Tree-based Mulches Influence Soil Properties and Plant Growth

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SUMMARY. The objective of this research was to determine the response of soil properties and plant growth to the application of various tree-based mulches and provide information specifically regarding attributes of eastern redcedar mulch (*Juniperus virginiana*). Eastern redcedar mulch, cypress mulch (*Taxodium distichum*), pine bark nuggets [southern yellow pine (*Pinus* sp.)], pine mulch (southern yellow pine), hardwood mulch [maple (*Acer* sp.), oak (*Quercus* sp.)], red-dyed mulch [maple, poplar (*Populus* sp.)], and grand eucalyptus mulch (*Eucalyptus grandis*), as well as two nonmulched controls (with and without chemical weed control) were tested. Volumetric soil moisture, soil nutrients, soil temperature, weed growth, and growth and survival of planted annuals and trees were measured. Compared with nonmulched controls, mulch treatments generally increased growth of annuals and trees and decreased weed growth, but few differences in measured variables were noted among mulch types. Mulched plots had greater volumetric soil moisture than nonmulched plots during extended periods without rainfall. Mulched plots had more moderate diurnal soil temperatures than nonmulched control plots. Soil pH and soil potassium increased with hardwood mulch during the 2 years of the study. These results indicate tree-based mulch benefits plant growth and survival by maintaining greater soil moisture, decreasing competition from weeds, and moderating soil temperatures compared with not using mulch. Eastern redcedar mulch provides similar benefits as other common wood mulches and is a viable forest product.

In the United States, the market for landscape mulch is increasing (Satkofsky, 2001). In 2006, demand for bagged mulch was predicted to increase by 5.5% per year and annual sales were predicted to increase from around \$550 million to \$915 million within a decade (Taylor, 2007). However, future availability of woody residuals for mulch is questionable because of increasing wood use as an energy source along with decreased timber production, which is the primary source of residuals (Lu

et al., 2006). Another concern is the harvesting of trees from intact, functioning ecosystems for use as mulch. Cypress wetlands form the basis of an important ecosystem that maintains water quality and provides critical habitat to many wildlife and fish species, and provides storm surge protection from hurricanes along some coastal areas. Currently, there is controversy concerning the harvest of cypress wetlands for production of mulch (The Save Our Cypress Coalition, Baton Rouge, LA).

With declining availability of popular wood mulches and increasing demand for mulch, alternative mulch

sources should be sought. One such possibility is harvesting unwanted trees that are encroaching onto grassland ecosystems. For example, eastern redcedar has invaded over 8 million acres in Oklahoma and causes \$218 million in losses annually due to decreased grazing, increased water consumption, reduced recreation opportunity, and increased wildfires (Drake and Todd, 2002). Conversion of eastern redcedar or other underused woody species into mulch is an environmentally friendly opportunity for the mulch industry.

When used for landscaping, wood based mulches generally reduce competition from weeds, maintain greater soil moisture, and moderate soil temperature (Cook et al., 2006; Iles and Dosmann, 1999; Johansson et al., 2006), which in turn often increases plant growth (Chakraborty et al., 2008; Greenly and Rakow, 1995; Sarkar and Singh, 2007; Zhang et al., 2009). The objective of this research was to compare the effects of various tree-based mulches on soil properties and plant growth. Soil moisture content, soil nutrients, weed suppression, rate of mulch decomposition, and growth and survival of planted trees, annuals and perennials were determined.

Materials and methods

Nine locations, including three each of tilled full-sun, nontilled full-sun, and nontilled shaded sites were included in the first year of the study. At each site, eastern redcedar (wood and bark), pine bark nuggets (bark), pine (bark and wood), cypress (bark and wood), and hardwood (bark and wood) mulch as well as a nonmulched, herbicide-treated control and nonmulched control were tested. The second year of the study, conducted in a full-sun environment only, included the addition of red-dyed mulch and grand eucalyptus mulch

