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Karst Landscapes and Associated Resources: A Resource Assessment

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Conservation and Resource Assessments for the Tongass Land Management Plan Revision

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Abstract

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The Tongass National Forest contains world class karst features and the largest concentration of associated dissolved caves known in the State of Alaska. This paper describes the dominant karst formation processes operating in southeast Alaska, the controlling geologic and hydrologic characteristics, and the influence of karst landscapes on associated forest resources. Recent sediment deposits and waterline marks in underground karst drainage systems suggest that timber harvesting has increased sediment and debris transport and the flooding of certain underground passages.

Keywords: Karst, epikarst, caves, paleontology, Tongass, Alaska.

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Background

The Tongass National Forest (Tongass) contains the largest concentration of dissolution caves known in the State of Alaska (Baichtal 1993b, 1993c). The Tongass also contains world-class karst features, particularly surface or epikarst in the alpine and subalpine zones (Aley and others 1993). Epikarst refers to the saturated zones within the intensely dissolved veneers developed at the surface of carbonate rock sections, either beneath soils or on exposed rock outcrops. The karst and cave features result from chemical weathering of limestone and marble bedrock. The karst and cave features and associated resources are a recently discovered and recognized attribute of the lands within southeast Alaska that are of international significance for a wide variety of reasons, including their intensity, diversity, and recreational values, as well as their biological, mineralogical, cultural, and paleontological components (Aley and others 1993).

Karst Processes

In southeast Alaska, these karst and cave features define an ecological unit or “landscape” found within and on top of almost pure carbonate bedrock that formed as the result of differential solution of these rocks by acid ground water. This acidic ground water is a direct product of abundant precipitation and passage of the water through organic-rich forest soils.

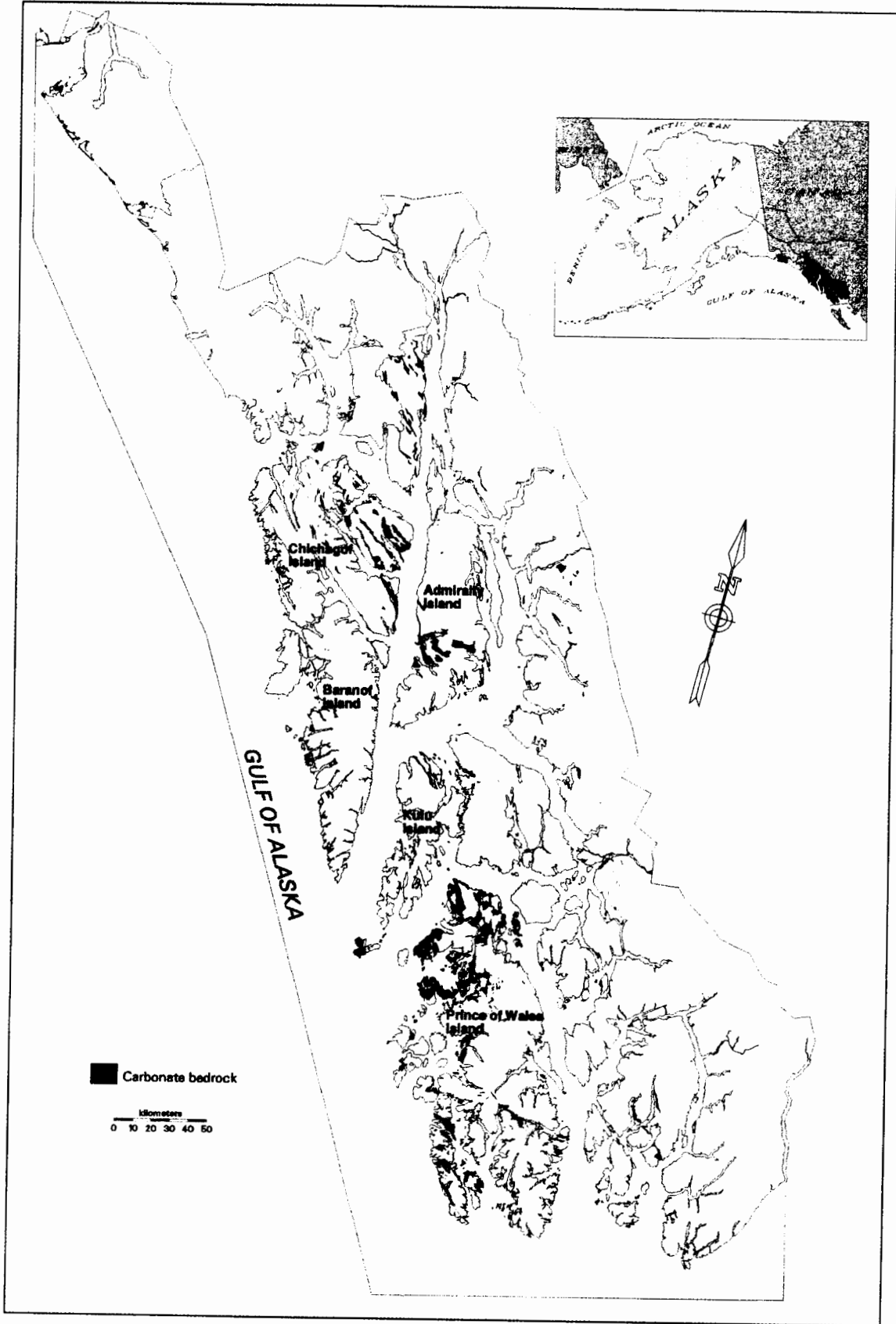
A few of the important characteristics of this ecological unit include mature, well-developed western hemlock-Sitka spruce forests (*Tsuga heterophylla* (Raf.) Sarg.-*Picea sitchensis* (Bong.) Carr.) along valley floors and low-gradient slopes, well-developed subsurface drainage, and underlying unique cave structures.

