Achieving Long-term Site Productivity in the Pacific Northwest: Research-Driven Databases to Guide Best Management Practices

A. Ares[1], T. A. Terry[1], R. A. Harrison[2], C. A. Harrington[3], K. B. Piatek[4], B. L. Flaming[2], C. W. Licata[2], B. D. Strahm[2], R. Meade[1], R. E. Miller[3], W.D. Devine[3], D. Peter[3], K. Petersen[2], H. W. Anderson[3], and T. Harrington[3]

Abstract: Achievement of long-term site productivity (LTSP) requires well-designed databases and decision-support tools that help formulate site-specific best management practices (BMPs). Progress is being made in the Pacific Northwest to expand the research base and databases that address LTSP questions. Collaborative research is directed at understanding the mechanisms of treatment response and the effects of biomass removal/manipulation, soil disturbance, vegetation management, and nutrient addition on tree growth, C and N stores, understory vegetation communities, and soil quality. An example of such research is the 6-year old Fall River study in coastal Washington that is linked to the USFS national LTSP program. Nitrogen removal from the site in the most intensive biomass-removal treatment was 925 kg ha^{-1}, only 6% of the total N store of the site to 80-cm soil depth. From years 2 through 4, annual N leaching to 1-m soil depth averaged 75 kg ha^{-1} in the treatment with the least biomass removed compared to 4.5 kg ha^{-1} in an adjacent uncut stand. At age 6, leaching rates across all treatments are similar to those in the uncut stand. Biomass removal by whole-tree harvest reduced Douglas-fir growth slightly at age 5 compared to BO. The study corroborated early studies in coastal Washington that demonstrated that compaction and surface-soil mixing in the A-horizon at harvesting did not reduce tree growth within skid-trails as soil bulk density, macro-pore space, and strength were altered but did not reach critical threshold levels. Vegetation control had the largest impact on tree growth increasing aboveground tree biomass to 12 Mg ha^{-1} versus 5 Mg ha^{-1} in the non-vegetation control treatment. Vegetation control increased soil water content during the growing season while foliage N concentrations in trees decreased at age 3 in plots without vegetation control at age 3, but not likely to a deficient level. Harvesting-traffic impacts on the Boistfort soil (Andisol) were low, and did not significantly reduce tree growth despite its silty clay loam texture. The Boistfort soil appears to have a low risk rating for harvest traffic provided the soil disturbance is confined to compaction and churning of the A horizon only. Results from Fall River support guidelines to conserve organic matter by scattering slash and minimizing slash-piling except where fire-risk abatement is necessary. The extent of the tree growth response to vegetation control was unexpected on this mesic site, and demonstrated the potential to increase tree growth by increasing soil water availability during the summer drought periods that are common in the Pacific Northwest. Using regionally-developed databases to refine management prescriptions in conjunction with reliable operational processes for implementing BMPs and tracking plantation productivity in an adaptive management model will help to reach sustainable productivity objectives.

Keywords: Sustainable forestry, biomass removal, vegetation management, Douglas-fir

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[1] Weyerhaeuser Company, 505 N. Pearl St., Centralia, WA 98531
[2] University of Washington, College of Forest Resources, Box 352100, Seattle, WA 98195
[3] U.S. Department of Agriculture Forest Service, Olympia Forestry Sciences Laboratory, 3625 93rd Avenue SW, Olympia,WA 98512
[4] West Virginia University, Division of Forestry, PO Box 6125, Morgantown, NW 26506

INTRODUCTION

Sustainable forestry requires knowledge about the long-term effects of forest practices on resource conservation and forest productivity. Regional databases designed to address the impact of cultural treatments across soil/climatic gradients provide information that allows development of decision-support tools and treatment guidelines for site specific best management practices (BMPs). Forest companies work in collaboration with other companies, universities, federal and state agencies, and other organizations to develop these databases, and in some cases, databases are developed internally by companies to refine their silvicultural prescriptions. Well-designed, multidisciplinary experiments carried out across soil and climatic conditions are most useful to fill knowledge gaps and address long-term soil productivity (LTSP) questions.

