Impact of Mulches on Landscape Plants and the Environment — A Review[1]

Linda Chalker-Scott[2]
Washington State University, Puyallup Research and Extension Center
7612 Pioneer Way E., Puyallup, WA 98371

Abstract

Mulches provide aesthetic, economic and environmental benefits to urban landscapes. Mulching is especially useful in the establishment of trees in landscapes that receive minimal care, such as restoration sites. In general, mulches improve soil health, creating healthy populations of plants and associated animals. These biodiverse, stable landscapes are more resistant to stress, are more aesthetically pleasing, require fewer applications of pesticides and fertilizers, and are ultimately more sustainable than those without mulch cover. All mulches are not created equally, however, and this review compares the costs and benefits of landscape mulches as reported in the scientific literature. It also presents real and perceived problems associated with various landscape mulches.

Key words: aesthetics, economics, inorganic mulch, living mulch, mulch management, organic mulch, pesticide reduction, plant establishment, soil protection, urban landscapes.

Significance to the Nursery Industry

There is a vast array of mulch materials available for landscape use, benefiting plants and soils through weed suppression, evaporation reduction, and other environmental modifications. Given the available choices, it can be difficult to determine which mulch materials are best suited for a particular landscape. The purpose of this review is to provide a comprehensive analysis of the scientific research on the benefits and drawbacks of mulches used in ornamental and urban landscapes. The article will be of particular value to industry professionals who sell, apply, or manage mulch materials, allowing them to make informed recommendations specific to their customers' landscaping needs.

Introduction

The term 'mulch' is derived from the Germanic word 'molsh', which means soft. Though not all mulches are soft, for many the word connotes the soft, spongy layer found in forest ecosystems. Mulches are defined as materials that are applied to, or grow upon, the soil surface, as opposed to materials that are incorporated into the soil profile (amendments). Therefore, any material laid or grown over the soil surface can be considered a mulch, though some materials are more beneficial than others.

Mulching received serious study as an environmental modification in forest, agriculture, and landscape applications beginning in the late 1930s, perhaps spurred by earlier studies examining the negative impacts of grasses on tree growth (9). 'Deep, permanent mulches' were recommended for shrubs and trees as early as 1941 (101) as a way of preventing drought stress (also 62, 131); likewise, prevention of freeze damage and frost heave were documented benefits (27, 72). In a comparative study, leaf material used as a mulch was found to be more effective in terms of water conservation than the same leaf material incorporated into the soil (116).

The increase in mulch research in the mid-1900s was closely tied to interest in reusing agricultural and forestry byproducts including wood pulp and shredded paper (22). More recently, other recyclables such as arborist trimmings, yard waste, and agricultural crop byproducts have been incorporated as mulching materials. Though landscape mulches were first reviewed in 1957 (2), there have been no analyses summarizing the scientific research on landscape mulches. Given the substantial use of mulch materials in the management of urban or ornamental landscapes, such a summary is long overdue.

Comparative Benefits of Mulches

Improved soil moisture. Exposed to heat, wind, and compacting forces, bare soil loses water through evaporation and is less able to absorb rainfall or irrigation as it becomes increasingly compressed. Weeds can increase evapotranspiration of soil moisture by 25% in a summer day (54). In contrast, mulches will increase soil water by increasing percolation and retention, reducing evaporation, and reducing weeds. An early study (105) demonstrated that a layer of straw only 3.8 cm (1.5 in) thick reduced evaporation by about 35% compared to bare soil. Later, Kacinski (62) demonstrated that most mulched soil has greater water retention than bare soil, with the exception of competitive living mulches such as turf.

What is less consistent is how different mulch types influence water movement. For instance, black plastic generally inhibits water movement (7, 12) between the soil and the above-ground environment, thus limiting recharge. Soil water recharge is dependent upon infiltration, which in turn is influenced by surface permeability. Activities and products that compact soils and/or create hydrophobic conditions will limit recharge while increasing runoff and erosion. Plastics, geotextiles, fine-textured organic mulches, sheet mulches, and mulches with waxy components are poor choices in this regard. Therefore, though these mulches may initially increase soil water retention since evaporation is reduced (68), over the long term they will create soils that are unnaturally dry.

[1]Received for publication May 12, 2007; in revised form July 24, 2007. Acknowledgements: I am most grateful for the thoughtful, constructive comments provided by two anonymous reviewers and for Dr. Fretz's assistance in preparing this Viewpoint article.

[2]Associate Professor. Email: <lindacs@wsu.edu>.

In contrast, there is a wide variety of mulching materials that do not limit soil water infiltration and retention: their one similarity is that they are all permeable materials. Most comparative studies among mulch types indicate that organic mulches conserve water more effectively than inorganic (6, 60); organic and inorganic are better conservers than synthetic (5, 73) and all are better than bare soil (6, 60, 65, 68, 76, 107, 112, 134). Mulches with demonstrated ability to retain water include gravel and stone (6, 60, 65, 112, 133), livestock manure (15), and a vast array of plant materials. These consist of rapid decomposers such as grass clippings (31, 107), leaves (116, 134) and local crop residues (68, 76, 92, 108, 127); moderate decomposers including hay and straw (73, 93, 103, 108, 133), coir pith (6, 53, 76), and jute (8); and slowly decomposing timber residues (46) including sawdust (5, 66), and barks and chips from both hard- and softwoods (31, 43, 60, 65, 68, 73, 96, 99, 131, 134). Cover crops are generally less effective than either organic or inorganic mulches (31, 68, 96, 107, 133) as they must compete with other landscape plant materials for water.