The carbonate rocks on which this landscape is developed are primarily Ordovician through Permian limestone and marble belonging to the Heceta, Descon, Saginaw Bay, Bay of Pillars, Pybus, Kennel Creek, White Stripe, and Iyokeen formations (Brew and others 1984, Gehrels and Berg 1992). The rock units susceptible to karst formation are almost-pure calcium carbonate (CaCO₃), characteristically fine grained and massive or thick bedded, and commonly fractured and fossiliferous. Thickness of the rock units may exceed 4000 meters in some exposures (Brew and others 1984). These rocks underlie 176 988 hectares of the Tongass in a northwest trending band extending from northern Prince of Wales Island to northern Chichagof Island (fig.1).¹

The differential solution or chemical weathering of these almost-pure carbonates results in development of well-defined surface features or epikarst, such as deep shafts, crevasse-like dissolved fissures, erosion or dissolution rills, and spires and spikes of carbonate bedrock (fig. 2). Subsurface solution channels and cavities along zones of weakness in the rock are defined by bedding planes, joints, and fractures.

The subsurface solution channels add a vertical, underground dimension to the karst landscape that is difficult to define and predict. Subsurface drainage networks generally operate independently of and with more complexity than the overlying surface drainage systems (Aley and Aley 1993, Huntoon 1992b). The watershed characteristics of the surface topography may have little or no relation to the subsurface karst drainage system. In karst landscapes, the many solution-widened fissures become injection points for surface and near-surface waters into a more complex subsurface drainage system. These fissures rapidly move water and

¹ Data are available from: Tongass Geographical Information System, Tongass Land Management Plan Office, 8465 Old Dairy Road, Juneau, AK 99801.



Controlling Geologic and Hydrologic Characteristics

sediment delivered from surface sources vertically downward and laterally to widely divergent points of resurgence, such as springs, channel upwellings, and direct drainages from cave entrances. Thus, sediment and water transported from the surface may emerge unexpectedly at one or more distant points frequently beyond surface watershed boundaries (Aley and others 1993).