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
645.1600	inch ²	mm ²	0.0016
28.3495	oz	g	0.0353
37.0798	oz/yd ³	g·m ⁻³	0.0270
1	ppm	mg·kg ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

treatments. Oven-dried particle size of the mulch ranged in size. The largest was pine bark nugget with only 9% of its particles (by weight) passing through a 0.5×0.5 -inch sieve. The smallest was grand eucalyptus with 87% of its particles passing through a 0.5×0.5 -inch sieve. For the other mulch types, 66%, 67%, 73%, 73%, and 84% of particles (by weight) passed through a 0.5×0.5 -inch sieve for redcedar, cypress, hardwood, red-dyed, and pine mulches, respectively. When a bulk sample was measured, grand eucalyptus and cypress had the lowest bulk density at $0.07 \text{ g}\cdot\text{cm}^{-3}$ compared with $0.08 \text{ g}\cdot\text{cm}^{-3}$ for pine bark nugget and redcedar, $0.09 \text{ g}\cdot\text{cm}^{-3}$ for red-dyed mulch, $0.11 \text{ g}\cdot\text{cm}^{-3}$ for pine, and $0.15 \text{ g}\cdot\text{cm}^{-3}$ for hardwood.

STUDY SITES. The research sites included plots located at the Natural Resource Ecology and Management arboretum and the adjacent Botanic Garden at Oklahoma State University in Stillwater. Soils were deep, well-drained fine silty loam in the Norge series (U.S. Department of Agriculture, 2010). The 30-year average annual precipitation for Stillwater, OK, is 36.6 inches. The precipitation over the 2 years of the study was 40.9 inches in 2009 and 35.4 inches 2010 (Oklahoma Agweather, 2011a). The average temperatures for Stillwater, OK, during the 2009 and 2010 growing seasons (April to September) were 73.2 and 76.3 °F, respectively. The 2009 growing season had temperatures ranging from a minimum of 23.0 °F to a maximum of 108.9 °F. The 2010 growing season had temperatures ranging from a minimum of 36.0 °F to a maximum of 108.0 °F. The minimum temperatures (January) were 7.2 and 1.0 °F for 2009 and 2010, respectively (Oklahoma Agweather, 2011b).

TREATMENTS. In Mar. 2009, nine locations including three environment types each of tilled full-sun (tilled), nontilled full-sun (full-sun), and nontilled shaded sites (shaded) were identified (2009 plantings). Plots were tilled to a depth of 3.0 inches using a rotary tiller, pulled behind a tractor before mulch treatments were applied. Existing vegetation at all sites was cut to ground level before mulch application. At each of the nine sites, seven 1.5-m-diameter circular plots (1.77 m^2) were established and randomly assigned one of

the following mulches; eastern redcedar (Eastern Redcedar Mulch, Stillwater, OK), pine bark nugget, pine, cypress, hardwood (Green Country Soil, Miami, OK), nonmulched control in which weeds were controlled using herbicide [control with herbicide (CWH)], or nonmulched control without herbicide [control no herbicide (CNH)] (63 plots total). Mulch was not reapplied to the 2009 plantings in 2010.

On 17 Apr. 2009, one containerized (3-gal pot) shumard oak (*Quercus shumardii*) and one containerized redbud (*Cercis canadensis*) (Cedar Valley Nurseries, Ada, OK) were planted within each of the plots. On 20 Apr.

2009, 46.5 gal of mulch was spread on each mulched plot to a depth of 3 to 4 inches. In addition to the trees, four individuals of six species of annuals were planted (Spring Creek Nursery, Tulsa, OK) on 21 Apr. 2009, which was after the last frost. Four green-leaf wax begonia [*Begonia semperflorens* (begonia shade)] and four impatiens (*Impatiens walleriana*) were planted in each shade plot. Four bronze-leaf wax begonia [*B. semperflorens* (begonia sun)] and one set of four lantana (*Lantana camara*) were planted in two-thirds of the full-sun plots, while the other third of full-sun plots contained four coleus (*Solenostemon scutellarioides*) and four salvia (*Salvia*

Fig. 1. Soil temperature per mulch treatment measured at 3.0 inches (7.6 cm) for 1 week (21–29 July 2009). Mean is average of hourly measurements during this period. Average maximum and average minimum are the average daily extremes. Maximum and minimum are the extreme high and low temperatures. CNH = control no herbicide, CWH = control with herbicide, CYP = cypress mulch, HW = hardwood mulch, PINE = pine mulch, PN = pine bark nugget mulch, RC = eastern redcedar mulch ($n = 9$); $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

Fig. 2. Change in soil pH for mulch treatments initiated in 2009 (2009 plantings). Soil measurements were taken before mulch application at the beginning of the first growing season, at the end of the first growing season, and at the end of the second growing season. CNH = control no herbicide, CWH = control with herbicide, CYP = cypress mulch, HW = hardwood mulch, PINE = pine, PN = pine bark nugget mulch, RC = eastern redcedar mulch ($n = 9$). Vertical bars represent SE.

splendens). For the tilled plots, two-thirds contained four coleus and four salvia and the remaining third contained four begonia sun and four lantana. The 2009 plantings with annuals were watered by hand every 3 d during periods without rain. A directed spray of glyphosate (2% a.i., Roundup®; Monsanto, St. Louis) was used to control weeds within the nonmulched herbicide plots. Fertilization treatments were not used in this study.

