Productivity and Soil Properties 45 Years After Timber Harvest and Mechanical Site Preparation in Western Montana

Luke M. Cerise, Deborah S. Page-Dumroese, Paul McDaniel, Cole Mayn, and Robert Heinse

ABSTRACT

Site preparation following timber harvests is widely used to increase seedling establishment postharvest. Historically, dozer piling and ripping were the most common forms of site preparation in the Intermountain West. Less commonly, terracing of hill slopes was another form of site preparation on the Bitterroot National Forest in western Montana from 1961–1970 on marginally productive lands. Our objective was to compare soil physical and chemical properties as well as timber productivity as evidenced by diameter-at-breast height (dbh) between terraced and standard-site preparation methods as well as unharvested stands. We collected and analyzed soil samples for bulk density, mineral cations, total C, total N, organic matter, particle size, and *p*H, forest floor measurements, tree dbh, and ground cover. Even after 45 years, visual soil disturbance in site-prepared stands was still observable with a majority of sites having some degree of compaction or rutting damage. Many soil chemical and physical properties were not significantly different among the two site treatments and the unharvested control stands. However, soil organic matter was significantly lower in the terraced and standard site-prepared stands than in the unharvested stands. Ponderosa pine dbh was greater in the terraced stands than in the nonterraced stands, but understory species diversity was low. The loss of surface soil organic matter and understory species associated with both forms of site preparation is a concern for future forest management. Leaving forest residue during harvest operations, limiting travel routes during management operations, and minimizing forest floor displacement may allow for limited soil impacts on future site-prepared stands.

Keywords: terracing, terracettes, soil management, site productivity, dozer piling

Maintaining long-term soil productivity in the Intermountain West is a requirement for sustainable forest management (e.g., Ares et al. 2005). However, heavy equipment used during harvesting and site preparation may cause soil degradation and thereby reduce tree growth. Forest productivity declines due to soil compaction, soil displacement, and brush removal have been noted in the Intermountain West (e.g., Clayton et al. 1987, Ross et al. 1986). In addition, lateral soil displacement and increased bulk density have been associated with decreased pine growth as evidenced by reduced tree diameter-at-breast height (dbh), tree height, and radial growth (Clayton et al. 1987). One major concern with site preparations has been the loss of surface organic matter that can reduce the amount of nitrogen (N) being mineralized into the soil profile (Jurgensen et al. 1997). While limited N on forest sites is a common concern, the loss of organic matter (OM) from periodic stand disturbances, such as thinning, is not well known (Page-Dumroese et al. 2010).

Timber harvesting on USDA Forest Service (USDA FS) lands in the Intermountain West was widespread and in some areas very intensive in the 1960s and early 1970s. Most harvest operations during this time used ground-based equipment, such as log skidders and tractors. Many, if not all, of the timber harvests were done by clearcutting the desired timber tree species. On harvesting, seedlings were planted either by hand or machine in areas with gradual slopes (<25%) (S. LaSalle, retired USDA FS Supervisor, pers. comm., Jan. 16, 2012). Site preparation was often conducted to reduce understory competition and make planting easier. At the time, terracing steep mountain slopes was considered an acceptable form of site preparation. Terracing was embraced by the Forest Service, in large part, to meet the agency's mandated policy of 100% seedling establishment and to increase timber production on all managed lands by as much as three times to increase income generated by timber sales (Nie 2008). As a site preparation method, terracing removes vegetation from the planting site thereby reducing seedling competition from understory plant species for water, nutrients, and sunlight. During the 1960s and 1970s roughly 6,500 ha of forested land were terraced on the Bitterroot National Forest (BNF) (Figure 1). These areas were steep (30–65% slope), had marginal soil conditions (low water holding capacity, rocky and thin A-horizon), and limited regeneration success (USDA FS 1970). Other site preparation methods included construction of skid roads, slash removal,

Manuscript received April 26, 2012; accepted May 24, 2013. http://dx.doi.org/10.5849/wjaf.12-013.

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We would like to thank Joanne Tirocke and the other employees at the Rocky Mountain Research Station in Moscow, Idaho for all their help and support with lab analysis, statistical consultation, and use of facilities. We are grateful to the Theresa Jain and two anonymous reviewers for helpful comments on the manuscript. This publication was made possible in part by the NSF Idaho EPSCoR Program and by the National Science Foundation under award number EPS-0,814,387. The authors are also grateful to the USDA Forest Service Northern Region for their financial and logistical support of this project.

This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; millimeters (mm): 1 mm = 0.039 in.; kilograms (kg); 1 kg = 2.2 lb; megagrams (Mg): 1 Mg = 2,204.6 lb; grams (g) 1 g = 0.035 oz; hectares (ha): 1 ha = 2.47 ac.