Epikarst is exceptionally well developed throughout the karst areas. In the subalpine, epikarst has virtually the same characteristics found in the bare alpine settings. Typical thicknesses of the epikarst zone range from more than 30 meters in the alpine zone to less than 2 meters along the coast and in areas less than 120 meters in elevation (Baichtal and others, in press). The epikarst thickness seems to be more a function of glacial history than altitude. The epikarst is extremely important in moving water, nutrients, organic matter, and soil from the land surface and rooting zone into the subsurface where these materials can move laterally to seeps and springs or to vertical collector structures, which channel them downward into cave networks (fig. 3; Aley and others 1993).

The openness of the drainage system is a major contributor to the vulnerability of the karst landscape to natural and anthropogenic disturbance (Aley and others 1993; Baichtal and others, in press; Ford and Williams 1989). For example, a particle of soil produced by disturbance in nonkarst landscapes is carried by gravity and surface water flow, sometimes over great distances, into a water course to become sediment. The sediment may be transported immediately or be stored on the channel floor and in streambanks for later distribution. Within a karst landscape, depending on the openness of the drainage system, a soil particle needs to be carried only a few centimeters before it is washed vertically through the surface and into karst conduits. Our field observations indicate that the degree to which the surface is connected to the underground conduits relates directly to the impact of any increases in sediment or water delivery on karst and cave ecology. The presence of a single sinkhole demonstrates a direct surface-to-subsurface connection, even if the sinkhole intermittently retains water. A high density of surface solution and collapse features indicates the presence of well-developed underground systems.

The basic principles of karst development and solution cave formation are well documented (Ford and Williams 1989, Gains 1993, White 1988, White and White 1989). The rate and processes controlling the areal extent of karst landscape and cave development along the north Pacific coast under cool, moist, heavily forested conditions is less fully understood.

Karst development in southeast Alaska is controlled by six main factors: (1) the purity of the carbonate bedrock, (2) the structural components of the bedrock (i.e., faulting, joints, fractures, bedding planes) that define zones of weakness along which ground water is directed to form solution cavities and channels, (3) occurrence of igneous intrusions that may block subsurface flows and alter the carbonates by contact metamorphism, (4) proximity of the carbonates to highly acidic drainage from peatlands and other forest vegetation, (5) modification of surface topography and drainage by glacial activity, and (6) precipitation and temperature that influence weathering rates and solution activity (Baichtal and others, in press).

Figure 1—Distribution of carbonate bedrock in the Tongass National Forest.



Figure 2—Well-developed surface or epikarst from the alpine zone on Dall Island. Note the cravasslike solution fissures developed along joints and fractures that lead directly to deep shafts and ultimately to subsurface drainage systems.



Figure 3—Water in Big Creek flows from an underground cave system below Twin Island Lake, northern Prince of Wales Island



Figure 4—Highly fractured and jointed limestone from the Heceta formation near Twin Island Lake, northern Prince of Wales Island.

The rocks most likely to contribute to any karst development have greater than 70 percent CaCO₃ (Ford and Williams 1989, White 1988). Maximum karst and cave development requires that the bedrock be at least 90 percent CaCO₃ (Ford and Williams 1989, White 1988). Chemical analysis of 67 limestone and marble samples collected from karst landscapes on the northern portion of Prince of Wales and surrounding islands showed the range of CaCO₃ to be from 92 to 99 percent. The samples averaged 98 percent CaCO₃ (Maas and others 1992).

These extremely pure carbonate rocks have had a long geologic history. The carbonates on which the karst has developed originated as marine reef and lagoon deposits near the equator during Silurian time, some 438 to 408 million years ago (Aley and others 1993; Brew and others 1984, 1992; Soja 1990). These deposits were rafted on spreading oceanic plates until they collided with the ancient continental margin of western North America (Brown and Yorath 1989, Coney and others 1980). These rocks are part of what is now recognized as the Alexander Terrane, one of five subcontinental blocks of rock that have combined to form the panhandle of southeast Alaska. The oblique collision of the Alexander Terrane with North America resulted in the rocks being compressed from east to west and smeared northward along the coast (Coney and others 1980). The Alexander Terrane was highly fractured and then fragmented at all scales as it was rifted apart and smeared northward (Coney and others 1980). This smearing occurred along large, northwest-southeast trending, strike-slip faults. Second-order, intersecting, north trending strike-slip faults allowed the terranes to break into huge blocks. Major blocks bounded by the large faults were broken into smaller blocks by smaller faults mimicking their large counterparts. This same fault pattern is mimicked again at the outcrop and hand specimen scales (fig. 4). The fractures serve two important functions in the karst landscape of the Alexander Terrane (Aley and others 1993). First, the intra-island-and mountain-block-scale faults commonly define individual karst landscape boundaries. Second, cave passages, chains of sinkholes, and many of the other karst features are localized along sets of small- to intermediate-scale fractures, joints, and faults. Epikarst development is mainly a function of these fractures and faults (Aley and others 1993).