Based on the results from the 2009 plantings, five new replications were established on 2 Mar. 2010 (2010 plantings). Each replication contained nine circular, 1.5-m-diameter plots randomly assigned with one of the treatments used in the 2009 plantings, along with two new mulch treatments; red-dyed mulch (Green Country Soil, Miami, OK) or grand eucalyptus mulch (AAAction Mulch, Fort Myers, FL) (45 plots total). Four of the five new replications (36 plots) were located and established on the arboretum and the fifth replication (9 plots) was established on the Botanic Gardens at Oklahoma State University. All replications for the 2010 plantings were established in an open, nontilled (full-sun) environment. On 12 Mar. 2010, 46.5 gal of mulch was applied 3 to 4 inches deep to each of the plots.

MEASUREMENTS AND EXPERIMENTAL DESIGN. For the 2009 plantings, measurements were conducted during the 2009 and 2010 growing seasons. For nutrient analysis, soil was collected from each plot to a depth of 3 inches using a 0.7-inch-diameter soil probe on 15 Apr. 2009 before the application of mulch, on 17 Dec. 2009 at the end of the first year, and on 17 Nov. 2010 at the end of the second year. On all dates, four samples per plot were combined into one composite sample. All soil pH and nutrient samples were analyzed by the Oklahoma State University Soil, Water and Forage Analytical Laboratory. Soil pH was analyzed using a Mettler, Seven Multi meter (Mettler-Toledo, Columbus, OH) with a Thermo Orion, Ross Sure-flow electrode (Thermo Fisher Scientific, Waltham, MA). Soil nitrate was analyzed with a flow injection analyzer (Lachat QuickChem 8500; Hach Co., Loveland, CO), using the cadmium reduction method (Gavlak et al., 2003). Phosphorus (P) and potassium (K) were analyzed using an inductively coupled plasma

(ICP) spectrometer (Spectro Arcos; AMETEK, Berwyn, PA). Soil temperature was measured hourly from 21 July 2009 to 29 July 2009 at a soil depth of 3 inches using WatchDog® model 425 and model 450 sensors (Spectrum Technologies, East Plainfield, IL).

Annual plants were harvested on 21 Aug. 2009 and dried to a constant biomass at 65 °C and then weighed. Tree height was measured from the soil to top of the terminal leader of the shumard oaks and from the soil to tallest point on the redbud trees when first planted and at the end of the first and second growing seasons. Tree diameter was measured ≈2 mm above the soil when planted and at the end of the first and second growing

seasons. Annual plant biomass was analyzed as a randomized complete block design ($n = 3$) with each species tested separately. Other variables were analyzed as a split-plot with environment type ($n = 3$) as the whole plot factor and mulch treatment ($n = 9$) as the sub-plot factor. When mulch treatment was significant ($P < 0.05$), differences among treatments were determined using Duncan's multiple range test.

For the 2010 plantings, volumetric soil moisture content (VWC) was measured every 7 to 10 d throughout the 2010 growing seasons at a soil depth between 0 and 15 cm by time domain reflectometry (Mini-Trase TDR system; Soilmoisture Equipment, Santa Barbara, CA). Weeds were

Fig. 3. Change in (A) soil nitrate (NO₃) concentration, (B) soil phosphorus (P) concentration, and (C) soil potassium (K) concentration for mulch treatments initiated in 2009 (2009 plantings) between 0 and 3.0 inches (7.6 cm) soil depth. Soil measurements were taken before mulch application at the beginning of the first growing season, at the end of the first growing season, and at the end of the second growing season. CNH = control no herbicide, CWH = control with herbicide, CYP = cypress mulch, HW = hardwood mulch, PINE = pine, PN = pine bark nugget mulch, RC = eastern redcedar mulch ($n = 9$). Vertical bars represent SE; 1 mg·kg⁻¹ = 1 ppm.

harvested at the mulch surface on 22 July 2010 using hand clippers, dried to a constant biomass at 65 °C, and then weighed. After determining weed biomass, plots were kept weed-free for the remainder of the growing season using directed sprays of glyphosate.