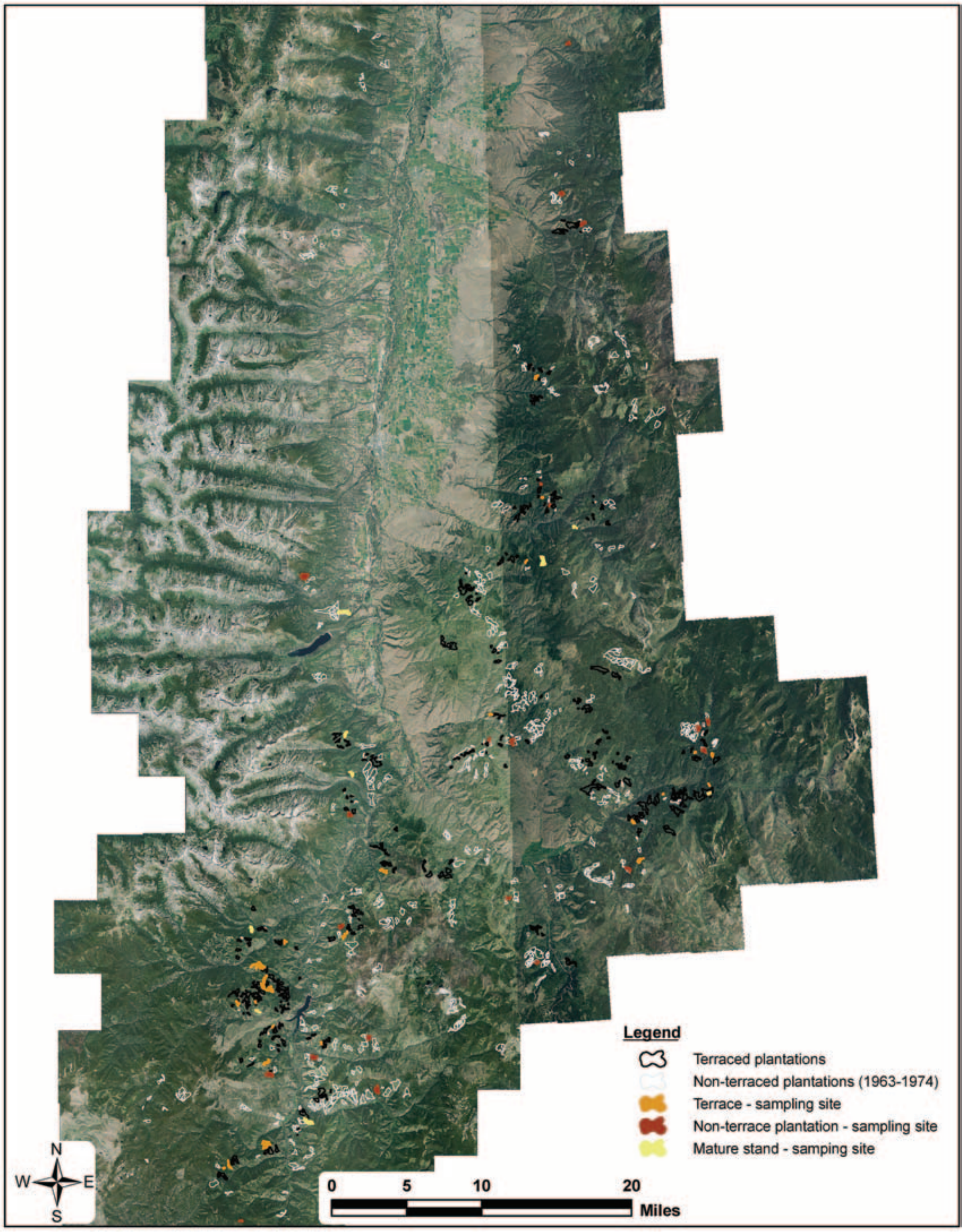

Figure 1. Study sites in the Bitterroot National Forest. Solid polygons indicate different treatment types.

and bulldozing or blading of the soil surface to remove understory vegetation. In many cases, terrace site preparation had roughly 40% more soil disturbance compared to these standard mechanical site preparations (S. LaSalle, retired USDA FS Supervisor, pers. comm., Jan. 16, 2012).

Terracing was thought to increase soil moisture by holding snow longer into the growing season, thereby increasing the effective growing season, and to increase soil water infiltration by decreasing runoff (USDA FS 1970, Querejeta et al. 2000). In addition, terraces were thought to better facilitate mechanical planting and harvesting methods (USDA FS 1970). While mechanical site preparation has been shown to increase the survival rate of conifer seedlings in some cases (McNabb et al. 1993), there are concerns of long-term negative impacts on soil quality, particularly for terraced sites (McNabb et al. 1993, Zlatnik et al. 1999). Initial reports filed in conjunction with National Forest Management Act (National Forest Management Act of 1976 [NFMA]) of 1976 stated that terracing mountain slopes in the Intermountain West would produce long-term soil degradation resulting in large tracts of land devoid of plant life.