Glacial activity during the Pleistocene epoch has strongly influenced the character of karst landscapes in southeast Alaska. For example, recent work on Prince of Wales Island has documented the existence of karst long before the latest Wisconsin glacial advance (Aley and others 1993). Passages in two caves have dissolved through Tertiary paleokarst breccias. One small cave contained a marmot (*Marmota* sp.) tooth that dated to more than 44,500 years before present (B.P.) (Baichtal 1995b). Most caves on the island predate the most recent glaciation, based on the presence of glacial clays, glacial sediments, wood, Pleistocene vertebrate remains, and possibly even ancient ice. The epikarst, which is exceptionally well developed in the alpine and subalpine zones, is subdued or is entirely absent locally at lower elevations. We have observed similar conditions in caves on Kuiu and Chichagof Islands and on islands seaward of Prince of Wales Island. Such evidence clearly suggests that glaciation modified a preexisting karst landscape, eroding some features, collapsing some passages and systems, gouging into others, and filling some with sediments. At lower elevations where epikarst still remains, vegetation recolonization has covered much of the surface, and in effect a forested alpine karst is preserved.

Peatlands have developed on compacted glacial sediments and glacial silts within the karst landscapes and on poorly drained lithologies adjacent to the karst landscapes. Many of these glacial deposits appear to have been left on collapsed karst features. Surface waters originating from these poorly drained areas seldom flow more than a few yards onto carbonate substrate before diving below the ground, down vertical shafts or into cave entrances (Baichtal 1993a, 1995b; Brock and others 1995). The highly acidic waters flowing from these sphagnum-dominated peatlands (pH ranges from 2.4 to 5.8) accelerate cave and karst development. Because the pH of waters flowing from the cave systems range from 7.5 to 9.0 (Aley and others 1993), the buffering capabilities of the pure carbonates is evident.

Most of the karst landscapes studied so far are hydrologically active. The subsurface hydrologic systems in these landscapes are best described as highly dynamic and subject to extreme variations in flows, especially during the fall rainy season. Rainfall in the areas dominated by karst landscapes varies greatly, ranging from annual average precipitation of 1.5 meters to more than 6.4 meters per year (Baichtal and others, in press). The highest flows occur during the fall rainy season or during winter and early spring when heavy rains fall on wet snow packs. Limited dye-tracing work on Prince of Wales Island has demonstrated that karst ground water systems routinely transport water for more than 1000 meters to receiving caves, springs, and surface streams (Aley and others 1993). The limited specific conductance information gathered to date from this same area suggests that specific conductance from karst systems in southeast Alaska are about half the mean values typically encountered in most other North American karst areas (Aley and others 1993; Wissmar and others, in prep.). However, annual runoff from karst areas in southeast Alaska is typically on the order of 8 to 16 times greater than that found in other North American karsts (Aley and others 1993). The net effect is that solution of soluble bedrock occurs at least four to eight times faster in southeast Alaska than elsewhere (Aley and others 1993).

