



Soil development in vegetation patches of *Pinus ponderosa* forests: Interface with restoration thinning and carbon storage



Scott R. Abella^{a,*}, Charles W. Denton^a, Rory W. Steinke^b, David G. Brewer^c

^a Department of Environmental and Occupational Health, University of Nevada Las Vegas, Las Vegas, NV 89154-3064, USA

^b U.S. Forest Service, Coconino National Forest, Flagstaff, AZ 86001, USA

^c Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011-5017, USA

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ABSTRACT

Frequent-fire conifer forests in western North America are undergoing restoration and fuel-reduction treatments to reduce chance of severe crown fire and re-balance tree and understory plant biomass. A central decision in these treatments remains where to retain trees within sites during tree thinning. To help inform thinning prescriptions by identifying patterns of soil development, we sampled and classified 48 soil pedons among three vegetation patch types (grassy openings, openings invaded by post-settlement trees <age 130 years, and pre-settlement tree patches) at 8 sites in northern Arizona *Pinus ponderosa* forests. We found that 69% of pedons in openings were classified as Mollisols (a soil order associated with grasslands), whereas 75% of pedons in pre-settlement tree patches were Alfisols (a forest soil order). Soil differences among patches primarily related to soil morphology and development of epipedons, not necessarily reflected in analyses of properties (e.g., horizon thickness, organic C) of horizons. Turnover in soil orders occurs on a scale of meters to tens of meters within sites on this landscape, corresponding with distribution of vegetation patch types. Owing to long time periods required for these soil patterns to develop, results provide additional support for an idea that locations of tree and herbaceous patches were stable for long time periods (centuries to millennia). Results suggest that soil development patterns warrant consideration when choosing spatial locations of 'leave' trees during forest thinning.

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1. Introduction

Pinus ponderosa forestlands in the southwestern United States have been important to local economies for grazing, wood products, and recreation. These vast forestlands furthermore are a rich biological resource, encompassing some of the largest, contiguous forested landscapes remaining in the continental United States. Unfortunately, more than a century of fire exclusion and other management practices have dramatically altered forest structure by producing high-density stands dominated by small-diameter trees (Allen et al., 2002; Churchill et al., 2013). These dense stands are susceptible to insect outbreaks, accelerated mortality of old trees, and stand-replacing wildfire (Covington et al., 1994). Present forests also seem ill adapted to a changing climate of warmer temperatures and more extreme climatic events projected for the semi-arid Southwest including longer durations of fire weather within years (Westerling et al., 2006). Current densely treed stands have little understory productivity and provide poor habitat for

species dependent on open stand structures characterizing evolutionary environments of *P. ponderosa* forests (Moore et al., 1999). Reducing densities of small-diameter trees through mechanical thinning is well supported in the scientific literature as a means to reduce hazardous fuels, increase understory productivity, improve individual tree growth, and enhance watershed and other values (Fulé et al., 2012; Stephens et al., 2012b).

While there is general consensus regarding benefits of tree thinning, numerous perspectives exist about specific prescriptions for how to perform tree thinning and their advantages and disadvantages (e.g., Allen et al., 2002; Abella et al., 2006; Larson et al., 2012). For example, a major source of variation among prescriptions is where within stands to spatially retain trees during thinning. At a spatial scale of meters to tens of meters within stands, contemporary *P. ponderosa* forests have three main vegetation patch types: herbaceous or shrubby openings; post-settlement tree clumps (containing two to hundreds of trees); and clumps of pre-settlement trees (frequently containing 2–10 trees), which often exhibit little encroachment of post-settlement trees in the fire-free period (Larson and Churchill, 2012; Fig. 1). A remnant-based thinning prescription suggests retaining post-settlement trees (those establishing after cessation of frequent fires in the late 1800s) as close as possible to remnant evidence (e.g., stumps, logs)

* Corresponding author.

E-mail address: scott.abella@unlv.edu (S.R. Abella).

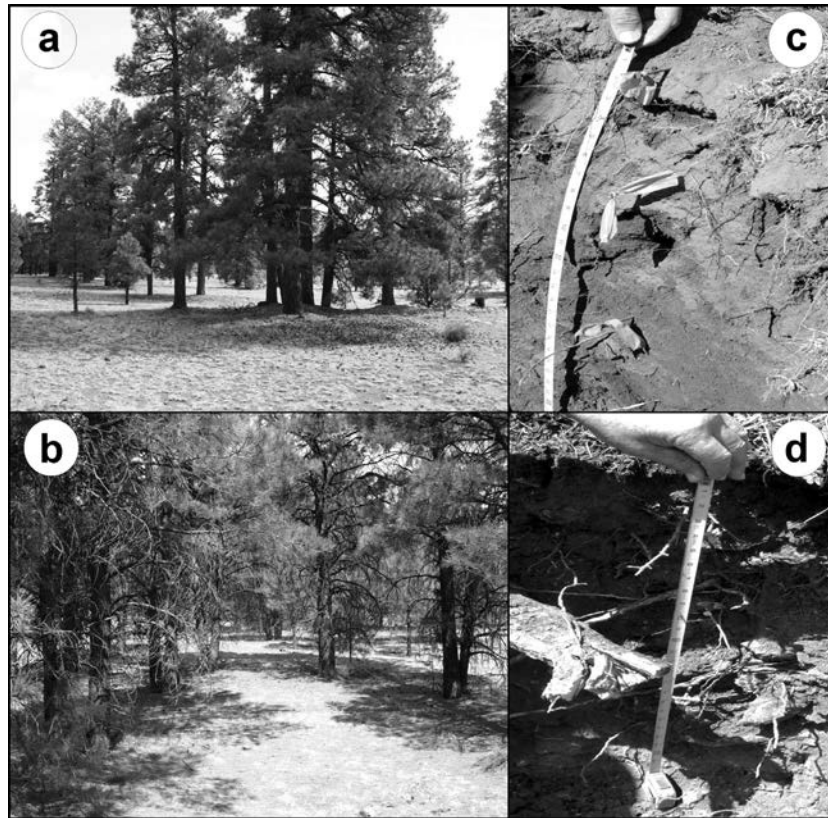


Fig. 1. Examples of vegetation patches and soil profiles in *Pinus ponderosa* forests of northern Arizona, USA. (a) Patch of pre-settlement trees with a grassy opening in the foreground on limestone soil. (b) Patch of post-settlement trees. The soil profile in (c) shows a Mollisol in a grassy opening where the A1 horizon occurs from the soil surface (there was no overlying O horizon) to a depth of 5 cm down to the first flagged nail, the A2 horizon occupies a 5–18 cm depth between the first and second nails down, the AB horizon encompasses the 18–36 cm depth between the second and third nails down, and the Bt1 horizon occupies a depth of 36–74 cm down starting at the third nail. The soil profile in (d) shows an Alfisol below a patch of pre-settlement trees, where an 8-cm thick O horizon occurs down to the first nail at the 3-in. (8 cm) mark on the measuring tape (scale in inches). The mineral soil starts at the first nail and consists of an 8-cm thick A&B horizon between the first and second nails down and a 15-cm thick Btk horizon between the second and third nails down. Note differences in root structure between the pedons where fine roots of grasses predominant in the Mollisol of (c) compared to the visible large roots of *P. ponderosa* trees in the Alfisol of (d). Photos by S.R. Abella, May 2010.

