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Use of Historical Logging Patterns to Identify Disproportionately Logged Ecosystems within Temperate Rainforests of Southeastern Alaska

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Abstract: *The forests of southeastern Alaska remain largely intact and contain a substantial proportion of Earth's remaining old-growth temperate rainforest. Nonetheless, industrial-scale logging has occurred since the 1950s within a relatively narrow range of forest types that has never been quantified at a regional scale. We analyzed historical patterns of logging from 1954 through 2004 and compared the relative rates of change among forest types, landform associations, and biogeographic provinces. We found a consistent pattern of disproportionate logging at multiple scales, including large-tree stands and landscapes with contiguous productive old-growth forests. The highest rates of change were among landform associations and biogeographic provinces that originally contained the largest concentrations of productive old growth (i.e., timber volume >46.6 m^3/ha). Although only 11.9% of productive old-growth forests have been logged region wide, large-tree stands have been reduced by at least 28.1%, karst forests by 37%, and landscapes with the highest volume of contiguous old growth by 66.5%. Within some island biogeographic provinces, loss of rare forest types may place local viability of species dependent on old growth at risk of extirpation. Examination of historical patterns of change among ecological forest types can facilitate planning for conservation of biodiversity and sustainable use of forest resources.*

Keywords: forestry, fragmentation, land-cover change, old-growth forest

El Uso de Patrones Históricos de Tala para Identificar Ecosistemas Talados Desproporcionadamente en Bosques Lluviosos Templados del Sureste de Alaska Albert & Schoen 11-839

Resumen: *Los bosques del sureste de Alaska permanecen en su mayoría intactos y contienen una proporción sustancial de los bosques lluviosos templados maduros de la Tierra. Sin embargo la tala a escala industrial ha ocurrido desde los 1950s dentro de un rango relativamente estrecho de tipos de bosque que nunca se ha cuantificado en una escala regional. Analizamos los patrones históricos de tala de 1954 hasta 2004 y comparamos las tasas relativas de cambio entre tipos de bosque, asociaciones de formaciones terrestres y provincias biogeográficas. Encontramos un patrón consistente de tala desproporcionada en escalas múltiples, incluyendo grandes fragmentos y paisajes con bosques maduros productivos contiguos. Las tasas más altas de cambio estuvieron entre las asociaciones de formaciones terrestres y provincias biogeográficas que originalmente contenían la mayor concentración de bosque maduro productivo (p.ej.: volumen de madera >46.6 m^3/ha). Aunque solo 11.9% de los bosques maduros productivos han sido talados a lo largo de la región, los fragmentos se han reducido al menos en 28.1%, bosques de karst en 37%, y paisajes con el volumen más alto de bosque maduro contiguo en 66.5%. Dentro de algunas provincias biogeográficas aisladas, la pérdida de tipos raros de bosque puede ubicar la viabilidad local de especies dependientes del bosque maduro en riesgo de extirpación. Examinar los patrones históricos de cambio entre tipos de bosque ecológicos puede facilitar la planeación para la conservación de la biodiversidad y el uso sustentable de los recursos forestales.*

Palabras Clave: bosque maduro, cambio en cobertura de suelo, fragmentación, silvicultura

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Introduction

Assessment of threats to rare ecosystems has become an increasing focus for global conservation, and factors such as geographical distribution and changes to ecosystem composition, structure, and function have been used in such assessments (Nicholson et al. 2008; Rodriguez et al. 2010). We used historical patterns of logging to assess change among forest ecosystems within the coastal temperate rainforests of southeastern Alaska and specifically to assess how current forest conditions differ from historical conditions.

Coastal temperate rainforests are globally uncommon. The largest (35% of this ecosystem worldwide) is distributed along the Pacific coast of North America from northern California through southern coastal Alaska (Kellogg 1992; DellaSala et al. 2011:16). Although the southern half of the Pacific coast rainforest is heavily developed, northern British Columbia and southeastern Alaska retain the largest amount of intact old-growth temperate rainforest on Earth and support abundant populations of species that have declined or are threatened in the southern portion of their historical ranges (e.g., Pacific salmon [*Oncorhynchus* spp.], brown bear [*Ursus arctos*], and Marbled Murrelet [*Brachyramphus marmoratus*]) (DellaSala et al. 2011:57).

In southeast Alaska, where fire is rare, natural patterns of disturbance such as wind storms, landslides, and flooding produce a fine-scale patchwork of forest types and structure that differ substantially from the more homogenous, even-aged stands that develop after clearcut logging (Kramer et al. 2001; Ott & Juday 2002; Alaback et al. 2013). Old-growth forests typically occur in a mixed-age mosaic dominated by old trees (>300 years) and have multilayered canopies, abundant understory vegetation, and high structural diversity (Harris & Farr 1974; Kramer et al. 2001). In contrast, clearcut logging is a stand-replacing event that initiates succession (0–5 years, shrubs; 5–25 years young conifers; 25–30 years, conifers that prevent light from reaching the forest floor) (Alaback 1982). Twenty to 30 years after clearcutting (stem-exclusion phase), the forest is characterized by a homogeneous structure, low understory diversity and productivity, and relatively low habitat value for native fauna. This stage typically lasts >100 years (Wallmo & Schoen 1980; DellaSala et al. 1996). Although timber volume sufficient for commercial harvest may regenerate <100 years after logging (Harris & Farr 1974), the structure and diversity of old-growth forests require several centuries to develop (Alaback 1982; DellaSala et al. 2011:49).

