not capture deer population and habitat dynamics accurately in this case study. Thus, our interpretation of the optimization solutions above are purely illustrative. It is possible, in fact highly likely, that mature forest cover habitat for deer also contains some nutritional resources (forage), which in turn could make deer populations less dependent on early-successional stage habitat than our model formulation assumed. In addition, we only modeled summer forage and cover habitat for deer without acknowledging the critical need for winter forage. It is possible that if we incorporated needs for winter forage, the resulting Pareto front would look different. It is therefore imperative to work with local wildlife experts on the model formulation, real data parameterization, and interpretation of the results that these optimization models provide. The same applies to carbon dynamics; we have made a number of assumptions as to how carbon is retained in live versus harvested trees. All these assumptions are illustrative of the model and not prescriptive.

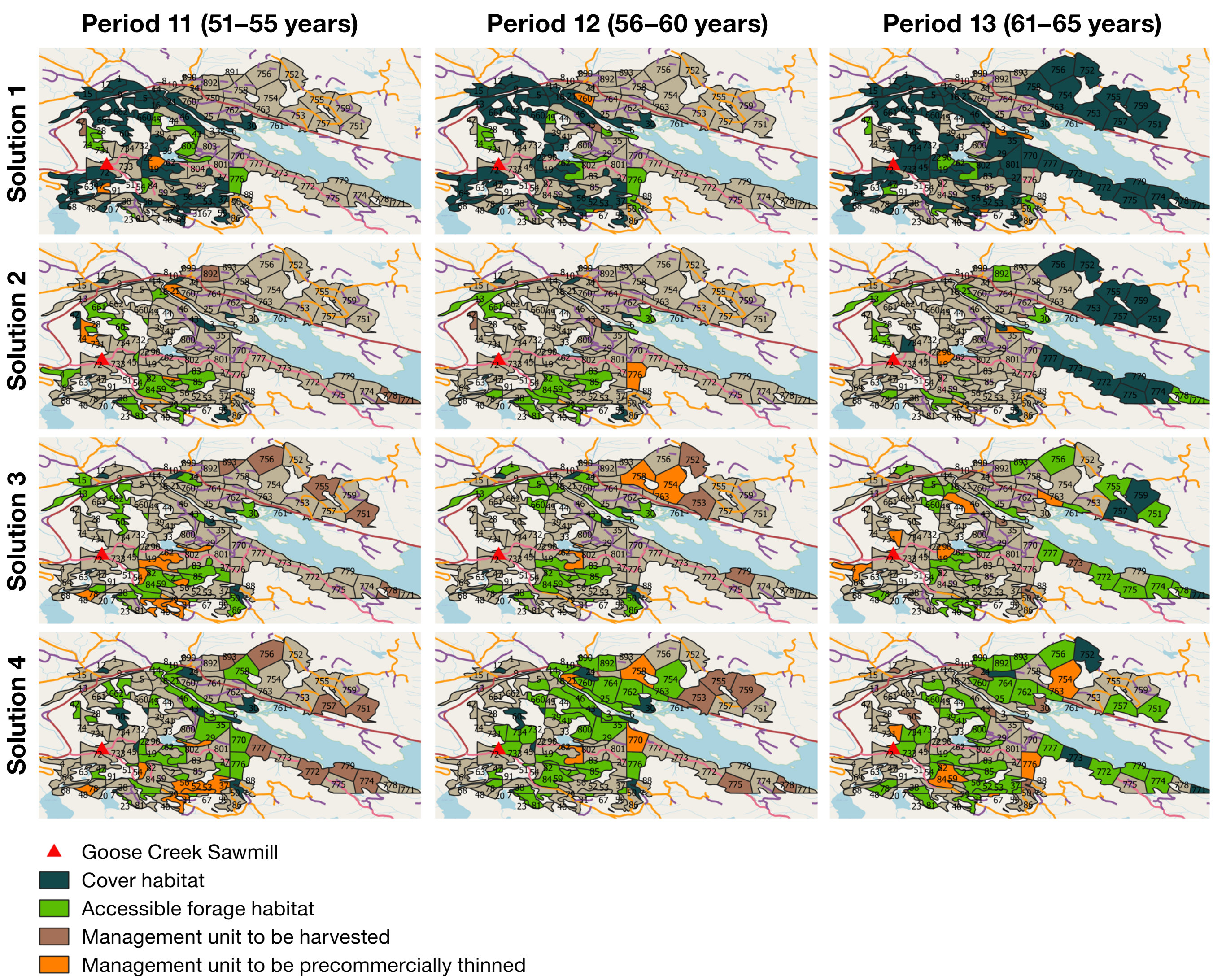

Figure 4—Maps of modeled solutions 1 through 4 during the 5-year planning periods 11 through 13 for deer habitats and planned forest treatments. Maps in each panel show the management units (polygons with black borders) in the Thorne Bay area, Alaska, that are scheduled to be harvested or precommercially thinned in the corresponding planning period under each of the four solutions: solution 1, maximal carbon, because it has more cover habitat (old-growth forest); solution 2, balanced strategy; solution 3, maximal timber and balanced carbon and accessible forage habitat; solution 4, maximal timber and accessible forage habitat. The area of accessible forage habitat can be different from the area of cover habitat in any given period because deer cannot access all forage habitat from cover habitats. We specifically chose planning periods 11 through 13 to show contrast among the four solutions in terms of the areas of thinning and harvesting activities, as well as the resulting area of habitat components for deer.

Conclusions

In this study, we identified a set of forest ecosystem services that stakeholders in the Tongass National Forest agreed were important for Prince of Wales Island communities. These were timber harvesting for local mills, deer habitat, and carbon sequestration. We conducted a comprehensive literature review of the underlying dynamics of, and interactions among, these services in Alaska. Our contribution was to introduce a multiobjective decision framework that could explicitly incorporate these dynamics and interactions and help stakeholders understand the tradeoffs or synergies among the competing or compatible services in a quantitative manner. We illustrated the benefits of the proposed model framework by applying it to a demonstrative case study in the Thorne Bay area of Prince of Wales Island. Although the case study was subject to many simplifying assumptions, we found that increasing deer habitat in second-growth forests was compatible with increased harvesting and thinning activities but incompatible with increasing carbon sequestration.

We expect that stakeholders who wish to use our proposed model to identify management alternatives on the Tongass National Forest would study the Pareto fronts that this method can generate and select a short list of candidate solutions representing the full spectrum of their interests and preferences. Stakeholders could further discuss pros and cons of these candidates to identify the best compromise. This work thus lays the foundation for more comprehensive analyses, which could be applied across the Tongass National Forest, as more and more second-growth timber reaches harvestable age.

U.S. Standard Equivalents

When you know:	Multiply by:	To find:
Centimeters (cm)	.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	.621	Miles
Hectares (ha)	2.47	Acres
Cubic meters (m^3)	35.3	Cubic feet
Cubic meters (m^3)	423.8	Board feet
Megagrams (Mg)	1.102	Tons
Petagram (Pg)	1,102,000000	Tons
Trees per hectare	.405	Trees per acre

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