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A Meta-analysis of Studies Published in *Arboriculture & Urban Forestry* Relating to Organic Materials and Impacts on Soil, Tree, and Environmental Properties

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Abstract. Organic materials are commonly used in urban landscapes to improve soil quality and tree health. Literature reviews suggest that the effects of organic materials are beneficial, but these impacts have yet to be evaluated using meta-analytical approach. This work presents a literature summary of 176 articles published in *Arboriculture & Urban Forestry* (*AUF*) and evaluates 33 of these papers using a meta-analysis. Research relevant to this topic is not published solely in *AUF*, but the meta-analysis is limited to *AUF* in an attempt to specifically focus on the information provided to *AUF* readers. This meta-analysis provides evidence of the mostly positive impacts organic materials have on shoot growth, root growth, tree physiology, and soil physical properties. It also identifies specific gaps in *AUF* literature for the effects organic materials have on soil chemical, soil biological, and environmental (e.g., climate, competition) properties. Further, this meta-analysis suggests the type of organic material and the mode of application have differential effects on tree, soil, and environmental properties.

Key Words. Environment; Meta-Analysis; Organic Materials; Soil Organic Matter; Soil Biological Properties; Soil Chemical Properties; Soil Physical Properties; Tree Health.

Soil organic matter (SOM) is derived from the decay of once living organisms and is composed of organic (C-based) compounds (Brady and Weil 2008). Organic matter is the most complex, dynamic, and reactive soil component (Tabatabai 1996). It positively contributes to tree and environmental health, through effects on soil physical, chemical, and biological properties (Magdoff et al. 1996). In urban landscapes, natural tree restitution avenues (e.g., leaf-litter fall) are often interrupted and as a result SOM dynamics altered (Craul 1985; Craul 1999). Consequently, organic materials are commonly applied as mulches and soil amendments to restore SOM inputs. A recent review by Chalker-Scott (2007) identified organic mulches consistently rated as the best or second best mulches for overall plant performance in comparative field trials.

Arboriculture & Urban Forestry (*AUF*), formerly *Journal of Arboriculture*, is a primary source for the exchange of scientific knowledge in the profession of arboriculture and urban forestry. This meta-analysis was limited to results published in *AUF* in order to assess information provided by *AUF*. *Arboriculture & Urban Forestry* has a wide circulation among professional arborists and urban foresters, and these practitioners rely on the scientific journal as a main source of scientific information for the care and management of urban trees. Furthermore, most arborists and urban foresters do not subscribe to technical soil science journals, such as *Soil Science Society of America Journal*, *Journal of Environmental Quality*, or *Soil Science*, and it is likely they acquire most of their soil-related technical knowledge through *AUF*. Consequently, a meta-analysis limited to *AUF* will assess the information that urban tree care professionals have been exposed to pertaining to organic materials. A recognized shortcoming of limiting a meta-analysis to studies published in *AUF* is that it does omit key papers published in other journals; but, by doing so the meta-analysis more accurately represents information available to the arboriculture profession. Because the meta-analysis was limited to *AUF*, it is a comprehensive examination of literature in this journal.

A meta-analysis (i.e., an analysis of analyses) provides an alternative analytical framework for the synthesis of results from separate studies (Cooper and Hedges 1994; Curtis 1996). Meta-analytical approaches have been used to synthesize research and examine ecological questions relating to competition (Gurevitch and Hedges 1993), elevated CO_2 (Curtis 1996), and animal ecology (e.g., Jarvinen 1991; Poulin 1994). A meta-analytical review involves a literature search to identify appropriate and relevant studies to answer a particular question. Treatment responses (i.e., % change relative to control or effect size) are calculated across independent studies for standardization, and then statistically evaluated to provide information for the question of interest (Curtis 1996).

The goal of the study was to assess information in the journal *Arboriculture & Urban Forestry* pertaining to the effects of organic materials on trees, soil, and environmental properties. The specific objectives of this study were: 1) perform a literature search and summary of *AUF* literature relating to organic materials; 2) identify studies meeting the specific criteria for inclusion in a meta-analysis; 3) compile parameter response data for those studies; and, 4) perform a meta-analysis to examine the impacts of organic materials on trees, soils, and the environment as presented in *AUF*.

METHODS

Every article of *Arboriculture & Urban Forestry* (1975 to 2008) was surveyed to address the question of how organic materials impact trees, soil, and the environment. Organic treatments were defined as C-based materials (e.g., organic mulch and compost), but did not include treatments such as biological inoculants and plant growth hormones. Our literature search of *AUF* produced 176 studies that related in some manner to organic materials. Of those studies, only 33 (Table 1) met our criteria for the meta-analysis. Our criteria for inclusion in the meta-analysis were that studies needed to: 1) provide data; 2) examine an organic treatment(s); 3) have a scientific control; and, 4) show significant results ($p \leq 0.05$). Results and conclusions from the remaining 143 studies not included in the meta-analysis were assessed and compiled in the first section of the discussion labeled, qualitative summary of literature search. These 143 studies were not included in the meta-analysis, but are included in the discussion because they provide a historical framework for the topic of interest.

Treatment effects were quantified by computing % change (Δ) relative to the control, where, X_t is the mean treatment response and X_c is the control (Equation 1) (Cooper and Hodges

Table 1. Species, specifications, soil types, and characteristics of organic materials for studies used in this meta-analysis.

