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Article

The Influence of Parent Material on Vegetation Response 15 years after the Dude Fire, Arizona

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Abstract: This study examined the effects of two types of parent material, sandstone and limestone, on the response of vegetation growth after the 1990 Dude Fire in central Arizona. The operating hypothesis of the study was that, given the right conditions, severe wildfire can trigger vegetation type conversion. Overall, three patterns emerged: (1) oak density increased by 413% from unburned sites to burned sites, with the highest densities occurring on sandstone soils; (2) weeping lovegrass (*Eragrostis curvula* Nees), a very aggressive non-native grass species seeded after the fire, now makes up 81% of the total herbaceous cover in the burned area; and (3) bare ground cover is 150% higher and litter cover is 50% lower in the burned area. Soil analysis was not definitive enough to differentiate impacts between parent materials however it was useful in quantifying the long-term impact of the fire on soils. The results of this study support the idea that catastrophic fire events can trigger vegetation type conversion and that perennial, non-native species used in rehabilitation efforts can persist within the ecosystem for long periods of time. Hence, the recovery period needed for the Dude Fire site to revert back to a pine-oak dominated forest could be on the scale of many decades to centuries.

Keywords: post-fire impacts; soil; trees; ecosystems: wildfire; biodiversity

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1. Introduction

Using historical records, stand reconstruction, and dendrochronology to recreate natural fire regimes, it is believed the average fire return interval within ponderosa pine forests of the southwest was around 2–47 years [1]. In addition to thinning the forests, these typically low severity fire events promoted fire resistant traits within the ponderosa pine species (*Pinus ponderosa* Douglas ex Loudon). These traits include thick bark to protect against heat damage, resinous needles, and flammable litter, which acts to decrease competition from seedlings found in the understory, while leaving the overstory intact [1,2]. Through these processes, fuel levels were kept in check and less severe wildfire events occurred.

However, within the past century, fire suppression has decreased the occurrence of low severity fire across the landscape leading to greater fuel loading and an increase in high severity fire events. It is estimated that in 1876, the last year of a frequent-fire regime, the average forest density in ponderosa pine dominate stands in the southwest U.S. was 60 trees·ha^{-1}. In 1992, the density was approximated at >3000 trees·ha^{-1} [3]. In a study conducted by Savage and Mast in 2005 [4], they re-sampled ponderosa pine plots originally sampled 100 years previously. They found that a 3–5 fold increase in density (stems·ha^{-1}) had occurred across most sites and noted some sites were an order of magnitude denser than the original survey. These findings support the idea that anthropogenic suppression of wildfire ignitions has increased fuel loading and shifted the fire regime to one that now favors low-frequency and high-severity fire events [2,5,6].

In June of 1990, Arizona experienced the most severe and largest wildfire in its recorded history to that date. Ignited by lighting, the Dude Fire burned over 10,500 ha of pine-juniper/oak woodland below the Mogollon Rim in the Tonto National Forest of central Arizona. Severe wildfires tend to consume larger areas of vegetation across the landscape and have far reaching impacts on the soil and watershed conditions [7]. Some negative aspects of wildfire include damage to timber resources, destruction of understory vegetation, depletion of nutrient capital, removal of the litter layer and the creation of hydrophobic soil layers which can increase erosion leading to degradation of hydrologic conditions [7–10]. When these consequences combine with the proliferation of non-native plant species after fire events (as in the case of the Dude Fire), vegetative composition can change drastically in the areas influenced by high severity wildfire [11].

Research on forest fires in the Mogollon Rim area of Arizona has noted shifts in vegetation from ponderosa pine forests to manzanita-oak shrubfields [4,12] in areas where the ranges overlap. Forest dynamic models have suggested that under high severity fire conditions, forest vegetation types can shift beyond a tipping point into chaparral conditions which are more prone to re-burn and create a self-perpetuating condition. It has been proposed that alternative stable states of forest structure and composition exist after crown fires and been hypothesized that wildfire is driving these forests past critical thresholds into new vegetative states [4]. However, the mechanisms for these changes are not well known or understood.

Parent materials are known to be influential on vegetative distribution across landscapes [13], however their influence on the recovery of vegetation after fire has not been well studied. The area impacted by the Dude fire burned across two parent materials, sandstone and limestone, which weather to form distinct soil types (Figure 1). Sandstone derived soils are coarse textured and typically more acidic, being better suited for ponderosa pine. They more readily form hydrophobic soil layers after a fire event which can decrease permeability and lead to greater impact from erosion [9,14,15]. On the other hand, limestone derived soils, weathering under the same conditions, produce finer-textured soils that are more favorable to hardwoods and many grass species. Their finer texture is also thought to make them less vulnerable to heat flux down into the soil profile during a fire event.