Mulch decomposition rates were determined by measuring weight loss of mulch subsamples. Three mesh bags $\approx 20 \times 20$ cm (3 mm² mesh opening) for each of the mulched plots (four replications $\times$ seven mulch treatments) were filled with a known weight of oven-dried mulch ranging from 70 to 127 g based on mulch type. The bags were placed in the plots on 27 May 2010 so that bags were above the soil, but below the surface of the mulch. Mesh bags were collected on 1 Aug. 2011 near the end of the second growing season and dried to a constant biomass at 65 °C and weighed. Percent loss from three bags per plot was averaged.

The experimental design for the 2010 plantings was a randomized complete block ($n = 5$) for soil measurements and plant measurements. Mulch decomposition measurements were also a randomized complete block design, but had $n = 4$ because no mulch decomposition bags were placed in the block on the Botanic Gardens at Oklahoma State University. For volumetric soil moisture content, a repeated measure analysis was conducted using 21 sampling dates during the growing season. Because of significant interactions between date and mulch treatment, soil moisture was further analyzed for each date separately.

Results

SOIL TEMPERATURE-2009 PLANTINGS. Mulch moderated soil temperature, decreasing daily maximum and increasing daily minimum temperatures (Fig. 1). Air temperature during the 8-d measurement period between 21 July 2009 and 29 July 2009 ranged from 14 to 39 °C and averaged 25 °C. Maximum soil temperatures at a depth of 3 inches during the period and average daily maximum soil temperatures of the mulched treatments and the CNH treatment were 4 to 6 °C lower than CWH treatment ($P = 0.001$) (Fig. 1). No differences occurred in maximum temperature among the mulched treatments. Minimum temperature and average daily minimum temperature

of the mulched treatments were similar, but 2 to 3 °C warmer than both nonmulched treatments ($P = 0.0002$). Average temperature did not differ among mulched treatments. However, the average temperature was cooler in the CNH treatment than in the CWH, eastern redcedar and hardwood treatments ($P = 0.02$). As expected, the temperature was lower in the shade than in full-sun or tilled environments by an average of 3 °C ($P < 0.0001$). Mulch type and environment did not interact ($P = 0.08$).

SOIL NUTRIENTS-2009 PLANTINGS. Initial average soil pH across all treatments was 6.45 ± 0.07 (mean $\pm$ SE). During the first growing season, soil pH was affected by mulch treatment ($P = 0.02$) and environment type ($P = 0.02$), but mulch type and environment did not interact ($P = 0.13$). Soil pH increased in the CWH and

hardwood mulch treatments but decreased in the other treatments (Fig. 2). The pH of the tilled environment plots increased 0.18 and was greater than the full-sun and shaded environments that changed in pH by -0.05 and -0.12 , respectively. Soil pH decreased during the second growing season for all treatments, but 2-year statistical results for treatment effects were similar to 1-year results. Hardwood mulch and CWH soil pH changed less over the entire 2-year period of the study compared with the other treatments ($P = 0.006$). The pH of the tilled environment plots increased by 0.03 and was greater than the shaded and full-sun environments, which changed by -0.26 and -0.28 , respectively, over the 2-year study ($P = 0.04$). Mulch treatment and environment type did not interact (mulch $\times$ environment $P = 0.16$).

Fig. 4. Biomass of annuals harvested in 2009. (A) Lantana, (B) coleus, (C) green-leaf begonia (begonia shade), (D) red-leaf begonia (begonia sun), (E) impatiens, (F) and salvia. Means with the same letter are not significantly different (Duncan's post hoc, $\alpha = 0.05$). CNH = control no herbicide, CWH = control with herbicide, CYP = cypress mulch, HW = hardwood mulch, PINE = pine mulch, PN = pine bark nugget mulch, RC = eastern redcedar mulch ($n = 3$). Weight (g) is the sum of all surviving plants per mulch treatment. Four plants were originally planted per treatment. Vertical bars represent SE; 1 g = 0.0353 oz.

