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GOSHAWK REPRODUCTION AND FOREST MANAGEMENT

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Nests of northern goshawks (*Accipiter gentilis*) are usually found within dense stands of large trees; thus, their nesting habitat may be adversely affected by timber harvest (Reynolds et al. 1982, Moore and Henny 1983, Crocker-Bedford and Chaney 1988). After considering goshawk natural history, many goshawk researchers and management biologists have recommended buffer zones with no tree harvest around nests. The recommendation of Reynolds et al. (1982) and Reynolds (1983) is the most well known. Their recommended 8-ha to 10-ha buffer (equivalent to the nesting stand) emphasized the area upslope or south of the nest, and best ameliorated the microclimate of the nest and protected most perching trees and prey plucking sites.

My study was the first to experimentally test the adequacy of nest habitat buffers for maintaining goshawk reproduction. In addition, I analyzed goshawk fidelity over time to nest trees and nesting stands.

STUDY AREA AND METHODS

The North Kaibab Ranger District of the Kaibab National Forest is located on the Kaibab Plateau immediately north of Grand Canyon National Park. Plant cover at upper elevations (120,000 ha) is ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), subalpine fir (*A. lasiocarpa*), Douglas-fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), quaking aspen (*Populus tremuloides*), several meadows, and a few small clearcuts. At its lower elevations, the ponderosa pine forest includes Gambel oak (*Quercus gambelii*) and grades into a pinyon pine (*Pinus edulis*) forest, where no goshawk nest is known.

Light partial (selection) harvesting occurred during the 1950's or 1960's over most of the study area. By 1980 stands dominated by ponderosa pine averaged 24 m^2/ha basal area, and stands comprised mostly of other conifers averaged 32 m^2/ha (D. Fordyce, unpubl. rep. for Kaibab Industries, Fredonia, Ariz., 1981). Canopy coverage in 1972 averaged 58% (Crocker-Bedford and Chaney 1988).

Each locale was a timber-sale preparation area (1,000 to 5,000 ha) where nearly every hectare that had trees large enough for lumber was searched for goshawk nests. The locales tended to be adjacent to others so that blocks of combined locales ranged from 4,700 to 19,600 ha.

Following light harvests in the 1950's and 1960's, control locales (n = 9; smallest contiguous block = 4,700 ha) received effectively no harvesting until after nest monitoring was completed in 1987. In contrast, treatment locales (n = 6; smallest contiguous block = 1,000 ha) were harvested around nest buffers prior to 1985, when nest monitoring began. Partial harvesting averaged one-third of the timber volume, of living trees >23 cm diameter at breast height, from 79% (range 73–86) of the hectares in treatment locales. The residual basal area of living trees in a harvested stand was usually between 10 and 25 m^2/ha. Almost all snags were left standing. An average of 17% of the treatment locales was left unharvested because of low-productivity ponderosa/pinyon and pinyon/oak communities or steep slopes. The remaining 4% was economical but left uncut to meet nontimber objectives.

Managers left unharvested buffers around all historical goshawk nest trees within treatment locales, even when no nest remained. Small buffers were 1.2 to 2.4 ha of uncut forest surrounding nest trees and were designed to best protect microclimate and perching trees. Large nest buffers were 16 to 200 ha (mean = 70 ha) of uncut forest that protected old-growth stand(s) of highest quality (largest trees with densest canopies) surrounding the nest trees. Despite intensive search efforts, some nests were not discovered prior to harvest.

Most nests were located by Forest Service personnel from 1973 to 1984 during timber sale preparation. Timber sale preparation at that time was entirely by take-tree marking, which involved looking at almost every tree in stands to be harvested. Because 80% of stands were marked for partial harvest, timber markers were likely to discover at least 1 of the alternate nests of any pair of goshawks. Later, wildlife biologists intensively searched vicinities of reported nests for alternate nests.

Every nest tree that could be relocated was monitored, mostly by the same biologist, between mid-June and late July in 1985, 1986, and 1987. A nest tree was considered reoccupied if a nest was reconstructed, if a nest contained new greenery, or if goshawks were present. A nest tree was considered active if egg fragments were found, or if young were in the nest tree. Some nest trees no longer contained nests.