Forest Characteristics

Although only limited empirical data are available, field observations by the authors indicate a definite association between karst landscape and the productivity of the western hemlock-Sitka spruce forests found in the Tongass. The controlling variables seem to be the nutrient richness of soils on the valley floors and along the slopes below 120 meters, well-developed subsurface drainage, and dissected bedrock surfaces that allow tree roots to hold fast and become somewhat more windfirm. At lower elevations, old-growth forest on the karst landscape provides a well-structured, multilayered canopy that is important winter habitat for Sitka black-tailed deer (*Odocoileus hemionus* Rafinesque) and other mammals (Baichtal 1995a, Gustafson 1993). The structure of the forest provides many forbs and shrubs for wildlife. Possibly the available forage contains, at a minimum, higher calcium levels that may allow for better bone, muscle, and antler development.

Exceptionally dense stands of very large-diameter western hemlock and Sitka spruce are characteristic of low-elevation karst landscapes. Past timber harvest on the karst landscapes, therefore, has been disproportionately high owing to this high percentage of large, dense forest stands. On central Prince of Wales Island, for instance, 66 percent of the commercial forest land on known karst landscapes has been harvested, whereas only 33 percent of nonkarst areas has been cut (Baichtal 1993b).

Wildlife Interactions

Many wildlife species find the epikarst features and the stable environment and shelter provided within the caves to be suitable habitat. Caves have been used as natal den sites by river otter (*Lontra canadensis* Schreber), and as resting and denning sites by Sitka black-tailed deer, bear (*Ursus* spp.), wolf (*Canis lupus* Linnaeus), and small fur bearers (Baichtal 1995b; Baichtal and others, in press). Sitka black-tailed deer are known to rest around cave entrances in summer, when the air coming from the caves is cooler, and in winter, when the cave entrance environment is warmer than elsewhere (Baichtal 1995b; Baichtal and others, in press).

Cave systems provide critical roosting and hibernating habitat for bats (Vespertilionidae) (Baichtal 1995b; Baichtal and others, in press). The stable environment within the caves provides roosting habitat in both summer and winter. Bats select cave sites because the caves fulfill specific habitat requirements, including cave structure, air circulation patterns, temperature profiles, humidity, and location relative to feeding sites (Hill and Smith 1984). Preliminary surveys show some bat-use of most of the caves inventoried (Baichtal 1995b; Parker 1996). Bats have been found within a few caves once outside temperatures drop below freezing. Roosting sites are beyond the point where outside freezing air temperatures penetrate from the cave entrance. Five species of bats have been reported from caves in karst landscapes in the Tongass: the little brown bat (*Myotis lucifuga* Le Conte), the California bat (*M. californica* Audubon & Bachman), and possibly the silver-haired bat (*Lasiorycteris noctivagans* Le Conte) (Parker 1996). In addition, two new records of Keen's myotis (*M. keenii* Merriam) and the first long-legged bat (*M. volans* H. Allen) known from southeast Alaska were collected from Prince of Wales Island in 1993 (Parker 1996; Parker and Cook, in press). In December 1991, the first recorded hibernating bat in Alaska was described and photographed from within El Capitan Cave on northern Prince of Wales Island (Parker 1996). A California bat collected in El Capitan Cave in February 1992 was the first live record of that species in Alaska (Parker 1996).

Cave systems provide habitat for many invertebrates. Preliminary studies conducted during July 1992 identified 77 species from collections made within several caves (Carlson 1993a). These species must be more completely identified before further biological associations can be made. One amphipod that was collected, *Cratigonyx obliquus-richmondensis*, is not known to occur elsewhere in northwestern North America (Carlson 1993a). Field work continued during the 1993 field season, with collections made from a number of additional caves. A troglobitic *Stygobromus* amphipod was collected on Heceta Island (Aley and others 1993, Carlson 1993a). This species is morphologically identical with *S. quatsinensis* from two caves on Vancouver Island, British Columbia (Holsinger and Shaw 1987). This discovery is possibly a high-latitude world record for a cave-adapted species (Aley and others 1993). Other members of the genus *Stygobromus* were discovered in caves and karst springs on the western shore of Dall Island (Carlson 1995).

Several birds, such as the dipper (*Cinclus mexicanus*), the thrush (Turdidae), and the swallow (Hirundinidae), use cave entrances for nesting and feeding (Baichtal 1995a). Rookeries for sea birds, including the cormorant (Phalacrocoracidae) and pigeon guillemots (*Cephus coluba*), occur in some littoral caves (Baichtal 1995b).