An earlier comparative study of terraced and nonterraced sites by Zlatnik et al. (1999) found a significant increase in the dbh of planted ponderosa pine (*Pinus ponderosa*) on terraced locations compared to nonterraced locations. The only significant difference in soil characteristics was an increase in silt content found at terraced locations (Zlatnik et al. 1999). Another study in Utah's Wasatch Mountains by Doty (1970, 1972) on trenched mountain slopes (similar to terracing) to reduce erosion from flooding and overgrazing showed similar results. The authors found that trenching did not significantly increase soil moisture through the summer months but that increased snow accumulation on the trenches did improve vegetation establishment. Similar terrace site preparation was done on the Oregon Cascades and resulted in higher growth and survival of Douglas-fir (*Pseudotsuga menzieii*) trees (Newton et al. 1974). In addition, the authors also reported that mechanically planted seedlings grew better than hand planted seedlings on their study sites. However, there were also concerns that early gains in tree growth associated with terracing or other forms of mechanical site preparation might not extend through to rotation or thinning age because of changes in soil quality or surface soil displacement (Zlatnik et al. 1999).

The longer-term impacts of terracing and mechanical site preparation are relatively unknown on the BNF, particularly as they pertain to ponderosa pine growth and changes in soil quality (bulk density, nutrient content, etc.). The purpose of this study was to evaluate changes in timber productivity as related to changes in understory vegetation and soil physical and chemical properties within terraced plantations in comparison to traditional nonterraced, machine-prepared sites for timber production and unharvested stands.

Methods

Description of Field Sites

This study was conducted on timbered stands in the BNF in southwestern Montana (45.917° N, 114.283° W) shown in Figure 1. We selected sites representing three distinct treatments: (1) clearcut and subsequently terraced sites, (2) standard (dozer piling and ripping) mechanical site preparation (nonterraced), and (3) unharvested stands. Slopes range from 25 to 60%, elevations from 1,220 to 2,000 m, and aspects vary from north to southeast. The climate is semiarid alpine, with hot dry summers and cold winters. Average annual precipitation at the West Fork Bitterroot River station near Conner, Montana, is 480 cm, occurring mostly as spring rains and winter snowpack; the mean annual temperature is 6° C (National Oceanic and Atmospheric Administration [NOAA] 2011).

Based on the Soil Survey of the BNF Area and field observations, dominant soil series are Sharrott (coarse-loamy, mixed, superactive, frigid Lithic Haplustepts) and Kellygulch (coarse-loamy, mixed, superactive, frigid Typic Haplustepts) (Soil Survey Staff 2012a, 2012b). These soils are formed in colluvium and slope alluvium derived from metasedimentary rock (Belt Supergroup) and granite, respectively (Soil Survey Staff 2012a).

Terraces were constructed with bulldozers creating a terrace bench approximately 2.5 m in width. Bulldozed material was sidecast to create the terrace riser. Ponderosa pine was mechanically planted with a Rocky Mountain single disk trencher that created a furrow 10 cm wide and 46 cm deep along the terrace bench location (S. LaSalle, retired USDA FS Supervisor, pers. comm., Jan. 16, 2012). The terrace risers were not planted. Standard site preparation included dozer piling soil to create microsite conditions for seedlings, and in some cases ripping was done to reduce understory vegetation (primarily pinegrass *Calmagrostis rubescens*).

Experimental Design

Twenty-four terraced sites and 24 standard mechanically prepared sites (nonterraced) were selected for soil and vegetation sampling. Ten adjacent unharvested units were also sampled (150+ year old trees with no signs of previous harvest activity). Terraced-bench, terraced-riser, nonterraced, and unharvested sites were randomly selected based on slope and aspect so as not to introduce bias. The number of soil sampling plots at each site varied by stand acreage: four plots on 2–10 ha plantations, five on 11–20 ha plantations, and eight on plantations over 21 ha.

As a first assessment, we used the Forest Soil Disturbance Monitoring Protocol (FSDMP) (Page-Dumroese et al. 2009) at each sample plot to assess soil attributes and assign a soil visual disturbance class. The FSDMP determines the proportion of points in each attribute (rutting, compaction, etc.) and the visual disturbance class (0, 1, 2, 3) plus the confidence interval (CI). Primarily designed for preharvest and immediate postharvest sampling, we used FSDMP to assess long-term soil disturbance and vegetation growth responses on these machine prepared sites by pooling 125 sample points from each treatment following Page-Dumroese et al. (2012) to accurately represent each treatment.

Forest Floor and Mineral Soil Analyses

We collected forest floor and mineral-soil samples by separating the forest floor (organic material above the mineral soil) from a 30 cm diameter plot ring to mineral soil. The separation was relatively distinct with little observed mixing of forest floor materials into mineral soil. Soil samples were then collected using a large diameter (10 cm diameter × 30 cm length) impact coring device described in Page-Dumroese et al. (1999) and split into three depth increments: 0–10 cm, 10–20 cm, and 20–30 cm. On terraced treatments, we sampled an equal number of bench and riser locations.