Initial average soil nitrate and P concentrations across all treatments were 4.17 ± 0.69 and 15.74 ± 1.75 $\text{mg}\cdot\text{kg}^{-1}$ (mean $\pm$ SE), respectively. Mulch treatments did not significantly alter soil nitrate or P concentration during the first growing season ($P = 0.52$, $P = 0.78$) or during the full 2-year study, ($P = 0.26$, $P = 0.85$) (Fig. 3A and 3B, respectively). Initial average soil K concentration across all treatments was 263 ± 12.54 $\text{mg}\cdot\text{kg}^{-1}$. During the first growing season, the change in soil K concentration depended on mulch treatment ($P < 0.0001$). Hardwood mulch increased soil K compared with the other treatments that exhibited a decrease in soil K (Fig. 3C). Likewise, during the 2-year duration of the study, the change in soil K due to hardwood mulch was greater than that of all other treatments ($P < 0.0001$). The change in soil nitrate, P, and K did not vary among environment types ($P > 0.10$) and environment type and mulch treatment did not interact ($P > 0.47$).

GROWTH OF ANNUALS-2009 PLANTINGS. Mulch increased growth of lantana ($P = 0.0004$) (Fig. 4A) and coleus (Fig. 4B) compared with non-mulched treatments. Also for coleus, hardwood mulch resulted in less growth compared with other mulches. Mulch did not significantly increase growth of the other four annual species; that is, begonia shade, $P = 0.21$ (Fig. 4C); begonia sun, $P = 0.25$ (Fig. 4D); impatiens, $P = 0.36$ (Fig. 4E); salvia, $P = 0.43$ (Fig. 4F). Although salvia biomass was not significantly affected by mulch, survival was lower for both non-mulched treatments (33% for CWH, 25% for CNH) than for the pine nugget (92%), cypress (100%), eastern redcedar (100%), and pine (100%) mulched treatments ($P = 0.04$). Salvia planted in hardwood mulch had 42% survival, but this did not statistically differ from other treatments. Survival of the other five annual species was unaffected by mulch application and was high when averaged across all treatments; that is, 100% for begonia shade and coleus, 99% for impatiens, 96% for lantana, and 90% for begonia sun.

REDBUD HEIGHT AND DIAMETER GROWTH-2009 PLANTINGS. Initial average height of redbud trees across all treatments was 0.97 m. Mulch increased height growth of redbuds for the 2009 growing season ($P =$

0.05), but did not significantly affect growth for the 2010 growing season ($P = 0.96$) (Fig. 5A). When growth over both years was calculated, mulch increased redbud height after 2 years compared with nonmulched treatments ($P = 0.03$). In 2009, redbuds in hardwood and eastern redcedar mulched treatments had greater growth than those in the CWH treatment. Total height growth for redbuds during the two growing seasons was greater in the hardwood and eastern redcedar mulched treatments than for both nonmulched treatments. Environment did not significantly affect redbud height growth during the 2009 growing season ($P = 0.33$ for environment effect, $P = 0.41$ for mulch $\times$ environment). Environment affected redbud height growth during the 2010 growing season ($P = 0.01$), but environment and mulch did not interact

($P = 0.51$). Redbud height increase in tilled treatments (0.57 m) was less than in full-sun treatment (0.87 m) but greater than in shade treatment (0.27 m).

Initial average diameter of redbud trees across all treatments was 8.7 mm. Mulch increased trunk diameter growth of redbuds in 2009 ($P = 0.05$) because redbuds planted in pine mulch had greater growth than those in nonmulched treatments. Trunk diameter growth was not significantly affected by treatments in 2010 ($P = 0.31$) (Fig. 5B). No significant differences in cumulative trunk diameter growth of redbuds occurred when calculated over two growing seasons ($P = 0.09$). Environment did not significantly affect redbud diameter growth during the 2009 growing season ($P = 0.11$ for environment effect, $P = 0.70$ for mulch $\times$ environment). Environment

Fig. 5. (A) Height increase and (B) diameter increase of redbud trees per mulch treatment planted in 2009 (2009 plantings) over 2 years. Means with the same letter are not significantly different (Duncan's post hoc, $\alpha = 0.05$). Lower case letters represent 2009 growing season and upper case letters represent 2010 growing season. CNH = control no herbicide, CWH = control with herbicide, CYP = cypress mulch, HW = hardwood mulch, PINE = pine mulch, PN = pine bark nugget mulch, RC = eastern redcedar mulch ($n = 9$). Vertical bars represent SE; 1 m = 3.2808 ft, 1 mm = 0.0394 inch.