Large-scale timber harvesting in the region developed, following passage of the 1947 Tongass Timber Act, within a framework of subsidized, long-term timber contracts (Beier et al. 2009). Later, harvest on private lands began under the 1971 Alaska Native Claims Settlement Act (Knapp 1992). Logging in the region peaked at 2.3 million m^3/year in 1990 and declined to approximately 0.4 million m^3/year in 2004 (USFS 2008*a*) as a result of combined political, economic, and institutional factors (Beier et al. 2009). Although the location and timing of past logging is known, the pattern of logging relative to the availability of forest types has not been analyzed at a regional scale to allow for evaluation of changes in diversity and abundance of forest ecosystems and determination of the potential implications for conservation of biodiversity (Lindenmayer et al. 2000) and timber supply (Beier 2010).

Our objectives were to document current forest conditions and historic patterns of logging; estimate the original distribution of ecosystems (ecological forest types) among biogeographic provinces; and map the distribution of old-growth ecosystems that have sustained disproportionate rates of logging in the past. Uniquely, we documented in a spatially explicit manner how southeastern Alaska forests have changed as a result of logging and how the present landscape differs from historical conditions. Although researchers have evaluated change in condition of old-growth forests over time in areas farther south in the Pacific Northwest (Staus et al. 2002; Wimberly & Ohmann 2004), few have provided a sufficiently fine-grained characterization of ecological systems to identify changes in rare forest types (Strittholt et al. 2006) or specifically investigated ecological correlates of anthropogenic change (Alig et al. 2005). Recent (60 years) patterns of old-growth logging in southeastern Alaska can provide a model for understanding other temperate rainforest regions that were less well documented and now reflect a more complex mosaic of human development (Huston 2005).

Methods

Study Area

Southeastern Alaska extends approximately 800 km between Dixon Entrance (55°N, 130°W) and Yakutat Bay (59°N, 140°W) and is dominated by the Alexander Archipelago, which has >5000 islands and a total land area of 8.7 million ha (Fig. 1). Approximately 80% of the region is contained within the Tongass National Forest (6.8 million ha). Our study area was in the perhumid rainforest zone, which is characterized by a maritime climate with cool summers (<15 °C), abundant precipitation (200–600 cm), and mild winters (rarely < −10 °C) (Alaback 1996). Although the region is characterized as a rainforest, a large proportion of the landscape is wetlands, alpine tundra, and recently glaciated terrain (Nowacki et al. 2001).

Closed-canopy conifer forests are widely distributed below 600 m and are typically dominated by associations of western hemlock (*Tsuga heterophylla*), Sitka spruce