Particle size was determined using the hydrometer method as described in Gee and Bauder (1986) for each soil location (terrace bench, terrace riser, and nonterrace) and depth per harvest unit. Soil samples were dispersed using a combination of physical (electric mixer with stirring paddles) and chemical (sodium-hexametaphosphate) means. No replicates or control samples were analyzed. Remaining soil samples were oven dried at 105° C for 24 hours to remove moisture after air drying and sieved through a 2-mm sieve. Rock fragments and roots were separated and weighed individually. Soil *p*H was measured on a 2:1 deionized water:soil suspension. No replicate measures were conducted; however, samples outside of ± 10% of within treatment variability were retested. Soil OM was determined by loss-on-ignition after combustion at 375° C for 16 hours following the procedure by Nelson and Sommers (1996). Soil C and N was determined using a Leco Tru-Spec CN analyzer (St. Joseph, MI) on 0.5 g homogenized samples. Homogenization and grinding was achieved using a ball mill. Soil exchangeable Ca, Mg, and K were extracted using 1 M ammonium acetate (Thomas 1982). Ca and Mg were analyzed by atomic absorption spectroscopy using a Perkin Elmer 5100PC Atomic Absorption Spectrometer (Waltham, MA). K was analyzed by flame emission. After filtering the soil for cations, the remaining soil was allowed to dry. A subsample of 2 g was then mixed with 2 M KCl and filtered. The filtered solution was then analyzed for extractable NH4 (Mulvaney 1996). Mineral soil C, N, OM, and cation contents were corrected for coarse-fragment content and extrapolated to a ha basis using the fine-fraction bulk density (e.g., Homan et al. 1995, Kulmatiski et al. 2003).

Forest floor samples were oven dried at 60° C until constant mass was attained. In some cases this took up to 72 hours, but most samples attained constant mass within 48 hours. We determined forest floor *p*H, and split samples for organic cations Ca, Mg, and K, and tested for organic C and N as described above. Forest floor samples were dry-ashed at 450° for 6 hours and leached with 2N HNO_3 and assayed by atomic adsorption/flame emission techniques to obtain organic cations (Karam 1993). The organic cation solution was analyzed using a Perkin Elmer 5100PC Atomic Absorption Spectrometer (Waltham, MA).

Vegetation Sampling and Analysis

Ponderosa pine dbh was measured on 2,145 trees within the three treatment types (terrace, nonterrace, unharvested) using a basal area factor (BAF) of 10 or 15, depending on the amount of ground cover (Green et al. 1992). In an effort to keep the tree ages consistent, trees with a tree ring count of 40–50 years were used for dbh measurements. Tree age was not used for selection of terraced stands because all terracing on the BNF occurred from 1964 to 1971 (Worf 1970) resulting in approximately uniform stand age across terraced sites. Natural regeneration and seed trees were not included in the surveys.

To measure ground cover by life form we sampled understory vegetation along 30.5 m long transects at each plot location. In 1 m increments along each transect, ocular estimates of percent cover by life form were made and recorded. Global positioning systems (GPS) coordinates were recorded at each soil sampling location using a Trimble Geo XT 3000 series GPS device and pictures were taken at each point for long-term monitoring of the established plots.

Statistical Analysis

Analysis of variance (ANOVA) was performed in PC-SAS Version 9.2 (SAS Institute, Inc., Cary, NC). Two-way ANOVA was performed on soil physical and chemical data, along with forest floor data using a general linear model with comparisons between treatment means made using Tukey's multiple range tests. Effects of treatments on measured soil variables were tested for significance at the 0.05 level. All soil data were analyzed by soil location (terrace bench, terrace riser, nonterrace) and soil depth. Each soil depth was compared to each soil location at the same depth, starting with 0–10 cm. Then the soil depths were compared against each other for significance (0–10 cm versus 10–20 cm, etc.). Tree dbh and cover by life form transects were analyzed with one-way ANOVA but were not tested for soil depth. The terraced units were not separated into bench/riser locations because all planted trees are on the terrace bench, and cover by life form transects crossed terrace locations. Tree dbh and cover by life form data were analyzed using treatment type (terrace, nonterrace), soil parent material type, slope, elevation, and aspect. Each variable used for tree dbh and cover by life form was tested for interactions using Tukey's multiple range tests.

Results

Forest Soil Disturbance Monitoring Visual Assessment

Forty-five years after harvesting, the majority of disturbance found on terraced units was due to topsoil displacement and soil compaction caused by the site preparation used to construct the terraced units (Tables 1 and 2). The standard site prepared units exhibited similar disturbance class ratings with topsoil displacement and soil compaction being the two main soil disturbances. Both site treatments had similar forest floor disturbance despite the different site preparation techniques. Unharvested units showed little or no soil disturbance due to lack of harvesting. However, in these units tree tip-ups due to wind partially accounted for the topsoil and forest floor displacement.

Table 1. FSDMP soil disturbance class for each treatment type on the BNF. Terraced treatment types have a combination of riser and bench locations within the harvested unit. Values are percent of occurrence for each class. Class 0 is undisturbed conditions and Class 3 represents most disturbed conditions.

Treatment type	Class 0	Class 1	Class 2	Class 3
Harvested terrace	15	41	31	13
Harvested nonterrace	12	70	15	3
Unharvested (control)	98	2	0	0

Tree Growth Diameter and Soil Cover

Comparing ponderosa pine dbh across terraced and nonterraced units showed a significant difference ($P < 0.04$) between the two site preparation treatments. Trees on terraced units had a dbh that was 2.2 cm larger on average than those of similar age in nonterrace units (Figure 2). The terraced treatment generally had less understory cover than the nonterraced sites (Table 3). Ground cover of shrubs and trees < 2 m tall was significantly less on terraced sites compared to nonterraced sites, whereas other ground cover categories were not significantly different between the two treatment types. Total vegetation cover was very similar between the two site preparation methods (Table 3); unharvested stands had greater understory ground cover than either stand treatment. Species compositions listed in Table 4 were similar for the harvested terraced and nonterraced sites, while unharvested sites showed a slightly different grass and forb composition.