Fisheries Interactions

The karst landscape influences productivity of its aquatic habitats in several ways. The geochemistry associated with karst development contributes to productivity of aquatic environments through its carbonate buffering capacity and carbon input dissolved from the limestone bedrock (Wissmar and others, in prep.). This action has significant downstream effects on the aquatic food chain and biotic community. Preliminary studies suggest that aquatic habitats associated with karst landscapes may be 8 to 10 times more productive than adjacent, nonkarst-dominated aquatic habitats (Bryant and others, in prep.). The karst-dominated aquatic habitats support a higher biodiversity than the noncarbonate-based systems, have higher growth rates for smolts and resident fish, reflect less variable water temperatures and flow regimes, and contain unique habitat affecting species distribution, abundance, and adaptations (Bryant and others, in prep.).

Paleontological and Cultural Resources

The potential cultural and paleontological significance of the karst landscapes is high. The Pleistocene paleontology of the area is primarily known from cave and rock shelter deposits, which often are intimately related to archaeological sites. The cool, stable, basic environmental conditions in the caves result in exceptionally good preservation of bone and organic materials (Aley and others 1993). Recent work on Prince of Wales and surrounding islands on the extensive karst resources, combined with botanical surveys of alpine areas and genetic studies on chum salmon (*Oncorhynchus keta* (Walbaum)) populations, strengthen the argument for a well-developed coastal refugium along the west coast of southern southeast Alaska. The evidence sheds new light on our understanding of glacial chronology, climatic change, biogeography, and archaeology along the western margin of North America (Autrey and Baichtal 1992, Dixon and others 1992, Heaton and Grady 1992).

To date, significant archaeological and paleontological materials have been discovered in more than 30 caves and rock shelters in the Ketchikan Area (Carlson 1993b). At least three new bone deposits were located during a summer 1993 inventory of cave resources (Heaton 1994).

Recently, remains have been discovered of seven black bear (*Ursus americanus* Pallas), one dating to about 39,000 years B.P., and 10 brown bear (*U. arctos* Linnaeus), one dating to about 35,300 years B.P. (Baichtal 1995b). Natal river otter dens dating to about 8000 B.P. have been described (Baichtal 1993a). Remains of red fox (*Vulpes vulpes* Linnaeus), caribou (*Rangifer* sp.), ringed seal (*Phoca hispida* Schreber), and marmot, now extirpated from the islands, have been recovered (Baichtal 1995b). The marmot dated to more than 44,500 years B.P. (Baichtal 1995b). Botanical evidence from Dall and Prince of Wales Islands suggest an ancestry for current plant populations from local remnant populations that escaped glaciation (Hultén 1968, Muller 1991). Studies of chum salmon populations from the Queen Charlotte Islands and southeast Alaska found that the greatest genetic variation exists along the western coastlines of Queen Charlotte and Prince of Wales Islands (Kondzela and others 1994). These significant genetic variations suggest longer habitation of streams in these areas and, therefore, the possibility of coastal refugia. The occurrence of the *Stygobromus* species on Heceta and Dall Islands also provides support for the presence of refugia (Carlson 1995). The apparent lack of troglobites on Prince of Wales Island seems to be correlated with the glacial history of the region (Aley and others 1993). This new information, combined with limited data on raised marine beaches in the area, provides additional evidence of a coastal refugium through which Pleistocene mammals and humans may have migrated south.

Management Effects

Quantitative information on the effects of forest management on karst landscapes in southeast Alaska is limited. In particular, it is not known what cumulative effects past timber harvest has had on the epikarst landscape. Hydrologic models currently used for estimating cumulative effects of proposed surface management activities are not designed to model effects of timber harvest on karst lands. We have observed recent sediment deposits and waterline marks in underground systems that suggest timber harvesting has increased sediment and debris transport and flooding of underground passages, many of which may have not previously flooded for centuries. Our observations in some caves also indicate that recent flooding has resulted in fragile ceiling formations becoming tannin stained and showing signs of dissolution. Many cave entrances are filled or blocked by logging slash, sediment, and debris. Additional runoff generated from road surfaces has commonly been diverted into karst features (Baichtal 1993b).