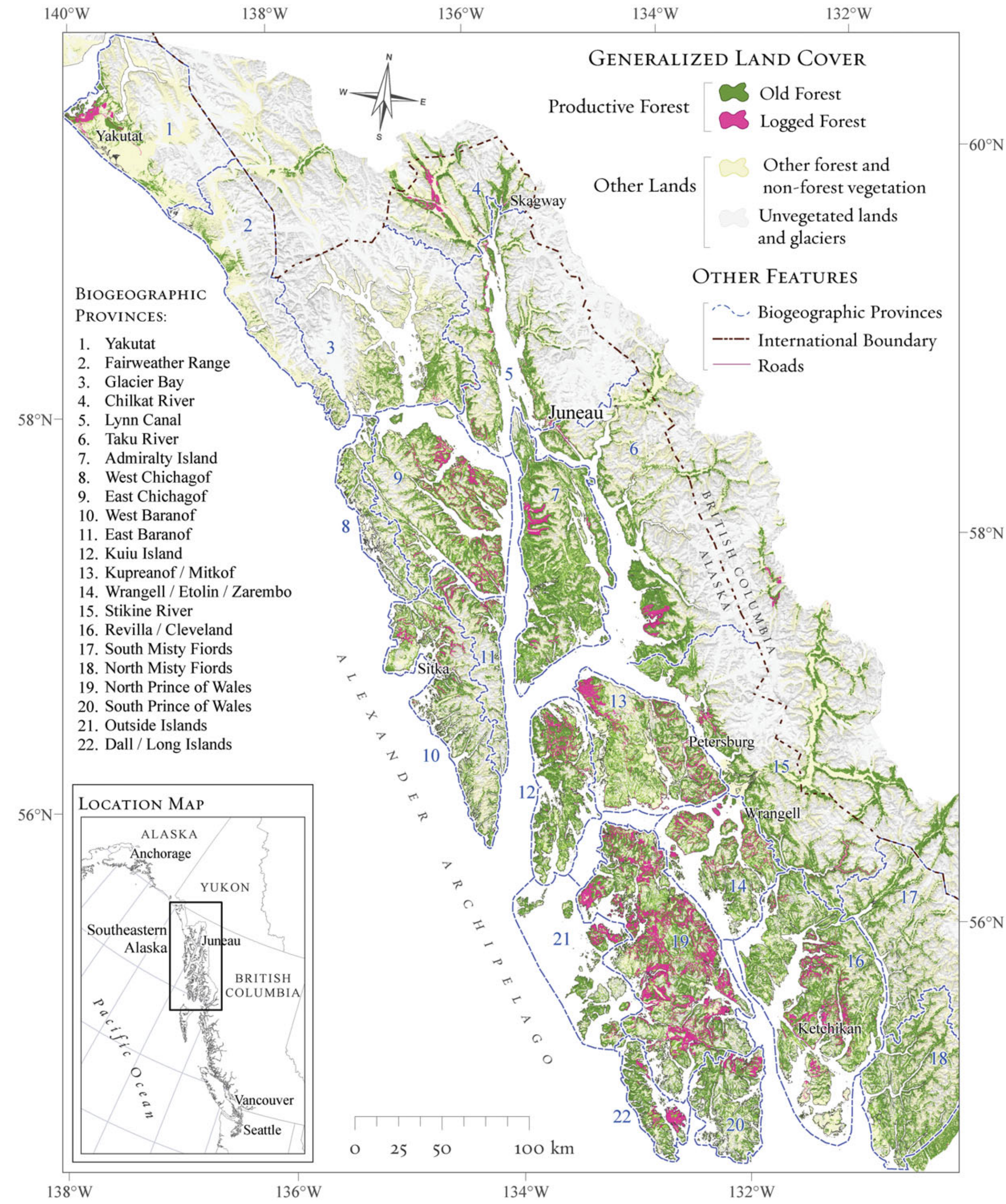

Figure 1. Generalized land cover and productive forest lands among biogeographic provinces in southeastern Alaska.

(*Picea sitchensis*), western redcedar (*Thuja plicata*), and Alaska yellow-cedar (*Chamaecyparis nootkatensis*) (Viereck et al. 1992). In general, large-tree (mean diameter >53 cm), old-growth forests are patchily distributed and tend to occur most frequently on well-drained sites, including lower elevation slopes, alluvial fans, and floodplains (Shephard et al. 1999) and on karst (i.e., porous limestone) substrates (Baichtal & Swanston 1996). We defined forest ecosystems on the basis of landforms and forest structural characteristics that correlate with important ecological processes, such as soil productivity and frequency of disturbance, species composition, and habitat value for native flora and fauna (Shephard et al. 1999; Caouette & DeGayner 2008).

Mapping of Forest Ecological Systems

To characterize forest types, we combined data on vegetation and landform associations to identify ecologically important distinctions not represented by vegetation mapping alone (Comer et al. 2003). Forest productivity is determined largely by soil characteristics and climatic gradients (Nowacki et al. 2001; USFS 2008*b*), and we followed the U.S. Forest Service (USFS 2008*a*) definition of forest productivity: a "productive forest" is land capable of producing >1.4 m^3/ha of wood fiber/year or with standing volume of timber >46.6 m^3/ha. Although not strictly a measure of net primary productivity, we assumed that given the region's low rate of forest disturbance under historical conditions (Alaback 1996; Kramer et al. 2001), characteristics of existing old-growth forest provided an index of site potential adequate for broad-scale comparison of forest productivity among landforms and biogeographic provinces (USFS 2008*b*).

Our primary source for mapping vegetation was the USFS (2008) Tongass timber inventory, which was completed in 1986. The inventory consisted of extensive ground surveys and aerial photography and periodic updates to reflect ongoing management. Productive old-growth forests are categorized by average tree size (Caouette & DeGayner 2005) and volume of standing timber. On the basis of mean diameter, productive old-growth forests are categorized as large-tree (>53 cm), medium-tree (43–53 cm), and small-tree (<43 cm) stands. Caouette and DeGayner (2008) report accuracy of 60–80% between this inventory and ground-based stand exams. Although characterization by tree size and timber volume differs from a typical forest classification that is based on species composition (e.g., Viereck et al. 1992), it is a useful indicator of structural gradients (Caouette & DeGayner 2008) that represents an important aspect of forest diversity (Noss 1990) and habitat functions for wildlife species (e.g., Schoen & Kirchhoff 1990; Iverson et al. 1996).

To map forests on lands outside the Tongass, we merged the timber inventory from the Haines State Forest (HSF) (ADNR 1985) and the Interim Land Cover Classification (ILC) (Shasby & Carneggie 1986). The HSF inventory categorizes stands on the basis of tree size, similar to the Tongass inventory. The ILC category "closed-canopy conifer" is roughly equivalent to the medium-tree old-growth category (i.e., middle 74%) of the Tongass inventory. Other ILC categories did not meet criteria for productive old growth and were excluded from further analyses. Following Caouette and DeGayner (2005), we categorized small-tree stands on hydric soils as low-volume strata, small-tree stands on nonhydric soils and medium-tree stands on hydric soils as medium volume, and all large-tree and medium-tree stands on nonhydric soils as high-volume strata (USFS 2008*a*). We used the National Wetlands Inventory (Cowardin et al. 1979) to identify hydric soils and calculated estimates of gross timber volume as a function of volume strata and geographic area (USFS 2008*a*). We digitized more recent road construction and logging activity outside the Tongass through visual interpretation of aerial photography (current in 1997) and Landsat Enhanced Thematic Mapper (ETM) imagery (current in 2000–2002).

To characterize forest conditions over a landscape matrix rather than as individual stands (Wiens 1995), we developed an index of old-growth forest density. We based the index on a moving-window analysis of gross volume within a 0.9-km radius (1.56 km^2). This index integrated information on forest structure and the degree to which productive old-growth forests are contiguous across this landscape.