Code	Date	Author(s)	Species (age, size, care, concerns, etc.)	Specifications	Soil type	Type[z]	Mode[y]
A	1982	Fraedrich & Ham	*Acer rubrum* and *A. saccharinum*	herbicide	sandy clay loam sandy loam	mulch	surface
B	1983	Litzow & Pellet	*Fraxinus pennsylvanica*	10 cm (dbh)	clay loam	mulch	surface
C	1988	Hensley et al.	*Magnolia grandiflora*	container 2 yr	Pope silt loam	mulch	surface
D	1988	Watson	*Acer rubrum, A. platanoides, A. saccharum, Tilia cordata, Fraxinus pennsylvanica, Quercus rubra, Q. palustris*	open grown, 20 yr, herbicide	not specified	compost	surface
E	1988	Myers & Harrison	*Viburnum opulus, Juniperus chinensis*	container, wetting agent, fertilizer	sandy loam, perlite, peat	mulch	surface
F	1989	Green & Watson	*Acer saccharum*	bare root tillage	compacted clay subsoil	compost	surface
G	1990	Appleton et al.	*Ilex crenata, Rhododendron obtusum, Acer rubrum*	herbicide, fertilizer	Tetotum loam	mix	surface
H	1990	Himelick & Watson	*Quercus alba*	45–76 cm (dbh), fertilizer	not specified	mulch	surface
I	1991	Watson	not specifcied	not specified	not specified	mulch	surface
J	1991	Watson & Kupkowski	*Acer saccharinum, Fraxinus pennsylvanica Gleditisia triacanthos, Malus* spp.	15–58 cm (dbh)	not specified	mulch	deep surface
K	1992	Smith & Rakow	*Fraxinus pennsylvanica, Malus* spp.	bare root whips 0.9 m (ht)	sandy loam	mulch	surface
L	1992	Watson et al.	*Fraxinus pennsylvanica*	B&B, hole shapes	compacted clay subsoil	compost	backfill
M	1993	Zajicek	*Lagerstroemia indica*	1 yr, inground pots	66% fritted clay 33% peat-lite	mulch	surface
N	1994	Lichter & Lindsey	not applicable	fabric, compaction	silt loam	mulch	deep surface
O	1995	Duchesne & Clark	*Thuga occidentalis*	seeds	O-Ae-B horizons	mulch	surface
P	1995	Greenly & Radkow	*Pinus strobus, Quercus palustris*	bare root and B&B 3–5 cm (cal), 1.2–1.5 m (ht)	Collamer silt loam	mulch	deep surface
Q	1995	Smalley & Wood	*Acer rubrum*	B&B 3 cm (cal)	Cecil sandy loam	mix	backfill
R	1996	Watson et al.	*Quercus alba, Tilia* spp., *Platanus acerfolia*	8.3, 9.1, 12.4 cm (dbh)	not specified	compost	backfill
S	1999	Duryea et al.	*Lactuca* spp.	seed	filter paper	mix	surface
T	1999	Foshee et al.	*Carya illinoensis*	container, fertilization	Cahaba fine sandy loam	mix	deep surface
U	1999	Iles & Dosman	*Acer rubrum*	bare root, 1.6–2.0 cm (cal), herbicide	Nicollet fine sandy loam	mulch	surface
V	2002	Watson	*Quercus alba*	79 cm (dbh)	not specified	compost	backfill
W	2004	Gilman	*Quercus virginia*	container, 5.1 cm (cal), irrigation	Milhopper fine sand	compost	backfill
X	2004	Gilman & Grabosky	*Quercus virginia*	6.5 cm (cal), herbicide	Milhopper fine sand	mulch	surface
Y	2005	Ferrini et al.	*Quercus robur*	B&B; 5 yr, 4.5 m (ht), 13 cm (dbh), fertilization	clay	compost	backfill
Z	2005	Arnold et al.	*Fraxinus pennsylvanica, Koelreuteria bipinnata*	126 cm (ht), 88 cm (ht), planting depth, fertilization	Bonnville fine sandy loam	mulch	deep surface
a	2006	Scharenbroch & Lloyd	various deciduous	2 to 7 m (ht)	Paulose silt loam	mulch	surface
b	2006	Roberts	*Acer rubrum, Fraxinus pennsylvanica*	plug seedlings, bare root, 2 yr, fertilization	not applicable	mix	backfill
c	2007	Ferrini & Baietto	*Acer platanoides*	B&B, 5 yr, 4.5 m (ht), 15 cm (dbh), covering type	clay loam	compost	surface
d	2007	Rivenshield & Bassuk	not applicable	compaction, wetting agent	sandy loam	clay loam	compost backfill
e	2007	Montague et al.	*Lagerstroemia indica, Forsythia × intermedia, Spirea × vanhouttei, Photinia × fraseri*	container, irrigation	Austin silty clay	mulch	surface
f	2008	Singer & Martin	not applicable	aridity	Rillito gravelly loam	mulch	surface
g	2008	Ferrini et al.	*Tilia × europaea, Aesculus × carnea*	B&B, 3 to 4 cm (dbh), herbicide	not specified	mulch	surface

[z] Mulch materials include: tree trimmings, wood chips, hay, chunk and shredded bark; composted materials include: food, humic acids, yard waste, leaves, grass clippings.
[y] Surface applications are application of 0 to 10 cm; deep surface application are > 10 cm; backfill amendments applied below the surface.