of pre Euro-American settlement tree locations (Covington et al., 1997). This prescription is partly based on White (1985), who hypothesized that locations of groups of trees, and interspersed grassy openings, were fairly stable for hundreds and possibly thousands of years in pre-settlement *P. ponderosa* forests. Tree establishment was thought to primarily occur as individual tree replacement on ‘safe sites’, near existing trees, where surface fires would burn litter to expose mineral soil free from grass competition on which tree seedlings became established (White, 1985; Mast et al., 1999). The location-based thinning prescription of Covington et al. (1997) seeks to emulate these patterns and preserve locations of canopy openings as closely as possible by maintaining locations of past openings and clumps of trees. In contrast, another perspective suggests that tree thinning to reestablish structure (e.g., clumping of trees) should leave trees primarily based on present tree locations (e.g., retaining desired young, but large, trees regardless of location), not past locations (Allen et al., 2002; Churchill et al., 2013). This prescription can maximize use of existing tree structure but can result in retaining post-settlement trees in former openings while converting former treed areas to openings. In other words, both prescriptions seek to reestablish forest structure, but they differ in emphasis on fidelity to past locations of openings and trees.

While stability of treed and opening locations and whether soil differs between these vegetation patches could be important to understanding tradeoffs among thinning prescriptions, few studies have compared soil development between tree and herbaceous patches in southwestern *P. ponderosa* forests (Welch and

Klemmedson, 1975; Kerns et al., 2003). If differences in soil morphology and other properties occur between these vegetation patches, when other site factors (e.g., parent material) are constant, it would suggest that locations of these patches have been stable sufficiently long for vegetation to influence pedogenesis. For example, two of the major soil orders (among 12 globally) differentiating soil developed under herbaceous or forest vegetation are Mollisols and Alfisols (Buol et al., 1997). Mollisols often develop under grassland vegetation and their major feature is formation of a mollic epipedon, a dark-colored, organic matter-rich upper layer of mineral soil (Anderson, 1987). The epipedon is darkened through the process of melanization, where decomposition incorporates organic matter into the mineral soil (Bockheim and Genadiyev, 2000). An epipedon is not necessarily synonymous with the A horizon, because the epipedon can also encompass upper parts of a B horizon (Soil Survey Staff, 2010). Alfisols, which usually develop under forest, are distinguished by containing a clay-enriched, high-base-status argillic horizon (Bt) and often contain a horizon sequence of A/E/Bt/C (Buol et al., 1997). Mollisols and Alfisols can require hundreds or thousands of years to develop through soil-forming processes, yet this time scale is not necessarily inconsistent with even the individual tree longevity of *P. ponderosa* (frequently >300 years and as old as >700 years; Swetnam and Brown, 1992). These observations suggest the possibility that major soil variation at the level of different soil orders might exist among vegetation patches at the within-stand spatial scale.

Variation in soil among vegetation patches could also have importance for soil C storage. Carbon storage is an increasingly

important consideration for forest management, as forest C is a key part of the global C cycle and strategies for sequestering C in forests are sought to slow global climate change (Dore et al., 2012). *P. ponderosa* forests are significant to C storage in western North America both because of their extensive distribution and ability to sequester C. Rasmussen (2006), for example, reported that *P. ponderosa* forests stored 10% of the entire soil organic C stock in Arizona, despite occupying only 6% of the state, and exhibited the highest ratio of C stored per area of any of Arizona's major vegetation types. Relative soil C storage of vegetation patches within these forests that make up the total is not clear. For example, one study in northern Arizona reported that 0–5 cm mineral soil organic C concentration was 1.6% greater in *P. ponderosa* compared to grassy opening patches (Welch and Klemmedson, 1975), while another study reported the exact opposite (Boyle et al., 2005). Moreover, soil depth and vertical C distribution can differ among soils, making it important to assess soil-profile C storage deeper than only surface soil.

The goal of this study was to compare soil classification, properties, and C storage among vegetation patches (grassy openings, openings in which trees of post-settlement origin have become established, and clumps of pre-settlement trees) of *P. ponderosa* forests. We assessed the following expectations: (1) soil morphology (e.g., horizon thickness) differs among patches, with characteristics such as A-horizon thickness decreasing along the gradient from grassy openings to pre-settlement tree patches; (2) soil chemistry differs among patches whereby pH, for example, is lower in tree compared to grassy patches; (3) grass patches contain Mollisols and pre-settlement tree patches contain Alfisols, with post-settlement tree patches exhibiting classifications of both patches; and (4) C storage of the soil solum is greatest in grassy patches.

2. Methods

2.1. Study area and study sites

We conducted this study within a *P. ponderosa* forest landscape in the Coconino National Forest surrounding the City of Flagstaff in northern Arizona, USA. Climate is semi-arid with most precipitation falling as snow in winter or as summer (July–September) rain in monsoonal storms. The Flagstaff Airport weather station, at an elevation of 2137 m, has reported an average of 52 cm/year of precipitation, -9°C daily January low, and 28°C daily July high (1893–2012 records; Western Regional Climate Center, Reno, NV). Topography is primarily flat to undulating, dissected by canyons, limestone ridges, and volcanic landforms such as cinder cones. In the centuries preceding 1880, the approximate date of Euro-American settlement and beginning of fire exclusion, fire frequency averaged 2–5 years based on six fire-history studies within the study area (Van Horne and Fulé, 2006). The frequent surface fires were believed to have limited *P. ponderosa* regeneration, maintaining open forests commonly with ca. 40–140 trees ha^{-1} in 1880 (Abella and Denton, 2009). Most forests were, and are, pure *P. ponderosa*. Euro-American settlement introduced new land-use practices including livestock grazing (cattle and sheep), timber harvest, and fire exclusion (Covington et al., 1994). Since settlement, density of *P. ponderosa* trees across the landscape has increased by orders of magnitude (Fulé et al., 1997). Graminoids (mainly native perennial grasses) historically dominated the landscape and do so today, although herbaceous vegetation has declined overall in many areas concomitant with the increase in tree density (Bakker and Moore, 2007). Cattle and sheep are still grazed in some areas, but at lower stocking levels than near the turn of the 20th century (Bakker and Moore, 2007).

The U.S. Forest Service in the study area completed a terrestrial ecosystem survey (TES), their ecosystem classification and mapping program for national forests in Arizona and New Mexico, and mapped ecosystems (which were designated by numerical codes) with a 16-ha minimum mapping unit (Miller et al., 1995). The ecosystem survey included climatic data, classified soil (at the 16-ha scale) to the family level, and soil parent material. In our study, we sampled across ecosystem types with soil parent material including basalt and limestone, which are predominant parent materials in the study area (Miller et al., 1995).