Our sources for mapping landform associations were the Tongass Soils Inventory, derived from aerial photography and ground surveys (USFS 1996), and Karst Inventory, derived from field surveys and U.S. Geological Survey data on bedrock geology (Baichtal & Swanston 1996). We categorized landform associations as coastal (marine deposits and wave-cut terraces uplifted by tectonic or isostatic forces), lowland (glacial till and outwash, low topographic relief, extensive wetlands), valley floor (glacially carved U-shaped valleys with alluvial and glacial deposits), hills (rolling terrain, heavily scoured by glaciers), mountain slopes (low-to-mid slopes of mountain features, angular terrain, carved by glaciers, alluvial, and colluvial deposits), mountain summits (higher elevation, angular terrain), and volcanic (postglacial, volcanic terrain). A detailed description of landforms and the interacting effects of geology, landform, and hydrology on vegetation in this area is available in Nowacki et al. (2001). For areas lacking data on landform association, we used a supervised classification of topographic features (elevation, slope, and topographic position index) and the Tongass Soils Inventory as the training set (Hengl & Rossiter 2003). Overall agreement of this model with the soils inventory was 68%. Because karst was relatively rare, we merged all landform associations in areas of karst to preserve sufficient sample size for analyses.

To analyze the geographic distribution of forests and logging activity, we used biogeographic provinces (USFS 2008*a*) that represent ecologically important patterns of climate, glacial history, and island biogeography (Nowacki et al. 2001; Cook et al. 2006). The resulting maps of forest condition and landform associations were evaluated and considered robust by biologists and foresters with knowledge of local areas. All mapping was conducted with ArcInfo (version 9.2, Environmental Systems Research Institute, Redlands California).

Assessment of Forest Change

Data on the original composition of logged stands were available for 98,023 ha within the Tongass that were logged after 1986. We assumed the proportional rates of logging within this sample among large- (29.3%), medium- (64.6%), and small- (6.1%) tree stands were representative of all logging that occurred from 1954 to 2004. To estimate historical timber volume, we assumed the distribution of hydric soils was a suitable variable to discriminate between medium-volume (i.e., hydric soils) and high-volume stands (i.e., nonhydric) (USFS 2008*a*). These assumptions are conservative and supported by anecdotal evidence that earlier logging (before 1979) was skewed more toward large-tree and high-volume stands than logging that occurred after 1986 (Rakestraw 1981; USFS 2008*a*). We used this information to compare average density of landscape forest and patch characteristics among the forest landscapes with the highest volume of forest (>18,762 m^3/km^2) between 1954 and 2004.

We determined patterns of selectivity in logging by comparing forest types selected for logging with their original availability (Alldredge et al. 1998). We evaluated selectivity among stand characteristics (tree size and timber volume), landscape-scale forest (timber volume per square kilometer), elevation (m), categories of landform associations and biogeographic provinces (percent productive forest). We used chi-square tests for categorical variables and Kruskal–Wallis for continuous variables (Conover 1980) to test for significance. We examined the correlation between rate of logging and forest productivity (as indexed by the percentage of land in productive forest) among biogeographic provinces and landform associations with Spearman's rank correlation (Conover 1980) and logistic regression (Hosmer & Lemeshow 1989).

Logistic-Regression Model of Forest Change

We developed a multiple logistic-regression model to identify the suite of forest variables most strongly predictive of whether forests had been logged or not logged and to map this relation within remaining old growth. To control for spatial autocorrelation at a regional scale, we explicitly included differences among biogeographic provinces as a potential explanatory variable in the logistic model. At the local scale, we spaced sample locations on a systematic grid at 1-km intervals and eliminated duplicate points that fell within any single forest stand. Each observation was coded as logged (1) or not logged (0) for the logistic model. We excluded federally protected lands from the logistic analyses.

Comparing all combinations of independent variables, we identified the best model with the Akaike information criterion (Hosmer & Lemeshow 1989) in STATISTICA software (StatSoft, Tulsa, Oklahoma). To account for an inadequate sample of logging within some biogeographic provinces, we grouped provinces of Admiralty Island with Chichagof Island; Glacier Bay and Fairweather provinces with Lynn Canal; and Misty Fiords with the Stikine River mainland (Fig. 1). We used the area under receiver operating characteristics (ROC) curve and percentage of observations correctly classified to evaluate the model (Guénette & Villard 2005). We interpreted the model by evaluating the significance of independent variables and the odds ratios (Hosmer & Lemeshow 1989).

We mapped the output of the logistic model as an index of selectivity that reflects the degree to which any combination of geographic, forest, and environmental variables were either preferentially selected or avoided for logging. For the purpose of calibrating the model to observed forest conditions, we determined the cut point that provided maximum accuracy in differentiating logged and old-growth stands (Guénette & Villard 2005). We used this criterion to estimate the remaining distribution of old-growth forest types that had sustained disproportionate rates of logging.

Results

Mapping of Forest Ecological Systems

Forested lands covered 4,488,848 ha in southeastern Alaska, approximately 50% of the total land base. Productive forests (including old-growth and younger stands) covered 2,657,154 ha, approximately 30% of the region's land base. Among landform associations, the proportion of land in productive forest was highest on karst (67%), followed by coastal areas (53%), hills (53%), mountain slopes (50%), valley floors (43%), volcanoes (31%), lowlands (31%), and mountain summits (2%).

Within productive old growth in 2004 (2,320,088 ha), large-tree stands represented 10.2%, whereas medium-tree stands represented 74.7% and small-tree stands represented 15.1% of the total (Table 1). Average timber volume among old-growth stands was 194.9 m^3/ ha (SD 46.4, range = 37–263), and at a landscape scale average volume was 4,330 m^3/km^2 (SD 5,029, range = 0–25,770). As a measure of availability, productive old-growth forests were most abundant on mountain slopes (58.7%), followed by lowlands (12.5%), valley floors (10.4%), hills (10.1%), and karst (4.1%). Among biogeographic provinces, North Prince of Wales had the largest proportion of all productive old growth (10.9%), followed by Admiralty Island (10.5%), Revillagigedo Island and Cleveland Peninsula (10.0%), and East Chichagof Island (7.6%). The remaining 16 provinces contained ≤6.2% of productive old growth each (Table 1).