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For nest trees in control locales, reoccupancy during 1985–1987 was compared between those first found in 1973–1978 and those first found in 1981–1984. Reoccupancy in 1985–1987 of individual nest trees was also compared between control locales and the 2 buffer classes of treatment locales. These analyses, where individual nest trees were the experimental units, only used nest trees found prior to 1985.

I also compared reoccupancy of goshawk nesting territories found before 1985, though some nests in these territories were found later (see next paragraph). A territory was the area where no more than 1 pair of birds nested. On the North Kaibab, goshawks in a territory used 2, 3, or 4 nests in different years (Crocker-Bedford and Chaney 1988). These alternate nests were clustered, usually within 300 m and always within 1,000 m of their nearest alternate nest. In contrast, nest clusters of adjacent territories were 1.4 to 4.5 km apart (mean = 2.6 km). No 2 nests within a cluster were ever active in the same year, while nests of adjacent clusters were often simultaneously active. A radiotelemetry study showed that nests belonged to the same pair of goshawks when clustered within an area 0.8 km in diameter (J. McGowan, unpubl. rep., Distribution, density and productivity of goshawks in interior Alaska, Final Rep., Fed. Aid Proj. W-17-3 to W-17-6, 1975).

A territory may have appeared unoccupied only because the occupied nest had not previously been found. To reduce such mislabeling, when no known nest was occupied by goshawks the territory received additional searches for nests. These additional searches typically involved 2 person-days (range = ½ to 10 person-days), depending upon the difficulty of observation in the forest cover and how soon an occupied nest was discovered.

Two analyses were conducted on territories. One combined occupancy data from 1985 to 1987. The second considered occupancy, activity, and number of young in 1987 only, when multiple monitoring trips and tree climbing permitted an accurate assessment of reproduction.

RESULTS

Nest trees were reoccupied on at least 3 occasions when little or none of the previous nest persisted. One nest tree was active in 1978, not checked from 1979 through 1981, without any nest remains from 1982 through 1985, then active in 1986.

For nest trees in control locales, reoccupancy at least once during 1985–1987 was equally likely between nests found in 1973–1978 (67%) or in 1981–1984 (65%) ($\chi^2 = 0.008$, 1 df, $P = 0.93$; Table 1). Because control nest trees found in the 1970's were as likely to be reoccupied as controls found during the early 1980's, nest trees from all years of first location (1973–1984) were grouped for further analyses.

Table 1. Reoccupancy (≥ once) of goshawk nest trees from 1985 to 1987, according to the year the nest was found and the size of the habitat buffer, on the North Kaibab Ranger District, Arizona.

Year nest found	Small buffers (1.2 to 2.4 ha)		Large buffers (16 to 200 ha)		Control locales (>4,700 ha unharvested)	
	Occupied	Not	Occupied	Not	Occupied	Not
1973–1978	0	0	1	3	6	3
1981–1984	1	6	0	6	13	7

Between 1985 and 1987, 66% of control nest trees were reoccupied at least once, while only 12% of buffered nest trees in treatment locales were reoccupied at least once ($\chi^2 = 12.5$, 1 df, $P < 0.001$). Occupancy of small buffers and large buffers was similarly low ($\chi^2 = 0.07$, 1 df, $P = 0.79$). The occupancy rate per individual nest tree per year averaged 30% for 29 control nest trees and 6% for 17 nest trees within no-cut buffers of treatment locales.

Between 1985 and 1987, 79% of 19 control territories were known to be reoccupied at least once, but only 25% of 12 treatment territories were reoccupied at least once ($\chi^2 = 8.79$, 1 df, $P = 0.003$). During 3 years, 32 nesting attempts (where occupancy occurred) were observed for 19 territories in control locales, an average of 56% known occupancy per year, but only 5 nesting attempts occurred for 12 territories in treatment locales, an average of 14% known occupancy per year.