We sampled four sites, selected for the study because they were representative of the basalt and limestone soil parent material types in the study area and because the sites had stem maps, tree age data, and understory compositional data available from previous research (Abella and Covington, 2006; Abella and Springer, 2008; Abella and Denton, 2009). Sites had been identified by randomly selecting mapping units of the ecosystem types and randomly generating a Universal Transverse Mercator (UTM) coordinate for the site location within a mapping unit (Abella and Covington, 2006). Each site consisted of a 100 m \times 100 m (1 ha) plot. Historical forest pattern in 1880 was reconstructed based on dead wood (stumps, fallen logs, and snags) and live, old trees following methods of Fulé et al. (1997).

P. ponderosa was the only tree species recorded at study sites both in the 1880 reconstructed and the present forest. Site 1, on basalt parent material in the 582 TES unit, had a reconstructed historical tree density of 132 stems/ha and was at an elevation of 2245 m (UTM: 423,775 m E, 3,904,005 m N, zone 12, North American Datum 1983). Also on TES 582 basalt, site 2 had a reconstructed density of 137 trees/ha and occupied an elevation of 2338 m (424,713 m E, 3,909,630 m N). On limestone parent material (536 TES unit), site 3 had a reconstructed density of 65 trees/ha and was at an elevation of 2143 m (439,919 m E, 3,886,756 m N). Also on limestone, site 4 had a reconstructed density of 57 trees/ha and was the driest site, occupying the lowest elevation (2083 m; 449,861 m E, 3,893,080 m N). Owing to establishment of post-1880 trees, current tree density exceeded 400 stems ha^{-1} at all sites. Understory vegetation was dominated by perennial graminoids at all sites, with basalt dominated by *Muhlenbergia montana*, *Festuca arizonica*, and *Carex geophila*; the drier limestone site by *Bouteloua gracilis* and *M. montana*; and the moister limestone site by a mixture of all those species. The vegetation spatial structure of sites consisted of clumps of old trees (establishing before 1880), grassy openings without evidence of historical trees inhabiting them nor tree establishment after 1880, and patches of young trees establishing in former openings.

2.2. Data collection

Within each plot, we selected for sampling the three largest patches of old (establishing before 1880) trees (designated as 'pre-settlement patches'), post-settlement trees (designated as 'post-settlement patches'), and grassy openings (designated as 'openings'). Distance between centers of these patch types could be as little as 5 m and rarely >20 m (Fig. 1, Appendix A). Pre-settlement patches were readily identifiable in the field based on the platy, orange bark that develops on old (\sim age 100 year) *P. ponderosa* trees (Schubert, 1974), combined with verification through increment coring in previous research at the sites (Abella and Denton, 2009), and a typical absence of post-settlement tree establishment (Fig. 1, Appendix A). Trees designated as 'pre-settlement' were ≥ 130 years of age (1880 establishment date) at the time of sampling in May 2010 and typically had diameters (at 1.4 m height) of 45–80 cm. There were between 2 and 8 live trees in the pre-settlement patches and between 0 and approximately 5 stumps (mostly from late 1800s or early 1900s selective timber

harvests), snags, or downed logs indicative of dead pre-settlement trees. Trees within patches were uneven-aged with establishment dates of trees within clumps often differing by several decades. Post-settlement patches contained between 3 and approximately 30 trees younger than age 130 years. Both pre- and post-settlement patches contained trees whose bole centers were within 6 m of each other, or connected via a path of trees ≤ 6 m apart, which was based on typical crown radii of *P. ponderosa* and used in previous research (Abella and Denton, 2009; Sánchez Meador et al., 2011). Openings were ca. 0.01–0.1 ha in size. On the contemporary landscape, understory plant cover was near zero in pre-settlement patches, intermediate in post-settlement patches, and greatest in openings (Abella and Springer, 2008). O horizons (litter layers) were thickest in pre-settlement patches (often exceeding 10 cm thick, all or almost all *P. ponderosa* litter), intermediate in post-settlement patches, and sparse or absent in openings (Kerns et al., 2003).

We excavated a soil pit at the center of each of the three patches per patch type (9 total pits site⁻¹) at each of the four sites using a U.S. Forest Service truck-mounted backhoe. Backhoe excavation allowed us to dig pits ≥ 1 m wide to as deep as possible (bedrock, or to >1 m for deep soils) and facilitated description and sampling of each horizon. Soil pits were described using standard procedures (Soil Survey Division Staff, 1993) by soil scientists (Steinke and Brewer) familiar with local soils. Soils were classified following Soil Survey Staff (2010). A mollic epipedon present for Mollisols partly distinguishes Mollisols from Alfisols, the other dominant soil order at these sites. Criteria for designating a mollic epipedon in these soils included: (1) a Munsell color of at least as dark as a 3/3 (value/chroma; moist soil) and organic C concentration $>0.6\%$ throughout; (2) base saturation $\geq 50\%$ throughout; (3) moderately hard or softer dry-soil consistency class and coarse fragments (>2 mm in diameter) occupying $<50\%$ of soil volume; and (4) ≥ 25 cm thick or occupying $\geq 33\%$ of the solum. These criteria were evaluated in the field, with the organic C and base saturation (as indicated through pH) criteria confirmed through subsequent laboratory analysis of samples. Soil pH and base saturation are positively correlated. Beery and Wilding (1971), for example, reported that all samples from A and B horizons of Mollisols in Ohio with pH (1:1 soil:water) ≥ 6.0 had base saturations exceeding 60%. Similarly, in *P. ponderosa* forests, Blosser and Jenny (1971) found that no sample with a pH > 6.0 had a base saturation $<65\%$ in A and B horizons from grass-shrub patches. In our study, samples from only 5 (3%) of the 151 horizons analyzed in the laboratory had a 1:1 soil:water pH (described below) < 6.0 , and the minimum was 5.3. None of the pedons containing these 5 samples were classified as Mollisols, indicating that all pedons classified as Mollisols exhibited pH > 6.0 throughout the solum.

We collected a sample of 300 cm³ for laboratory analysis from each mineral horizon within the solum (above the C horizon). Air-dried, sieved (<2 mm) soil samples were analyzed for pH (1:1 soil:water and 1:2 soil:0.01 M CaCl₂), total C, and total N (dry combustion, vario MAX CN analyzer, Elementar, Hanau, Germany). Free carbonate, even for the limestone soils, was rare in the examined soils and pH in CaCl₂ (which corrects for salts) was <7 for 88% of the 151 samples, so total C was considered to approximate organic C (Abella and Zimmer, 2007). Soil volume occupied by coarse fragments (>2 mm in diameter) was estimated through water displacement for each sample. We estimated bulk density for each horizon using texture, coarse fragment content, and organic C following Saxton and Rawls (2006). Using bulk density and C and N concentrations, we calculated contents of C (kg m⁻²) and N (g m⁻²) for each horizon. We further calculated solum C and N content by weighting the

values for each horizon by the proportion of the solum thickness a horizon composed.