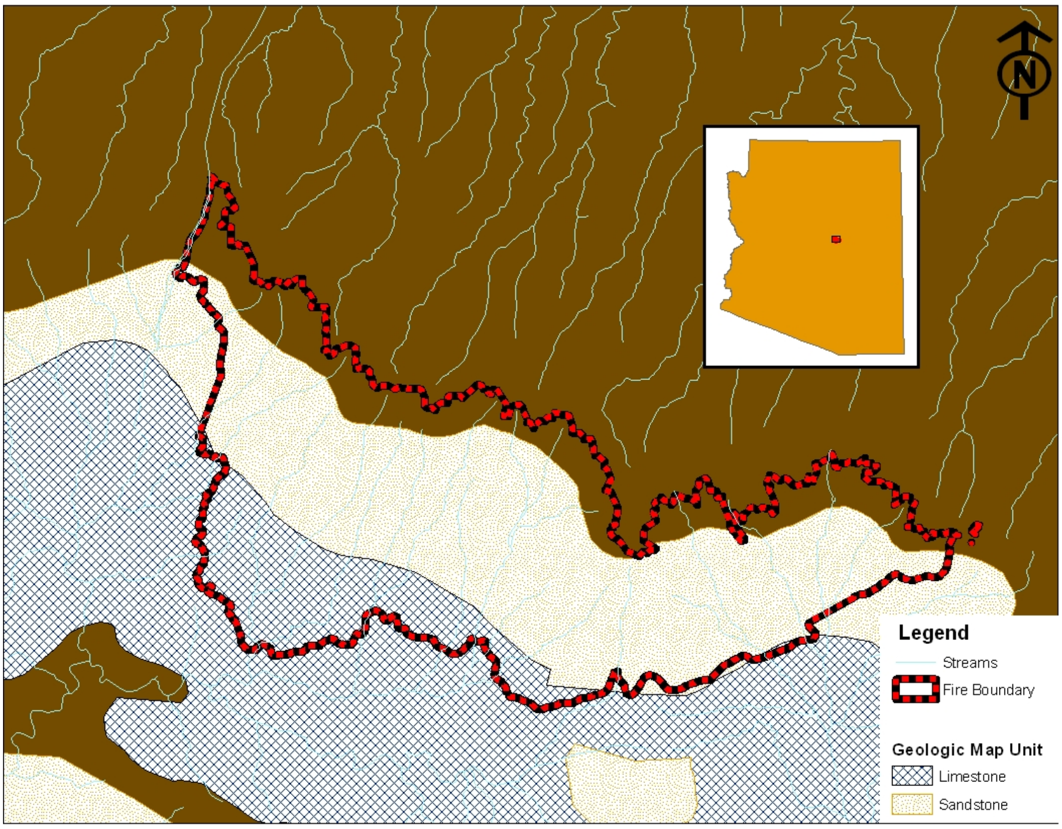

Figure 1. Boundary of the Dude Fire, Tonto National Forest, overlaying the geologic map of the area. The fire burned primarily over limestone and sandstone parent materials.

In addition, after the Dude Fire, weeping lovegrass (*Eragrostis curvula* Nees), a very aggressive non-native grass species, was used in rehabilitation efforts to decrease erosion [16,17]. Recent studies have questioned the need and effectiveness of seeding wildland sites with grass species following fire [1,18–26]. The practice has been found to negatively influence the diversity of native flora, be ineffective in erosion control, and exacerbate erosion due to community type conversion [18,26–28]. However, little information is known about the long-term effects of seeding non-native grass species on natural biodiversity [29].

The Dude Fire offers a unique opportunity to study the effect of parent material and rehabilitation efforts on vegetation response after severe wildfire. Two study hypotheses were selected: 1. Sandstone soils will have a greater recovery of ponderosa pine due to their more acidic pH levels and 2. Fine-textured, limestone derived soils will have greater herbaceous cover resulting in less bare soil compared to sandstone derived soils. The long-range goal of this research is to better understand post-wildfire vegetative successional processes, which can hopefully lead to more effective management actions after wildfire.

2. Materials and Methods

2.1. Study Area

The study site is located in central Arizona immediately below the Mogollon Rim in the Tonto National Forest. Elevations range from 1450 m where pinyon—juniper—oak (*P. edulis* Engelm.—*Juniperus* spp.—*Quercus* spp.) predominates, to 2350 m where ponderosa pine (*P. ponderosa* Douglas ex Loudon) occurs. Precipitation occurs primarily during the summer monsoons and winter rainfall and snowfall events. The average annual precipitation for the area is 635 mm. According to the National Weather Service records dating back to 1940, the temperature in the area ranges from −22 °C to 42 °C with an average temperature of 14 °C [30]. The geology of the study area has a complex lithology of sandstones in the higher elevations and on ridgetops, and Fort Apache limestone in lower elevations [31]. The USDA Forest Service Terrestrial Ecosystem Survey (TES) classified the soils as Udic Haplustalfs, fine, mixed, mesic, deep gravelly loams [32].

2.2. Field Measurements

A total of 62 vegetation plots were established inside and outside of the burned area. Sixteen sites were located on unburned limestone-derived soils (Figure 2), and 16 on unburned sandstone ones. A second set of sites was established within the Dude Fire perimeter—15 sites on burned limestone-derived soils (Figure 3), and 15 sites on burned sandstone ones. Twenty eight of the 62 plots were established in August of 2002 and the remaining 34 plots were established in the summer of 2005.

Figure 2. Unburned transect adjacent to the Dude Fire, Tonto National Forest, 2005.

A 10 × 40 m modified Braun-Blanquet sampling plot was used to measure density, diversity, and frequency of all woody vegetation, as well as percent cover estimates of all ground cover components (*i.e.*, soil, rock, litter, and live plants) [33,34]. Random selection of transect locations was stratified within treatment combination. Individual transect orientation was randomized. In order to maintain site homogeneity among factors such as slope, aspect, and elevation certain areas of the landscape were excluded for potential site establishment.

Figure 3. Transect established in 2005 on the area burned by the Dude Fire of 1990.

Each sampling plot consisted of a 40 m center line over which a microplot was established at each meter mark. Macroplots were established by measuring 5 m from the 40 m centerline and then 8 m parallel to the line. Herbaceous plant cover for each species and ground cover (e.g., bare soil, rock, litter) estimates were recorded at each of the 0.1 m^2 microplots and reported as a percentage of the total area within each microplot. Cover classes were used to estimate ground cover [35]. Plant frequency and species richness were determined from plot data. At each of ten 5 × 8 m macroplots, woody plant density was estimated. The presence and number of each woody species within the macroplot were measured. Plot densities were converted to stems per hectare values for each species. In addition to the vegetation data, GPS location, slope, and bearing data were recorded on all transects.

Soils were extensively sampled ten years after the fire on 14 burned sites (5 limestone sites and 9 sandstone sites) and 12 unburned sites (5 limestone sites and 7 sandstone sites) for the purpose of assessing differences in nutrient status due to geology and wildfire, aid in determining probable linkages between soil and vegetation responses, and characterize the soils between burned and unburned sites. During the 2002 sampling period a soil pit was excavated to bedrock or to 1 m in depth determination of total cation exchange capacity (CEC), nitrate (NO_3^-), calcium (Ca^{+2}), magnesium (Mg^{+2}), potassium (K^+), sodium (Na^+), as well as percent total carbon (TC), and percent total organic carbon (TOC).

Exchangeable cations (Ca^{+2}, Mg^{+2}, K^+, Na^+) and effective CEC of the soils were measured by flame atomic adsorption spectrophotometer (Perkin-Elmer AAnalyst 100, Waltham, MA, USA) using the method described by Hendershot *et al.* (1993) [36]. This method was used because it measures cation exchange at the pH of the sampled soil. Exchangeable cations were extracted using 30 mL of 0.1 M $BaCl_2$ from a 1 g sub-sample of sieved (<2 mm), air-dried soil. Each individual cation was measured by adsorption at appropriate wavelengths. Cation exchange capacities were calculated using the summations of the individual cations.