1994). The effect size parameter (d) was calculated with (s), the pooled standard deviation of the means and (J) a weighting term that approaches one as sample size increases (Cooper and Hodges 1994) (Equation 3). The weighting factor (J) was calculated with treatment replication, n_t and control replication, n_c (Cooper and Hodges 1994) (Equation 2). The effect size parameter (d) is very important as it corrects for an overestimation bias when sample sizes are small (Cooper and Hodges 1994), and d can be used for statistical tests of unequal sample sizes (Hunter and Schmidt 2004). Effect size will increase with increasing % change, decreasing variance, and increasing sample size. Consequently, effect size values close to zero (i.e., -0.2 to 0.2) relate weak responses relative to values farther from zero.

$$\% \text{ change } (\Delta) = [(X_t - X_c) / X_c] * 100$$

$$\text{Weighting factor } (J) = 1 - (3 / (4 * (n_t + n_c - 2) - 1)$$

$$\text{Effect size } (d) = (\Delta / s) * J$$

Treatment effects (Δ and d) were coded as positive or negative according to their interpreted impact on tree, soil, or environmental quality. For instance, a significant decrease in bulk density due to an organic treatment was assigned positive Δ and d values, even though the observed treatment response was a decrease relative to the control. Treatment effects were only calculated for data showing significant ($p \leq 0.05$) response on at least half of the data presented. For example, if soil temperature under mulch was significantly less than under bare ground on six of the ten measured dates, then treatment effects were quantified. Conversely, if soil pH was only significantly less under mulch compared to turf at one of the six measured depths, treatment effects were not quantified. The 33 studies in the meta-analysis spanned many different tree species, growing conditions, soil types, organic treatments, controls, and potential treatment interactions (Table 1). Details on species, soil characteristics, and other specifications (ages, care, potential interactions, etc.) were used for data interpretation.

Meta-analysis class variables (i.e., attribute categories) were established to lump significant responses into ecologically heterogeneous groups (Lipsey 1994). All significant responses were coded into the following seven attribute categories: 1) shoot growth, 2) root growth, 3) physiological, 4) soil chemical, 5) soil physical, 6) soil biological, and 7) environmental (Table 2). Treatment groups were identified according to the type of organic material (mulch, compost, and mix of mulch and compost) and mode of application [deep surface > 10 cm (4 in), surface 0 to 10 cm (0 to 4 in), and applied as in backfill] (Table 1).

Statistical tests were performed to identify differences relating to the type of organic material (mulch, compost, or mix) and mode of application (surface, deep surface, or backfill). The interaction between type and mode of application was not significant for any of seven attribute categories ($p \geq 0.844$). However, the availability of data likely limited our ability to adequately test for this interaction. No studies reported data for mulch as backfill or compost as a deep surface application. Only two studies used mixed materials as backfill. Only three studies reported data for compost applied to the surface and mixed materials on the surface. Other statistical tests were performed, such as the effect of experimental realm (e.g., field versus container environment), but these tests did not reveal any significant ($p \geq 0.270$) differences in field versus container studies for the entire data set or for any of the attribute categories.

Frequency distributions were compiled and data normality was tested with the Shapiro-Wilk test (SAS 2005). Analysis of variance with Tukey-Kramer HSD and Student's t-test were used to identify significant differences for various statistical tests (SAS 2005). All statistical differences are reported at the $p \leq 0.05$ probability level.

RESULTS

In total, 79 significant tree, soil, and environmental responses were identified in 33 studies (Figure 1). The distribution for percentage change (Δ) was nonnormal ($W = 0.778$; $p < 0.0001$) and heavily weighted (69%) in the 0% to 100% response relative to control range (Figure 1). The mean Δ for all significant responses was 44.8 (SE±9.1), and this value was significantly ($p < 0.0001$) greater than a null hypothesis, zero response (Figure 1). The effect size (d) parameter removed the bias associated with small sample sizes. The distribution of d was also nonnormal ($W = 0.581$; $p < 0.0001$) and heavily weighted (83%) in the zero to one response range (data not depicted). The mean d value for all responses was 0.58 (SE±0.2); also significantly greater than a null response of zero ($p = 0.0034$).

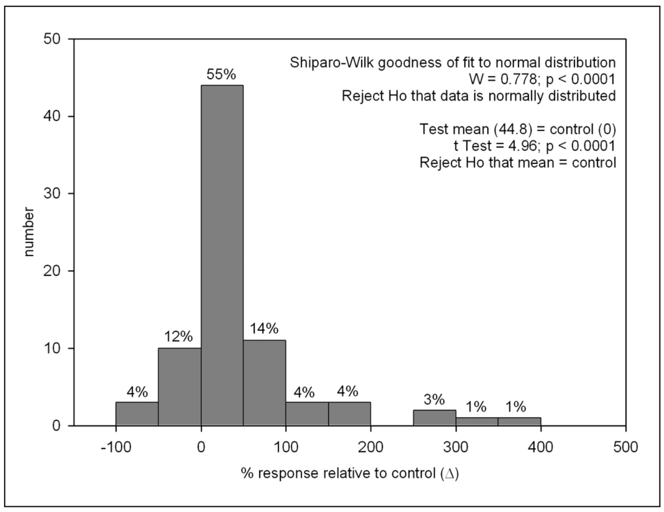

Figure 1. Frequency distribution of % response relative to control (Δ) for seventy-nine significant tree, soil, and environmental attribute responses to organic materials, detected in 33 studies.

The distribution of significant responses among attribute categories was: shoot growth (18), root growth (9), physiological (20), soil chemical (5), soil physical (18), soil biological (4), and environmental (5) (Figure 2; Table 2). Significant differences were identified for both Δ and d across these attribute categories (Figure 2). Percent response relative to control was significantly ($p = 0.0028$) greater for soil biological (160.0) compared to environmental (7.2), soil chemical (10.8), physiological (25.2), shoot growth (34.7), and soil physical (36.8) (Figure 2). Although not significant, root growth Δ (113.7) was less than soil biological and greater than other attribute categories (Figure 2). The d value was significantly ($p = 0.0444$) greater for soil physical (2.10) compared to soil biological (0.00), environmental (0.00), physiological (0.29), and shoot growth (0.46) (Figure 2). Soil chemical (1.02) and root growth (1.15) d values were intermediate (Figure 2).