The Fall River study in coastal Washington is an example of collaborative research carried out to expand regional a regional LTSP database. The study was designed to fit into existing database matrices to expand the area from which inferences could be made about the impact of treatments such as biomass removal, ground-based harvesting impacts, and vegetation control. Other studies in Matlock, WA and Molalla, OR are being carried out by the USDA Forest Service on sites with lower precipitation or soil nutrient supply that those at Fall River (Harrington et al. 2005). These studies compliment other regional databases that assess the impacts of cultural treatments on Douglas-fir growth, e.g., skid-trail disturbance (Miller et al. 1996; Heninger et al. 2002) on tree growth, carry-over effects of stand fertilization on next rotation seedling growth, and silvicultural treatments in many studies installed by the University of Washington Stand Management Cooperative (Stand Management Cooperative 2005).

The Fall River study is an affiliated location to the USFS LTSP network that includes more than 100 core and affiliated sites on major soil and forest types in the United States and Canada (Powers et al. 2005). These studies examine the effects of biomass removal, soil compaction and vegetation control on forest productivity, and have at least two treatments in common.

The objectives of this paper are to provide a summary of key findings from the Fall River LTSP study, and show how this study fits into a regional database strategy that is used to develop decision-support tools and best management practices to meet soil stewardship and site productivity objectives.

MATERIALS AND METHODS

The Fall River research site is in the Coast Range of Washington State at 46° 43’ N lat. and 123° 25’ W long. The climate is maritime with wet, mild winters and warm, relatively dry summers. Mean annual temperature is 9.2 °C with monthly means of 2.6 °C in January and 16 °C in August. Estimated mean annual precipitation is 2260 mm mostly as rain.

The experimental site is between 305 and 362 m elevation on gentle slopes (< 10%) facing west. The soil is a medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudand (Soil Survey Staff 2003) of the Boistfort series developed from weathered Miocene basalt and with volcanic ash in the upper horizons. The soil is deep, well-drained, mostly stone-free, and has low bulk density, high organic C content and high water-holding capacity. Total soil N to 80-cm depth is 13,140 kg ha^{-1}. The site quality class for Douglas-fir is I to II+ with an average site index of 42 m at breast-height age 50 years (King 1966). The Fall River site is within the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) vegetation zone (Franklin and Dyrness 1973). The old-growth stand previously occupying the site was cable yarded in 1952-53 followed by broadcast burning and planting of Douglas-fir. The Douglas-fir stand was pre-commercially thinned in 1971, and fertilized four times between 1970 and 1995 with a total of 820 kg N ha^{-1} as urea.

The study was installed from April to July of 1999. The study was designed to contain 12 treatments with seven treatments imposed as of 2006. Each treatment was replicated four times in a randomized complete-block design. Fertilization treatments will be applied in five additional treatments if nutrient deficiencies become evident. Treatment plots are 30 m by 85 m (0.25 ha) with an internal 15 m x 70 m (0.10 ha) measurement area.

All harvested trees were directionally hand-felled between May and July of 1999 to keep all plot biomass within plot boundaries. Biomass-removal treatments were: (i) commercial bole-only up to 8- to 13-cm small-end diameter removal (BO), (ii) bole-only to 5-cm small-end diameter removal (BO5), (iii) total tree (aboveground portion) removal (TT), and (iv) total tree plus all legacy wood removal (TTP) (Figure 1). For these treatments, logs were cable-removed using a CAT 330L (Caterpillar, Peoria, IL) two-drum shovel yarder, and a CAT tractor used as a cable tail-hold to minimize site disturbance. Two additional treatments were (v) soil compaction (BO+SC), and (vi) soil compaction plus tillage (BO+SCT) both on BO plots with vegetation control. In plots with soil compaction, trees were yarded in May 1999 with a CAT 330L shovel with 70 cm-wide pads when the soil was at or near field water capacity (Figure 2). Soil tillage to 60-cm depth was applied on traffic lanes with a small CAT 322BL excavator shovel fitted with a PSM bucket with two 70 cm-long tillage tines. Details on soil physical and N leaching measurements were presented in Ares et al. (2005), and Strahm et al. (2005).

