Relationship between Biosolids Applications and Understory Development in Douglas-fir Stands in Western Washington: Management Implications

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Abstract–Biosolids are routinely applied to Douglas-fir forests in Western Washington. Heavy applications made in the 1980s at >50 dry Mg ha^{-1} have significantly changed understory composition, promoting nitrophytic species, red elderberry, and stinging nettle as dominant understory species and significantly reducing the cover of the low-N species salal. Current applications at rates of 11 Mg ha^{-1} every 5 years may not trigger the threshold levels of N availability and site disturbance required to change species composition and abundance in the same way.

An investigation of the interactions of biosolids and understory dynamics in Douglas-fir stands in Western Washington was conducted at Pack Forest and at the Weyerhaeuser Snoqualmie Tree Farm in 1996-1997 (Cowley 1998). Specific interactions that may be caused by fertilization with biosolids include:

- Increased understory competition with tree saplings in stands that have not achieved crown closure.
- Altered understory species composition, abundance, and diversity, which affect wildlife habitat, food sources, and stand aesthetics.
- Increased biomass production, N accumulation, and accelerated recycling of nutrients in young stands by understory vegetation.

Within the range of Douglas-fir stands in Western Washington, biosolids are generally targeted at N-deficient sites, which have salal as one of the predominant understory species. Biosolids change resource availability and the physical environment, improving soil water-holding capacity, increasing nutrient availability and altering forest floor characteristics (Henry et al. 1993). The growth stages most subject to significant effects are stand initiation and understory re-initiation after thinning.

EFFECT OF BIOSOLIDS APPLICATIONS ON SPECIES COMPOSITION

The 68-year-old Silvicultural Demonstration Site (SDS) and the 75-year-old Highway Thinning Trial (HTT) at Pack Forest were sampled to examine the changes caused by biosolids application to Douglas-fir stands. These sites have had from 3,000 to 8,000 kg N ha^{-1} applied as biosolids during a 12-19-year period. Characteristics of these trials were described by Cole (1988) and Smith and Brallier (unpubl. rep.).

Measurements of abundance and composition of current vegetation in treated and untreated stands were made using the line-intercept method, with the differences assumed to be caused by the biosolids and thinning treatments. In stands treated with biosolids, red elderberry was the tallest understory species on 25% of the transect length on both thinned and unthinned sites. Red elderberry did not occur in untreated stands. In the thinned, biosolids-treated stands, stinging nettle was the tallest understory species on 11 to 20% of the transect length. In unthinned and in untreated sites, stinging nettle was absent.

Cover of salal was significantly reduced from 69% on untreated sites to 14% on biosolids-treated areas. Salal was not significantly affected by thinning alone; however, a significant interaction exists between biosolids and thinning. On thinned, treated sites, salal cover was reduced more after biosolids application than it was on unthinned sites. Although salal cover was reduced on biosolids-treated sites, it was not eliminated. Visual observations showed salal was often present on raised ground around rotting logs, old stumps, or around tree stems.

In all stands, the percentage of Oregon grape cover was not significantly affected by biosolids application. Oregon grape was significantly less prevalent on thinned sites, but the interaction between biosolids and thinning

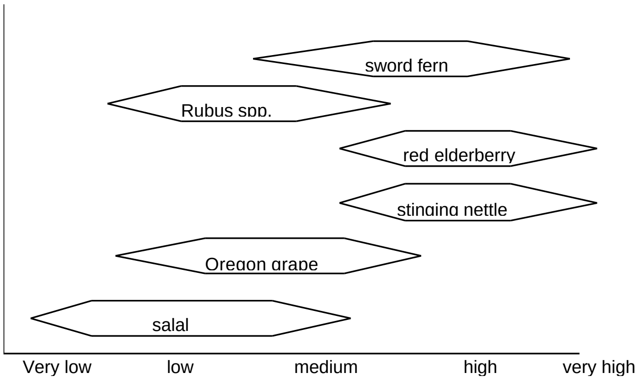

Figure 1. Schematic ecological amplitudes for main species found in the study areas as a function of mineralizable soil nitrogen (from Klinka et al. 1989).

was not significant. Sword fern cover at the HTT site was significantly greater on treated sites but was unaffected by thinning.