Assessment of Forest Change

Although a large majority of productive forests in 2004 were old-growth forests (88.1%), the relative rate of logging differed among forest types and biogeographic provinces (Table 1). Large-tree stands were logged

Table 1. Distribution and condition of productive forest lands and the relative rate of logging among categories of tree size, landform association, and biogeographic province in southeastern Alaska.

	Productive forest lands					
	old forest		*logged forest*			
Variable	*(ha)*	*(%)*	*(ha)*	*(%)*	*Logged (%)*[a]	*Relative proportion logged*[b]
Tree size						
large	237,591	10.2	92,900[c]	29.3	28.1	2.36
medium	1,748,187	74.7	204,825[c]	64.6	10.5	0.88
small	354,310	15.1	19,341[c]	6.1	5.2	0.43
Landform						
Karst	95,596	4.1	56,217	17.7	37.0	3.11
valley floor	242,429	10.4	45,521	14.4	15.8	1.33
Coastal	36,576	1.6	5138	1.6	12.3	1.04
Hills	235,914	10.1	28,391	9	10.7	0.90
mountain slopes	1,373,992	58.7	149,879	47.3	9.8	0.83
Lowlands	293,484	12.5	30,681	9.7	9.5	0.80
Volcanic	6,571	0.3	521	0.2	7.3	0.62
mountain summits	55,526	2.4	718	0.2	1.3	0.11
Biogeographic province						
North Prince of Wales	255,884	10.9	119,699	37.8	31.9	2.68
Dall and Long Islands	44,056	1.9	10,880	3.4	19.8	1.66
Yakutat Forelands	33,525	1.4	7402	2.3	18.1	1.52
Kupreanof and Mitkof	144,764	6.2	27,364	8.6	15.9	1.34
Wrangell, Etolin, and Zarembo	93,341	4	16,713	5.3	15.2	1.28
East Chichagof	177,353	7.6	28,928	9.1	14.0	1.18
Outside Islands	47,951	2	7448	2.3	13.4	1.13
East Baranof	36,952	1.6	5,583	1.8	13.1	1.10
Chilkat River Complex	56,064	2.4	8,069	2.5	12.6	1.06
Revilla Island and Cleveland Peninsula	234,832	10	29,476	9.3	11.2	0.94
South Prince of Wales	68,218	2.9	7,236	2.3	9.6	0.81
Kuiu Island	117,705	5	12,007	3.8	9.3	0.78
West Baranof	95,561	4.1	7,869	2.5	7.6	0.64
Taku River	139,349	6	8,717	2.7	5.9	0.49
Stikine River	135,547	5.8	6,083	1.9	4.3	0.36
Admiralty Island	245,417	10.5	10,968	3.5	4.3	0.36
Lynn Canal	85,929	3.7	2,542	0.8	2.9	0.24
Glacier Bay	61,880	2.6	81	0	0.1	0.01
South Misty Fiords	128,030	5.5	0	0	0	0
North Misty Fiords	87,883	3.8	0	0	0	0
West Chichagof	30,107	1.3	0	0	0	0
Fairweather Icefields	19,741	0.8	0	0	0	0
All productive forest	2,340,088	100	317,066	100	11.9	1.0

[a] *Percent original availability.*
[b] *Ratio of percentage change within each category to the average change for all forest types (11.9%).*
[c] *Estimated by extrapolating the observed rates of logging from 1986 to 2004 (n = 98,023 ha) of large (29.3%), medium (64.6%), and small trees (6.1%) in all forest lands logged (n = 317,066 ha).*

2.4 times more than their relative availability, whereas medium-tree and small-tree stands were logged less than their availability (Table 1). Logging also occurred disproportionately at broader spatial scales. Logging was significantly higher in productive forests that were contiguous at a landscape scale (Wald $\chi^2 = 2910$, 1 df, $p < 0.0001$) and in the most productive landforms (Spearman's $R = 0.48$, $p = 0.02$) and biogeographic provinces, such as North Prince of Wales ($R = 0.802$, $p = 0.01$) (Fig. 2), than in noncontiguous forests and provinces and landforms with less productive forest lands.

As a result of selective patterns of logging, characteristics of remaining old-growth forests differed from forest types that occurred historically. Average landscape volume of old-growth forest declined region-wide by 16.8% from 1954 ($\bar{X} = 11{,}958$ [SD 5,009]) to 2004 ($\bar{X} = 9{,}941$ [SD 4,666]; $Z = 81.65$, $n = 26{,}538$, $p < 0.01$). This trend reflects a process by which large, contiguous old-growth landscapes were fragmented and interspersed with young growth and the remaining old-growth stands contain a smaller proportion of large trees than historically. The highest volume landscape forests in 1954 (>18,762 m^3/km^2) were reduced by 66.5% region-wide from 243,373 ha in 1954 to 81,611 ha in 2004. This reduction was accompanied by similar declines in the number of patches (1954 $n = 2{,}464$; 2004 $n = 1{,}660$), average