We augmented the intensive sampling of the 36 pedons described above at four additional sites where we only classified soils and did not collect samples for laboratory analysis. Two sites were on basalt parent material (582 TES), one site was on limestone (536 TES), and one site was on red volcanic cinder soil (513 TES), again selected *a priori* based on their inclusion in previous historical forest reconstruction research (Abella and Denton, 2009). At each site, one pit was excavated by hand to a depth of ≥ 50 cm in the largest patch of each of the three patch types, for a total of 3 pedons described site⁻¹ and an overall total of 12 additional pedons. Profiles were described following Soil Survey Division Staff (1993) as at the other sites.

2.3. Data analysis

Percentage of pedons classified by soil order was calculated for each patch type, and standard descriptions of pedons were prepared following Soil Survey Division Staff (1993). For the four intensively sampled sites, we analyzed several measures of soil characteristics among patch types. The three pedons of each patch type per site were averaged for each site, resulting in four mean values for analysis for each patch type for each soil variable. To compare soil variables across patch types, sites were included as blocks in an analysis of variance (ANOVA), with Tukey tests for mean separation, performed in SAS (PROC GLM; SAS Institute, 2009). Degrees of freedom (DF) for whole models were 11 (model = 5, error = 6), with 3 DF for site and 2 DF for patch type. Total A horizon thickness; B horizon thickness; A and B horizon C and N concentration and content; solum C and N content; A and B horizon pH; and C, N, and pH of the first A horizon were compared across patch types. The two pH measures were strongly correlated (Pearson $r = 0.94$, 151 samples), so we used 1:1 soil:water pH in statistical analyses.

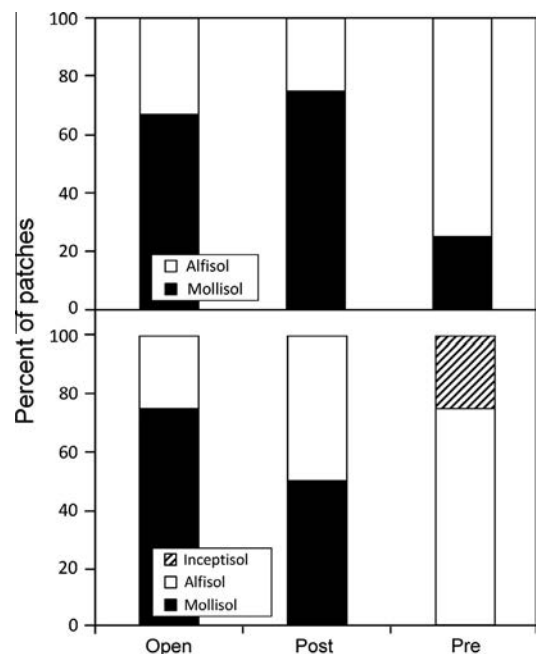


Fig. 2. Representation of soil orders by vegetation patch (pre-settlement tree, post-settlement tree, or grassy opening) for the intensively analyzed sites (top) and the additional sites (bottom) in northern Arizona *Pinus ponderosa* forests, USA.

Table 1
Soil properties in vegetation patches of *Pinus ponderosa* forests in northern Arizona, USA. Values are mean \pm 1 SD calculated by averaging 3 patches per patch type per site.

Site	A horizon ^a								B horiz.	Solum ^d		
	Patch	Thick. (cm)	Rock (%) ^b	C (%)	N (%)	C (kg m ⁻²)	N (g m ⁻²)	pH ^c		pH ^c	Thick. (cm)	C (kg m ⁻²)
Basalt 1	Open	10 \pm 5	10 \pm 10	3.1 \pm 0.9	0.15 \pm 0.04	2.9 \pm 1.2	143 \pm 67	6.5 \pm 0.2	7.2 \pm 0.4	95 \pm 12	9.5 \pm 1.1	503 \pm 74
	Post	7 \pm 1	17 \pm 12	2.8 \pm 0.6	0.12 \pm 0.04	1.9 \pm 0.2	81 \pm 4	6.3 \pm 0.1	7.1 \pm 0.2	103 \pm 3	8.8 \pm 2.0	426 \pm 98
	Pre	6 \pm 1	13 \pm 6	4.1 \pm 2.2	0.21 \pm 0.10	2.2 \pm 0.9	112 \pm 37	6.2 \pm 0.3	7.0 \pm 0.2	97 \pm 7	8.8 \pm 0.7	753 \pm 338
Basalt 2	Open	11 \pm 6	7 \pm 6	2.2 \pm 0.1	0.12 \pm 0.02	3.0 \pm 1.5	165 \pm 103	6.3 \pm 0.0	7.0 \pm 0.1	105 \pm 6	9.7 \pm 1.7	606 \pm 95
	Post	18 \pm 14	10 \pm 1	1.8 \pm 0.3	0.10 \pm 0.01	3.8 \pm 2.8	213 \pm 152	6.4 \pm 0.2	6.9 \pm 0.2	98 \pm 11	9.6 \pm 1.9	571 \pm 97
	Pre	13 \pm 13	10 \pm 9	2.6 \pm 0.3	0.13 \pm 0.01	3.4 \pm 3.1	166 \pm 153	6.2 \pm 0.2	6.7 \pm 0.3	93 \pm 13	11.5 \pm 3.0	573 \pm 52
Limestone 3	Open	25 \pm 14	3 \pm 3	1.6 \pm 0.6	0.08 \pm 0.03	4.5 \pm 0.8	235 \pm 57	6.3 \pm 0.1	6.7 \pm 0.1	86 \pm 22	7.1 \pm 0.7	407 \pm 47
	Post	32 \pm 15	6 \pm 1	1.3 \pm 0.2	0.06 \pm 0.01	5.2 \pm 2.0	258 \pm 103	6.4 \pm 0.0	6.7 \pm 0.4	76 \pm 22	7.6 \pm 0.3	398 \pm 21
	Pre	29 \pm 15	5 \pm 0	1.7 \pm 0.8	0.08 \pm 0.03	5.5 \pm 1.7	246 \pm 57	6.4 \pm 0.4	6.4 \pm 0.4	87 \pm 17	8.4 \pm 0.9	417 \pm 53
Limestone 4	Open	19 \pm 5	13 \pm 13	1.0 \pm 0.2	0.04 \pm 0.01	2.7 \pm 1.4	104 \pm 50	7.7 \pm 0.3	8.2 \pm 0.1	85 \pm 32	9.4 \pm 2.9	334 \pm 142
	Post	25 \pm 19	7 \pm 12	1.2 \pm 0.1	0.05 \pm 0.01	4.1 \pm 3.4	158 \pm 119	7.2 \pm 0.2	8.2 \pm 0.1	72 \pm 35	10.1 \pm 3.3	363 \pm 125
	Pre	7 \pm 6	35 \pm 7	3.6 \pm 0.8	0.13 \pm 0.04	1.9 \pm 2.0	72 \pm 80	7.2 \pm 0.1	8.1 \pm 0.2	47 \pm 21	7.0 \pm 3.6	254 \pm 122

^a Thickness was summed for sub-horizons (e.g., A1 and A2 horizons) to calculate total A horizon thickness. Rock, nutrient, and pH values were measured by sub-horizon and weighted according to the proportional thickness of the sub-horizon relative to the total A horizon thickness.