Coward (1993) also reported decreases in salal, twinflower, and moss and increases in trailing blackberry, red elderberry, and bedstraw at the HTT site. In young stands in British Columbia, she also showed that the overall effect of biosolids treatment after 2 years was a decrease in shrub cover, particularly salal, and an increase in fireweed and bracken fern cover.

One explanation for species change is that different plants have different requirements for temperature, nutrients, light, and moisture. Klinka et al. (1989) described the ecological amplitudes of environmental factors that give certain species competitive advantages. The gradients for soil nitrogen for major species on these sites are shown in Figure 1. Red elderberry and stinging nettle are nitrophytic species that require soil high in N, while salal grows best in lower N soil.

The increase in red elderberry on both thinned and unthinned, treated sites suggests that the significant process in the re-initiation of this species is nutrients rather than increasing light penetration to the understory. However, the absence of nettle in unthinned sites at the HTT site where biosolids were applied may show that stinging nettle primarily requires higher light levels–characteristic of a thinned site–combined with increased soil moisture, moder and mull humus, nitrogen additions, and the presence of a seed source.

Generalizations that forest age-classes are homogeneous units do not explain the spatial or stand variability present. Within treated sites, variability in salal density is associated with other stand factors or application practices. Microsites with more salal normally had noticeably less nettle and red elderberry. Possible reasons include:

- Lack in the uniformity and intensity of thinning has failed to achieve the minimum level of canopy reduction needed to allow understory re-initiation of early successional understory plants.
- Thinning did not occur simultaneously across the entire site, thereby allowing earlier thinned sites more time to establish understory before biosolids were applied. The extent to which biosolids affect the growth and survival of established understory should differ substantially from the impact on less developed younger plants.
- Salal is often associated with raised ground around logs and stumps where biosolids flow off, suggesting that positive effects on mycorrhizae could still be present.
- Biosolids are not always applied evenly within sites. The old roadside buffers for liquid biosolids operations in the SDS are still heavily dominated with meter tall salal, while salal cover is significantly reduced in the non-buffered areas. These buffers received minimal biosolids from the initial liquid applications, then routine rates in the subsequent dewatered application (about 600 kg N ha^{-1}). The effect of low application rates on salal growth is similar to that at Shawnigan Lake on Vancouver Island where urea fertilization combined with thinning treatments benefited the salal undergrowth, and heaviest thinning and moderate fertilization provided the most benefits (Stanek et al. 1979).

Oregon grape cover at Pack Forest was not affected by biosolids application. Oregon grape is generally <60 cm tall and survives competition from salal and other understory plants. It has significantly greater relative coverage in unthinned stands where light is limited. Oregon grape does not seem to increase biomass rapidly or outcompete more rapidly growing early successional plants; however, it is not detrimentally affected by any added nutrients in biosolids nor adversely impacted by increased competition from plants having accelerated growth from fertilization.

Sword fern is an indicator species of higher SQ Douglas-fir stands (Franklin and Dyrness 1988) and has significantly greater coverage on the treated sites. The increased moisture and nutrients from biosolids should improve site quality and generate a favorable edaphic environment for sword fern.

EFFECT OF BIOSOLIDS APPLICATION ON GROWTH AND SURVIVAL OF 2-YEAR-OLD DOUGLAS-FIR SAPLINGS IN STANDS WITH SUBSTANTIAL UNDERSTORY

Douglas-fir stands are routinely fertilized with urea when the trees are 10-15 years old and able to compete for nutrients effectively. Plantation managers are concerned that early stand fertilization increases competition with understory plants (Turner 1981), increases damage from leader browsing (Rochelle 1981), and produces a lower internal rate of return on fertilizer investments. At Weyerhaeuser's Snoqualmie Tree Farm, most biosolids are applied to stands between the ages of 5 and 15 years after a thinning operation or when the canopy is high enough to allow application beneath it. However, biosolids application to young stands is operationally easy, so investigation of its effects (without additional herbaceous weed control) on survival and growth of stands younger than 5 years is important for logistical reasons. It is particularly important to assess the negative impact of increased understory growth resulting from the higher nutrient levels.