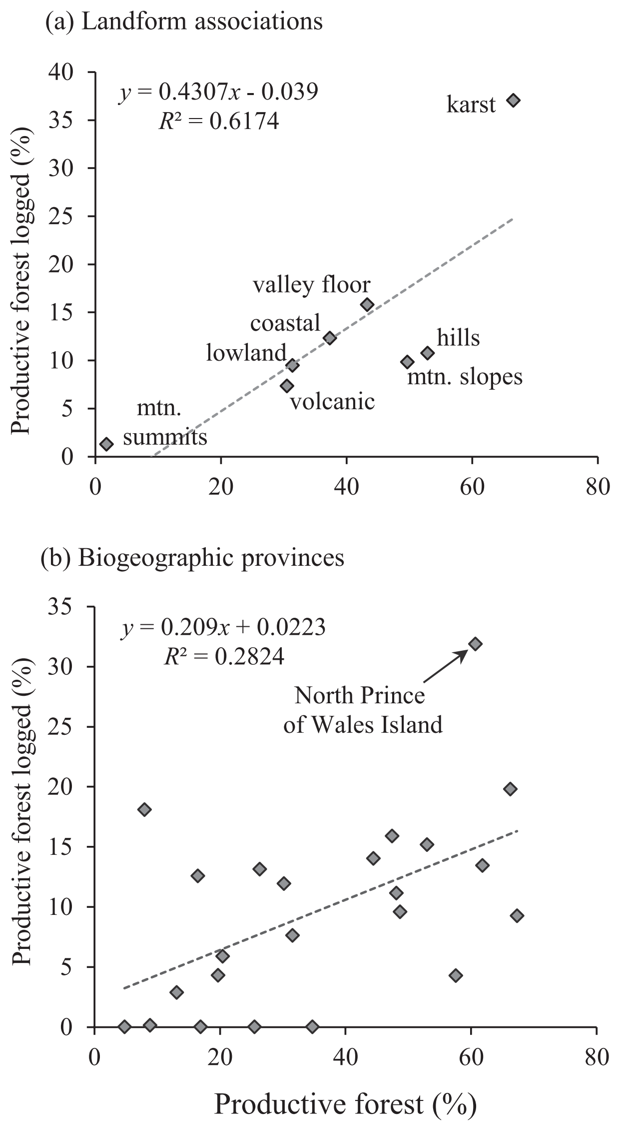

Figure 2. Percentage of lands in productive forest relative to percentage of those forests logged among (a) landform associations and (b) biogeographic provinces.

patch size (1954 $\bar{X} = 169$ ha [SD 848.4]; 2004 $\bar{X} = 105$ ha [SD 403]), and largest patch size (1954 max = 19,434; 2004 max = 9,433 ha). Due to natural fragmentation, high-volume forests contiguous at a landscape scale were always rare. The largest proportion (31%) of contiguous high-volume forest occurred on northern Prince of Wales Island, where such forests have been reduced by 93.8% (77,536 ha in 1954 to 4,801 ha in 2004) (Fig. 3) and average patch size declined from 264 ha in 1954 (SD 1,186.5) ($n = 435$, max = 11,692) to 73 ha in 2004 (SD 176.6) ($n = 164$, max = 1,321).

Logistic-Regression Model of Forest Change

With the exclusion of federally protected lands, the logistic-regression analyses included 1,727,483 ha, or 73.8%, of all productive forest lands in the region. The logistic model identified 4 variables that provided the best discrimination between logged and unlogged sites ($G = 4{,}438.58$, 18 df, $p < 0.0001$) (Table 2). The most significant predictor variable was landscape forest (Wald $\chi^2 = 1175.5$, 1 df, $p < 0.0001$), followed by biogeographic province ($\chi^2 = 614$, 15 df, $p < 0.0001$), stand volume ($\chi^2 = 499.5$, 1 df, $p < 0.0001$), and elevation ($\chi^2 = 479.2$, 1 df, $p < 0.0001$). Due to inadequate sample size, landform was not included in the final model. The goodness-of-fit chi-square test indicated the logistic model was apt ($p = 0.95$). The ROC indicated a good fit to the observed data (AUC = 0.859) and an optimal cut point of $p = 0.18$ to differentiate between logged and unlogged stands in the logistic model.

Regression coefficients showed that with other factors held constant, landscapes with higher forest density, stands with higher volumes of timber, and those located at lower elevations had higher rates of logging, whereas more sparsely distributed forests, lower volume stands, and those at higher elevations were logged at lower rates (Table 2). Although the highest proportion of all productive forests logged during this period was on North Prince of Wales (Table 1), the logistic model indicated that with other factors held constant, the relative rate of logging on East Baranof Island was similar to that on North Prince of Wales, both of which were 2.34 times greater than the regional average (Table 2).

With a cut point of 0.18 the logistic model correctly classified 75.8% of productive forest as either logged or unlogged. Forest types most commonly selected for logging, such as high-volume contiguous forests at lower elevations ($p \geq 0.18$), accounted for 34.6% (597,052 ha) of all productive forest, had sustained rates of logging 3.43 times greater than average, and consequently had a relatively high proportion of area in second growth (40.8%). In contrast, forest types not typically selected for logging such as lower volume fragmented forests and those at higher elevations ($p < 0.18$) represented 65.4% (1,130,386 ha) of all productive forest lands, sustained less than the average rate of logging (0.48-times), and remained largely in old-growth condition (94.3%).