Forest Floor

Forest floor biomass, OM content, C, N, Ca, and Mg were similar for the terrace bench and riser sites and the harvested nonterraced stands (Table 5). However, in the nonterraced stands, K was significantly higher than in the terrace locations but was equal to that found in the unharvested stands. The unharvested stands had greater forest floor biomass, OM, C, Ca, and Mg than the treated stands. Interestingly, forest floor N was unaffected by treatment type.

Soil Bulk Density

Table 6 shows significant total bulk density differences among sample locations (bench, riser, no terrace) and soil depth, the main differences being at the 0–10 cm and the 20–30 cm depth. Nonterrace (1.35 Mg/ha) and terrace riser (1.29 Mg/ha) locations had similar total bulk densities, but the terrace bench (1.53 Mg/ha) location showed an increase in total bulk density at the 0–10 cm depth. However, total bulk density decreased with depth on the terrace bench location, but increased on the other two treatment types (Table 6). Fine fraction bulk density indicated no significant differences between the different site treatments. The only soil depth that was found to be significantly different was the 10–20 cm depth among the site treatments where harvested nonterrace had a lower fine-fraction bulk density than the other site treatments.

Table 2. FSDMP visual site assessment measurements for three treatment types on the BNF. Values are percent of occurrence found on each treatment type, and values in parentheses are ± CI.

Treatment type	Forest floor impacted	Topsoil displacement	Rutting	Compaction	Platy
Harvested terrace	71 (63–79)	43 (34–52)	20 (11–33)	96 (72–120)	20 (9–36)
Harvested nonterrace	73 (63–82)	69 (60–78)	32 (19–48)	39 (24–55)	32 (20–47)
Unharvested (control)	24 (15–32)	14 (7–21)	0	2 (0.05)	2 (0.05)

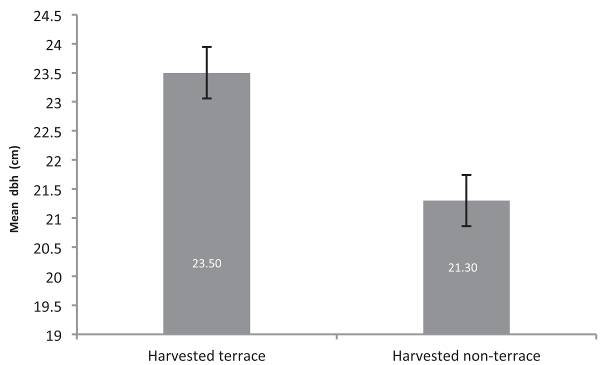

Figure 2. Ponderosa pine mean dbh values for trees measured on both land management treatments in the BNF. Larger dbh values generally relate to larger total tree biomass estimates and indicate an increase in usable timber (e.g., Ter-Mikaelian et al. 1997).

Soil OM, Carbon, Nitrogen, and pH

Soil OM was significantly higher in unharvested soils at all soil depths compared to site prepared locations (Table 7). At the 0–10 cm depth OM content was 19.2% in the surface soil of the unharvested stands and 7.6% in the nonterraced soil as compared to 4.7% and 5.6% in the soil of the terrace bench and riser locations, respectively. At the 10–20 cm depth there was no significant difference in OM for each of the harvested sample locations (bench, riser, nonterrace). The OM at the 20–30 cm soil depth was not significantly different between the terrace bench location and unharvested stands, but they were both significantly different from the terrace riser and nonterraced sample locations.

There was a significant decline in total C with increasing soil depth in all treatment types. However, no significant differences among the treatment types were found (Table 8). Soil C was higher in the riser and bench locations but was not significantly different from the nonterraced treatment. Soil N was significantly different between sample location and depth. The terrace riser and bench locations were significantly higher in soil N compared to the nonterraced locations at the 0–10 cm and 10–20 cm depths. The 20–30 cm depth was significantly different across all treatment types and sample locations. No significant differences were found in soil *p*H across the treatments (Table 7).

Discussion

Forty-five years after site preparation we were still able to detect changes in soil visual classes on both terraced and harvested nonterraced treatments. Most of the soil disturbance on these sites was topsoil displacement and surface compaction (Tables 1 and 2). Topsoil displacement and compaction were found to be light or moderate based on the FSDMP results. Harvested and site prepared stands had a majority of Visual Disturbance Classes 1 and 2; whereas the soil in the unharvested stand was primarily in Disturbance Class 0. Given that terraced sites were 100% disturbed initially, these results suggest that some soil recovery has taken place since. Similarly, standard site prepared stands had approximately 60% soil disturbance immediately after harvesting. Visual classification systems define the attributes and severity class of the disturbance, but ultimately they must reflect the impact of site-specific vegetation growth and hydrologic function (Page-Dumroese et al. 2012). Although we could still detect visual disturbance attributes (Table 1) in the harvested stands after 45 years, there was little or no difference in the measured soil properties. In addition, dbh (Figure 2) did not seem to be diminished due to the soil disturbances, and understory vegetation was present on all of our sites, although not as diverse as the unharvested stands (Table 4). Despite the intensive nature of terracing, tree dbh is actually higher on terraced units in the BNF compared to traditional mechanical site prepped units of the same age class, which is consistent with the findings by Zlatnik et al. (1999). Greater dbh in the terraced stands may be partially attributed to mechanical planting versus hand planting on the nonterraced locations considering that soil conditions were comparable across harvested treatments.