All biomass-removal treatment plots received intensive vegetation control for the first 5 years after harvest (2000-2004), except for the plots in the BO treatment that was specified not to receive vegetation control (BO-VC) (Figure 3). Details on herbicides, doses and time of applications are in Ares et al. (2006).

All plots were shovel planted with 1 + 1 Douglas-fir seedlings at 2.5- by 2.5-m spacing (1,600 trees ha^{-1}) in March 2000. Seedlings were produced from a mixed seed lot of 23 first-generation half-sib families. The study area remained fenced until year 5 to eliminate deer and elk browsing and reduce rabbit clipping.

Total height (TH) was measured in all treatments in years 1 to 5. Stem diameter was measured in BO+VC, BO-VC, TTP and BO+SC in years 1 to 5, and in BO+SCT, BO5 and TT in years 3 and 5. Stem measurements included stem basal diameter at 15 cm above ground (BD) in years 1 to 3, and stem diameter at 1.3 m above ground (DBH) in years 2 to 5. Both BD and DBH were measured in BO+VC, BO-VC and TTP in years 2 through 5 on a specified sub-set of trees. To represent the basal stem diameter growth from years 1 to 5, basal diameter at age 4 and 5 was estimated from DBH using separate allometric equations for BO+VC and BO-VC. A stem volume index (SVOL) was calculated as DBH^2 TH.

Douglas-fir foliage (needles plus twigs) were collected from the upper third of the crown of 15 trees randomly chosen per plot in February 2003 (i.e., age 3) from all plots in three treatments: BO+VC, BO-VC, and TTP. Samples composited by plot were analyzed as reported in Roberts et al. (2005).

We calculated N removal in each biomass-removal treatment by subtracting the N in coarse woody debris and forest floor left after harvest from the sum of the standing crop N stored in bole wood, bark, live and dead branches, foliage, dead trees and snags, coarse woody debris and forest floor before harvest (Ares et al., in press).

Treatment effects on tree size, foliar N, and competing vegetation canopy cover and biomass were analyzed as a mixed model with treatments as fixed-effects and block as random effect. Comparison of treatment means for each year of the study was made using one degree of freedom orthogonal contrasts. Procedure MIXED in SAS 8.2 that estimates variance components using restricted maximum likelihood methods was used for the analyses of variance. An $\alpha = 0.05$ was used in all statistical analyses for determining significance

RESULTS AND DISCUSSION

The key elements of an adaptive management process to achieve LTSP objectives are shown in Figure 4. The keystone of the process is a sound scientific database that is the basis for decision support tools that guide BMPs. The feedback monitoring process ensures that data gaps are addressed with additional research, and that standards and training are adequate for quality treatment implementation that will meet productivity and soil stewardship objectives.

We illustrate the process components with an example of managing soil disturbance impacts from harvesting operations (Figure 5). In this case, **Decisions** are matching logging equipment (e.g., ground-based or cable yarding) and BMPs to the site, minimizing negative impacts, and ameliorating the impacts when needed (e.g., with tillage). Required **data** are information on the extent of soil disturbance, disturbance impacts on soils and trees, amelioration effects, and equipment operability. **Tools** are appropriate soil surveys available in GIS-format for easy access, a soil disturbance classification developed for assessment of ground-based harvesting impacts, and soil risk rating to estimate the vulnerability of soils to compaction and puddling. It is necessary that the soil surveys map soil properties that are relevant for management. Growth and yield/forecast models are used to assess long-term growth and yield impacts. Field monitoring processes are designed to provide statistically sound data on whether standards and BMPs have been met, and desired results have been achieved (e.g., topsoil removal or displacement has been avoided).