In 1987, the year of intensive nest monitoring, goshawk occupancy rates were 63% for 19 territories in control locales and 17% for 12 territories in treatment locales ($\chi^2 = 6.42$, 1 df, $P = 0.012$). Eggs were laid in all territories occupied in 1987. Occupied territories averaged 2.1 nestlings (range 1–3) in control locales but only 0.5 nestling in treatment locales ($t = 4.0$, 12 df, $P = 0.003$). For the 2 occupied treatment locales, the eggs at 1 nest broke be-

Table 2. Known occupancy of goshawk territories according to number of nest trees known in each territory by 1987, in unharvested locales of the North Kaibab Ranger District, Arizona.

No. known nest trees per territory	No. territories sampled	Percent occupied ≥ once 1985–1987	Percent occupied per year 1985–1987	Percent occupied during 1987
1	5	80	33	20
2	8	75	58	75
3–5	6	83	72	83

fore hatching, and only 1 egg hatched at the other nest. Considering both occupied and unoccupied territories in 1987, control territories averaged 1.32 nestlings and treatment territories averaged 0.08 nestling ($t = 4.6$, 29 df, $P < 0.001$).

The yearly probability of recording an occupied nest in a control territory roughly tripled with an increase in known nest trees per territory from 1 to 3 ($\chi^2 = 29$, 2 df, $P < 0.001$; Table 2). In contrast, a control territory with only 1 known nest tree was as likely to be occupied at least once during a 3-year period as was a control territory with 3 or more known nest trees ($\chi^2 = 0.02$, 1 df, $P = 0.89$).

Only 1 nest was found in 26% of control territories and 25% of treatment territories ($\chi^2 = 0.007$, 1 df, $P = 0.93$). The mean number of known nest trees per territory was similar among 15 control territories occupied at least once during 1985–1987 (2.33 nest trees), 4 control territories never occupied in 1985–1987 (2.25), 3 treatment territories occupied at least once (2.33), and 9 treatment territories never occupied in 1985–1987 (2.44 nest trees) ($F = 0.026$; 3,27 df; $P = 0.994$).

Other raptors often replaced goshawks in treatment territories but never did so in control territories. Red-tailed hawks (*Buteo jamaicensis*) nested in former goshawk nests in 3 of the 9 treatment territories never reoccupied by goshawks. Four of these 9 treatment territories were occupied by great horned owls (*Bubo virginianus*) or long-eared owls (*Asio otus*): their nesting occurred in 2 former goshawk nests and within 100 m of 2 others. In contrast, none of these 3 species was ever observed to nest within 1 km of any goshawk nest tree in control territories nor within 1 km of goshawk-occupied nests in treatment territories ($\chi^2 = 18.2$, 1 df, $P < 0.001$). Goshawk nest buffers in use by other raptors averaged 26 ha (range = 1.2–45 ha).

Logged areas outside the studied treatment locales contained the only 2 nests of Cooper's hawks (*Accipiter cooperii*) ever observed at elevations above the open-canopied, ponderosa-pinyon and pinyon-oak communities. One of these nests was formerly a goshawk nest.

DISCUSSION

Thoroughness of the Search Efforts

Although the average territory included 2.3 known nest trees, I believe that the true number of nest trees averaged 3 per territory. Recall that the yearly occupancy rate per territory was higher when 3 nests were known than when 1 or 2 nests were known. However, the number of known nests did not affect the probability of a territory being recorded as occupied at least once over a 3-year period, because a pair of goshawks truly having 3 nests were as likely to be recorded sometime during 3 years whether 1 nest was known or 3 nests were known. If the true number of nests per territory was 3 rather than 2.3, then one-fourth of all nest trees were never found.

Thoroughness of searches was similar in control locales and treatment locales. In each, the same proportion of territories had only 1 known nest tree. Mean nest trees found per territory was also similar. Therefore, higher occupancy rate recorded for control territories was not because of greater search effort or more known nest trees.

Fidelity to Nest Trees and Stands

Reoccupancy of historical nest trees did not decrease over time in control locales. Reoc-

:upancy occurred even after a tree's nest had :otally disappeared for 4 years. Between 1985 ınd 1987, control nest trees first located during :he 1970's were reoccupied as frequently as those found during the early 1980's. Because some goshawk mortality probably occurred, it is apparent that nest trees may be reused by different goshawks.