^b Rock content as percent of total soil volume.

^c Measured as 1:1 soil:water.

^d Solum represents the A and B horizons. Nutrient contents were calculated by weighting values of sub-horizons according to their proportional thickness of the total solum thickness.

3. Results

At the four intensively sampled sites, 71% of the 24 total described pedons in opening and post-settlement tree patches were Mollisols (Fig. 2, upper panel; Appendix A). In pre-settlement patches, in contrast, 75% of pedons were Alfisols and only 25% were Mollisols. A similar pattern characterized the four less intensively sampled sites: 75% of pedons in openings were Mollisols, whereas pre-settlement patches were predominately Alfisols including one pedon with minimal soil development classified as an Inceptisol (Fig. 2, lower panel).

Results of Mollisols in openings and post-settlement patches versus Alfisols in pre-settlement patches were generally consistent across sites (Appendix B). The major exception was that on limestone site 3 and on red volcanic cinder soil, openings and post-settlement patches often contained Typic Haplustalfs, frigid (Mollic Eutroboralfs in earlier taxonomy). These soils demonstrated partial Mollisol development but did not meet taxonomic criteria of Mollisols.

In contrast to soil classification, little difference was evident among vegetation patches in properties of mineral soil horizons and solum C content (Table 1). Site was significant in ANOVA for several variables (e.g., A horizon thickness: $F = 9.9$, $P < 0.01$; A horizon pH: $F = 114.4$, $P < 0.01$), but patch type was not, consistent with lack of patterning in means (Table 1).

4. Discussion

Variation in soil orders most frequently characterizing vegetation patches occurs on scales of meters to tens of meters within sites on this landscape. Among 8 study sites, openings and former openings invaded by post-settlement trees most frequently contained Mollisols, whereas patches of pre-settlement trees most frequently contained Alfisols. These findings are consistent with expected patterns of soil development in grasslands (Mollisols, characterizing openings) and in tree-dominated systems (Alfisols, characterizing patches of pre-settlement trees). Moreover, soils in former openings invaded by post-settlement trees during the past ca. 100 years were predominately Mollisols. Soil variation among patches centered on these differences in taxonomic traits and classification, because little difference was evident in means of properties such as C, N, and pH of mineral horizons among patches.

Classification of a pedon to soil order represents a different focus than statistical analysis of mean properties of horizons. Field identification of a mollic epipedon, for example, hinges upon assessing several criteria of the upper mineral soil, which can span multiple genetic horizons, and thus is not necessarily synonymous with analysis of genetic horizons (Soil Survey Staff, 2010). The following sections discuss: (1) ecological differences among vegetation patches that can affect soil-forming processes, (2) tree recruitment patterns that might relate to observed patterns of soil development, (3) potential influences of time and soil parent material, and (4) ecological implications for forest management and soil C storage.

4.1. Ecological differences among patches

Based on principles of soil genesis and plant–soil feedbacks (e.g., Anderson, 1987; Buol et al., 1997; Kulmatiski et al., 2008), the observed patterns of soil development among vegetation patches likely relates to dramatic differences in biomass and nutrient distribution between grassy opening and pre-settlement tree patches. In a comprehensive study of biomass and nutrient distribution in northern Arizona *P. ponderosa* forests, Welch and Klemmedson (1975) illuminated several differences between grassy and tree patches. Tree patches contained an order of magnitude greater total plant biomass m⁻² (including live + dead matter above- and below-ground) than grassy patches. However, there were striking differences in distribution of the mass among plant parts and vertical distribution of below-ground root mass. Root mass comprised 39% of total plant biomass in grassy patches but only 6% in tree patches. Root mass was 7-fold greater in the upper 0–5 cm mineral soil in grass patches than in tree patches, whereas the deeper 5–30 cm layer contained 4-fold greater root mass in tree than grassy patches. Additionally, the C:N ratio of total plant mass was 17 in tree patches compared to only 4 in grass patches. This also has implications for decomposition rates and soil nutrient cycling in the vegetation patches (Welch and Klemmedson, 1975). Findings of Welch and Klemmedson (1975) of greater proportion of total plant mass harbored in roots, and in upper soil layers, in addition to plant mass lower in C:N indicative of rapid decomposition, in grass than tree patches are consistent with Mollisol development in grass patches. Following a principle of plant–soil feedbacks (Kulmatiski et al., 2008), the different vegetation patches likely

influenced soil properties which in turn can influence plant development and reinforce soil-development patterns. An example would be Moir's (1966) finding that perennial grasses grew larger when experimentally grown in soil collected from openings compared to soil collected below *P. ponderosa*. This represents a positive plant–soil feedback where the grasses grew better in their own soil.

Studies in contemporary forests further highlight differences in ecological processes among patches that can influence soil development. For example, Boyle et al. (2005) reported that early summer soil respiration in a northern Arizona site was twice as high in grass than pre-settlement tree patches, with intermediate values in post-settlement tree patches. Kaye and Hart (1998) reported similar results for mineral soil N mineralization and nitrification: rates were twice as high in grass than in pre-settlement tree patches. Comparable results for nitrification (Erickson et al., 2005) and denitrification potential (Griffiths et al., 2005) being greater in openings than below conifers have been reported for Sierra Nevada and Pacific Northwest mixed conifer forests. These results collectively suggest that soil processes such as decomposition and nutrient cycling are fastest in openings, become rapid quickly (often with a few years) when tree patches convert to openings (Kaye and Hart, 1998), and would relate to soil genesis over time (Bockheim and Gennadiyev, 2000).

4.2. Tree recruitment and grassy opening development

P. ponderosa recruitment processes and patterns in historical forests would seem tightly linked with patch-scale soil-forming processes. Except in rare cases such as extremely coarse cinder soils where tree spatial patterns were random, within-site distribution (1-ha sites) of *P. ponderosa* trees in pre-settlement (before 1880) forests in northern Arizona was clumped (Abella and Denton, 2009). Clumps contained two to maximums of 24 or more trees (Sánchez Meador et al., 2011; Larson and Churchill, 2012). Moreover, trees within clumps are uneven-aged (White, 1985; Abella, 2008), not even aged as was assumed in some early research (Cooper, 1961). Dendroecological analysis of temporal tree recruitment patterns has indicated that recruitment was relatively continuous (during life spans of trees), with only three decades without tree establishment over a 320-year period (1550–1870) recorded by Mast et al. (1999) on a northern Arizona basalt site and all 29 decades between 1600 and 1890 having tree establishment at a northern Arizona volcanic cinder site (Abella, 2008). Within an existing tree clump, White (1985) suspected that 'safe' sites for tree recruitment could originate when fire 'scorched' the O horizon to expose mineral soil as a seed bed for *P. ponderosa* establishment free from grass competition. After germination, seedlings would likely require a fire-free interval for development of bark sufficiently thick to withstand surface fires. Fire-free intervals might occur at the site scale associated with climate or spatial patterns of ignitions, or at the microsite scale (square meters) of small areas with minimal fuel loads.