The study at Fall River is providing information on biomass removal, soil disturbance/compaction and vegetation control on forest productivity. In the Pacific Northwest, N is generally the major nutrient limiting growth of Douglas-fir (Gessel et al. 1990). Nitrogen removal from the site at harvest in TTP was 925 kg ha^{-1}, only 6% of the total N store of the site to 80-cm soil depth (Figure 6). In the 5 years following harvest, N leaching to 1-m soil depth was approximately 260 kg ha^{-1} in BO and 100 kg ha^{-1} in TTP compared to 20 kg ha^{-1} in the adjacent uncut stand. These are conservative estimates because N leaching assessments started in March 2000. Greater leaching occurred in BO where logging slash and foliage material were left on the site. Nitrogen leaching rates across treatments are currently similar to the rate in the uncut stand (B. Strahm, 2006, personal observation). Biomass removal by whole-tree harvest reduced Douglas-fir growth slightly at age 5 compared to BO (Figure 7), likely because of soil water reduction rather than nutrient limitation. It has been proposed that values of a nutrient stability ratio > 0.3 (30% removal) indicate serious long-term nutrient loss concerns, whereas a ratio > 0.5 (50% removal) points to immediate stability concerns (Evans 1999).

Ground-based harvesting disturbed about 50% of the area in the compacted plots. Approximately 60% of the Douglas-fir seedlings were planted on microsites with some degree of disturbance. Soil bulk density increased with disturbance class and, also in depth when compared to the undisturbed condition. On average, it reached a maximum of 0.86 g cm^{-3}, a value not likely to affect root growth of Douglas-fir. Soil strength measured during the driest period of the second year after harvesting similarly increased in disturbed areas compared with the undisturbed condition. On average, soil strength in traffic lanes did not exceed 1300 kPa, below the 2000-3000 kPa strength range that is considered severely limiting for root growth (Sands et al. 1979). Tillage restored soil strength to its initial condition down to 50-cm depth.

Total porosity decreased by about 10% in compacted soil compared with non-compacted, and compacted and tilled soil whereas macroporosity decreased by 40-50%. Macroporore volume, however, was above the threshold value of 10%, that for soils of similar texture generally signifies reductions in aeration detrimental to root growth. Available water capacity (AWC) between -10 and -1500 kPa increased in compacted soil compared to the non-compacted condition by about 60%. For the -10 to -200 kPa tension range, AWC in compacted soil more than doubled that in non-compacted soil. The -10 to -200 kPa range is probably more meaningful to relate Douglas-fir growth with soil water conditions as it appears that Douglas-fir slows down its growth at soil water tensions as high as -60 or -70 kPa. Compacted soil generally retained more water than non-compacted and compacted + tilled soil all the way from -10 to -1500 kPa at 0- to 10-cm and 10- to 20-cm depth. Volumetric water content at saturation was greater for non-compacted soil because of changes in pore size distribution. Soil compaction was not detrimental to tree growth; if anything, the effect of compaction was positive.

Because tree growth was not negatively impacted by ground-based harvesting at Fall River, some threshold estimates are too conservative for soils like the Boistfort series (Table 1), which was considered a moderate risk site because of the silty clay loam texture. This corroborated early studies in coastal Washington that demonstrated that compaction and surface-soil mixing in the A-horizon at harvesting was not detrimental to tree growth as soil bulk density, macro-pore space, and strength were altered but did not reach critical levels (Miller et al. 2004). Results from Fall River support practices to conserve organic matter by scattering slash and minimizing slash-piling and perhaps burning except where fire-risk abatement is necessary, although tree growth reductions were very small (TT) to not significant (TT+) where total tree, and total tree plus coarse woody debris was removed.

Vegetation control had the largest impact on tree growth (Figure 7) increasing aboveground tree biomass accumulated at year 5 to 12 Mg ha^{-1} versus 5 Mg ha^{-1} in the non-vegetation control treatment. Vegetation control increased soil water content during the growing season (Devine and Harrington 2006), while tree foliage-N concentrations decreased at age 3 in plots without vegetation control (Roberts et al. 2005), but not a level normally considered as deficient. The extent of the tree growth response to vegetation control was unexpected on this mesic site, and demonstrated the potential to increase tree growth by increasing soil water availability during the summer drought periods that are common in the Pacific Northwest

Figure 1. Views of biomass removal treatments: (Top left) Bole-only removal, (Top right) Bole-only to 5-cm top removal, (Bottom left) Total tree removal, and (Bottom right) Total tree plus all legacy wood removal.