Nesting stands within territories have greater potential to be reoccupied by goshawks many decades into the future than individual nest trees. One control nest tree was unused because it blew over, and 2 others may have been unoccupied because they had recently been defoliated by pandora moth (*Coloradia pandora*) caterpillars. In both cases alternate nest trees continued to be occupied.

Nesting in Harvested Versus Unharvested Locales

Nest buffers, either large or small, did not maintain goshawk reproduction. The recorded occupancy rates were 75–80% lower where timber harvest occurred around buffers, and nestling production was 94% lower. Actual decreases were probably even greater, because I estimate one-fourth of existing nest trees were never found. In control territories all of these unlocated nest trees had the opportunity to be used, while in treatment territories about one-third of the unlocated nest trees would have been removed during the partial harvesting.

"Because the time-scale over which habitat reduction and fragmentation occurred was short by comparison with that of species' population dynamics, then it is likely that the attainment of equilibrium will lag some way behind the process of habitat destruction" (McLellan et al. 1986:309–310). Indeed, indications are that some goshawks persist 1 to 5 years in their territories following logging, though with little successful reproduction (C. Crocker-Bedford, unpubl. data). Furthermore, nest trees of the 3 treatment territories that were reoccupied at least once during 1985–1987 lay only 0.2, 0.5, and 1.1 km from large tracts (>2,000 ha) of suitable foraging habitats that were planned for future harvests.

Because the true annual occupancy of control territories was higher than recorded, and the occupancy of treatment territories can be expected to decline still further, the type of harvesting studied actually causes an even larger drop in occupancy and reproduction than directly indicated in the results. I suggest a 90% drop in occupancy and a 97% drop in nestling production.

The microclimate of the nesting stand, as well as large trees for nesting and nearby perching, are important for goshawk nesting (Hennessy 1978, Saunders 1982, Reynolds et al. 1982, Hall 1984, Crocker-Bedford and Chaney 1988). My treatments with large buffers should have protected the nesting stands, yet reproduction nearly ceased. Factors other than nesting habitat appear critical for goshawk reproduction.

Direct disturbance during harvest operations was not the problem. It may be that no harvesting occurred during the nesting season within 0.4 km of any nest of treatment locales. Of the 4 treatment territories where such harvesting possibly occurred, all were occupied during 1 or more years following logging; thus, any disturbance had no long-term effect.

Some nest stands were inadvertently harvested. Although other nest trees remained within buffers, perhaps the loss of a nesting stand caused goshawks to abandon a territory.

Other raptors replaced goshawks in most logged territories in my study. In eastern Oregon where 60–80% of the forest had been logged, mostly through selection harvests, half the natural nests of great grey owls (*Strix nebulosa*) were vacated goshawk nests and usually occurred in unharvested stands (Bull et al. 1988).

Because red-tailed hawks, great horned owls, long-eared owls, and Cooper's hawks were never found nesting closer than 1 km to any goshawk nest in goshawk-occupied treatment territories, or in unoccupied control territories, other raptors may be inhibited both directly by goshawks or by extensive, closed-canopy conditions. The 4 species nested in goshawk buffers in logged locales, even though forest habitats within the buffers were denser than where I usually saw these raptors. Carey (1984) suggested that decreasing the quality and quantity of old-growth habitat could cause early successional species to dominate the landscape and outcompete old-growth dependent species, even in the remaining old-growth stands.

In addition to competition by open-forest raptors, and perhaps predation (Moore and Henny 1983), goshawks in logged locales probably suffered from a reduction in quality of habitat for hunting and from lower prey density. Goshawks are adapted to hunting in dense forest, and Kenward (1982) found that goshawks preferred hunting and were more successful in woodlands than in openings with scattered trees. Furthermore, harvests on the North Kaibab tended to result in the establishment of tree saplings and brushy species such as Gambel oak and New Mexico locust (*Robinia neomexicana*), and dense understories may impair goshawk detection and pursuit of prey (Reynolds and Meslow 1984). Finally, in Southwestern forests, partially harvested stands produce less potential prey than do unharvested stands: fewer birds (Franzreb 1977; Scott and Gottfried 1983; Galeano and Crocker-Bedford, unpubl. rep. Comparison of bird communities in 8 timber sales harvested at 2 intensities on the North Kaibab Ranger District, Kaibab National Forest, Fredonia, Ariz., 1984) and fewer tree squirrels (Vahle and Patton 1983, Patton et al. 1985).