Response parameters with the most number of significant detections included root density (7), soil moisture (7), soil temperature (7), tree diameter (6), shoot growth (6), transpiration (5), and tree height (4) (Table 2). Twenty-six of the 35 response variables (74%) had mean values that were positive. The greatest Δ positive values were for mycorrhizae density (324), germination (169), litter (158), root density (138), particulate organic matter (120), and soil porosity (103) (Table 2). Fourteen d-values were positive and two were negative (Table 2). Nineteen d-values were zero; indicating only one significant data point for that particular response parameter. The greatest positive d values were for soil porosity (4.9), soil pH (4.1), soil moisture (1.8), transpiration (1.6), and root density (1.4) (Table 2).

The mode of organic material application had a significant impact on soil physical properties (Figure 3). The mean Δ response was significantly (p = 0.0046) greater for studies that applied organics as backfill compared to those that applied organics to the surface and deep surface applications. Shoot growth tended (p = 0.1066) to be negatively impacted by backfill amendments compared to surface applications.

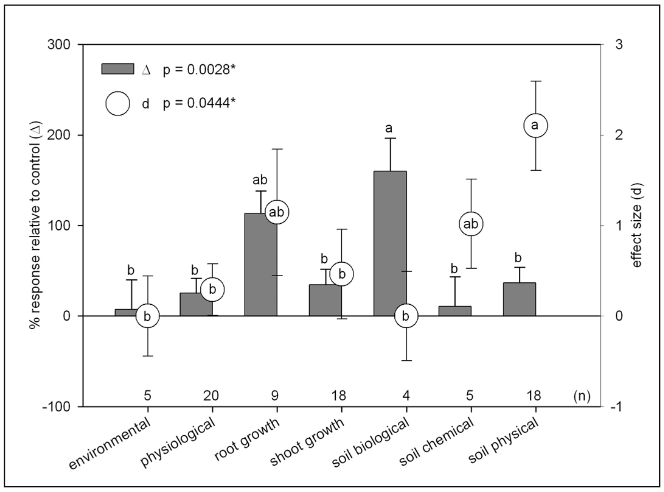

Figure 2. Mean % response relatives to control (Δ) [bars] and effect size (d) [circles] for the effects of organic materials on ecological attribute categories. Significant (p ≤ 0.05) differences for each matrix are identified by different letters. Errors bars indicate the 95% confidence interval. Numbers show the sample size.

Table 2. Attribute categories, mean % responses relative to control (Δ) with standard error estimates of mean (SE), effect sizes (d), and citations for response parameters used in this study.

Response parameter	Attribute category	Δ	SE	d	Reference[z]
tree height	shoot growth	14.8	14.2	0.5	ACWa
tree diameter	shoot growth	50.2	23.5	0.9	ABCFXg
shoot increment	shoot growth	46.8	34.8	0.6	ACFPbg
shoot biomass	shoot growth	-8.0	43.0	-0.1	be
root density	root growth	137.6	27.6	1.4	DFILQRV
root biomass	root growth	30.0	20.0	0.9	We
survival	physiological	-3.0	0.0	0.0	Z
germination	physiological	169.0	227.0	0.4	OS
root to shoot	physiological	30.0	0.0	0.0	b
leaf color	physiological	27.0	0.0	0.0	H
leaf biomass	physiological	-16.0	61.0	-0.1	bc
leaf stress	physiological	-37.0	0.0	0.0	Z
leaf phosphorus	physiological	-41.0	0.0	0.0	H
leaf manganese	physiological	9.0	0.0	0.0	U
photosynthesis	physiological	18.5	13.5	0.8	Yc
chlorophyll	physiological	26.5	18.5	0.8	Yc
water use efficiency	physiological	13.0	0.0	0.0	c
transpiration	physiological	22.0	6.1	1.6	KMXcg
soil moisture	soil physical	45.9	9.7	1.8	ABDGIPT
soil temperature	soil physical	13.3	5.4	0.9	ABEGPTf
soil density	soil physical	20.5	15.5	0.8	HN
soil porosity	soil physical	103.0	12.0	4.9	Yd
soil nitrate	soil chemical	-33.0	0.0	0.0	J
soil potassium	soil chemical	30.0	0.0	0.0	U
soil pH	soil chemical	10.9	1.1	4.1	HT
total SOM	soil chemical	35.0	0.0	0.0	a
litter	soil biological	158.0	0.0	0.0	a
particulate organic matter	soil biological	120.0	0.0	0.0	a
carbon mineralization	soil biological	38.0	0.0	0.0	a
mycorrhizae density	soil biological	324.0	0.0	0.0	H
long wave radiation	environmental	-35.0	0.0	0.0	f
surface temperature	environmental	-38.0	0.0	0.0	M
air temperature	environmental	-15.0	0.0	0.0	M
evaporation	environmental	44.0	0.0	0.0	K
weed density	environmental	80.0	0.0	0.0	P
all		*44.8*	*9.1*	*0.6*	*79*

[z] Reference codes are identified in Table 1.

The mean Δ across all attribute categories was greater (p = 0.1044) for backfill compared deep surface organic application.