Figure 2. Areal views of plots after cable yarding (Top) and shovel yarding (Bottom). Note the traffic lanes along the bottom plot. Treatment plots are 85 m by 30 m.

Figure 3. Views of plots with complete vegetation control (Left) and no vegetation control (Right) at age 2 at Fall River.

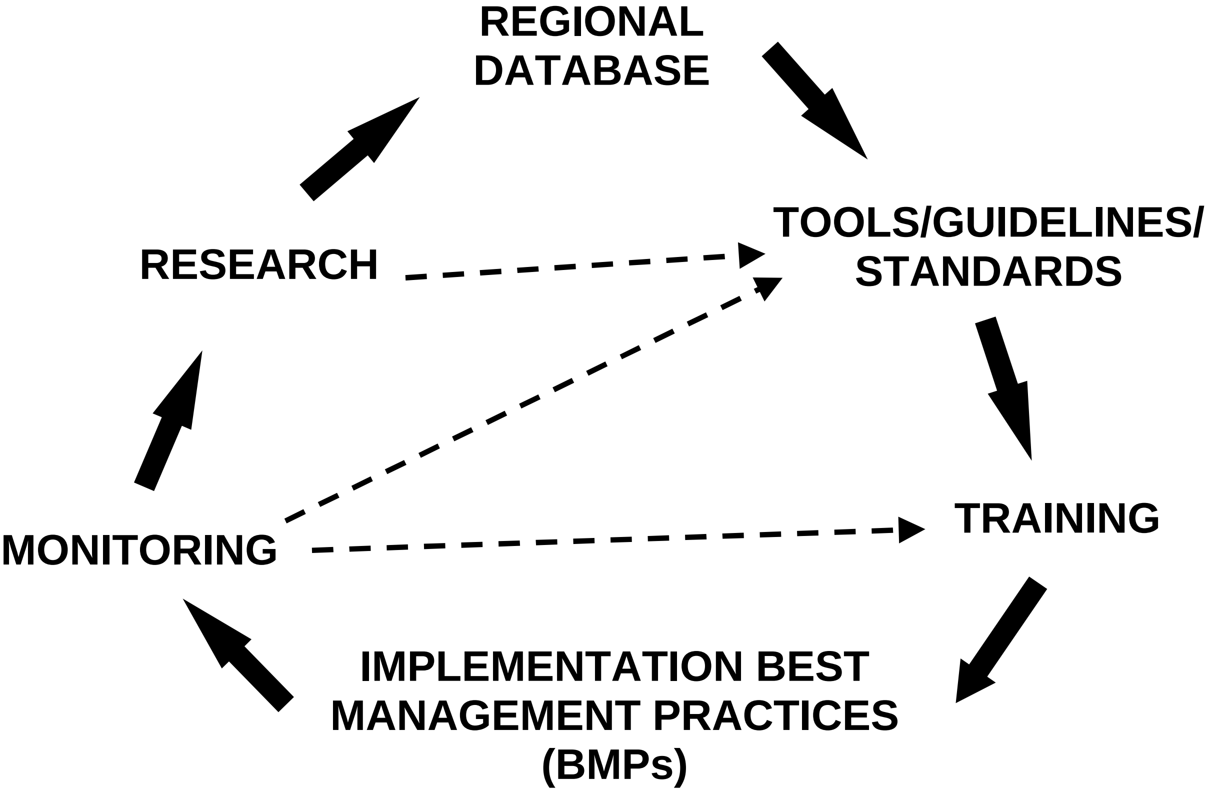

Figure 4. Schematic diagram of the critical process elements of adaptive management for achieving long-term soil productivity stewardship objectives.