Field observations and aerial photo interpretations also show strong evidence of greatly increased surface runoff on karst landscapes and adjacent surfaces after harvest, which increases sediment, nutrient, and debris transport capability of associated drainage networks.

Tree regeneration information from Prince of Wales Island indicates few regeneration problems in low-elevation stands on karst landscapes (see footnote 1). As a consequence, most easily accessible, low-elevation karst areas on the island have been harvested. Timber harvest is now concentrated on steeper, higher elevation karst landscapes characterized by shallower, excessively well-drained soils. Our field observations suggest that trees are smaller and regeneration problems greater at these steep, upper elevation sites. This condition may result from several factors, including (1) shallow soils with low nutrient availability, (2) excessive drainage of surface and soil waters into subsurface karst systems, (3) removal of much of the shallow soil because of inadequate log suspension, and (4) continued desiccation of the soil once the protective forest canopy is removed. Once the timber is removed, high rainfall can rapidly transport these fragile soils into the well-developed epikarst.

On karst landscapes worldwide, timber harvesting has led to serious, often long-term declines in soil depth and fertility, in some cases culminating in permanent deforestation (Harding and Ford 1993; Huntoon 1992a, 1992b; Kieman 1993). Trees growing on karst generally have roots extending into dissolved cracks in the bedrock. These roots translocate water and nutrients back up into the forest canopy. Much of the site productivity is tied up in this nutrient cycle and in the forest canopy; when trees are harvested, the cycle is disrupted. On these karst areas, soils tend to be thin and residual. As the epikarst becomes more developed, the surface-to-subsurface connection increases, as does the likelihood that soil and nutrients can be transported vertically beyond the rooting depth of vegetation and into the conduit systems of the karst drainage. Vertical migration of nutrients and soil becomes possible in areas of heavy rainfall and well-developed subsurface drainage once the forest canopy is removed (Gains 1993; Harding and Ford 1993). Karst systems are productive, but fragile (Huntoon 1992a, 1992b; Streveler and Brakel 1991).

Conclusions

Field reconnaissance has shown that in southeast Alaska, wherever carbonate bedrock crops out, karst landscapes have developed. This development occurs because of the unique geologic, biologic, and climatic conditions that result in dense, nearly pure carbonate bedrock and the acid ground water that fosters rapid chemical weathering and solution of the carbonates along well-developed, structural weaknesses in the rock. In select areas, karst landscape development is extreme, with surface or epikarst solution fractures extending to more than 15 meters in depth (Baichtal and others, in press). Some areas of alpine and subalpine karst commonly have more than 380 sink holes per square kilometer (Baichtal and others, in press). Karst development to this extent is rare globally (Aley and others 1993).

The functions and biological significance of the karst landscape are only just beginning to be understood. Preliminary investigations suggest an increased productivity for plant, animal, and aquatic communities that develop on top of or otherwise benefit from karst landscapes. Some of the most productive western hemlock-Sitka spruce forests exist on top of karst landscapes in areas where past and planned timber harvest activities have focused. The waters issuing from subsurface karst drainage systems are 8 to 10 times more productive for associated aquatic communities (Bryant and others, in prep.). In areas where karst development is most intense, soils on slopes and intervening benches and ridges tend to consist of shallow organic mats. Much of the mineral soil has been displaced into dissolved fissures and eroded dissolution rills. These surface or epikarst features tend to be more than 2 meters deep and to open directly into extensive subsurface drainage systems (Aley and others 1993; Baichtal and others, in press). This direct surface-to-subsurface connection and the presence of disturbed and displaced soils make these areas the most sensitive to natural and human disturbance. Sediment, debris, and pollutants can rapidly be transferred into the karst groundwater systems to reappear at springs and resurgences kilometers away.

English Equivalents

<i>When you know:</i>	<i>Multiply by:</i>	<i>To find:</i>
hectares	2.47	acres
meters	3.28	feet
square kilometers	0.39	square miles

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