The only logged locales still occupied by goshawks had unusually small amounts of canopy volume removed and had nests near large unharvested tracts. On the North Kaibab, densities of the 71 known goshawk territories, which included 157 known nest trees, varied by locale and appeared closely associated with dense overstory canopies and open understory canopies (C. Crocker-Bedford, unpubl. data). Crocker-Bedford and Chaney (1988) believed that nesting stand characteristics were highly correlated with characteristics of prime foraging stands. Their results and literature review both demonstrated that goshawks preferred stands of dense-canopied, large trees, and that most nesting occurred in stands with relatively open understories. The North Kaibab once had higher breeding densities of goshawks than any reported elsewhere (Crocker-Bedford and Chaney 1988), I believe due to abundance of prey related to large trees and dense overstories, and due to understories open enough to facilitate goshawk pursuit and capture of prey.

Changes in Population of North Kaibab

Given the mean of 1.1 nesting pairs of goshawks per 1,000 ha for locales last harvested in the 1950's and 1960's (Crocker-Bedford and Chaney 1988), and 120,000 ha of potential habitat (see Study Area), I estimate that the 1972 breeding population on the North Kaibab Ranger District was 130 pairs.

From 1972 to 1988, sale areas totaling 71,000 ha received harvesting under the regime tested. Because sale areas included 60% of all goshawk habitat, and harvesting caused an estimated 90% drop in occupancy within sale areas, then nesting pairs were probably reduced to half the 1972 breeding population.

Furthermore, pre-1972 harvests probably had already reduced the population. Locales last harvested in the 1950's or 1960's had a mean of 3.2 known nests per 1,000 ha (Crocker-Bedford and Chaney 1988). The 2,750-ha locale that had received the lightest pre-1972 harvesting had a high nest density, 5.1 known nests per 1,000 ha, which was exceeded only by a 1,050-ha virgin locale where 12 goshawk nests were found. Thus, it is possible that the goshawk breeding density had already been cut in half by 1972.

In summary, the North Kaibab Ranger District may have once supported roughly 260 pairs of breeding goshawks. The population fell to about 130 pairs by 1972 and to approximately 60 nesting pairs in 1988.

Recommendations on Habitat Management

Attention needs to be given to the general habitat over the entire foraging range of a pair of goshawks, because nest buffers by themselves are ineffectual. After partial harvesting over extensive locales around nest buffers, reoccupancy decreased by an estimated 90% and nestling production decreased by an estimated 97%. Decreases were probably due to increased competition from open-forest raptors, as well as changes in hunting habitat and prey abundance. Even though buffered nest trees have been abandoned, I recommend leaving their buffers intact in hopes that surrounding habitat may adequately recover in the future.

Goshawk nesting density appears to be closely associated with dense overstories and open understories. Goshawk habitat may therefore be improved by silvicultural activities which reduce the densities of shrubs, saplings and small poles, while maintaining or enhancing the canopy of large trees.

Kenward (1982) concluded that goshawks depended heavily upon hunting along edges between forests and openings. I believe that his conclusions have little bearing on most forest management situations, because Kenward's tamed goshawks were feeding primarily on high densities of recently released pheasants (*Phasianus colchicus*). I was unable to find any benefit from clear-cuts to goshawks on the North Kaibab (unpubl. data). Common forester folklore in North America states that goshawks prefer to forage in clear-cuts, but I agree with Reynolds (1983) that goshawks are simply more easily seen there. In situations where brush and small trees are quickly established, or where major prey items are not increased by clear-cutting, then clear-cuts certainly do not benefit goshawks but may benefit competitive raptors.