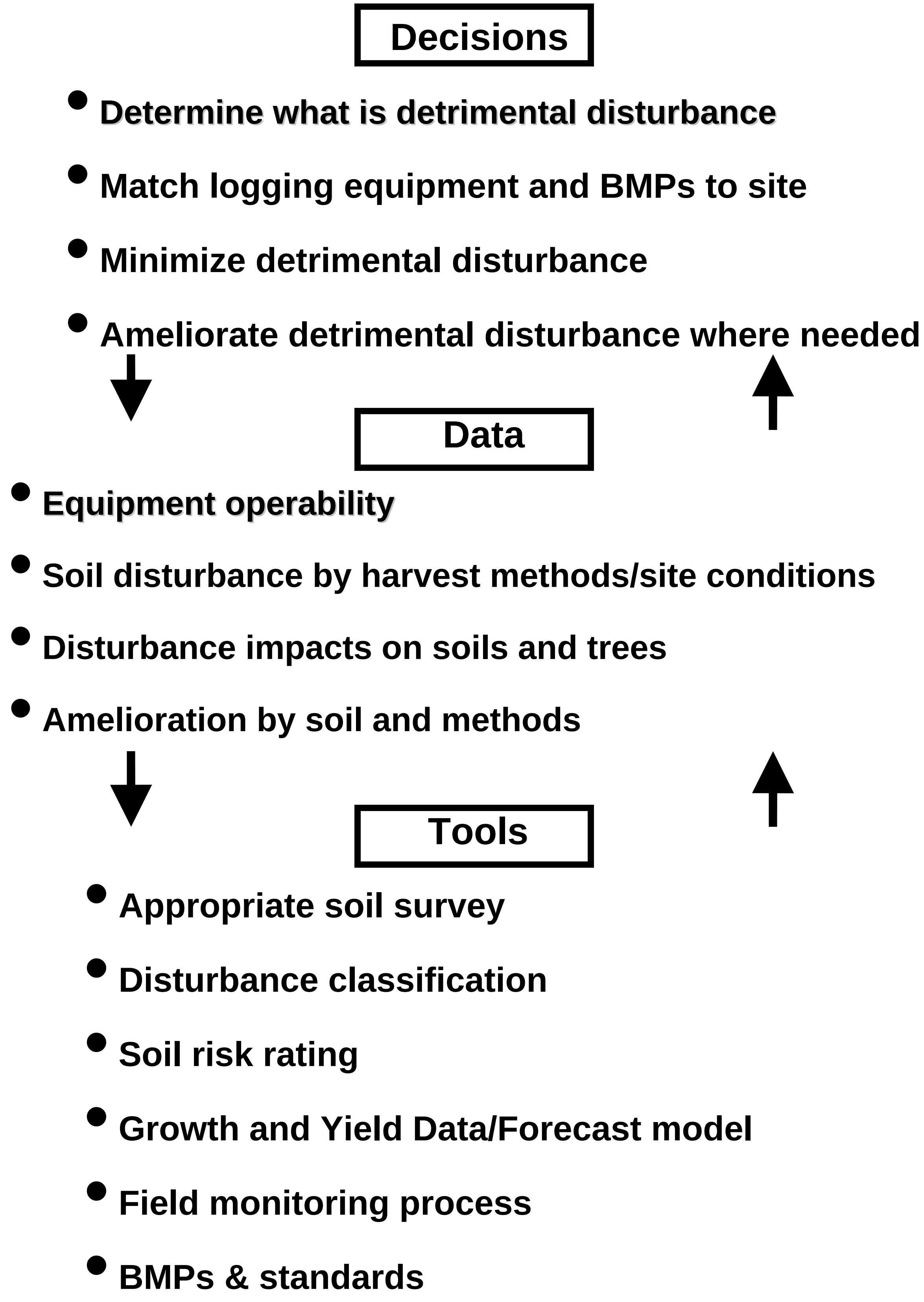

Figure 5. Process elements for managing ground-based harvesting impacts. Analogous types of decisions, data requirements, and decision support tools could be outlined for managing soil organic matter, vegetation competition and stand nutrition/fertilization.

Table 1. Comparison of proposed thresholds for changes in soil characteristics for Andisols in the Pacific Northwest region of the United States of America compared to changes after ground-based harvest at Fall River that caused no detrimental impacts to tree growth.