Fig. 6. (A) Height increase and (B) diameter increase of shumard oak per mulch treatment planted in 2009 (2009 plantings) over 2 years. Means with the same letter are not significantly different (Duncan's post hoc, $\alpha = 0.05$). Lower case letters represent 2009 growing season and upper case letters represent 2010 growing season. CNH = control no herbicide, CWH = control with herbicide, CYP = cypress mulch, HW = hardwood mulch, PINE = pine mulch, PN = pine bark nugget mulch, RC = eastern redcedar mulch ($n = 9$). Vertical bars represent SE; 1 m = 3.2808 ft, 1 mm = 0.0394 inch.

did significantly affect redbud trunk diameter growth in 2010 ($P = 0.04$), but environment and mulch did not interact ($P = 0.72$). The redbud trunk diameter increase in tilled treatments (6.6 mm) was less than in the full-sun treatment (11.0 mm) but greater than in shade treatment (3.5 mm).

SHUMARD OAK HEIGHT AND DIAMETER GROWTH-2009 PLANTINGS. Initial average height of shumard oaks across all treatments was 1.6 m. Mulch did not significantly affect height growth of shumard oaks in 2009 ($P = 0.76$), but resulted in increased growth in 2010 ($P = 0.01$). For the 2010 growing season, shumard oaks in pine and pine bark nugget mulched treatments had greater growth than those in CNH, hardwood, and eastern redcedar treatments (Fig. 6A). No significant differences in cumulative height growth of shumard oaks

occurred when calculated over two growing seasons ($P = 0.25$). Environment did not affect shumard oak height for either growing season ($P > 0.06$ for environment effect, $P > 0.11$ for mulch $\times$ environment).

Initial average diameter for shumard oaks across all treatments was 14.1 mm. Similar to redbuds, mulch significantly increased trunk diameter growth of shumard oaks in 2009 ($P = 0.02$), but not 2010 ($P = 0.69$). For the 2009 growing season, shumard oaks mulched with cypress, pine, pine bark nugget, and eastern redcedar had greater growth than those in CNH treatments (Fig. 6B). Shumard oaks receiving pine mulch had greater cumulative trunk diameter growth over the two growing seasons than those receiving hardwood mulch or those in nonmulched treatments ($P = 0.05$). Environment did affect shumard oak

trunk diameter growth ($P < 0.0001$) in 2009, ($P = 0.01$) in 2010, and ($P < 0.0001$) over the 2 years. Cumulative trunk diameters over 2 years of growth were 8.2, 14.2, and 14.7 mm for the shade, tilled, and open environments, respectively. No mulch $\times$ environment effect occurred for shumard oak trunk diameter ($P > 0.07$).

SOIL MOISTURE-2010 PLANTINGS. Mulch conserved soil moisture during drier periods and little difference occurred among mulched treatments (date $\times$ mulch treatment, $P < 0.0001$). Soil moisture was similar among treatments at the beginning of the growing season (first two measurement dates, Fig. 7). As the soil dried, differences developed between the mulched and nonmulched treatments. On 15 Apr. 2010, 5 May 2010, 19 July 2010, 28 Sept. 2010, and 7 Oct. 2010, soil moisture of both the CNH and CWH treatments were lower than the mulched treatments, while on 5 May 2010, 11 May 2010, 30 May 2010, 24 June 2010, and 1 July 2010, soil moisture of only the CNH was lower than the mulch treatments. On 17 Sept. 2010, only soil moisture of the CWH was lower than the mulch treatments. The only differences among mulch types was that grand eucalyptus mulch had lower VWC than hardwood mulch from 24 June 2010 (10th measurement date Fig. 7) to 11 July 2010 (12th measurement date).

WEED GROWTH-2010 PLANTINGS. Weed growth was suppressed by mulch ($P < 0.0001$) with the CNH plots having greater weed growth than all other treatments (Fig. 8). As expected, the CWH treatment had the least weed growth of all treatments. Mulch treatments did not significantly differ in weed growth.