Soils used for total C and N contents were air-dried prior to analysis. Uniformly mixed dried subsamples were ground, sieved (100 mesh, 0.149 mm), then analyzed for total C and N contents on a commercially available elemental analyzer (Flash EA 1112, CE Elantech, Lakewood, NJ, USA). Total organic carbon of the mineral soil utilized air-dried soils that had been pre-treated with a 10% solution of HCl. Following reaction with soil and dilute acid, soils were further diluted with deionized water then dried at 40 °C, with this step being repeated until no reaction occurred with addition of HCl. Uniformly mixed dried subsamples were then ground, sieved (100 mesh, 0.149 mm), and analyzed for total C and N contents on a commercially available elemental analyzer (Flash EA 1112, CE Elantech, Lakewood, NJ, USA).

Soil pH was determined using a glass electrode immersed in a 1:5 soil-to-0.01 M $CaCl_2$ solution [36] coupled to a Orion 550A pH meter (Thermo Fisher Scientific, Inc., Waltham, MA, USA). Available NO_3^- was determined colorimetrically from the KCl extracts using a Flow Injection Analyzer [37,38]. Analytical values were corrected for soil moisture content and reported on a dry weight basis.

2.3. Data Analysis

The study design consisted of two factors: parent material and burn condition. A two factor generalized linear fixed-effects model was used to assess main effects and interactions within univariate responses. Responses consisted of stem counts and percent cover. Count responses were modeled using a negative binomial distribution and percentage responses were modeled using a beta distribution analysis of variance (ANOVA) in order to assess interaction between the factors (see Tables 1 and 2). The multivariate responses of percent cover and stem density for each species and cover type respectively were each modeled on parent material and burn condition using a multi-response permutation procedure [39] (see Table 3). MRPP is a nonparametric procedure which tests the hypothesis that there is no difference between two or more groups or entities. It was used because none of the univariate responses were normally distributed. Statistics were run using the SAS/STAT PROC GLIMMIX (SAS Institute Inc., Cary, NC, USA) [40] and Excel (Microsoft Corp., Redmond, WA, USA). The dependent variables used in the study were shrub and tree densities and diversity. The independent variables used were parent materials (sandstone and limestone) and burn condition (burned and unburned).

Table 1. Two factor analysis of variance for total number of trees and shrubs. Bold numbers indicate significance at $\alpha = 0.10$.

Statistics	**Vegetation**	
Factor	Shrubs	Trees
Geology	0.74	0.16
Burn condition	**0.04**	**0.004**
Geology X Treatment	0.25	0.69

Soils were described with respect to their physical and chemical attributes to examine differences and similarities between geology and burn treatments. Wilcoxon rank sum tests (Wilcoxon-Mann-Whitney or MWW test) were performed on soil data of the upper soil layer (0–25 cm) to determine differences due to treatment and geology for the respective parameters [41]. These non-parametric tests [42] were most appropriate since the soil data were not normally distributed. They test the null hypothesis that the two populations, in this case treatment or geology, are the same *versus* an alternative hypothesis. The U statistic was calculated as:

$$U1 = R1 - n1(n1 + 1)/2$$

where R1 = the sum of the ranks in sample 1

$n1$ = the sample size for sample 1

U1 = test statistic

Table 2. *p*-values for two-way analysis of variance tests comparing the effects of fire on woody plant density. Bold numbers indicate significance at α = 0.10.

Statistic	**Analysis of Variance by Species**							
Factor	*Ponderosa pine*	*Oak spp.*	*Juniper spp.*	*Manzanita*	*Mountain mahogany*	*Skunkbush sumac*	*Catclaw*	*Fendler's Ceanothus*
Geology	***0.0047***	*0.6667*	***0.0686***	*0.8526*	***0.0178***	*0.9668*	*0.8728*	*0.8410*
Burn condition	***<0.0001***	***<0.0001***	***<0.0001***	*0.1355*	***0.0074***	***0.0639***	*0.2965*	*0.**0373***
Treatment X Geology	***0.001***	*0.8057*	*0.5768*	*0.3916*	***0.0138***	*0.8184*	*0.9030*	*0.4917*

Exact *p*-statistic values were calculated for respective parameters given the small sample sizes [41].

Table 3. Mean number of stems/plot (median number of stems/plot) for woody species across sandstone and limestone parent materials and burned and unburned conditions. Within a column, strata with the same letter are not significantly different according to the Peritz closure multiple comparison procedure, α = 0.10 [43].

Geologic Substrate	**Species**							
	Ponderosa pine	**Oak spp.**	**Juniper spp.**	**Manzanita spp.**	**Mountain mahogany**	**Skunkbush sumac**	**Catclaw**	**Fendler's Ceanothus**
Burned limestone	13.5b (5)	39.4b (62)	5.7c (0)	35.9bc (55)	0.3c (0)	0.6c (0)	7.3c (2)	36.5c (4)
Burned sandstone	2.3c (0)	37.8b (80)	3.7c (2)	49.4b (83)	7.4bc (0)	0.6c (0)	7.1c (0)	57.5c (26)
Unburned limestone	18.5a (20)	11.4c (19)	22.4b (7)	31.4c (15.5)	9.7bc (1)	2.0c (1)	3.7c (0)	18.7c (2)
Unburned sandstone	17.1a (16)	9.7c (17)	10.3b (10)	25.6c (21)	9.1b (10)	1.7c (0)	3.0c (0)	14.5c (0)

3. Results

3.1. Vegetation

3.1.1. Tree and Shrub Species

The following results are from comparisons of key woody species found in the area of the Dude Fire. These species include catclaw acacia (*Acacia greggii* A.Gray), Fendler's ceanothus (*Ceanothus fendleri* A.Gray), alligator and rocky mountain juniper (*Juniperus* spp.), Pringle's and pointleaf manzanita (*Arctostaphylos* spp.), mountain mahogany (*Cercocarpus montanus* Raf.), ponderosa pine (*P. ponderosa* Douglas ex Loudon), Arizona white oak (*Q. arizonica* Sarg.), emory oak (*Q. emoryi* Torr.), and skunkbush sumac (*Rhus trilobata* Nutt.). These populations were distributed across both sandstone and limestone parent materials as well as burned and unburned areas to make statistical comparisons among these treatments possible. Species richness was greater on unburned limestone and unburned sandstone sites with 30 and 27 woody species, respectively, compared to burned sites of limestone and sandstone, which had 20 and 16 woody species, respectively. All woody species in the study sites were native species.