The type of organic material had significant impacts across all attribute categories and on physiological attributes (Figure 4). Studies that used compost materials had significantly (p = 0.0012) greater Δ values compared to studies with mulch or a mixed materials. Physiological Δ values were significantly (p = 0.0326) greater for compost and mulch studies compared to studies using a mix. Shoot growth, root growth, and soil physical Δ were greater (p = 0.1282, 0.3237, and 0.1171, respectively) for compost studies compared to mulch and mix.

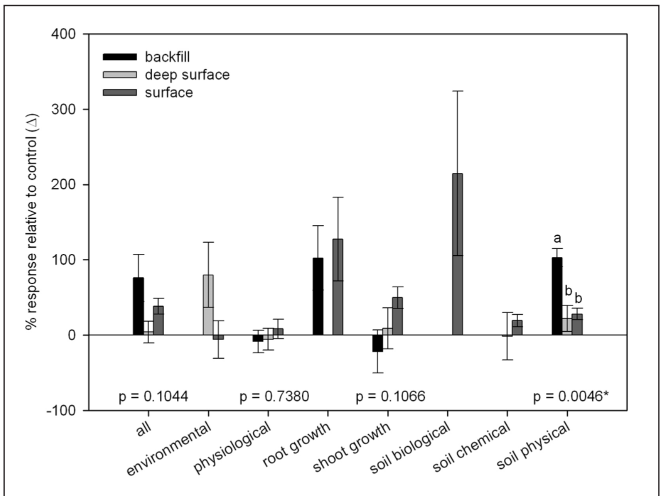

Figure 3. Mean % response relative to control (Δ) for surface mulches (0–10 cm), deep surface mulches (>10 cm), and backfill organic amendments across ecological attribute categories. Significant (p ≤ 0.05) differences for each are identified by different letters. Errors bars indicate the 95% confidence interval.

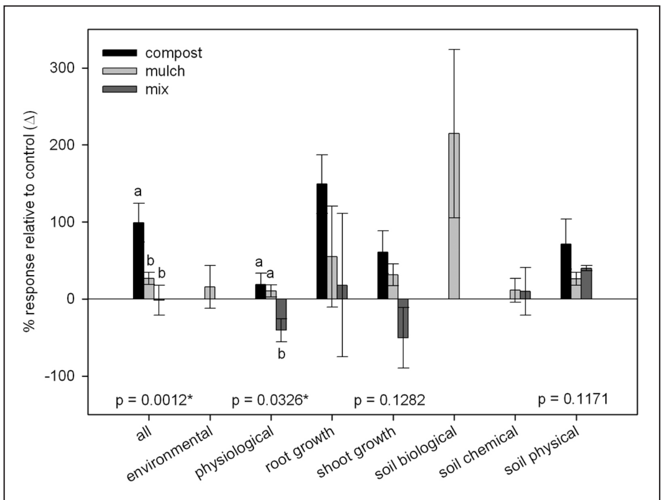

Figure 4. Mean % response relative to control (Δ) for compost, mulch, and mixed organic materials across ecological attribute categories. Significant (p ≤ 0.05) differences for each are identified by different letters. Errors bars indicate the 95% confidence interval.

DISCUSSION

Summary of Literature Search

Trends and conclusions from the 143 studies not included in the meta-analysis were compiled and are summarized in the following section. Although only selected references are given for the general trends, a full bibliography of these studies can be acquired by contacting the author.

Studies published in the *Journal of Arboriculture* in the 1970s were often qualitative tree evaluations. These studies suggest: 1) inorganic fertilization is required for establishment and maintenance; 2) organic material may be beneficial for tree establishment; 3) organic material may have benefits for controlling weeds and root rots; 4) plastic under mulch should be avoided; and 5) organic mulches are alternative uses of arboricultural waste (e.g., Hoitink et al. 1975; Schulte and Whitcomb 1975; Swisher 1976; Walker 1977; Smith 1979; Whitcomb 1979).

In the 1980s, the *Journal of Arboriculture* published more quantitative data on tree and soil responses to organic materials. Studies published in the 1980s: 1) increased awareness of the importance of soils and site factors for urban tree growth; 2) showed that the effects of inorganic mulches on trees and soils are different compared to organic mulches; 3) demonstrated that the environment under organic mulches is quite different from under turf-grass (e.g., Whitcomb 1980; Hamilton et al. 1981; Peck 1981; van de Werken 1981; Whitcomb 1981; Funk 1983; Craul 1985; Dyer and Mader 1986; Kozlowski 1987).

During the 1990s, the *Journal of Arboriculture* continued to publish more quantitative data on tree and soil, as well as, environmental responses to organic materials. Research in the 1990s suggested that: 1) organic materials have many benefits as soil surface covers; 2) urban soil organic matter cycling is unique from other systems; 3) organic materials may be useful to offset inorganic fertilization; 4) biological inoculants and plant growth hormones may have benefits for urban soils and trees (e.g., Dixon and Johnson 1992; Wager and Barker 1993; Craul 1994; Cregg 1995; Burch et al. 1996; Close et al. 1996; Marx et al. 1997; Smiley et al. 1997; McPherson 1998; Perry and Hickman 1998).

From the years 2000 to 2008, studies relating to organic materials published in *Journal of Arboriculture* and *AUF* detailed: 1) chemical and physical properties of mulches; 2) depth and placement mulches; 3) pathogens and flammability of mulches; 4) reviews of N availability and tree fertilization; 5) effects on soil biology and urban ecological function (e.g., Jin et al. 2002; Nowak et al. 2002; Struve 2002; Steward et al. 2003; Koski and Jacobi 2004; Scharenbroch and Lloyd 2004; Jacobs 2005; Wells et al. 2006; Day and Harris 2007).