MULCH DECOMPOSITION-2010 PLANTINGS. Cypress and pine bark nugget mulch decomposed the slowest and were significantly slower than red-dyed, pine, hardwood, and grand eucalyptus (mulch effect, $P = 0.0001$) (Fig. 9). Eastern redcedar and grand eucalyptus mulch decomposed slower than pine and red-dyed mulch.

Discussion

Use of tree-based mulches in this study increased plant growth (annuals and trees) and survival, maintained greater soil moisture, suppressed weed growth, and moderated soil

Fig. 7. Volumetric soil moisture content (%) per mulch treatment, measured between 0 and 15 cm (5.9 inches). An asterisk (*) below the data represents dates when mulch effect is significant ($P < 0.05$). CNH = control no herbicide, CWH = control with herbicide CYP = cypress mulch, HW = hardwood mulch, PINE = pine mulch, PN = pine nugget mulch, RC = eastern redcedar mulch, EUC = grand eucalyptus mulch, RED = red-dyed mulch ($n = 5$).

Fig. 8. Weed growth for mulch treatments initiated in 2010 (2010 planting). Means with the same letter are not significantly different (Duncan's post hoc, $\alpha = 0.05$). CNH = control no herbicide, CWH = control with herbicide, CYP = cypress mulch, EUC = grand eucalyptus mulch, HW = hardwood mulch, PINE = pine mulch, PN = pine bark nugget mulch, RC = eastern redcedar mulch, RED = red-dyed mulch ($n = 4$). Vertical bars SE; 1 g = 0.0353 oz.

temperature. Benefits were primarily associated with the use of mulch compared with not using mulch, rather than specific to mulch treatments. Other studies found similar results with the use of mulch (e.g., Cook et al., 2006; Iles and Dosmann, 1999; Johansson et al., 2006).

As in our study, shading and insulation by mulch moderated soil temperature in previous studies (Cook et al., 2006; Skroch et al., 1992). Mulch color may affect soil temperatures (Harris, 1992). A study conducted in the warmer months of August and September showed that

soil temperature under organic mulches such as wheat straw, which is lighter in color, was lower than under darker mulches or no mulch (control) (Cook et al., 2006). Our study did not detect differences in soil temperature under the various mulch types tested, perhaps because the mulch was deep (3 inches) and perhaps because the color of all mulches tested was generally similar ranging from brown to red. In our study, CNH plots contained lower temperatures than the CWH plots. The lower temperatures in the CNH plots is likely due to the presence of weed growth in these plots that kept soil temperatures at lower levels due to shading compared with the CWH plots which were bare and directly exposed to the sun, thus causing them to heat up faster and to a greater extreme than the weed-infested CNH plots.

Previous research indicated that mulch can increase (Iles and Dosmann, 1999), decrease (Billeaud and Zajicek, 1989; Duryea et al., 1999; Himelick and Watson, 1990), or not alter soil pH (Broschat, 2007; Tukey and Schoff, 1963). The effect of mulch appears to depend on the relative difference between the soil pH and that of the mulch. Based on our data, all treatments

Fig. 9. Mulch decomposition rate per mulch treatment planted in 2010 (2010 plantings) over 2 years, measured as percent loss in dry weight. Means with the same letter are not significantly different (Duncan's post hoc, $\alpha = 0.05$). CYP = cypress mulch, HW = hardwood mulch, PINE = pine mulch, PN = pine bark nugget mulch, RC = eastern redcedar mulch ($n = 9$). Vertical bars represent SE.

for the 2009 plantings decreased soil pH during the first and second year except for hardwood mulch, which increased soil pH in year 1. The initial soil pH was 6.4, while the pH of the mulches were 5.6 for eastern redcedar, 7.9 for hardwood, 6.0 for cypress, and 4.5 for both pine bark nugget and pine. Therefore, our finding is consistent in that hardwood mulch had a pH higher than the soil, while the other mulch treatments all had a pH lower than the soil.

Mulches can alter soil fertility as they leach or decompose. Mulches also create an environment favorable for microorganisms in the underlying soil; that is, moisture and temperature are moderated, which can increase nutrient mineralization in the soil (Harris, 1992). The lack of soil nitrate response in our study may be due to several factors. Soil nitrate depends on moisture content and temperature at the time of sampling (Gaines and Gaines, 1994). More extensive measurements of in situ nitrogen mineralization would improve the estimates of mulch effects on nitrogen. While measurements of soil P are more stable over time, we also did not find any effect of mulch. Increased K under the hardwood mulch may be related to its faster decomposition. The general lack of soil nutrient response to mulch in our study differs from results of other studies (Broschat, 2007; Tukey and Schoff, 1963). Immobilization of nutrients may occur

with the application of high carbon, low nutrient materials such as tree-based mulch (Pickering and Shepherd, 2000) and may cause a lag between mulch application and nutrient release. Measurement beyond 2 years may have revealed a mulch effect on soil nutrients. However, based on our results, tree-based mulches do not appear to be an important contributor to soil available nutrients.