Dendroecological analyses of the uneven-aged structures of tree patches combined with paleoecological and other research suggest some temporal stability of vegetation patches for at least multiple generations of trees. In a 7-ha old-growth (not harvested) *P. ponderosa* basalt site in northern Arizona, White (1985) found that a clump contained pre-settlement-origin trees ranging in age by 268 years from age 138 to 406 years and all clumps contained trees varying in age by at least 33 years. On a volcanic site of red cinder used in the present study, Abella (2008) also found extreme uneven ages within clumps, with a maximum age range of trees within clumps of at least 156 years. The grassy openings also appeared persistent *in situ* for long time periods, based on lack of evidence of historical trees in openings (Sánchez Meador et al., 2011), enrich-

ment of grass phytoliths in openings (Kerns et al., 2001), and experimental work showing that perennial grasses are highly competitive with *P. ponderosa* seedlings and likely were a major constraint to tree recruitment in openings (Pearson, 1942). These multiple lines of evidence, coupled with results of soil developmental patterns that require long time periods to develop, suggest some temporal stability on the order of centuries to millennia in spatial locations of many tree and grass patches in historical forests.

4.3. Influence of time and parent material

Several studies provide insight as to time required for formation of a Mollisol and conversely time required for a Mollisol to convert to an Alfisol under tree cover. In a Minnesota prairie-forest ecotone, Severson and Arneman (1973) found that two millennia were sufficient for Mollisols under prairie to convert to Alfisols under forest, and *vice versa*. In a chronosequence of *Pinus banksiana* establishment (300–2500 years of *Pinus* occupancy) on prairie Mollisols, Almendinger (1990) found that sites invaded by *Pinus* for <600 years were still Mollisols whereas sites containing *Pinus* for >600 years were Alfisols or Entisols. Buol et al. (1997, p. 190) reported that mollic epipedons required 400 years to form in Wisconsin prairies. These soil-formation estimates are consistent with the ≥centuries to millennia time scales of tree residence in *P. ponderosa* tree patches reported in dendroecological studies (White, 1985; Mast et al., 1999; Abella, 2008).

The full length of time these soil patterns might have existed and how original patterns formed is an intriguing, unanswered question. This may hinge upon how 'self-reinforcing' (Binkley and Giardina, 1998) the pattern was under frequent-fire conditions either through plant–soil feedbacks (Kulmatiski et al., 2008), 'safe-site' tree recruitment mechanisms (White, 1985), competitive herbaceous environments hostile to tree recruitment in openings (Pearson, 1942), or other factors. Under the past 130 years of fire exclusion, *P. ponderosa* has become established in many former openings and clearly can grow in soil of former openings (Kerns et al., 2003). Additionally, the role of individual trees not part of clumps warrants investigation. Individual trees typically comprise <25% of total stand density in northern Arizona *P. ponderosa* forests (Abella and Denton, 2009; Sánchez Meador et al., 2011). It is unclear whether these individuals were part of former clumps now reduced to single trees, part of former clumps simply transitory as single trees that would again become part of clumps, the beginnings of a new clump, or simply single trees that remain *in situ* or ephemerally move across landscapes as small components of total tree density.

It is noteworthy that many pedons in openings not classified as Mollisols displayed partial Mollisol characteristics, and this might reflect constraints by soil parent material to soil development. For example, all patches were classified as Alfisols on a site with red volcanic cinder parent material (TES = 513). However, pedons in open and post-settlement tree patches were Typic Haplustalfs, frigid (Mollic Eutroboralfs in earlier taxonomy), and thus while still classified as Alfisols, showed partial development of Mollisol traits which was not observed in the pre-settlement patch. Volcanic cinder soils contain the coarsest, driest, most nutrient-poor surface soils that have the lowest understory plant productivity in the study area (Abella and Covington, 2006). These soil parent materials might have limited inherent capability for supporting Mollisols, and the partial development of mollic characteristics we observed in openings might reflect near-maximum soil development on these soils. While the number of pedons (48) we described and sites (8) we examined are large relative to many other studies of soil development (Kerns et al., 2003), numerous factors limited our ability to sample more sites and achieve additional replication

across parent materials to examine a potential interaction between parent material and soil development in vegetation patches. It should be noted, however, that we did find that Mollisols or trends toward mollic development consistently occurred more frequently in openings than in pre-settlement tree patches across the 8 sites encompassing three major parent material types. Magnitude of soil development, however, might vary between vegetation patches among parent material types (Binkley et al., 1995).

4.4. Ecological and management implications

The observed distributional pattern of soil types among vegetation patches could have several ecological implications. *P. ponderosa* clearly can become established in former openings, and the trees grow as well or better on the Mollisol soils of openings than on Alfisols (Abella et al., 2006). The converse for perennial grasses may not be true, however. In Washington *P. ponderosa* forests, Moir (1966) found that biomass of the perennial grass *Festuca idahoensis* averaged 24% greater when experimentally grown in soils collected in unburned openings than in soils collected from below *P. ponderosa*. Several experiments in contemporary forests have reported that numerous measures such as soil respiration and N mineralization are greater in soil of grass patches than below *P. ponderosa* trees (e.g., Boyle et al., 2005; Laughlin et al., 2010). A key point is that soil taxonomic layers such as epipedons can have important ecological functions, such as mollic epipedons that support rapid production and decomposition of fine-material organic matter (Anderson, 1987). These observations suggest that at least two potential outcomes of expansion of Alfisols at the expense of Mollisols could be reduced grass productivity and slower nutrient cycling.

Ecological implications of fire to these soil patterns could be important but need evaluation. Based on the multi-century time scales required for formation of Mollisols and Alfisols, the observed soil patterns formed or were maintained before 1900 during a frequent-fire regime with burns at particular locations at least as frequent as every 6 years on this landscape (Van Horne and Fulé, 2006). What is not known, however, is whether frequent fire, or conversely exclusion of fire since 1880, would influence soil development. Fire's role in soil genesis would likely hinge upon fire effects on plant–soil feedbacks and nutrient cycling. For example, fire is considered to have limited *P. ponderosa* recruitment by killing seedlings and saplings, which could have maintained openings (Fisher et al., 1987). Exclusion of fire since 1900 has correlated with *P. ponderosa* establishment in openings, raising the possibility of existing Mollisols in openings increasingly influenced by trees toward development of Alfisols. Fire is often thought to increase rates of nutrient turnover between plant material and soil (Grady and Hart, 2006). This could strengthen plant–soil feedbacks to speed development of grass or forest soils, but the converse of slowed soil development could also occur. Soil development could slow, for example, if greater proportions of herbaceous biomass are burned in fire and thus unavailable for decomposition and incorporation in soil (Grady and Hart, 2006). Contemporary experiments evaluating soil-forming processes under or free from influences of fire might provide insight into effects of fire management on soil development.