There were significant differences in density of ponderosa pine, oak spp., juniper spp., mountain mahogany, skunkbush sumac, and Fendler's ceanothus between the burned and unburned sites (see Table 2). From the multi-response permutation procedure (MRPP), we found that ponderosa pine and juniper had higher densities on unburned sites, while the oak and manzanita had higher densities in the burned area. Additionally, ponderosa pine and juniper spp. densities were higher on limestone sites compared to sandstone sites, while mountain mahogany density was higher on sandstone sites compared to limestone sites (see Tables 3 and 4).

Table 4. Mean stem densities and (median stem densities) reported as stems per hectare for woody species. Median stem densities are included to give an indication of skew in the data distribution in order to provide a more complete summary of the data.

Geologic Substrate	Geologic Substrate							
	Ponderosa pine	Oak spp.	Juniper spp.	Manzanita spp.	Mountain mahogany	Skunkbush sumac	Catclaw	Fendler's Ceanothus
Burned limestone	337 (125)	1972 (1550)	142 (0)	1795 (1375)	8 (0)	13 (0)	182 (50)	912 (100)
Burned sandstone	58 (0)	1888 (2000)	93 (50)	2468 (2075)	185 (0)	15 (0)	177 (0)	1438 (650)
Unburned limestone	463 (500)	534 (462)	559 (225)	1473 (388)	243 (25)	50 (25)	92 (0)	467 (50)
Unburned sandstone	427 (400)	456 (413)	258 (250)	1200 (525)	228 (250)	42 (0)	75 (0)	363 (0)

Unburned areas were mainly populated by ponderosa pine, juniper, manzanita, some Fendler's ceanothus, and mountain mahogany (see Tables 3 and 4). In the burned areas, manzanita, oak, and Fendler's ceanothus were dominant with some presence of other woody species such as ponderosa pine and juniper (see Tables 3 and 4). It is not surprising that significant differences exist between the burned and unburned areas. The burned area lost most, if not all, of the vegetation that existed prior to the fire. Resilient species (e.g., oak, Fendler's ceanothus and manzanita) that recolonize burned areas quickest became dominant over the landscape.

3.1.2. Herbaceous Species and Ground Cover

Unburned areas had higher total numbers of grass and forb species, with 26 species of grass and 52 species of forbs. Comparatively, burned sites contained 14 species of grass and 22 species of forbs. While forb cover was greater in the unburned sites, there were no significant differences for forb or native species cover between geologic strata (see Table 5). Introduced grasses, bare soil, and gravel/rock/soil were all significantly greater on sandstone sites compared to limestone sites in the burned area (see Table 6). Litter and gravel cover were significantly greater on the limestone sites compared to the sandstone sites in the burned area. Conversely, litter cover was significantly greater in the unburned area compared to the burned area (see Table 6).

Table 5. Two factor analysis of variance comparison using parent material and burned/unburned treatment. The bold values are significant at α = 0.10.

Statistic Factor	Introduced Grass	Forbs	Native Grass	Litter	Gravel	Bare Soil	Rock	Gravel/Rock/Bare Soil
Parent material	**0.041**	0.168	0.948	**0.001**	**0.089**	**<0.001**	**<0.001**	**0.001**
Burn condition	**0.002**	**0.013**	0.112	**<0.001**	**<0.001**	**<0.001**	**0.022**	**<0.001**
Geology X Treatment	0.5542	0.559	0.803	0.943	0.192	0.522	0.436	0.558

Table 6. Mean percent cover/plot (median percent cover/plot) for important cover categories across sandstone and limestone parent materials and burned and unburned conditions. Within a column, strata with the same letter are not significantly different according to the Peritz closure multiple comparison procedure, α = 0.10 [43].

Substrate	Vegetation and Geologic Cover Conditions—Percent							
	Introduced Grass	Native Grass	Forbs	Litter	Gravel	Bare Soil	Rock	Gravel/Rock /Soil
Burned Limestone	3.9b (1.4)	2.7c (0)	0.2bc (0.2)	59.6b (58.5)	16.2a (12.2)	12.7b (10.2)	2.8c (2.8)	10.6b (35.5)
Burned Sandstone	5.2a (5.5)	3.7c (0)	0.0c (0.1)	44.9c (43.9)	4.7b (3.9)	28.2a (31.5)	10.9b (9.4)	14.6a (43.5)
Unburned Limestone	0.3c (0.1)	3.5c (0.1)	0.2a (0.4)	84.0a (94.5)	4.8c (0.8)	5.2c (0.9)	1.6c (1.3)	3.9c (3.8)
Unburned Sandstone	1.6c (0)	3.1c (0.1)	0.2ab (0.6)	77.4a (80.3)	2.2c (1.2)	8.1c (6.2)	8.1b (6.4)	6.1c (14.5)

3.2. Soils

Because of the unpredictable nature of wildfires, it was impossible to obtain a pre-fire and post-fire sampling of the same soil profiles. The approach of comparing burned *versus* unburned areas was used to assess fire effects on these soils. It is possible that some of the measured effects are due to inherent differences between sampling sites.

Soil chemistry parameters in the A horizons are uniformly lower or not changed (Na^{+1} only) in the burned site A horizon samples (Table 7). B horizon samples indicate a mixture of decreases, increases, and no change. The lack of sampling pre- and post-fire as well as the long time frame (10 years) make the assignment of cause and effect less certain.

Comparing burned *versus* unburned sites across both geology types, there were significantly lower values ($p < 0.05$, U Test) for all soil chemical parameters in the upper 25 cm of soil within the burned area (Table 7). The largest and most significant soil decreases were exhibited by Ca^{+2} and Total CEC, which dropped 20.32 and 21.25 cmol·kg^{-1}, respectively from their unburned state. The values of TOC declined less (2.60% to 0.83%), but the change was highly significant ($p < 0.0001$, U Test). Changes in the Mg^{+2}, K^{+1}, and Na^{+1} mineral soil nutrient pools were much smaller but represented 25% to 47% of the upper soil (0 to 25 cm) nutrient pools.

Table 7. Wilcoxon rank sum test results with medians in cmol·kg^{-1} for Ca^{+2}, Mg^{+2}, K^{+1}, Na^{+1}, and Total CEC; medians in percent for Total Carbon and Total Organic Carbon; and medians in mg·kg^{-1} for NO_3 for differences between burn treatments of the A horizon (0–25 cm). Sample sizes for burned ($n1$) = 14 and unburned ($n2$) = 12. Values in bold exhibited significant differences in populations distributions across geologic substrate.