In our study, mulch had a positive effect on soil moisture, especially during drier periods. These results agree with previous studies, in which soils under organic mulch treatments contained more moisture than other treatments during long periods without rainfall (Greenly and Rakow, 1995; Zhang et al., 2009). Mechanisms for maintaining greater soil moisture under mulch include decreased soil temperatures resulting in lower evaporation, moisture in the mulch buffering losses from the soil, and decreased transpiration due to weed suppression. After heavy rainfall, soil moisture did not differ between mulched and nonmulched plots since all soils were fully saturated (Greenly and Rakow, 1995).

Mulch can control competition by suppressing weed seed germination and establishment. The reduced competition from weeds allows more water, light, and nutrients to be available for plants used in the landscape (Harris, 1992). Decreases in weed growth were related to the use of

mulch but not mulch type. Similar evidence was found in other studies (Abouzienna et al., 2008; Broschat, 2007; Stinson et al., 1990). Considerable variation in weed growth occurred among plots of the same treatment due in part to variation in weed species. Large, strong stemmed weeds grew through the mulch in some plots, while other plots were invaded by bermudagrass (*Cynodon dactylon*). Applying herbicide to kill existing vegetation before adding mulch would be beneficial (Greenly and Rakow, 1995).

All annual species increased in size during the growing season, but the positive mulch effects were species specific. Similar results occurred in studies where mulch increased crop growth and yield, and benefits were attributed to increased soil water (Chakraborty et al., 2008; Sarkar and Singh, 2007; Zhang et al., 2009). In our study, mulch increased growth of lantana and coleus. Both of these species were growing in full-sun treatments that might have experienced greater soil drying and perhaps benefited the most from mulch application. Lower survival of the salvia in the nonmulched treatments also was probably related to lower soil moisture and in the case of the CNH treatment, perhaps above-ground competition with weeds for light.

Mulch increased growth of redbuds and shumard oaks. Another study showed similar results in which mulch increased trunk diameter growth of planted trees (Greenly and Rakow, 1995). Difference in timing of height growth response to mulch of the redbuds and shumard oaks was probably related to their growth characteristics. Redbud trees are free growers (i.e., no predetermination of annual growth), making their response to the mulch treatments more immediate and manifest in the first year. Shumard oaks are semideterminant growers, which can limit the amount of annual growth. As a result, shumard oaks in our study may have expressed the benefits of mulch to height growth in the second growing season because of beneficial effects of the mulch from year 1 on growth potential the subsequent year.

Pine and red-dyed mulch decomposed more than other mulches during the 2-year study, which contrasts with results by Duryea et al. (1999) who found that mulch comprised of

hardwood prunings and clippings and grand eucalyptus mulch decomposed faster than all other mulch treatments tested. The difference in results could be related to species contained in generic mixes. The hardwood and red-dyed mulches we tested were commercially available products that combine a mixture of various species and can be different at certain times of the year or vary by manufacturer. The hardwood mulch we used consisted of a mixture of oak and maple and the red-dyed mulch we used consisted of poplar and maple. As poplar is less dense than oak (Vick, 1985), it is not surprising that the red-dyed mulch decomposed faster than the hardwood mulch in our study. Similar differences in species can confound comparisons between studies. In addition, the quality of the wood of a given species (e.g., growth rate and percent heartwood) will affect decomposition rate.

Conclusion

This study indicates that all mulch treatments maintained greater soil moisture, moderated soil temperatures, reduced weed growth, and increased plant growth and survival similarly and provides evidence that use of mulch is beneficial in landscape settings. Given concerns about the future availability of woody residuals and harvesting trees of intact, functioning ecosystems for use as mulch, sources such as eastern redcedar harvested during ecosystem restoration or plantation grown grand eucalyptus may provide alternatives to traditional cypress, hardwood, and pine mulch.

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