	Proposed thresholds for the PNW[1]	At Fall River
Area disturbed (%)	15	**50**
Bulk density (% increase)	20	**Up to 37%**
Macroporosity (% decrease)	50	40-**52 %**
Rut depth (cm)	15	12.5 cm
Topsoil removal (%)	50	None

[1] From Powers et al. (1998)

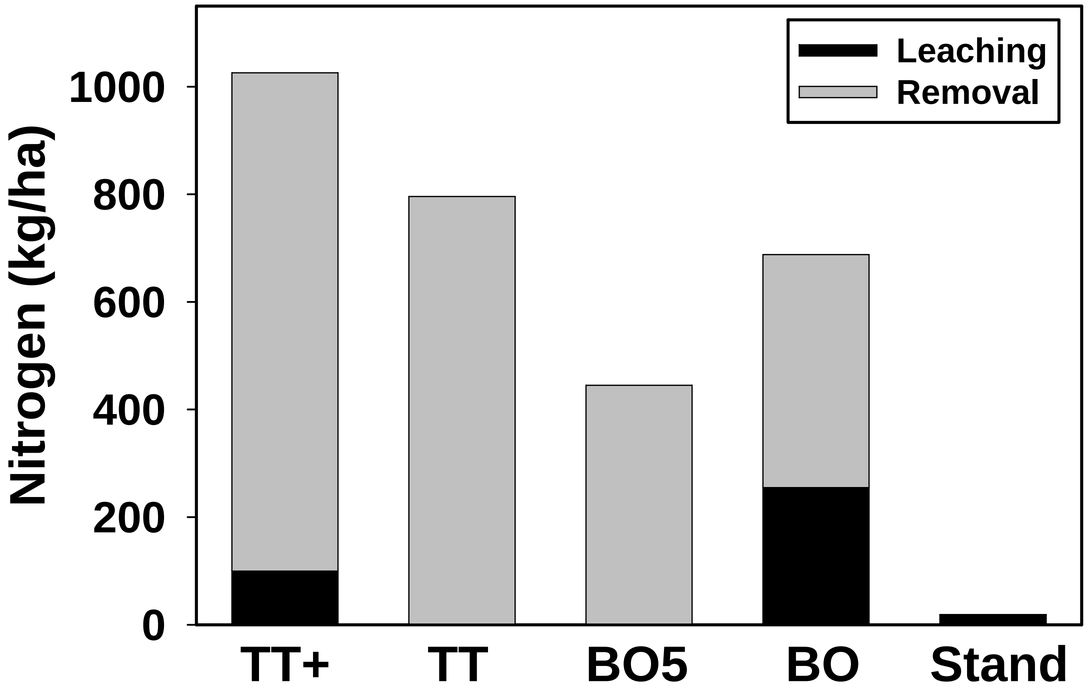

Figure 6. Nitrogen removal, and years 2- to 5 leaching to 1-m soil depth in TTP and BO biomass removal treatments, and in adjacent Douglas-fir/Western hemlock uncut stand at Fall River. Nitrogen leaching was not determined for TT and BO5.