Category	Chemical Parameter								
	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	Total CEC	Total Carbon	TOC	NO_3	pH
Burned	3.91	0.87	0.1	0.06	5.25	1.18	0.83	0.24	5.84
Unburned	24.23	1.65	0.38	0.08	26.5	3.47	2.6	1.06	6.5
U Statistic	225	214	217	211	224	232	238	103	207
p-value	**0.0006**	**0.0064**	**0.0037**	**0.01**	**0.0008**	**0.0001**	**<0.0001**	**0.079**	**0.02**

Contrasting the source geology of the Dude Fire soils, unburned limestone derived soils had a higher chemical status for all parameters except for Na^{+1} (Table 8). The median concentration of Na^{+1} in unburned sandstone soils was higher than the median for limestone. However, the median concentration of Na^{+1} in unburned sandstone soils (0.78 cmol·kg^{-1}) was not statistically significantly different from that of limestone soils (0.08 cmol·kg^{-1}, $p > 0.05$, U test). Within unburned limestone soils only Ca^{+2}, Total CEC, and TOC were significantly higher ($p < 0.05$, U test). The levels of Ca^{+2} and Total CEC were 25.33 and 24.52 cmol·kg^{-1} higher, respectively, for Ca^{+2} and Total CEC. As expected, unburned limestone soils were slightly basic and unburned sandstone soils were slightly acidic (Table 8). Except for NO_3 in sandstone, burning reduced the status of most chemical parameters. Limestone NO_3 concentrations followed the same pattern as the other chemical patterns. None of the changes were statistically significant. The largest declines were measured for Ca^{+2} and Total CEC in limestone soils.

Table 8. Wilcoxon rank sum test results with medians in cmol·kg^{-1} for Ca^{+2}, Mg^{+2}, K^{+1}, Na^{+1}, and Total CEC; medians in percent for Total Carbon and Total Organic Carbon; and medians in mg·kg^{-1} for NO_3; and sample sizes (n) for respective parameters for differences between treatment and geology of the top soil layer (0–25 cm). Values in bold exhibited significant differences in population distributions across geology.

Category	Chemical Parameter								
	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	Total CEC	Total Carbon (%)	TOC (%)	NO_3 (mg·kg^{-1})	pH
Burned limestone	8.0 (5)	1.2 (5)	0.1 (5)	0.1 (5)	9.3 (5)	1.2 (5)	1.1 (5)	0.2 (5)	6.0 (5)
Burned sandstone	3.0 (9)	0.6 (9)	0.1 (9)	0.1 (9)	3.6 (9)	1.13(9)	0.7 (9)	0.3 (6)	5.7 (6)
Unburned limestone	**35.2** (5)	1.7 (5)	0.4 (5)	0.1 (5)	**37.4** (5)	**5.4** (5)	4.8 (5)	1.2 (5)	**7.2 (5)**
Unburned sandstone	**9.8** (7)	1.4 (7)	0.2 (7)	0.8 (7)	**12.9** (7)	**2.6** (7)	1.9 (7)	0.3 (7)	**6.3 (7)**

Soil horizon depths exhibited high variability within geology and across all soils depending on landscape position (see Tables 9 and 10 and Figure 4). The depth ranges are across the profiles for each individual geology and burn condition, and are meant to give an indication of profile variability. Deeper soils were found on toe-slope positions in drainage bottoms where alluvium accumulated. Ridgetops and sideslopes were thinner due to water erosion and dry ravel. The thickest surface horizons were found on burned sandstone soils (25 cm). The soil profiles were not stratified by slope position (ridge, side, and toe), only by substrate geology (limestone and sandstone) and burn condition (not burned and burned).

Table 9. Physical and chemical characterization of unburned limestone (n = 5 sites) and sandstone (n = 7 sites) soils on the Dude Wildfire study area 10 years postfire. Depths ranges are in centimeters for the sample size n, with soil chemistry parameter means by horizon. Values for Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}, and total cation exchange capacity (CEC) are in cmol·kg^{-1} with standard error of the mean (se); and values are in percent for Total Carbon and Total Organic Carbon with standard error of the mean (se). pH is dimensionless.

Geologic Substrate	Chemical Parameter										
	Soil Horizon	Sample n	Depth Range cm	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	CEC	pH	Total C	TOC
Unburned limestone	A	5	0–16	38.5 (7.9)	1.7 (0.2)	0.4 (0.04)	0.1 (0.02)	40.8 (8.1)	6.9 (0.2)	6.3 (1.5)	4.7 (1.2)
	B1	5	6–40	24.4 (3.5)	1.0 (0.1)	0.2 (0.03)	0.1 (0.02)	25.7 (3.4)	6.9 (0.1)	3.9 (0.8)	1.5 (0.4)
	B21t	5	13–63	19.9 (0.9)	1.3 (0.5)	0.1 (0.03)	0.1 (0.03)	21.4 (1.2)	6.9 (0.1)	3.6 (1.3)	0.7 (0.1)
	B22t	5	19–100	17.7 (0.8)	1.4 (0.4)	0.2 (0.05)	0.1 (0.03)	19.4 (1.3)	7.0 (0.2)	3.9 (1.4)	0.5 (0.1)
Unburned sandstone	A	7	0–19	14.3 (4.1)	1.4 (0.3)	0.4 (0.1)	0.1 (0.01)	16.3 (4.3)	6.0 (0.3)	3.2 (0.8)	2.6 (0.6)
	B1	7	3–70	10.3 (3.8)	1.6 (0.6)	0.2 (0.1)	0.1 (0.03)	12.2 (4.4)	5.4 (0.3)	0.9 (0.2)	0.7 (0.1)
	B21t	7	10–83	10.5 (4.2)	1.9 (0.6)	0.2 (0.1)	0.1 (0.03)	12.7 (4.5)	5.2 (0.4)	0.5 (0.1)	0.3 (0.1)
	B22t	7	33–100	12.2 (4.7)	2.0 (0.5)	0.2 (0.1)	0.2 (0.04)	14.5 (5.0)	5.5 (0.5)	0.5 (0.1)	0.3 (0.04)

In general, the concentrations of most chemical parameters in unburned soils decreased with depth as was expected (Tables 9 and 10). Burning caused some reversals of that trend (Table 10). For instance, Ca^{+2} in unburned limestone soils (Table 9) decreased from 38.5 cmol·kg^{-1} in the A horizon of the unburned condition to 17.7 cmol·kg^{-1} in the B22t horizon. The opposite occurred after burning where the Ca^{+2} concentrations increased from 7.8 to 11.6 cmol·kg^{-1} with increasing depth. The Ca^{+2} concentrations in the B22t and B21t of the limestone soils were similar 17.7 (unburned) *vs*. 11.6 (burned) cmol·kg^{-1}, but were quite different in the A horizon. This would suggest that some erosion has occurred. Ash washoff was definitely observed by Forest Service personnel (Rinne, J.N.; Personal Communication). However, the degree of erosion immediately post-fire was never investigated so it is not known with absolute certainty that this process was instrumental in the apparent decline.