Where management goals include both timber harvests and goshawks, I suggest silviculture that maintains much prime goshawk habitat (dense large trees with open understory) within foraging range of nests (≥2,000 ha, Reynolds 1983). It is also critical to maintain dense habitat in large enough blocks to inhibit open-forest and edge-benefitted raptors. These objectives may possibly be accomplished using an even-aged system of silviculture with the rotation length extended well beyond that which maximizes timber yield. However, regeneration harvests should not be dispersed evenly around a cluster of alternate goshawk nests. Instead, the watershed surrounding the nests should be divided into thirds, with the nest concentration at the junction of the thirds. The first third, 1,000 to 2,000 ha, would be regenerated over the first one-third of the extended rotation period. The second 1,000 to 2,000 ha would be regenerated over the second third of the rotation period, and so on.

As a result at any one time, a 1,000-ha to 2,000-ha block near a territory's nests would be in prime foraging habitat (fully mature forest older than the age which maximizes timber production), while a second block would be in marginal foraging habitat (medium-sized, mature trees). Only one block near the cluster of alternate nests would be supporting open-forest and edge-benefitted raptors, so hopefully goshawks could maintain a competitive advantage.

Foraging habitat in nesting stands is critical to brooding adults and recently fledged young (Schnell 1958). Also, in unlogged locales reoccupancy of nesting stands did not decrease over time. Therefore, managers should continue to seek out and protect goshawk nesting stands. If possible, nesting stands should be managed in perpetuity in a manner that maintains both prime foraging conditions and nesting structure. Where impossible to maintain existing nest stands, the most mature block of forest described above may possibly provide suitable nesting stands.

To provide more assurance of goshawk reproduction, it would seem important to also protect or carefully manage the portion of home range used most intensively for foraging. A recent radiotelemetry study found an average of 168 ha in core areas of females and their fledged young, and an average of 648 ha in core areas of breeding males (P. Kennedy, Los Alamos National Laboratory, pers. commun.). Accurate delineation of core areas during timber sale planning is problematic, but probably should include all area between alternate nests as well as prime foraging habitat near nests.

On the North Kaibab Ranger District, more intensive surveys for goshawk nests occurred than at any other place that I have heard of, and the protection of known nesting stands was as extensive as any I know of outside of national parks and designated wildernesses. Despite such careful management, goshawk reproduction plummeted. Multiple-use forest managers elsewhere should intensify their goshawk surveys, management, and monitoring. To assure reproduction, timber harvesting should avoid the entire feeding ranges of goshawks (>2,000 ha) until more is known about how to manage timber in a manner compatible with goshawks.

Often timber goals will force harvesting before perfect knowledge is available, in which case some variation of my silvicultural recommendations may work. I caution that my proposals still allow more habitat change than occurred in my large control locales. Also, I did not consider some factors which led Thomas et al. (1990) to recommend leaving intact habitat blocks large enough for 20 pairs of northern spotted owls (*Strix occidentalis caurina*). Further, even more careful management of goshawk habitat may be necessary as general declines in migratory, neotropical forest birds (Terborgh 1980, Morton and Greenberg 1989) affect abundance of some prey. Note that my proposals for even-aged management and understory thinning would not apply to any habitat types where high prey populations associated with understory vegetation more than offset understory impairment of goshawk hunting. Finally, it is possible that severe declines in goshawks, associated with logging, may not occur where dense populations of suitable prey occur within abundant, well-protected riparian areas. Such factors will induce managers to try different schemes.

Considerable effort has been spent on goshawk habitat management in many locations, yet to my knowledge the North Kaibab is the only place where the management effectiveness has been accurately monitored. My study demonstrates that habitat management based upon natural history should always be monitored as to its effectiveness. Scientific monitoring requires replications of both treatments and controls. Nest surveys elsewhere should enable my study design to be improved upon by including territories from broader geographical areas. Since my study's completion most of my control territories have been logged, which demonstrates the importance of finding long-term controls in lands not subject to harvesting.