The *Arboriculture & Urban Forestry* literature search showed that organic materials are a relevant *AUF* topic. Some recurring themes pertaining to organic materials in *AUF* literature relate to specifics of type of organic, how it is placed (i.e., mode), and quantification of impacts on trees, soil, and the environment. The following sections discuss these themes in the context of this meta-analysis.

Type of Organic Material

In general, mulches in these studies were coarser organic materials from tree trimmings, wood chips, hay, bark, etc. (Table 1). Compost was finer, more stabilized organic material, and mixed material contained some of both types. Most studies in

AUF did not provide specific chemical information (e.g., C/N ratios) for the organic materials. Twigs, wood chips, dead leaves, and residues of dead plants are rich in C and low in N and these materials often have C/N ratios exceeding 200/1 (Stratton et al. 1995). As substrates are decomposed (i.e., composted), C is lost via respiration and N is gained through immobilization, thus substrate C/N will decrease with time, and C/N of compost is commonly observed to be 20/1 to 35/1 (Stratton et al. 1995).

Microbial decomposition and mineralization kinetics of organic materials are controlled by substrate quality (e.g., C/N ratio, lignin, and polyphenol content) and environmental conditions (e.g., temperature, water, oxygen, and pH) (Bardgett 2005). Nitrogen immobilization occurs when the C/N ratio of the substrate exceeds approximately 20/1 to 25/1 (Sylvia et al. 1999). Lignin contents greater than 20% and polyphenol contents greater than 3% are suspected to slow decomposition (Melillo et al. 1982; Northup et al. 1995). Relative to C/N ratios, even less study has been directed to lignin and polyphenol content of urban landscape organic materials. Duryea et al. (1999) studied the biochemical composition of mulch as it impacts lettuce seed germination, but controlled experimentation is required for impacts on trees, soils, and environmental quality.

The meta-analysis of *AUF* literature supports others whom have found that nutrient-rich, fine-textured compost favors mineralization and is an excellent nutrient source (Lloyd et al. 2002). It is worthwhile to note that mulches made from diseased plant materials potentially contain those pathogens, thus high-temperature composting may be preferential in cases where disease may be an issue. Although compost is a fertile base, it is also a potential seed bank for weed establishment and growth (Chalker-Scott 2007). Compost is not effective at weed suppression relative to coarse mulch (Maynard 1998). This meta-analysis found greater improvements in soil physical properties with compost incorporated into the soil compared to surface-applied mulch; but, others have suggested coarser mulches may be better at water retention (Chalker-Scott 2007) and temperature buffering (Tilander and Bonzi 1997).

Tree attribute responses tended to be greater for compost relative to mulch, but both compost and mulch were associated with positive root growth, shoot growth, tree physiological responses. The negative responses associated with mixed compost-mulch studies are derived from observations of decreased germination of lettuce seeds (Duryea et al. 1999) and short-term decreases in shoot growth of containerized seedlings grown in a variety of composted biosolids (Roberts 2006).

Schulte and Whitcomb (1975) observed a decrease in tree height of young silver maples with an increase in pine bark mulch, and they attribute this decrease to a "tie-up" of nitrogen by soil microorganisms (i.e., N immobilization). Hensley et al. (1988) also observed a decrease in tree height with organic materials, but only during the first year, and the trend was reversed after 22 months, likely as C/N decreased. Long-term N immobilization or growth suppression is not likely to occur with mulch (Greenly and Rakow 1995; Pickering and Shepherd 2000). Experimental research has found increased soil and/or foliage nutrient levels with mulch (Arthur and Wang 1999; Foshee et al. 1999; Szwedo and Maszczyk 2000).

Mode of Organic Material

Research in *AUF* suggests backfill organic amendments improved soil physical properties relative to surface applications. Particle density of organic matter is 1.0 g cm^{-3} (62.4 lb ft^{-3}), which is less than mineral soil, 2.65 g cm^{-3} (165.4 lb ft^{-3}) (Rühlmann et al. 2006); thus, direct incorporation of organic material in planting holes will reduce soil bulk density.

The *AUF* meta-analysis shows that surface applications tended to improve shoot growth, root growth, and physiological response relative to backfill amendments. It has been proposed that when backfill soil differs from the site soil, roots may have difficulty crossing the interface (Pellet 1971; Schulte and Whitcomb 1975); but, Watson et al. (1992) did not observe root confinement to planting holes with organic backfill. The interface created in the planting hole between the organic and mineral soil is likely to impact soil water movement; but, to my knowledge, this has yet to be conclusively demonstrated in experimental study. The negative responses associated with backfill applications in this meta-analysis are from decreases in shoot growth and physiological properties, reported with containerized seedlings (Roberts 2006).

This meta-analysis found that normal surface applications of 0 to 10 cm tended to have more positive impacts on shoot growth and physiological attributes compared to deep surface applications. Arnold et al. (2005) reported negative impacts of decreased water penetration, increase soil tension, decreased shoot growth and increased plant stress with > 15 cm (6 in) of mulch. Conversely, Watson and Kupkowski (1991) did not observe detrimental effects on root density, temperature, moisture, or aeration from 45 cm (18 in) of mulch. Thicker layers of mulch may be better able to resist compaction and be beneficial as better temperature buffers and weed suppressors (Chalker-Scott 2007).