Table 10. Physical and chemical characterization of burned limestone (n = 5 sites) and sandstone (n = 9 sites) soils on the Dude Wildfire study area 10 years postfire. Depths are ranges in centimeters for the sample size n, with soil chemistry parameter means by horizon. Values for Ca^{+2}, Mg^{+2}, K^+, Na^+, and total cation exchange capacity (CEC) are in cmol·kg^{-1} with standard error of the mean (se); and values are in percent for Total Carbon and Total Organic Carbon with standard error of the mean (se). pH is dimensionless.

Geologic Substrate	Soil Horizon	Sample n	Depth Range cm	Chemical Parameter							
				Ca^{+2}	Mg^{+2}	K^+	Na^+	CEC	pH	Total C	TOC
Burned limestone	A	5	0–14	7.8 (2.9)	1.0 (0.2)	0.1 (0.04)	0.1 (0.002)	9.1 (2.8)	6.0 (0.1)	1.2 (0.1)	1.0 (0.1)
	B1	5	5–36	3.5 (0.9)	1.6 (0.4)	0.1 0.01)	0.1 (0.02)	5.3 (0.7)	5.4 (0.2)	0.7 (0.05)	0.5 (0.1)
	B21t	5	18–90	11.6 (3.9)	4.8 (1.7)	0.2 (0.03)	0.2 (0.03)	16.8 (5.6)	5.4 (0.2)	0.7 (0.05)	0.4 (0.05)
Burned sandstone	A	9	0–25	4.6 (1.3)	0.8 (0.2)	0.2 (0.1)	0.1 (0.01)	5.7 (1.4)	5.7 (0.1)	1.3 (0.3)	1.0 (0.2)
	B1	9	2–45	2.8 (1.7)	0.6 (0.1)	0.1 0.04)	0.1 (0.004)	3.5 (1.8)	5.3 (0.2)	0.7 (0.2)	0.5 (0.2)
	B21t	9	12–93	6.0 (2.5)	2.8 (1.1)	0.2 (0.1)	0.2 (0.04)	9.1 (3.3)	4.8 (0.2)	0.5 (0.1)	0.3 (0.1)

The values of K^+ and Na^+ were mostly uniform down the profiles under both burn conditions and parent material type. The value for CEC decreased with depth in unburned limestone areas (Table 9; 40.8 to 19.4 cmol·kg^{-1}) but increased with depth after the wildfire (Table 10; 9.1 to 19.2 cmol·kg^{-1}). The Dude Fire also reduced C pools substantially (Tables 9 and 10). Total C in limestone soils dropped to 19% of pre-fire levels. In sandstone soils, the decline produced Total C of only 40% of the pre-fire condition.

4. Discussion

4.1. Fire Effects

The results of this study support the premise that catastrophic fire events can trigger vegetation type conversion. Plant physiology, fire severity, precipitation and soil type all influence how plant species respond to fire. The unburned area is dominated by woody species, namely ponderosa pine. It also has high amounts of litter cover, allowing for little grass or forb cover. It is not uncommon for forb and graminoid cover to be suppressed in dense ponderosa pine stands where soil and light resources are scarce [44–46]. The burned area has transitioned to a plant community structure almost entirely made up of a manzanita/oak overstory with a weeping lovegrass dominated understory. Oak density has increased by 413% from unburned sites to burned sites. Similarly, Fendler's ceanothus has increased drastically, especially on burned sandstone sites where a 396% increase in density was measured.

It is worth noting that ceanothus is an important browse component of wildlife habitats in the region and may help speed soil recovery because of its ability to fix nitrogen (N). In some unique places, native grasses such as blue grama (*Bouteloau gracilis* Vasey *)* can be found in small patches, but most native grasses and forbs are transient or absent. There are large areas of bare ground between shrubs with little organic material present. These results are similar to those found in Crawford *et al.* (2001) [45], where areas subjected to severe wildfire remain visibly altered decades after the fire event.

Figure 4. Soil horizon depths exhibited high variability both within and across parent material types.

4.2. Woody Plants

After the fire, the goal of the Tonto National Forest [46] was to reforest 1012 ha of land from 1991 to 1993, using approximately 1.7×10^6 ponderosa pine container seedlings. In 2005 after 15 years of recovery, 17 of the 30 study sites established in the burned area were found to have no evidence of ponderosa pine recruitment (see Figure 5). These results are similar to studies conducted after the Rodeo-Chediski fire where approximately 40% of the plots studied showed no evidence of ponderosa pine survival or regeneration 3 years after the fire [12]. Consequently, some areas within the Dude Fire may not recover to a pine-dominated forest within the foreseeable future. In reality, this constituted a fire-driven type vegetation conversion.

Several factors may have prevented or at least slowed the pace of recovery to a ponderosa pine dominated habitat. First, the site conditions of the burned area have changed, due in part to the removal of the pine canopy and the subsequent dominance of grasses and chaparral species (see Figures 2 and 3).

With dense, shallow root systems, weeping lovegrass has been shown to negatively affect germination and establishment of woody-plant seedlings due to a competitive advantage in sequestering soil moisture and nutrient resources within the upper layers of the soil profile [23,47,48].

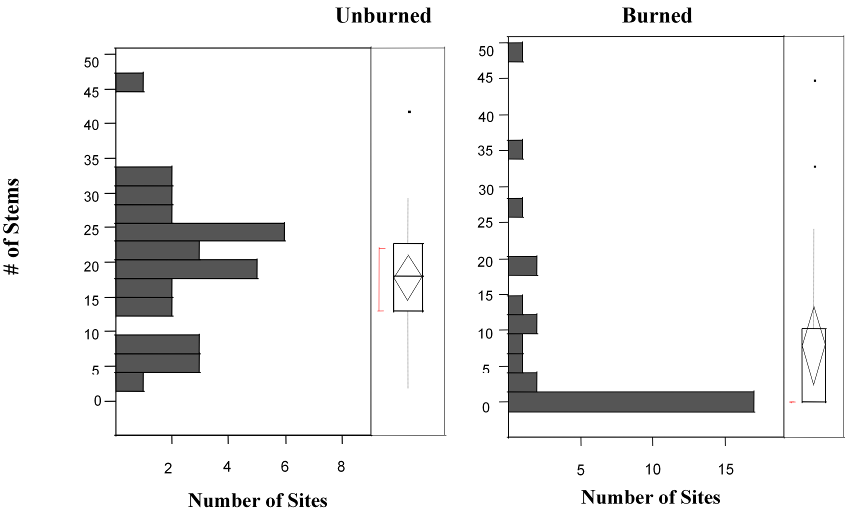

Figure 5. Ponderosa pine frequency (stems/plot) in burned and unburned sites. In the unburned area, ponderosa pine was present at all sites. In the burned area, ponderosa pine was absent in 17 of 30 sites.