Soil conditions were only minimally affected by both mechanical treatments and on these soil types (rocky with a thin A-horizon) do not seem to reduce soil nutrients (Table 8).

Bulk density differences between the machine prepared units were not significant and did not seem to limit tree growth. Other studies have also found that terraces tend to have similar bulk densities as their nonterraced counterparts (Querejeta et al. 2000, Ternan et al. 1996). However, we did observe that the terrace bench location had a 12% decrease in bulk density from 0–10 cm depth to 20–30 cm depth compared to a 16% increase in bulk density with depth on the terrace riser, 8% increase in bulk density with depth on the nonterraced units, and a 28% increase in bulk density with depth on the unharvested units (Table 6). Decreased bulk density along the terrace bench location may be partially attributed to subsoiling actions during the terrace construction. We found that soil OM content was generally greater at lower depths on the terrace bench compared to the same depths in terrace riser and nonterrace locations suggesting that topsoil was redistributed across the hill slope and that the initial organic horizons were mixed into the soil profile. Above all, the soil types present on the BNF are very rocky and coarse textured and may not be as susceptible to compaction as finer textured soils (e.g., Andisols).

Overall, soil nutrients were similar across the mechanical site preparation treatments after 45 years. Soil nutrients were similar at each depth when compared among the mechanically prepared sites (Table 8); although C was slightly higher in the mineral soil of the unharvested stands than in the mechanically treated units. This indicates that these soils were relatively nutrient limited from the beginning, and therefore, harvesting impacts were minimal. Similar soil nutrient results were found on a site-specific study done in the West Fork Ranger District of the BNF by Zlatnik et al. (1999). The authors also mentioned that if sufficient nutrients had been released

Table 3. Cover by life form transects as affected by land management treatment on the BNF. Within each column, means followed by the same letter are not significantly different ($P < 0.05$) from different treatment types. Values in parentheses are standard error of the mean.

Treatment type	% forbs	% grasses	% shrubs > 2 m	% shrubs 0.5–2 m	% shrubs < 0.5 m	% trees > 2 m	% trees < 2 m	% total all vegetation
Harvested terrace	6 a (±1.2)	10 a (±0.95)	4 a (±0.45)	7 a (±1.15)	4 a (± 1.11)	47 a (±3.21)	6 a (±0.95)	71 a (±2.26)
Harvested no terrace	9 a (±1.8)	21 b (± 2.1)	9 a (±1.0)	12 ab (±1.92)	11 ab (±2.05)	33 b (±2.49)	6 a (±0.95)	72 a (±2.37)
Unharvested control	12 a (±1.1)	19 b (±1.7)	5 a (±0.67)	16 b (±1.53)	17 b (±1.94)	46 a (±3.05)	10 a (±1.16)	83 b (±2.79)

Table 4. Dominant understory vegetation found on each treatment type on the BNF. Ponderosa pine was the main tree species planted.

Plant taxonomy			Treatment		
Genus	Species	Common name	Harvested terrace	Harvested nonterrace	Unharvested control
Achillea	*millefolium*	yarrow	X	X	
Amelanchier	*alnifolia*	serviceberry	X		
Arctostaphylos	*uva-ursi*	bearberry		X	
Arnica	*cordifolia*	heart-leaved arnica	X		X
Balsamorhiza	*sagittata*	arrowleaf balsamroot		X	
Berberis	*repens*	Oregon grape	X	X	
Calamagrostis	*rubescens*	pinegrass	X	X	X
Carex	*geyeri*	elk sedge	X	X	
Centaurea	*stoebe*	knapweed	X	X	
Chimaphilia	*umbellata*	prince's pine			X
Erigonium	*umbellatum*	sulfur buckwheat			X
Festuca	*idahoensis*	Idaho fescue			X
Fragaria	*virginiana*	strawberry	X	X	
Koeleria	*pyramidata*	junegrass			X
Linnaea	*borealis*	twinflower			X
Lupinus spp.		lupines	X	X	
Physocarpus	*malvaceus*	ninebark			X
Symphocarpos	*albus*	snowberry	X	X	X
Thalicerium	*occidentale*	meadow rue			X
Vaccinium spp.		huckleberry		X	X
Xerophyllum	*tenax*	beargrass	X	X	X

Table 5. Forest floor measurements as affected by land management treatment on the BNF. Within each column, means followed by the same letter are not significantly different ($P < 0.05$) from different treatment types. Values in parentheses are standard error of the mean.