SUMMARY

The North Kaibab Ranger District provided small habitat buffers (1.2 to 2.4 ha) or large buffers (16 to 200 ha) around all goshawk nests located prior to timber harvests. Partial harvesting removed one-third of the trees from 80% of the stands in treatment locales. Contiguous control locales were unharvested blocks exceeding 4,700 ha. I compared occupancy of individual nest trees as well as occupancy and production of goshawk territories, which typically included 3 nests.

Reoccupancy of control nest trees, from 1985 to 1987, was as high for nest trees discovered during the 1970's as for those discovered during the early 1980's. Nest trees were sometimes reoccupied after former nests had totally disappeared.

Even with nest buffers, recorded reoccupancy dropped by 80% and recorded nestling production dropped by 94% following logging. The true decreases were greater. Other raptors replaced goshawks in most logged territories but in no control territory. Goshawk foraging habitat is degraded by activities which decrease the canopy of large trees and promote the development of a dense brush, sapling, or pole understory.

Timber harvesting on the North Kaibab Ranger District caused goshawks to decline from an estimated 260 nesting pairs to approximately 60 pairs by 1988. I speculated on a silvicultural system which might reduce the decline.

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program and organization infrastructure enter into choices of laboratory analyses. It is clear, however, that laboratory-procedure selection should be made with ample consideration of sample variability and cost in order to optimize efficiency of research expenditures.

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Timber Harvest Trafficking and Soil Compaction in Western Montana

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ABSTRACT

Little evidence is documented regarding the effects of timber-harvest traffic on volcanic-ash-mantled glacial till soils and clay-rich Tertiary volcanic-derived soils of northwestern Montana. We identified and characterized differences in the soil physical properties between trafficked and nontrafficked areas. Soil-clod bulk density, infiltration, and soil-clod water retention were measured on 54 pedons from nontrafficked and moderately and severely trafficked sites. Soil mechanical properties were characterized using 18 nontrafficked pedons. Compared with nontrafficked areas, bulk densities in severely trafficked areas at the 15-cm depth were 76, 21, and 21% greater in ash over limestone till, ash over quartzite till, and Tertiary volcanic soils, respectively. Water retention at 0.002, 0.010, and 0.033 MPa was significantly lower at the 15-cm depth in trafficked than in nontrafficked areas of ash over limestone till. Similar differences were observed in ash over quartzite till. Compared with nontrafficked areas, cumulative 1-h infiltration in severely trafficked areas was 81% less in ash over limestone till, 79% less in ash over quartzite till, and 87% less in Tertiary volcanic soils. Similar but smaller differences were detected in moderately trafficked areas. Three independent measurements demonstrated significant differences in surface horizon physical properties between trafficked and nontrafficked areas. We detected significant physical manifestations of traffic-induced soil compaction below 30 cm.

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IN THE TIMBERLANDS of northwestern Montana, field personnel observed that trafficking by heavy machinery during timber harvesting often affected forest regeneration and productivity. Most trafficking occurs when rubber-tired skidders or crawler tractors drag logs to landings for loading, collect and pile slash and stumps, and scarify the soil in preparation for planting seedlings. These activities can compact soils and, as a result, reduce plant growth.

Soil factors such as texture, water content, structure, and organic matter that control, in part, the process of soil compaction have been previously described (Snider and Miller, 1985; Howard et al., 1981; Means and Parcher, 1963; Lull, 1959; Trask, 1959; Langston et al., 1958; Trask and Close, 1958).

Previous workers (Trimble and Weitzman, 1953; Steinbrenner and Gessel, 1955; Tackle, 1962; Hatchel et al., 1970) reported decreased infiltration and increased overland flow and erosion on skid trails and other highly trafficked areas.

Compaction can alter the water-holding capacity of soils. Compaction generally reduces the available water-holding capacity of fine-textured soils; in coarse-textured soils, compaction can reduce the size of very large pores and increase water retention (Hyder and Sneva, 1956; Rashid and Sheikh, 1977).

It is important to identify soil compaction because of its potential for reducing plant growth. Veihmeyer and Hendrickson (1948) concluded that several species of plants from various climatological settings were