Impacts of Organic Materials on Trees, Soil, and Environment

This meta-analysis showed that *AUF* research found that organic materials had generally positive impacts on tree, soil, and environmental parameters (Figure 2). The strongest positive responses were observed for soil physical (n = 18; Δ = 36.8; d = 2.1), root growth (n = 9; Δ = 113.7; d = 1.1), shoot growth (n = 18; Δ = 34.7; d = 0.5), and physiological (n = 20; Δ = 25.2; d = 0.3) attributes. Percent changes were highest for soil biological attributes (n = 4; Δ = 160.0; d = 0.0), but the low sample sizes suppressed d values. Soil chemical properties had positive, but variable responses with low repetition (n = 5; Δ = 10.7; d = 1.1). The detectable response for environmental attributes was minimal, likely due to low number of studies reporting these values (n = 5; Δ = 7.2; d = 0.0).

Responses to organic materials observed in the literature summary and meta-analysis are compiled in a conceptual model (Figure 5). Changes in soil physical properties associated with increased organic materials include temperature buffering, reduced evaporation, increased infiltration, increased retention, increased drainage, reduced splashing, decreased density, and increased porosity. This meta-analysis did provide substantial evidence that organic materials are associated with buffering of soil temperature, improving soil moisture status, decreasing density, and increasing porosity.

There are many proposed soil biochemical improvements from organic materials (Figure 5). However, this meta-analysis did not identify many studies in *AUF* literature with data showing significant improvements in chemical or biological properties. It is logical to expect that organic materials would increase SOM, but only one *AUF* study provided significant data demonstrating this relationship (Scharenbroch and Lloyd 2006). Due to low sample sizes, we were unable to identify any trends as-

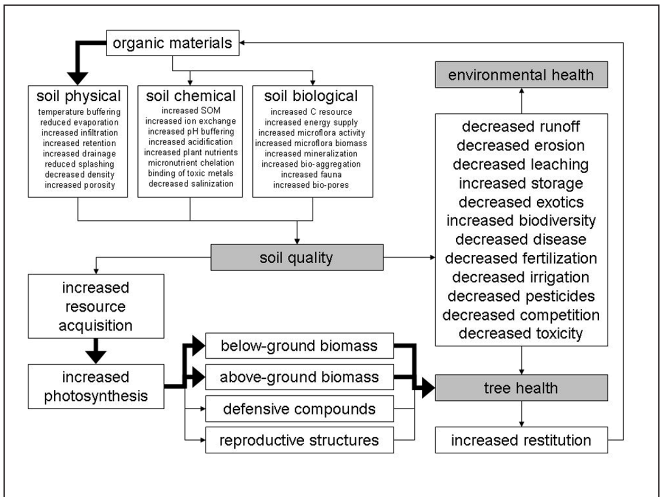

Figure 5. Conceptual model for the effects of organic materials on soil quality, tree health and environmental health. Size of arrow indicates relative support in literature published in *Arboriculture and Urban Forestry.*

sociated with soil available nutrients. A significant increase for potassium (Foshee et al. 1999) was detected, but Watson and Kupkowski (1991) detected a significant decrease in soil nitrate. Soil organic matter can chelate micronutrients making them more available for plant uptake (Evangelou 1998), and this is consistent with observed leaf Mn increase with organic materials (Foshee et al. 1999). The controls on the soil available nutrient pool (i.e., moisture, temperature, microbial activity) are erratic, thus a single temporal measurement of extractable nutrients is not a good indication of site fertility (Scharenbroch and Lloyd 2006).

Studies in this meta-analysis show a decrease in soil pH with organic materials. Although the pH change was consistent, conclusions drawn from this meta-analysis regarding soil pH should be tempered as the data is based on only two responses. One would expect that soil pH may be more impacted if the study were performed in a container rather than in a field setting, but the observed pH decreases with organic materials were observed for both conditions (Himelick and Watson 1990; Foshee et al. 1999). Studies not included in this meta-analysis suggest that acidification is generally beneficial as many urban soils are too alkaline for optimal plant nutrient availability (Kelsey and Hootmann 1988; Craul 1999). Soil organic matter is a soil acidification source via H^+ dissociation from carbonic acid and other acid functional groups (e.g., malic, carboxylic, and citric acids) (Evangelou 1998). Soil organic matter forms soluble complexes with nonacid cations, and as these cations leach, pH decreases (Sikora et al. 1996). Soil organic matter fuels microbial-mediated processes such as nitrification and sulfur oxidation, and through H^+ production, they acidify soils (Paul 2007).

Soil organic matter is the C and energy source for many soil organisms (Bardgett 2005). Consequently, activity and biomass tend to increase with increasing SOM (Sikora et al. 1996). Himelick and Watson (1990) found increased mycorrhizae infection and density with organic materials. Scharenbroch and Lloyd (2006) reported significantly greater labile substrate (i.e., particulate organic matter) and potential C mineralization (i.e., microbial respiration) with organic materials. This meta-analysis suggests positive impacts on soil organisms with organic materials, but the effects of organic materials on urban soil organism activity, biomass, and diversity have not been adequately studied.

It is probable that organic materials improve overall soil quality (e.g., decreased root resistance, increased aeration, water and nutrient availability, etc.), and these improvements would likely lead to increased resource acquisition. This meta-analysis did confirm an association between organic materials and increased shoot and root growth. There is much evidence in the literature showing that soil resources do impact physiological function (i.e., photosynthesis), C allocation patterns, and ultimately tree health (Matson and Waring 1984; Lorio 1986; Christiansen et al. 1987; Herms and Mattson 1992; Herms 2002; Glynn et al. 2003). Results from this meta-analysis generally support this explanation, but significant data demonstrating that organic materials directly improve soil properties, increase resource acquisition, increase photosynthesis, impact C allocation, and improve tree health were not available from any study in the meta-analysis.