Treatment type	Biomass Mg ha^{-1}	% O.M.	pH	C (Mg ha^{-1})	N (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})	K (kg ha^{-1})
Harvested bench	83 a (±3.54)	38 a (±1.02)	5.6	24 a (±1.71)	10 a (±0.58)	599 a (±62.15)	51 a (±7.58)	60 a (±13.47)
Harvested riser	107 a (±3.02)	38 a (±0.94)	5.6	36 a (±2.09)	20 a (±0.42)	784 a (±66.41)	71 a (±8.21)	81 a (±10.29)
Harvested nonterrace	110 a (±3.14)	32 a (±0.91)	5.5	34 a (±1.94)	10 a (±0.63)	651 a (±64.98)	74 a (±7.75)	202 b (±15.32)
Unharvested control	168 b (±3.87)	61 b (0.85)	5.7	65 b (±3.15)	20 a (± 0.46)	1,292 b (±72.64)	125 b (±8.96)	194 b (±17.05)

Table 6. Soil total bulk density, fine fraction bulk density, and particle size distribution as affected by land management treatment on the BNF. Within each column, means followed by the same letter are not significantly different ($P < 0.05$) from different treatment types. Particle size distribution represents entire 30 cm soil core. Values in parentheses are standard error of the mean.

Treatment type	Sample location	Soil depth (cm)	Total bulk density (Mg ha^{-1})	Fine fraction bulk density (Mg ha^{-1})	% Sand	% Silt	% Clay
Harvested terrace	Riser	0–10	1.29 a (±0.05)	0.92 a (±0.06)	73 a	19 a	8 a
	Riser	10–20	1.35 a (±0.05)	1.07 a (±0.06)			
	Riser	20–30	1.49 a (±0.05)	0.97 a (±0.06)			
Harvested terrace	Bench	0–10	1.53 b (±0.05)	1.01 a (±0.05)	72 a	21 a	7 a
	Bench	10–20	1.45 a (±0.05)	1.00 ab (±0.05)			
	Bench	20–30	1.34 a (±0.05)	0.98 a (±0.05)			
Harvested nonterrace		0–10	1.35 a (±0.04)	0.99 a (±0.05)	62 b	28 b	10 a
		10–20	1.37 a (±0.04)	0.87 b (±0.05)			
		20–30	1.46 a (±0.04)	1.00 a (±0.06)			
Unharvested (control)		0–10	1.27 a (±0.04)	0.69 b (±0.06)	64 b	26 b	10 a
		10–20	1.36 a (±0.04)	1.06 a (±0.06)			
		20–30	1.63 b (±0.05)	1.12 a (±0.06)			

from the decomposition of OM on terraced and harvested nonterraced units, there would be no observable differences in soil nutrients. This appears to hold true for our study on the BNF and is likely due to similar forest floor biomass and nutrient concentrations on both the terraced and harvested nonterraced units (Table 5). Given these results, it appears that soil nutrient additions through needle fall and OM decomposition will be comparable among site prepared treatments provided that there is stand regeneration.

Table 7. Soil organic matter and *p*H by depth and land management treatment type on the BNF. Within each column, means followed by the same letter are not significantly different ($P < 0.05$) from different treatment types at each depth. Values in parentheses are standard error of the mean.

Treatment	Sample location	Soil depth	% S.O.M.	Soil *pH*
Harvested terrace	Bench	0–10 cm	4.7 a (± 0.42)	5.5 a
		10–20 cm	3.5 a (± 0.43)	5.3 a
		20–30 cm	3.4 a (± 0.47)	5.3 a
Harvested terrace	Riser	0–10 cm	5.6 a (± 0.44)	5.6 a
		10–20 cm	3.2 a (± 0.45)	5.5 a
		20–30 cm	2.3 b (± 0.47)	5.5 a
Harvested nonterrace		0–10 cm	7.6 b (± 0.31)	5.3 a
		10–20 cm	3.7 a (± 0.33)	5.3 a
		20–30 cm	2.1 b (± 0.38)	5.4 a
Unharvested control		0–10 cm	19.2 c (± 0.51)	5.3 a
		10–20 cm	6.5 b (± 0.58)	5.2 a
		20–30 cm	4.2 a (± 0.54)	5.2 a

Table 8. Soil nutrients as affected by land management treatment on the BNF. Within each column, means followed by the same letter are not significantly different ($P < 0.05$) from different treatment types. Values in parentheses are standard error of the mean.