Growth and survival of planted saplings were measured in a 2-year-old Douglas-fir stand at the Snoqualmie Tree Farm. The stand had an initial stocking of 570 (SD 84) stems ha^{-1} of 0.2-1.5 m tall saplings. Herbaceous and woody understory on the site consisted mainly of fireweed, vine maple, grass, red elderberry, bracken fern, and trailing blackberry. Five randomly selected control blocks (60 times 60 m) were excluded before routine application of dewatered biosolids to the rest of the site. Two plots were randomly established in each control and treatment block. Approximately 30 saplings were marked and measured in March 1996 and remeasured in March 1997 to assess changes in the growth and survival of the saplings in the year after biosolids were applied.

Biosolids application had no significant impact on either diameter or height increment. ANCOVA (analysis of co-variance) for height increment showed both initial height and tree browsing were significant covariates, but biosolids treatment was not a significant variable. Height increment increased with larger initial height and decreased if the tree was browsed. Regardless of treatment, maximum annual biomass on all sites was dominated by herbaceous shrubs. The effect of biosolids treatment on sapling mortality was not significant (p=0.14), but trends suggest greater mortality in treated sites. Fifteen percent of the saplings died in plots treated with biosolids compared to 9% in the adjoining untreated plots. Mortality was greatest in the smallest saplings.

Future management must recognize that target trees need to be a minimum size to compete effectively with understory vegetation in the use of added nutrients. If no weed control is planned, the smallest tree should be taller than 2 m before application of biosolids to minimize mortality and to achieve a beneficial growth response; application seems better targeted to slightly older stands with greater site occupancy.

NITROGEN ACCUMULATION BY UNDERSTORY PLANTS AFTER BIOSOLIDS APPLICATION

The objective of the study was to compare changes in aboveground understory biomass and N content after biosolids application. Biomass and N content of understory were sampled at the beginning and end of the growth phase (i.e., midsummer and the end of winter). Trials were established on separate sites in both 2- and 9-year-old plantations at the Snoqualmie Tree Farm and in 68-year-old thinned stands in the SDS at Pack Forest. The 2-year-old plantation had an initial application at 8.3 dry Mg ha^{-1} in April 1996. In the 9-year-old plantation, which was initially treated in 1992, 12.8 dry Mg ha^{-1} were reapplied in March 1996. The Pack Forest sites underwent application by hand in March 1996 at an average rate of 11 dry Mg ha^{-1}.

In both Snoqualmie Tree Farm trials, paired transects were located in controls and adjacent treated areas, with five sets of 2 m times 2 m plots established at 10 m intervals along each transect. Each plot was divided into 1 m^2 subplots with all understory vegetation covering the central 0.5 times 0.5 m area harvested in either midsummer or the end of winter. At Pack Forest, nine transects were randomly located with 2 times 2 m plots created at 10 m intervals along the transects. The plot was subdivided into two 1 m^2 subplots. One subplot was treated with biosolids in March. A control subplot was established 4 m to the right of the central peg. All understory plants covering the central 0.5 times 0.5 m area of each initial subplot were clipped and collected in late March. The treated subplots and controls were sampled in midsummer.

All samples were separated into leaf and stem material by species. Nitrogen content for every sample was determined by multiplying the sample's biomass by the average N concentration for that species, plant part, treatment history, and transect location. Statistical analyses were performed on transect-level data. Paired transects were considered a randomized block design with differences in biomass and N content compared using two-factor analysis of variance (ANOVA) without replication with a post-hoc Tukey Studentized range test. Differences in N concentration of foliage after biosolids application were compared using ANOVA.

The N concentration for major understory species in all cases was higher in the leaf than in the stem component. In the 2- and 9-year-old stands, N concentration of stem and leaf material from fireweed stems was not different, there was a substantial increase in leaf N concentration for both red elderberry and vine maple, and there was a statistically significant difference for bracken fern stem and leaf as well as for hardhack leaf between plots treated with biosolids and controls.

In the 2-year-old stand, the untreated site, although accumulating significantly less N in understory than the treated area, still increased its N content by 50 kg N ha^{-1} during the growing season. Since negligible residual nitrate was present at this site in pre-application assessments (King Co. 1995), most plant-available N must have been mineralized from the active and stable organic N pools in the soil. An additional 72 kg N ha^{-1} was removed from the soil by understory vegetation on the treated 2-year-old sites. As the N in the biosolids was not traced with isotopes, the exact source of the N accumulated by the plant is unmeasurable. However, the available inorganic N in the biosolids was likely the first source accumulated, followed by the easily mineralized N from organics in the biosolids.