Results raise several further considerations for forest management and restoration. Long-term soil developmental patterns warrant consideration when developing tree thinning prescriptions for restoration and fuel reduction in *P. ponderosa* forests. For example, Allen et al. (2002) suggested that leaving large, post-settlement trees that had invaded openings would help more rapidly reestablish historical tree structure, as opposed to leaving potentially smaller trees growing near clumps of historical trees that had died. However, our study combined with another study of soil development (Kerns et al., 2003) and evidence derived from dendroecology

and other types of research (e.g., White, 1985; Fisher et al., 1987), suggest that locations of soil patches have been stable for time periods sufficient for their formation. Thus, leaving post-settlement trees in former openings might gain some decades of development of old trees and diameter growth, but occur at the expense of centuries of soil-pattern formation. On the other hand, this 'switching' of tree and opening location might simply 're-set' a new cycle of Alfisol–Mollisol development in different locations. As noted earlier, however, there might be at least some short-term tradeoffs such as potentially reduced herbaceous productivity and slowed nutrient cycling on Alfisol soils. Moreover, there could be a period of 'diluting' soil patterns during potential initiation of Mollisol development on former Alfisols and Alfisol development under trees establishing in former Mollisol openings. 'Pedodiversity' is an important component of ecological site diversity that in turn can affect numerous other ecosystem elements of diversity such as invertebrates, vascular plants, and wildlife (Phillips and Marion, 2004). Forest management can increase, decrease, or maintain pedodiversity, and post-management density and location of trees can affect pedodiversity (Scharenbroch and Bockheim, 2007; Miesel et al., 2008). In *P. ponderosa* forests, clarifying time required for soil patterns to develop below vegetation patches and potential soil development trajectories that are initiated when spatial locations of tree and opening patches are 'switched' during tree thinning might further help evaluate tradeoffs of different thinning prescriptions.

Solum C content showed no trend to consistently differ among vegetation patches, suggesting that tree and grass patches can equivalently store soil C. Welch and Klemmedson (1975) reported that total ecosystem C (standing crop + roots + litter + mineral soil) was 23 kg m⁻² in patches of *P. ponderosa* trees 50 years old compared to 9 kg m⁻² in grassy patches in northern Arizona. The storage components dramatically differed: tree patches stored only 32% of total ecosystem C in mineral soil whereas grass patches stored 91%. Moreover, high C storage in litter/woody debris and standing crop of *P. ponderosa* systems is not necessarily sustainable. Carbon in woody plant material, and the corresponding fuel load, has escalated in these forests during the past ~130 years of exclusion of frequent surface fire (Fulé et al., 2012). Large wildfires are increasingly converting *P. ponderosa* forests to grasslands and shrublands, with these severely burned areas being net sources of C to the atmosphere for at least 15 years (Dore et al., 2012). Research is increasingly demonstrating that while tree thinning temporarily (<20 years) reduces ecosystem C storage, this tradeoff is dramatically offset compared to C losses from likely inevitable stand-replacing wildfires (e.g., Dore et al., 2012; Stephens et al., 2012a). Stand structure including mixtures of tree and open patches – similar to forest structure under historical frequent-fire regimes – is considered the most sustainable type of *P. ponderosa* forest for sequestering C, in addition to providing balanced habitat values (Dore et al., 2012; Stephens et al., 2012a). Our result of no difference in total solum C storage between tree and grass patches is important in indicating no negative tradeoff in mineral soil C storage with increasing proportions of forests occupied by openings.

Another important consideration is area occupied by the patch types and their corresponding soil types on a site basis. Sánchez Meador et al. (2011) reported that area occupied by trees in pre-settlement forests was only 11–19%, while openings occupied 81–89%, at six sites in northern Arizona *P. ponderosa* forests. This suggests that with regards to reference conditions, most area was occupied by mollic soil historically and still is presently because most post-settlement tree patches harbored Mollisols. While we did not find that average soil C storage differed among patch types, on an area basis total C storage in Mollisols would overwhelm that of Alfisols on a site basis because of area dominance by Mollisols.

Results suggest that the soil development pattern of mostly mollic-like soil with minor components of Alfisol soil associated with tree patches across sites can be added to Moore et al.'s (1999) inventory of reference conditions as an ecological basis for management in southwestern *P. ponderosa* forests.

5. Management recommendations and further research

Turnover in soil taxonomic classes occurred on scales of meters to tens of meters corresponding with distribution of vegetation patch types in northern Arizona *P. ponderosa* forests. Results suggest that Mollisols predominated in grassy openings and openings invaded by post-settlement trees <130 years old, whereas Alfisols dominated patches of pre-settlement-origin trees. These findings illuminate a potential tradeoff regarding spatial locations of 'leave' trees during forest thinning projects: leaving young, large trees in former openings may gain decade's worth of tree growth relative to retaining young, smaller trees in former tree patches, yet result in 'homogenization' of potentially centuries to millennia of soil development. At any given site, the magnitude of this tradeoff likely hinges upon how many young trees (and their sizes) are growing in former openings relative to young trees in pre-settlement tree patches and whether soil developmental patterns are given consideration in the thinning prescription (Abella et al., 2006). Maintaining pedodiversity, such as spatial patterns of soil orders, can be an important goal in forest management for balancing numerous management objectives such as promoting large-tree structure, herbaceous productivity, and C storage (Scharenbroch and Bockheim, 2007).

If maintaining existing soil patterns is a goal in restoration tree thinning and fuel reduction projects, a conservative approach likely is maintaining locations of openings and old tree patches through prescriptions that remove young trees from openings and leave trees near evidence of historical tree locations. Examples of these remnant-based prescriptions are discussed in Covington et al. (1997), Abella et al. (2006), and Roccaforte et al. (2009). When evidence of historical trees is not available (e.g., if stumps were burned by wildfire or removed by harvest operations) or when maximizing use of existing tree structure is a goal (Allen et al., 2002), prescriptions such as Larson et al. (2012) that restore/maintain the structure of tree clumps and openings – but not necessarily in their past locations – might be appropriate. This prescription might initiate new long-term soil development patterns in different locations than in the past. The possible tradeoffs of soil 'homogenization' and reduced herbaceous productivity warrant consideration in this situation, but so does a possible benefit of the prescription of more rapidly achieving clumps of large trees regardless of their location. Given the strength of soil patterns we found on this landscape, including soil development as an evaluated ecological response when experimenting with a range of possible restoration and fuel reduction prescriptions in today's forests is warranted.