Treatment	Sample location	Soil depth (cm)	C (Mg ha^{-1})	N (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})	K (kg ha^{-1})
Harvested terrace	Riser	0–10	29.84 a (±2.46)	1,361.6 a (±93.88)	2,094.9 a (±170.26)	194.92 a (±20.72)	424.79 a (±39.19)
	Riser	10–20	20.99 b (±2.59)	966.1 b (± 98.91)	1,323.6 b (±170.26)	120.21 b (±20.30)	253.84 b (±39.08)
	Riser	20–30	18.76 c (±2.60)	845.5 c (± 99.55)	1,283.7 c (± 181.11)	92.38 c (± 22.70)	248.65 c (±41.74)
Harvested terrace	Bench	0–10	29.75 a (±2.45)	1,53.8 a (± 93.6)	1,542.8 a (± 161.15)	142.10 a (±18.60)	314.40 a (±37.22)
	Bench	10–20	24.68 b (±2.57)	948.9 b (± 98.36)	1,335.4 b (± 170.26)	141.43 b (±19.72)	275.02 b (± 38.9)
	Bench	20–30	18.52 c (±2.76)	398.6 d (± 99.45)	785.1 c (± 186.08)	62.61 c (±22.75)	240.28 c (± 42.8)
Harvested nonterrace		0–10	24.21 a (±1.71)	964.9 e (±65.25)	2,071.3 a (± 105.01)	196.85 a (±11.11)	385.85 a (±23.78)
		10–20	20.61 b (±1.81)	816.8 f (± 69.25)	1,188.1 b (± 112.21)	128.05 b (± 11.99)	222.88 b (±25.46)
		20–30	19.98 c (±2.05)	792.9 c (± 78.20)	1,062.2 c (± 126.41)	135.06 b (±14.06)	218.58 c (±28.88)
Unharvested control		0–10	32.6 a (± 3.12)	1,102.7 a (±95.26)	1,419.66 a (± 131.01)	143.90 a (±11.49)	335.36 a (±24.36)
		10–20	21.3 b (±3.19)	789.5 f (± 96.32)	941.48 b (± 112.08)	114.76 b (±10.99)	288.34 b (±29.57)
		20–30	19.8 c (± 3.22)	696.0 g (±96.98)	1,235.35 c (± 135.24)	161.81 ab (± 11.38)	325.03 c (±25.14)

Long-term impacts of mechanical site preparation can be seen in the reduction of forest floor biomass (Table 5) where even after 45 years of site recovery, the forest floor biomass in the harvested stands was ~40% less than the unharvested stands. More importantly, species composition and diversity differed with site treatment. For example, Idaho fescue, junegrass, sulfur buckwheat, and prince's plume are only found in the unharvested stands (Table 4). Idaho fescue was previously found on nonterraced sites by Zlatnik et al. (1999) but was not found in the current assessment. In addition, the authors found ninebark on terraced sites, but none was observed on our terraced sites. Spotted knapweed was very prevalent on our harvested sites (terraced and nonterraced) but was not observed in the unharvested mature stands, nor was it noted in the study by Zlatnik et al. (1999). Spotted knapweed is an invasive species that invades disturbed areas and degrades desirable plant communities (e.g., Watson and Renny 1974). While differences in species composition and diversity may be partially explained by different successional stages in understory vegetation between the site-prepared treatments and the control, we do find it interesting to note that site preparation may encourage knapweed invasion given that the disturbance occurred 45 years ago (though we do not have enough replicates to statistically infer this). Considering the long-term effects of invasive species, the presence of spotted knapweed begs the question whether increased erosion and degraded soil properties may negatively affect timber development in the future.

Past studies have indicated that mechanical terracing increases soil water storage by reducing runoff and retaining more snow, making water more available deeper within the soil profile (Querejeta et al. 2001). In addition, terracing has been shown to increase water infiltration and rooting depth in the subsoil (Ternan et al. 1996, Martínez-Casasnovas et al. 2010). Combining these mechanisms, Gallart et al. (1994) showed that terracing may facilitate soil moisture recharge based on modeled natural hillslope conditions before and after terracing using the TOPMODEL. Given that soil conditions are nearly the same for terrace and nonterrace locations in the BNF, it stands to reason that seasonal snowpack is retained longer on terrace bench locations, reducing runoff and, consequently, increasing infiltration by reducing overland flow. We speculate that this occurred for the terraces on the BNF and resulted in greater dbh growth but was not directly assessed in this study. In addition, encouraging the terrace riser location to establish ground cover helped reduce the amount of erosional soil losses thereby giving the terraces more stability on the mountain slope (Li and Lindstrom 2001).

Conclusions and Management Implications

Standard and terracing site preparation techniques on the BNF did not express detrimental impacts on timber productivity after 45 years on sites in our study area. Our results show that bulk density among the harvested and terraced plots was not different from unharvested stands illustrating that these soil types have recovered to predisturbance levels. Changes in soil bulk density also did not appear to have had a significant impact on ponderosa pine seedling establishment and growth. Soil disturbance on both mechanically prepared treatments was still detectable but appeared to be recovering from the previous disturbances. However, there was reduced understory vegetation cover, species diversity, and reduced forest floor biomass and OM content on the mechanically treated locations. Terrace construction created more horizontal surface area along the contour of the hill slope, benefiting young ponderosa pine seedlings by offering a larger soil volume to establish rooting systems on otherwise marginal lands. Most of the mechanical site preparation areas had low nutrients or low OM soils. Site preparation on these particular soil types may have enhanced these marginal conditions and given plantation trees a competitive advantage. In addition, the high rock content of these soils may have buffered the soil fine-fraction from compaction and were less impacted than finer textured soils. Our findings provide baseline data on soil recovery after extraordinary mechanical site preparation treatments on the BNF. This study can also provide land managers with data for developing best management practices (BMP) for proposed timber harvesting or other land management goals that may require the use of machines on forested land.

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