Improvements in soil quality from organic materials can impact environmental health via numerous mechanisms (Figure 5). Organic materials protect soil and decrease losses with runoff and erosion (Lal et al. 2003). The end-products of humification (i.e., humus) are stable colloids with large exchange capacities, thus are very effective at nutrient, water, and toxin retention (Sikora et al. 1996). If organic materials are able to improve the water and nutrient status of soils, then reliance on inorganic fertilization and irrigation should decrease (Rechcigl 1995). Organic materials are proposed to create more diverse soil food webs (Coleman et al. 2004) and decrease weeds (Stinson et al. 1990), thus increasing competitive pressure on disease-causing organisms and weeds and our reliance on pesticides and herbicides. Globally, twice as much C is stored in the soil, 3340 Pg ($3.68 * 10^{12}$ tons) as in the vegetation, 550 Pg ($6.06 * 10^{11}$ tons) and atmosphere, 760 Pg ($8.38 * 10^{11}$ tons) combined (Batjes 1996; Soloman et al. 2007); yet, benefits of soil C sequestration with urban organic materials were not quantified in this meta-analysis or elsewhere.

The assumption that a meta-analysis uniformly represents the final and accurate viewpoint of an area of research is not warranted. A meta-analysis has a number of areas with the potential for bias, such as the inclusion or exclusion criteria used to select the studies for the meta-analysis. A particular bias in this study is that the responses were compiled solely from *AUF* research, and these responses may be a product of the research interests or perhaps the associated ease of measurement. On the other hand, no or low responses may suggest specific needs in *AUF* literature for identifying the impacts organic materials have on certain parameters (e.g., soil chemical, soil biological, and environmental properties). Attempts were made to limit bias by applying relatively stringent criteria (significant results on at least half of reported data for a given response) and including a robust suite of parameters in the meta-analysis (any and all parameters measured by any study published in *AUF* relating to organic materials).

CONCLUSION

At the coarse scale, positive responses for organic materials were detected for all attribute categories (Figure 2). Divergences in positive response occur when the type and mode of organic materials are considered separately (Figure 3; Figure 4). Studies in *Arboriculture & Urban Forestry* reported more responses for shoot growth, root growth, physiological and soil physical properties with organic materials; and, relative to those attribute categories, soil chemical, soil biological, and environmental responses, are less reported in *AUF* literature (Table 2; Figure 2). More *AUF* research is needed on the impacts of organic materials on soil biological diversity and function. Experimentation on organic materials and atmospheric quality (e.g., denitrification, CO_2 efflux, etc.) and water quality (e.g., N-leaching, P-erosion. etc.) is scarce in *AUF*. Additional research in *AUF* should be directed towards the mechanisms, not just associations, of how organic materials improve soil quality and ultimately tree health. The goal of this meta-analysis was to assess the state of knowledge for organic materials in *Arboriculture & Urban Forestry*, but future meta-analytical approaches should span entirety of scientific study.

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Zusammenfassung. Organisches Material wird gewöhnlich im Landschaftsbau zur Verbesserung von Boden, Bäumen und Umwelt eingesetzt. Eine Literaturübersicht zeigt, dass die Einflüsse von organischem Material positiv sind, aber dass diese Einflüsse noch durch meta-analytische Ansätze bewertet werden müssen. Diese Studie präsentiert eine Literatursammlung von 176 in der AUF veröffentlichten Artikeln und bewertet 33 davon mit Hilfe einer Meta-Analyse. Die themenrelevante Forschung wurde nicht nur in der AUF publiziert, aber die Meta-Analyse ist begrenzt auf die AUF in einem Versuch, einen Fokus auf die Information von AUF-Lesern zu richten. Diese Meta-Analyse liefert den Nachweis für höchst positive Einflüsse von organischem Material auf das Trieb- und Wurzelwachstum, Baumphysiologie und Bodenphysik. Es identifiziert auch Lücken in der AUF-Literatur bezüglich der Einflüsse organischen Materials auf Bodenchemie, -biologie und Umweltbedingungen. Darüberhinaus zeigt es, dass der Typ des organischen Materials und seine Aufbereitung unterschiedliche Wirkungen in Boden, Bäumen und Umwelt verursachen.

Resumen. Los materiales orgánicos son comúnmente usados en paisajes urbanos para mejorar el suelo, los árboles y la salud ambiental. Las revisiones de literatura sugieren que los efectos de los materiales orgánicos son benéficos, pero estos impactos deben ser evaluados usando aproximaciones meta-analíticas. Este trabajo presenta un resumen de literatura de 176 artículos publicados en *Arboriculture & Urban Forestry (AUF)* y evalúa 33 de estos reportes usan meta-análisis. La investigación relevante a este tópico no está publicada solamente en *AUF*, pero el meta-análisis está limitado a *AUF* en un intento de especificar la información provista a los lectores de *AUF*. Este meta-análisis provee evidencia de los impactos mayormente positivos que los materiales orgánicos tiene en el crecimiento de los brotes, crecimiento de raíces, fisiología del árbol y propiedades físicas del suelo. También se identifican espacios en la literatura de *AUF* para ver los efectos que los materiales orgánicos tienen en la química del suelo, biología del suelo, propiedades ambientales (clima, competencia, etc.). Además, este meta-análisis sugiere el tipo de material orgánico y el modo en que la aplicación tiene efectos diferentes en el árboles, suelo y propiedades ambientales.