Our results further highlight some important topics for future research. It could be informative to explore precisely how long formation of Mollisols and Alfisols require (or switch from one to the other under different vegetation) in western coniferous forests; to better understand potential interactive effects on soil development between soil parent material and vegetation patches; and to more fully examine numerous ecological responses (e.g., nutrient cycling, herbaceous productivity) to 'rotating' locations of soil patches. Moreover, understanding how widespread the soil pattern highlighted by our results is in western North American frequent-fire coniferous forests is important, because thinning and fuel reduction are similarly needed for restoration and fire manage-

ment across the region (Fulé et al., 2012; Stephens et al., 2012b; Churchill et al., 2013). Perennial grasses dominate understory vegetation on our landscape, for example, whereas shrubs or forbs dominate understories of other landscapes which might influence soil development. Linkages of soil genesis with existing, and post-management, within-site vegetation patterns warrant consideration and further investigation in restoration and fuel reduction forest management activities.

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Appendix A.

Representative examples of pedon descriptions for a Mollisol in a grassy opening patch and an Alfisol in a pre-settlement tree patch in a *P. ponderosa* forest in northern Arizona, USA. Profiles were on limestone parent material (U.S. Forest Service ecosystem unit No. 500) on site 4 of our study and correspond to Fig. 1c (Mollisol) and Fig. 1d (Alfisol).

Patch type: grassy opening, Mollisol.

Taxonomic class: fine-loamy, mixed, Typic Argiborolls.

Description: These soils consist of deep, well-drained soils formed in residuum from Kaibab limestone. This representative pedon was described within a *P. ponderosa* forest in a 200-m² treeless opening of mixed native perennial grass dominated by *M. montana* and *B. gracilis*. Colors are for moist soil unless otherwise noted.

A1 – 0–5 cm; dark brown (7.5YR 3/2) sandy loam, dark brown (7.5YR 3/3) dry; weak fine granular structure; friable; common fine tubular pores; common fine roots; neutral.

A2 – 5–18 cm; dark brown (7.5YR 3/2) loam, dark brown (7.5YR 3/3) dry; weak fine and medium granular structure; friable; common fine tubular pores; common fine roots; neutral.

AB – 18–36 cm; dark reddish brown (5YR 3/3) loam, dark reddish brown (5YR 3/4) dry; moderate fine and medium subangular blocky structure; many fine tubular pores; common very fine and medium roots; neutral; contained charcoal.

Bt1 – 36–74 cm; dark reddish brown (5YR 3/4) gravelly clay loam, reddish brown (5YR 4/4) dry; moderate medium subangular blocky structure; common distinct clay films on ped faces and pores; many fine tubular pores; common very fine and medium roots; neutral.

Bt2 – 74–104+ cm; strong brown (7.5YR 4/6) very cobbly sandy clay, strong brown (7.5YR 4/6) dry; strong medium subangular blocky structure; many distinct clay films on ped faces and pores; common fine tubular pores; few fine roots; neutral.

Geographic setting: These soils occupy elevated plains on uplands at elevations from 1975 to 2200 m above the Mogollon Rim on the Coconino National Forest and in close proximity to Flagstaff, Arizona. These soils occur in *P. ponderosa* forests and in ecotones between *P. ponderosa* forests and *Pinus-Juniperus* woodlands. Slope gradients of 0–5% are most common while the full range is from 0% to 15%. These soils formed in residuum from limestone. Mean annual precipitation is 46–56 cm, and mean annual air temperature is 5 °C with a frost-free period of 100–110 days.

Pedon location: Coconino County, Arizona, 4 km southeast of the City of Flagstaff, at an elevation of 2083 m and geographic coordinates of 449,851 m E, 3,893,077 m N (UTM, North American Datum 1983).



Photos of the sampled grassy opening in the foreground. Note the absence of evidence of tree occupancy. Photos by C.W. Denton, August 2013.

Patch type: pre-settlement tree patch, Alfisol.

Taxonomic class: loamy-skeletal, mixed, frigid, very cobbly sandy loam, Lithic Haplustalfs.

Description: These soils consist of shallow, well-drained soils formed in residuum from Kaibab limestone. This representative pedon was described within a *P. ponderosa* forest in a patch containing trees of pre-settlement origin. Colors are for moist soil unless otherwise noted.

Oi – 8–3 cm; slightly decomposed *P. ponderosa* needles.

Oe – 3–0 cm; moderately decomposed *P. ponderosa* needles.

A&B – 0–8 cm; dark reddish brown and reddish brown (5YR 3/3 & 4/4) very cobbly sandy loam, reddish brown and yellowish red (5YR 4/3 & 4/6) dry; weak fine subangular blocky and weak fine granular structure; very friable; common fine tubular pores; few very fine and fine roots; non-effervescent.

Btk – 8–23 cm; dark reddish brown (5YR3/4) extremely cobbly fine sandy loam, yellowish red (5YR 4/6) dry; weak fine subangular blocky structure; friable; common faint clay films on ped faces and pores; few fine tubular pores; few fine and medium roots; disseminated lime threads on ped faces; violently effervescent.

Evidence of pedoturbation from animal activity was common throughout this soil.

Geographic setting: These soils occupy elevated plains on uplands at elevations from 1975 to 2200 m above the Mogollon Rim on the Coconino National Forest and in close proximity to Flagstaff, Arizona. These soils occur in *P. ponderosa* forests and in ecotones between *P. ponderosa* forests and *Pinus-Juniperus* woodlands. Slope gradients of 0 to 5% are most common while the full range is from 0% to 15%. These soils formed in residuum from limestone. Mean annual precipitation is 46–56 cm, and mean annual air temperature is 5 °C with a frost-free period of 100–110 days.

Pedon location: Coconino County, Arizona, 4 km southeast of the City of Flagstaff, at an elevation of 2083 m and geographic coordinates of 449,909 m E, 3,893,067 m N (UTM, North American Datum 1983).



Photos of the sampled pre-settlement tree patch. Note the thick O horizon of needles below the trees and minimal understory plant cover. Photos by C.W. Denton, August 2013.

Appendix B.

Soil classification results by vegetation patch type for 8 sites in a *P. ponderosa* forest landscape in northern Arizona, USA. There were two sets of sites: 4 intensively sampled sites including soil laboratory analysis and 4 sites only of soil classification. Three pedons were described per patch type for intensive sites and one pedon was described per patch type for the classification-only sites.

Site	Patch	Mollisol	Alfisol	Inceptisol
<i>Intensively sampled sites</i>		Number of pedons		
Basalt 1	Open	2	1 ^a	
	Post	3		
	Pre	1	2 ^a	
Basalt 2	Open	3		
	Post	3		
	Pre	1	2 ^a	
Limestone 3	Open	1	2 ^a	
	Post		3 ^a	
	Pre		3 ^a	
Limestone 4	Open	2	1	
	Post	3		
	Pre	1	2	
<i>Classification-only sites</i>				
Basalt 5	Open	1		
	Post	1		
	Pre		1	
Basalt 6	Open	1		
	Post		1	
	Pre		1	
Limestone 7	Open	1		
	Post	1		
	Pre			1
Cinder 8	Open		1 ^a	
	Post		1 ^a	
	Pre		1 ^a	

^a Notes: Alfisols classified as Typic Haplustalfs, frigid (Mollic Eutroboralfs in earlier taxonomy), indicative of partial development of Mollisol characteristics.

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