Similarly, deep-rooted chaparral species are highly effective at obtaining water and sequestering plant nutrients in the lower layers of the soil profile, which makes them adaptable to burned and eroded areas [49]. This dynamic, combined with the ongoing drought, likely makes water a limiting factor for pine seedlings [1]. Second, much of the O and A horizons in the burned area were lost, either during the fire or by the erosion that followed, removing much of the seed bank as well as significant nutrient capital. The loss of legacy seed sources along with the reduction of new seed sources, particularly within the interior of a burned area has been shown to slow the process further [50]. Lastly, the grazing influence by elk (cattle were excluded until 2010), which are known to forage on pine readily and can account for plantation losses [51], may also be adversely affecting ponderosa pine regeneration. We regularly observed young ponderosa pine trees (1–20 years) grazed to within reach 2 m of ground level within the burned area. While most of the trees appear to survive, their growth rates and form have become substantially affected due to grazing pressure (see Figures 6 and 7).

The conversion of forested ecosystems to grassland or shrubland ecosystems after high severity wildfire is growing increasingly common, particularly in the Southwestern United States, due in part to a warming trend which has be occurring in the region for the last 25 years [52–54]. Williams *et al.* (2010) [54] estimate that forested areas in the Southwest could be reduced or converted by >50% over the coming decades if drought recurrences and wildfire frequency persist. According to McDowell *et al.* (2010) [55], ponderosa pine mortality and vegetation type conversion tend to occur most frequently at the lower elevations of the distribution range. Given these trends, the vegetation recovery trajectory described for the Dude fire could be similar to future trends of recovery underway in more recent high severity wildfire events, e.g., Cerro Grande (2000), Rodeo-Chediski (2002), Wallow (2011) Las Conchas (2011).

Figure 6. Typical terminal bud grazing damage on ponderosa pine seedlings caused by elk after the Dude Fire.

Figure 7. In the foreground is a grazed ponderosa pine sapling. In the background ponderosa pine saplings have begun rapid vertical growth after escaping the reach of browsing elk.

The shift from a dense ponderosa pine structure to a dense shrub-woodland structure presents problems. First the pyrophytic nature of the chaparral ecosystems are subject to a high-severity burn feedback loop, that once established can continually reset the succession process and cost resources to control. This is especially evident near the edge of the fire where ponderosa pine recovery is progressing more quickly. In these areas a potentially combustible composition of vertical fuel continuity is developing involving the lovegrass/chaparral understory and the emerging pine overstory. Second, the ability of chaparral species to control available water and soil resources results in reduction of ponderosa pine recruitment and low native herbaceous production [56]. Third, mature chaparral has been argued to have relatively low value for livestock and wildlife, affecting recreation and economic opportunities in the area [26]. Lastly, the loss of forested habitats could have negative consequences on carbon sequestration from the atmosphere [56–58].

4.3. Herbaceous Plants

In the first year after a severe wildfire, the success of erosion control methods including seeding, barriers, and mulching are dependent upon factors such as burn severity, rainfall events (intensity, duration, amount), topography, soils, and natural recovery rate [6,18,28]. In the southwestern United States, where high severity wildfire events are often followed by intense rainfall events, erosion control methods are usually overwhelmed. Robichaud *et al.* (2000) [18] suggest that because the success rate is low, rehabilitation should only be performed if the risk to life and property is high.

We expected to see a significant increase in native grass species in the burned area after the fire. However, 15 years later, the results of this study do not show an increase in native grass species cover from unburned to burned areas (see Tables 5 and 6). We also expected that bare soil would be in greater abundance on sandstone sites, and that litter cover would be greater on limestone sites because limestone derived soils are generally more productive. The results support both hypotheses where fire occurred.

In many cases, exotic species are long-lasting plants that can set up feedbacks that perpetuate their own persistence [59,60]. In this instance, weeping lovegrass has filled the understory space between the manzanita and oak in the burned areas. The shrub-field species combined with the weeping lovegrass appear to exhaust the limited resources available and increase the chance of a future shrubland crown fire occurring. Thus, it is a possibility that current stands of shrubs and weeping lovegrass could be long-lived and self-perpetuating due to recurring wildfire.

Nearly $2 million was spent on seeding and reforestation efforts between 1991 and 1995 to control erosion and aid vegetative recovery (Dude Fire Long Range Rehabilitation Implementation and Monitoring Plan 1991 [46]). In the Fall of 1993, as the burned area began to stabilize after the fire, total graminoid cover on intensely burned upland sites was estimated by the Forest Service using photo point surveys to be about 26% of total ground cover, with forb species cover making up an estimated 4% of total ground cover. In addition, weeping lovegrass which was seeded primarily on the uplands, was estimated to be about 14% of total ground cover or make up 54% of total graminoid cover. The effectiveness of the herbaceous canopy cover to prevent erosion or excessive runoff varied in classification across the burned area from sufficient to insufficient [17].

In 2005, measurements indicated that all herbaceous cover amounts in the burned area had decreased greatly from the 1993 estimates. Weeping lovegrass cover was 4.5% of total ground cover across the burned area, making up 60% of the total herbaceous cover. Native grass species in the burned area made up a little over 3% of total ground cover, and forb cover was about 0.3% of total ground cover.

In comparison, within the unburned area native grass species make up a little over 3% and forb species make up about 0.65% of total ground cover. Consequently, increases that were seen initially after the fire in native grass and forb species seem to have fallen off in the last decade to levels more in line with the unburned area. Most of this reduction is most likely due to the growth of oak and manzanita in the burned area, the ongoing drought conditions, and the persistence of weeping lovegrass in the ecosystem.