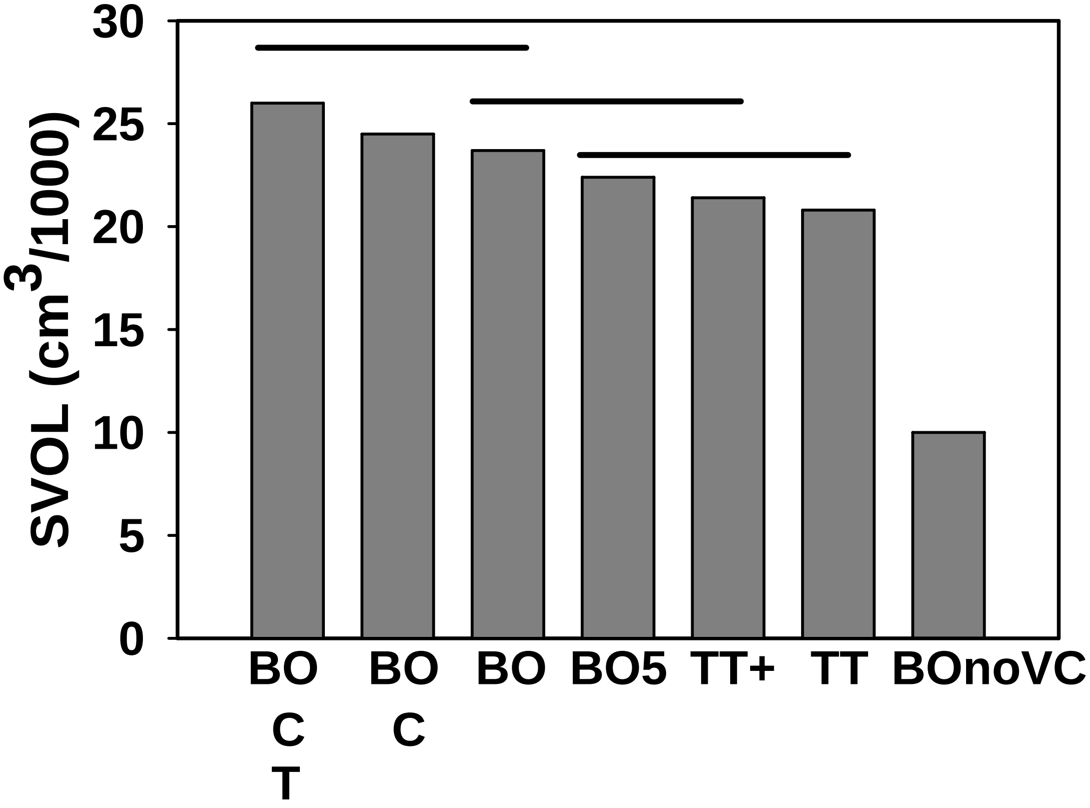

Figure 7. Growth response at age 5 of Douglas-fir as indicated by the volume index (SVOL) to soil compaction, biomass removal at harvest, and vegetation control at Fall River. Treatments are bole-only removal (BO), bole-only to 5-cm top diameter removal (BO5), total-tree removal (TT), total-tree plus all legacy wood removal (TTP), VC = Vegetation control, C = Soil compaction, and T = Soil compaction and tillage. All treatments except BOnoVC received vegetation control. Treatment means under the same horizontal line did not differ at ≤ P 0.05.

CONCLUSION

We encourage forest managers and forest scientists in the Pacific Northwest to continue thinking and working in an adaptive management way to develop sound databases on cultural treatment impacts on tree growth and soil processes that can be used to refine regional and local thresholds for soil quality and health, and update BMPs on a continued basis. This along with plantation monitoring will help us meet LTSP stewardship objectives.

Based on 5-yr results on a soil with high organic matter content and low bulk density, it was concluded that herbaceous vegetation was the main limiting factor for early tree growth. Understory vegetation reduces water supply to trees in summer dry periods that are typical in the PNW. Increasing biomass removal had a small to not significant impact on tree growth. Ground-based harvesting effects were not detrimental for tree growth. Proposed soil quality thresholds for area disturbed and bulk density changes were exceeded without any negative impact demonstrating the importance of adding information to the database so these metrics can be refined. The results confirm Powers et al. (1998) approach of adjusting soil quality thresholds for andic soils. Experimental treatment effects on growing-season soil water availability seemed to be more important than impacts on this site on nutrient supply as less than 7% of the site N store was removed in the most extreme biomass removal treatment. The Boistfort soil is well suited for intensive forest management because of its favorable soil physical properties and high N store. Vegetation control to increase growing season water supply can increase early growth, but longer term assessments are needed to evaluate the economic viability of this treatment on this site.

To fill some remaining knowledge gaps would require additional regional studies including:

- Complete vegetation control impacts on tree growth across a wider range of sites
- Potential gains from operational levels of vegetation control which are less than the "complete" vegetation control during 5 years after planting imposed at Fall River.
- Response to biomass removals, soil disturbance/compaction and vegetation control on dry sites.
- Soil water and nutrient supply and demand, and C fluxes and dynamics across sites.

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