Discussion

Although only a small fraction of all old-growth forests in southeastern Alaska have been logged (11.9%), the systematic way the most productive stands and landscapes have been targeted indicates that the likelihood of maintaining the natural abundance of forest types, including important fish and wildlife habitat, may be lower than this percentage suggests. Landscape-scale blocks of productive forest, stands of larger trees, and forests at lower elevations were disproportionately targeted for logging, and rate of logging was positively correlated with broad-scale forest productivity among landforms and biogeographic

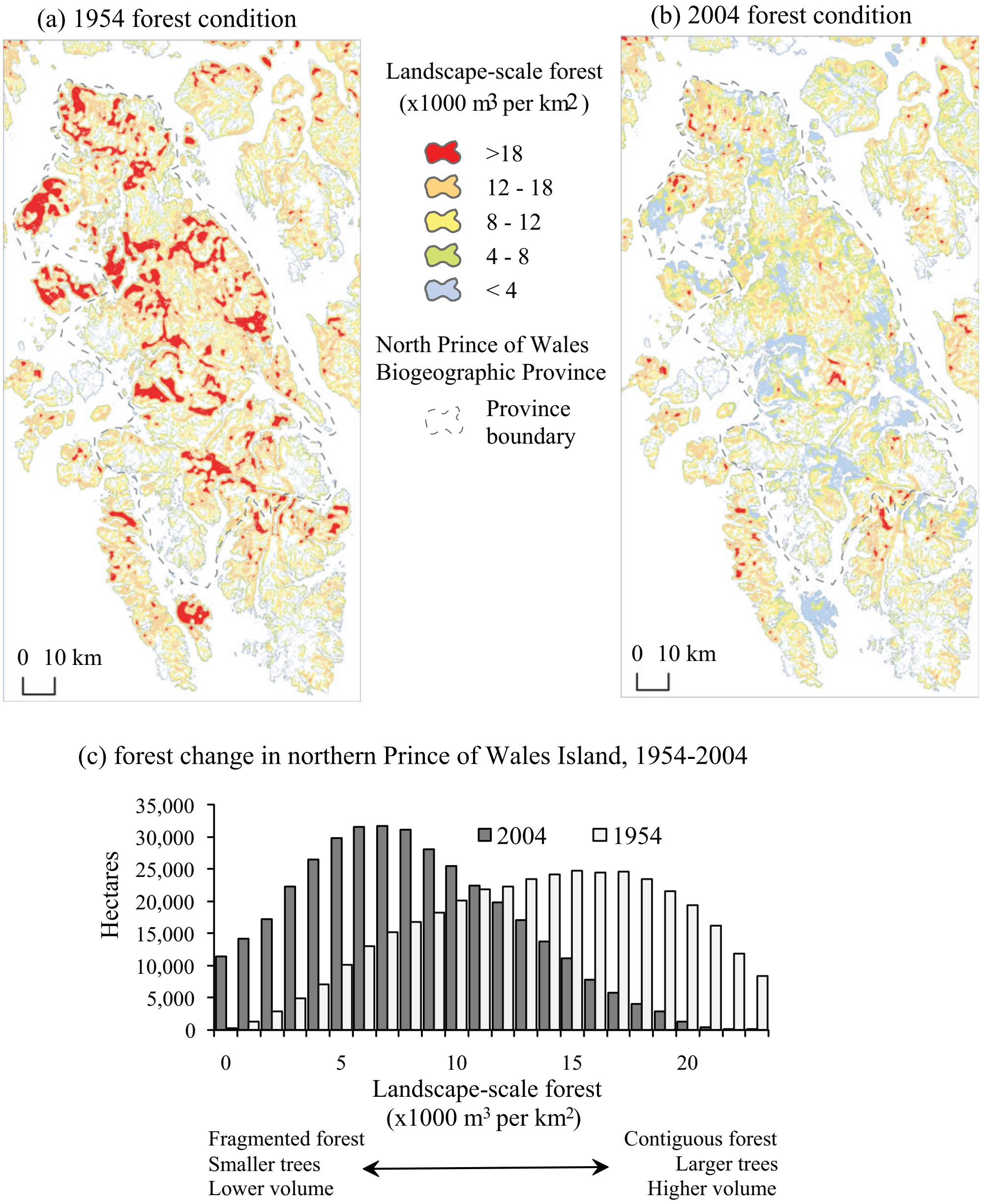

Figure 3. Change in the landscape-scale distribution of productive (i.e., timber volume >46.6 m^3/ha) old-growth forest in southeastern Alaska from (a) 1954 to (b) 2004 and (c) change in availability of remaining old-growth forests in the North Prince of Wales biogeographic province.

provinces. This spatial correlation of logging to forest productivity was consistent with patterns of change observed in coastal forests of western Oregon (Alig et al. 2005), and the more general relationship of resource development to ecosystem productivity as a common aspect of human development (DeFries et al. 2004; Huston 2005).

A consequence of depletion of rare forest types, such as large tree stands, karst forests, and high-volume forests that are contiguous at a landscape scale, is that habitat quality may also decline and adversely affect populations of fish and wildlife. For example, results of studies show a range of functions associated with large-tree forests, including provision of black bear (*Ursus americanus*) dens (Erikson et al. 1982), winter habitat for Sitka black-tailed deer (*Ococoileus hemionus sitkensis*) (Schoen & Kirchhoff 1990), nesting habitat for Northern Goshawk (*Accipiter gentilis*) (Iverson et al. 1996), and woody debris in streams that serves as structural habitat for salmon and other species (Heifetz et al. 1986; Willson & Halupka 1995). Similarly, karst exhibits attributes that make it highly productive for salmon (Bryant et al. 1998), yet

Table 2. Results of logistic regression model of forest types in southeastern Alaska that were either logged (1) or not logged (0) during 1954–2004.