In the 9-year-old stand, the average N accumulation was 99 kg N ha^{-1} after biosolids application, which represented only a small increase compared to that on untreated sites. Substantial available N still appears in the system as understory in untreated plots which accumulated 81 kg N ha^{-1} during the growing season, with no readily visual negative growth effects on overstory. The previous application in 1992 had already primed deciduous and herbaceous understory growth. It is expected that large amounts of N are annually returned to the soil from litterfall with high N concentration and that mineralization is significant. It is unlikely that additional applications of biosolids will cause significant net immobilization in these N-enriched sites, so additional N should be readily available for overstory accumulation.

The minimal accumulation of N in the understory of the 68-year-old stand is obviously limited by the small scale of the application plots and the single growing season that was monitored. Minimal understory accumulation suggests:

- The soil is heavily N deficient and the bulk of the applied inorganic and mineralized organic N from the biosolids was immobilized into the soil organic N pool and was unavailable to either the understory or the trees, contrary to the positive growth responses reported by Henry et al. (1993) for these sites.
- The understory has already reached a mature growth stage and may continue in a steady-state condition rather than showing accelerated growth. The mature salal understory present on this site has relatively low N requirements, which can be met partly through mycorrhizal associations.
- Salal's ericoid mycorrhizae are adept at assimilating complex organic N and P (Read 1993) but are incapable of accumulating N from biosolids. Prescott et al. (1993) described how high concentrations of ammonium and nitrate (>600 kg N ha^{-1}) can inhibit ericaceous plants like salal. However, Stanek et al. (1979) showed that inorganic N fertilizer applied at rates similar to total N in this study (120-200 kg N ha^{-1}) increased salal cover and biomass. Prescott and Weetman (1994) reported greenhouse studies showing that salal seedlings can accumulate ammonium and nitrate in solution. Salal should not be considered incapable of accumulating inorganic N, but rather as capable of meeting part of its relatively low N requirements through its mycorrhizal associations.

These studies show a range of short-term fertilizer responses and predicted long-term responses in different stand types. The past site history, fertilization rate, edaphic and vegetation factors all affect the variability of the response. Fertilization effects could be prolonged if the understory is actively recycling nutrients in the stand, as assumed in the young stands of this study (estimated that biosolids increased potential litterfall N by 35% in the 9-year-old site and 102% in the 2-year-old stand). Alternatively, if the stand is dominated by mature evergreen shrubs that do not respond substantially to added nutrient, the longevity of the fertilizer effect could be minimal.

The differing rates of understory N accumulation have substantial implications for calculating application rates for stands of differing age, understory composition, and past treatment history. Young stands like the 2-year-old Douglas-fir at the Snoqualmie Tree Farm which have not received recent biosolids applications and have understory composition exhibiting substantial vigorous annual growth can be expected to accumulate about 100 kg N ha^{-1} (U.S. EPA 1995). Young stands like the 9-year-old one at the Snoqualmie Tree Farm have vigorous annual understory growth. However, these already have enriched levels of available N from previous applications and enriched litter turnover and thus should additionally accumulate only from 0 to 20 kg N ha^{-1}. This rate should be used in future re-application calculations to young stands at Weyerhaeuser's Snoqualmie Tree Farm. In stands like the 68-year-old HTT, with established evergreen understory, it seems reasonable to include only minimal additional understory N in calculating accumulation rates. Alternatively, understory N accumulation in older stands that have been thinned recently and dominated by more deciduous or early successional species, or evergreen species just starting to expand in biomass after thinning, could have a higher N accumulation of about 30 kg N ha^{-1} (U.S. EPA 1995). In summary, designers of application rates need to take into account not only stand age and extent of existing understory, but also species composition, stage of understory development, and past treatment history.

IMPLICATIONS FOR FOREST MANAGEMENT

Operational biosolids application has been prevalent in Western Washington Cascades forests for the last 10 years, much of it on private lands out of view of the general public. Arrangements under the Mountains to Sound Greenway Biosolids Program allow for continued application of biosolids to private land and also for increased application of biosolids in areas of high visibility like Tiger Mountain. These public forests are highly visible and extensively used for public recreation, so quantification of the impacts on site values other than improved timber productivity is important.