Greater amounts of weeping lovegrass cover was measured in burned sandstone sites (5.1%) compared to burned limestone sites (3.9%). This difference is probably due to the degree to which the sandstone sites were impacted by the fire and the hardy nature of weeping lovegrass, which allowed it to persist in some of the most heavily impacted sandstone sites. These findings support other studies which have found that the weeping lovegrass can thrive under harsh conditions [16,20,49]. This would also suggest that limestone sites may not have been as greatly impacted by the heat flux associated with the fire and postfire conditions as the more porous sandstone sites. Unburned limestone sites had a greater amount of litter cover and a lower amount of bare soil than unburned sandstone sites. These differences would have modified heat flux into the limestone soils during the fire by insulating the limestone mineral soil to a greater degree [7]. In addition, the light colored sandstone soils would have re-radiated more heat after the fire because of reflectance off of the lighter colored surface. The darker colored limestone soils would have retained more heat, reducing the flux to re-establishing native herbaceous species. Because of these two processes, the time required for native herbaceous species to recover on limestone derived soils may be lessened relative to sandstone sites.

Erosion continues to impede the recovery of many of the upland sites in this study. In many areas, bunches of weeping lovegrass have created a channeling effect which has concentrated water flow during runoff events, evident by the "pedestal" appearance of many of the grass bunches and rills formed in between bunches (see Figure 8). This suggests that the weeping lovegrass is having little effect on preventing erosion and may be enhancing it. Due to these kinds of physical and biological conditions in the burned areas, the re-establishment of an organic soil layer has been significantly slowed, further delaying the recovery of herbaceous species.

Figure 8. Weeping lovegrass bunch with a "pedestal" appearance in a burned area of the Dude Fire.

4.4. Soils

The decline in chemical parameters followed a pattern exhibited by some wildfires where deep heating and combustion followed by erosion, and leaching deplete soil reserves of anions, cations, and organic matter [6]. Immediately after a fire there is usually an increase in cations due to the deposition of ash and a decrease in total and total organic carbon due to combustion. Post-fire runoff can flush off much of the ash and initiate significant erosion of the A and upper B horizons [7,15]. Since the soil sampling took place 10 years after the Dude Fire, it is not possible to state with certainty the chemical conditions immediately after the wildfire or the degree of erosion. The high severity of much of the Dude Fire area added to the thermal decomposition of organic matter in the Udic Haplustalf soils.

Overall, total bare ground cover (soil, gravel, rock) was 38% on the burned sites in contrast to 15% in the unburned sites. Litter cover on the burned sites was 52% compared to 81% on the unburned sites. The large amount of bare ground cover in the burned sites combined with the sloping topography has made retention of organic soil and litter materials difficult. Thus, there are still sizeable areas of bare, mostly sandy-textured substrates within the burned area. Erosion in the years since the wildfire has removed litter and parts of the A horizon. Other wildfires in Arizona have had the A horizon and parts of the B horizon completely stripped off by post-fire runoff [61].

The Dude Fire may have had some significant impacts on soil chemistry. While there were declines in all chemical parameters, Ca^{+2}, Total CEC, and TOC were impacted the most. Although wildfires increase the cation content of soils immediately after burning, erosion of mineral soil material and ash could have had a big impact on long-term nutrient status [6]. The apparent post-fire declines in chemical status of these Udic Haplustalf soils were most likely the result of combustion of organic matter and erosion processes over the 10 years after the fire. Recovery of C resources in the Dude Fire soils will occur over time depending on vegetation recovery. Losses of other nutrients are more problematic. The burned landscape will need time measured in centuries to recover these parameters back to pre-fire levels [6,8,61].

4.5. Soil-Vegetation Relationships

Principal differences between soils were observed between burn and unburned sites for most parameters. When stratified on geology (limestone *versus* sandstone) differences were much more subtle but significant (Tables 5 and 6). There are also some clear differences in nutrient content (Table 8) that reflect the generally higher nutrient status and productivity of limestone sites. This suggests that stratification is needed to obtain a clearer understanding of post-fire effects on soils, and potential vegetation-soil relationships [6]. Calcium, pH, total C, and total CEC appear to be more susceptible to fire-induced changes than the other soil chemical parameters measured in this study (Tables 9 and 10). Physical attributes provided little discriminating power, although they are important to differentiate ecological site units and differences. These results suggest that the Dude wildfire, that had easily observable and significant effects at the landscape level, produced effects that were limited or obscured at the site level. Small changes in site physical, chemical, or biological parameters after wildfires may have greater ramifications for vegetation recovery than is currently credited. This needs to be investigated. In addition, post-fire erosion is a significant process that is not well understood in terms of its impact on soil nutrient status and vegetation re-establishment.

5. Conclusions

In the Southwest USA, the Dude fire is one of a growing list of large-scale, catastrophic wildfires, which now includes the Cerro Grande fire in 2000, Rodeo-Chediski fire in 2002, and more recently the Wallow and Las Conchas fires in 2010, among others [8]. Rehabilitation costs for the Rodeo-Chediski fire alone exceeded $49 million dollars, which excludes the $43–$50 million for suppression [62]. Currently, 90% of the 2.95×10^6 ha of ponderosa pine forest in Arizona and New Mexico are considered to be at moderate or high risk for stand-replacing fire [63]. This developing trend raises questions about how long it takes severely burned areas to recover, what factors influence that recovery, and what factors may promote or delay recovery. By better understanding the processes that lead to vegetative succession patterns after a severe wildfire, the appropriate resources can be marshaled to speed the recovery of these ecosystems.

Additionally, several studies have attempted to develop broad succession models to predict the development of vegetation after severe wildfire [11,26]. They have suggested that among other factors, climate can strongly influence succession and have a significant effect on the recruitment of ponderosa pine after wildfire [2,11]. Both drought and fire may represent mechanisms by which a broader dynamic, climate change, is inducing shifts in plants communities [52,54,57,64]. In that light, the changes observed after the Dude Fire may represent the accelerated arrival of an inevitable shift toward more drought-tolerant communities.

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Author Contributions

Jackson Leonard is the lead author. He participated in the study design and modification, and field work along with his supervisor, Alvin Medina. Jackson used the study data for his M.S. thesis, prepared for the School of Forestry, Northern Arizona University, Flagstaff, AZ, USA. Alvin Medina was responsible for the initial study design and study establishment. Aregai Tecle co-supervised all the work from thesis proposal to implementation along with Daniel Neary. Both corrected all versions of the manuscript that related to the thesis. Daniel Neary co-supervised the M.S. thesis project, wrote parts of the manuscript relating to soils, and was the lead scientist in preparing the manuscript for submission to MDPI Forests.

Conflicts of Interest

The authors declare that no conflicts of interest occur.

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