Variable	*Odds ratio*[a]	*Coefficient*[b]	*SE*	*Wald* χ^2	*p*
Intercept	0.00	−7.35	0.17	1910.01	<0.0001
Landscape forest ($m^3 \times 1000/km^2$)	1.22	0.20	0.01	1175.52	<0.0001
Timber volume (m^3/ha)	1.02	0.02	0.00	499.51	<0.0001
Elevation (m × 100)	0.66	−0.42	0.02	479.22	<0.0001
Biogeographic province					
North Prince of Wales	2.34	0.85	0.05	277.46	<0.0001
East Baranof Island	2.34	0.85	0.15	30.92	<0.0001
Chichagof and Admiralty Island	2.16	0.77	0.07	119.22	<0.0001
Wrangell, Etolin, and Zarembo	2.14	0.76	0.10	62.78	<0.0001
Kupreanof and Mitkof	1.89	0.64	0.08	68.14	<0.0001
West Baranof Island	1.77	0.57	0.13	19.01	<0.0001
Revilla Island and Cleveland Peninsula	1.36	0.31	0.07	18.35	<0.0001
Dall Island Complex	1.25	0.22	0.12	3.53	0.0603
Outside Islands	1.00	0.00	0.15	0.00	0.9962
Chilkat River	0.90	−0.11	0.12	0.76	0.3836
Kuiu Island	0.56	−0.57	0.10	30.01	<0.0001
Taku River	0.44	−0.82	0.12	47.72	<0.0001
Yakutat Forelands	0.43	−0.84	0.16	25.84	<0.0001
Stikine River and Misty Fiords	0.39	−0.94	0.13	49.62	<0.0001
Lynn Canal and Glacier Bay	0.20	−1.61	0.21	56.56	<0.0001

[a] *Odds ratio represents the change in likelihood that a site was logged with a 1-unit change in a continuous predictor variable or the relative likelihood of logging among biogeographic provinces.*
[b] *Multiple logistic-regression coefficients indicate the overall preference for (coefficient > 0) or avoidance of (coefficient < 0) specific forest types or locations on the basis of historical patterns of logging with other factors held constant.*

karst is sensitive to increased soil erosion from road construction and logging (Baichtal & Swanston 1996). Landscape-scale blocks of old-growth forest are habitat for northern flying squirrels (*Glaucomys sabrinus*) on Prince of Wales Island and a key indicator of population persistence over time (Smith & Person 2007). Although both brown bears and wolves (*Canis lupus*) use a variety of areas, including old growth, they are particularly sensitive to fragmentation of landscapes by logging roads because roads increase risks of human-induced mortality (Schoen et al. 1994; Person & Russell 2008).

The sensitivity of species to changes in forested areas is recognized in the 1997 Tongass Land Management Plan that designated the Northern Goshawk as a "sensitive species," the northern flying squirrel and Marbled Murrelet as "species of concern," and the brown bear, wolf, and Sitka deer as "management indicator species" (USFS 2008*a*). Concerns regarding population viability of some species led the USFS to establish an Interagency Viable Population Committee that designed a landscape conservation strategy to address viability of species associated with old growth (USFS 2008*b*).

Nowhere are these factors more evident than on northern Prince of Wales Island. This province has extensive low-elevation karst, landscape-scale tracts of productive forests, high-quality habitat for a range of species (Albert & Schoen 2007), and is an important center of endemism (Cook & MacDonald 2001; Cook et al. 2006). The island has also sustained the highest rates of logging in the region (Albert & Schoen 2007; DellaSala et al. 2011:58). Although northern Prince of Wales contained only 10.9% of all productive forests in the region in 1954 it received 37.8% of all the logging. Consequently, 93.5% of its highest volume landscape-scale blocks of old growth had been logged.

The specific threshold at which habitat alteration affects population viability is difficult to determine (Fahrig 2001). However, results of a review of habitat thresholds literature (to inform forest planning in coastal British Columbia) indicated that maintaining loss of habitat below 40% of historical abundance poses a low risk to most species, whereas declines above that level result in less confidence that risks of extirpation will remain low (Price et al. 2009). On the basis of this criterion, rare forest types that have been reduced by >40% of historical abundance such as landscape-scale blocks of high-volume old growth, and particularly those on Prince of Wales Island, may warrant special consideration (Cook et al. 2006). Such a proactive approach to maintain forest diversity is particularly important because declines in the abundance and distribution of local populations of plants and animals may not be quantitatively measured for decades or centuries after habitat modification has occurred (Tilman 1994).

From a global perspective, southeastern Alaska supports a relatively low human population density, has developed industrially later than regions to the south, and continues to support populations of species such as salmon, brown bears, wolves, and Marbled Murrelets that have become rare or have been extirpated from more developed regions (DellaSala et al. 2011). Locally, the focus of logging within areas of higher productivity is typical of agrarian expansion into previously undeveloped lands (Huston 2005) and likely reflects processes that contributed to the decline of these species elsewhere. Our model provides a spatial framework within which to identify remaining old-growth forests that have been disproportionately logged and provides a historical reference for planning restoration of functional attributes such as landscape-scale connectivity among forests blocks. Such tools may be particularly relevant in the context of recent petitions to list endemic subspecies associated with productive old-growth forest such as Queen Charlotte Goshawk (*A. g. laingi*), Prince of Wales flying squirrel (*G. s. griseifrons*), and Alexander Archipelago wolf (*C. l. ligoni*) for protective status under the U.S. Endangered Species Act. These results provide a baseline for assessing the distribution and abundance of rare ecosystems (e.g., large-tree old growth) on the basis of historical patterns of change and have implications for planning for ecological sustainability (Lindenmayer et al. 2000) and future management of forest resources in southeastern Alaska and elsewhere (DeFries et al. 2004; Turner et al. 2007).

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