The analysis of the changes in understory vegetation composition at Pack Forest helps to quantify stand visual changes after heavy application of liquid biosolids. After odor at application, the next most obvious impact of biosolids application is the change in visual appearance of the site. The initial visual impact of biosolids from application of dewatered product is generally short term and limited to minor adherence of biosolids to tree stems and foliage.

In time, the visual effect of dewatered biosolids application is limited to the presence of residual portions of biosolids on the forest floor and any changes in understory vegetation. The understory vegetation will generally be denser and taller after biosolids application. Whether there are further changes affecting species composition depends on application rate and site factors. There may be an increase in nitrophytic species and greater biomass of deciduous understory following heavy applications on recently disturbed, low SQ sites. With the lower rate of application typical of current practice, changes in understory species can still occur but are unlikely to equal those that resulted from the earlier heavy applications at Pack Forest. At the Snoqualmie Tree Farm the main understory impact was increased biomass in current species, although small clumps of nettle were present at certain microsites. Increased understory growth combined with the potential introduction of unfavorable species like stinging nettle to the site makes walking in the stand harder and limits some uses for public recreation.

If management strategies are using biosolids to accelerate stand development, the introduction of weedy, nitrophytic species could move the stand into a different successional pathway and may induce different development of the forest. It is more likely, however, that nitrophytic and early successional species may be short-term occupants that are rapidly building and recycling the N pool. In the longer term (10-20 years), they will be replaced by slower growing species. Although the short-term pathway may be different, the resultant forest structure may be similar.

If biosolids application and overstory thinning are intended to improve wildlife habitat, it is essential that other silvicultural practices are implemented to provide stand heterogeneity. Modification of the understory is only one critical habitat structural component. Dead wood, hollows, and vertical and horizontal heterogeneity are all stand components needing development to attract certain wildlife.

The effects of biosolids application on forest biodiversity may vary with spatial scale. In the small scale of a particular site, increased N application from biosolids may temporally follow the trends reported by Tilman (1982) and Frequez et al. (1990): increased understory biomass but decreased plant density and species diversity. However, regulation of biosolids application ensure that on a landscape scale a mosaic of treated and untreated forest generally exists. Additionally, as more land area becomes available for biosolids application, the intensity and frequency of application to individual sites can be managed to ensure that biodiversity is affected minimally.

If the introduction of nitrophytic or weedy species in adaptively managed stands is considered detrimental from any perspective (i.e., long or short term), biosolids (or any fertilizer) application will need to be conducted so that thresholds that induce species change are not crossed. This would involve:

- Applying biosolids at lower rates of N than those that seemed to change species composition in the older Pack Forests trials. Current applications at agronomic rates to older thinned stands do not seem to be changing species composition as did the heavy liquid applications of the past.

- Reviewing the stage of understory species development so that existing or desired species have competitive advantage. This may involve allowing the desired understory to establish for 2-5 years after thinning before biosolids are applied. Such delays may slightly increase the time overstory trees take to achieve the desired diameter, but the later biosolids application should still induce a significant growth response.
- Manipulating overstory density through reduced thinning. Biosolids may increase the availability of nutrients for understory plants, but other stand factors (e.g., light intensity) may prevent compositional change. Reduced thinning would favor slower growing species like Oregon grape that develop under lower light conditions. Again, this practice would be a tradeoff with the time required for the stand to reach the desired individual tree diameter or overstory basal area.

As with any silvicultural practice, multiple combinations of biosolids application rates, thinning intensity, and stage of understory development will also adjust the resultant stand structure, overstory tree size, and understory composition and abundance.

The legislative framework of forest management needs to be considered in developing biosolids application protocols. In states where harvested stands must be regenerated to certain minimum stocking and "free to grow" requirements, very early application of biosolids could make achieving these targets more difficult. If biosolids are applied in the first 2 years after planting or applied 2-3 years before the final harvest of mature stands, the risk of greater understory competition and increased sapling mortality increases. Acceptable stocking must be achieved within 3 years of harvesting in Western Washington, so practices that increase understory vigor and therefore detrimentally affect seedling survival and growth are of concern to forest managers.

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