From a practical viewpoint, an appropriate mulch will significantly reduce the amount of irrigation needed for all landscapes, and in some cases can eliminate it altogether (99). In addition to protecting soil reserves, coarse organic mulches will hold water much like a sponge, thereby capturing rainfall and irrigation water for later release and preventing runoff. An early study demonstrated that 1.5 cm (0.6 inch) of straw mulch reduced water runoff by 43% (10); mowed sod and bark were likewise found to reduce runoff (87). Less runoff and improved retention will translate to reduced needs for supplemental irrigation. In addition, mulch protection from drought stress can also protect trees and shrubs from subsequent environmental stresses such as cold injury (118).

Reduced soil erosion and compaction. Mulch will protect soils from wind, water, and traffic-induced erosion and compaction, all of which contribute directly to root stress and poor plant health. Though living mulches are often the most effective in this regard, holding the soil matrix together even on the steepest slopes, they may not be the best practical or economic choice. Grass sowing, for instance, can reduce erosion but often increases runoff compared to other mulch choices (104, 126) as did barley (*Hordeum vulgare*) (109).

Adding even a thin organic mulch will protect soils: Borst and Woodburn (10) found that a 1.5 cm (0.6 in) layer of straw mulch reduced soil erosion by 86%. Straw from rice (*Oryza sativa*) and other grains continues to be commonly used (107) and in some cases can outperform living mulches such as legumes and grasses (107, 126). Straw mulch in combination with an erosion net was found to decrease erosion by 95% over bare soil treatment in a forest plantation (84). Fallen pine (*Pinus* spp.) needles resulting from beetle attack helped prevent soil erosion (80), and logging debris was used to intercept water and reduce overland flow (104). These studies all underscore the importance of leaving fallen vegetation on forest sites. [It is important to note that mulches cannot be use to 'stabilize' slopes but only reduce soil loss. Slope stabilization requires an engineering solution, not a horticultural one.]

Compaction is a common aliment of urban soils; while the impacts of foot and vehicular traffic are self-evident, it's less obvious that rainfall will compact unprotected soils. Adding organic mulch such as bark (96) or jute (8) disperses the direct impact of water droplets, feet, and tires, thus restoring soil aggregation and porosity. It is better to apply mulch before compaction occurs rather than after the fact. Research has demonstrated that proactive mulching will protect soil integrity, while the same mulch applied after compaction could not reverse bulk density changes even after two years (30).

Maintenance of optimal soil temperatures. Mulches protect soils from extreme temperatures in that soils can be kept cooler in hot conditions (37, 43, 74) and warmer in cold conditions (66). Temperature extremes will kill fine roots and while rarely killing established plantings, they can induce a chronic stress as the plant expends energy to generate new fine roots. Temperature modification is especially important near the soil surface, where fine roots can be killed by freezing and frost heaving (49). Hot or cold surface soils can kill new transplants that have not had time to generate a large root mass and establish into deeper, more moderate, surrounding soils.

This moderating effect is especially important during the winter and/or in alpine and arctic regions, where warmer soil can enhance root growth and thus establishment of desirable plants. Cold hardiness of the plants, however, is not lessened by this treatment (140). Protection of sensitive root systems from freezing has the added benefit of preventing opportunistic root rots from attacking stressed seedlings (128). In summer months or in hotter geographical regions, organic mulches have been shown to lower soil temperature nearly 10C (50F) compared to unprotected soil (76).

Coarse mulches are more temperature moderating than finely textured mulches of the same general category; for example, the soil under cobbles is cooler than that under gravel, and the soil under leaf mulch is cooler than that under compost (127). Likewise, thicker applications of organic mulches are more temperature moderating than thin applications (131). Once again, coarse mulches are better in this regard (57) as thick layers of finely textured mulches can inhibit both water and gas transfer.

Among mulch categories, living (133) and organic (6, 60, 76, 89, 133) mulches are more temperature moderating than inorganic mulches. Chunky inorganic mulches such as gravel and lava rock are more effective temperature moderators (6, 60, 89) than solid inorganic surfaces such as concrete. Synthetic mulches including asphalt, fabrics and plastics are poorest in this regard (73, 89, 133), routinely raising the underlying soil temperature as deep as 30 cm (12 in) below the surface (33). For some special applications (such as soil solarization to kill pests [82]), this might be desirable, but not for general landscape or garden maintenance. Black plastic mulches can either raise (73) or lower soil temperatures (130), probably depending on how much light is absorbed by the plastic and whether heat is retained or reflected. Clear plastic mulches routinely raise soil temperatures since radiation (including infrared wavelengths) is transmitted through the plastic and heat is retained.

While the impacts of mulches on soil temperature have been well documented, there is also an effect of mulch type on surface temperature. There are far fewer studies on this phenomenon, but it is clear that some mulches heat the soil as a function of solar radiation absorption more than bare soils and living mulches (89). The increased surface temperature due to pine bark mulch caused nearby leaves to lose more water (143), though at greater distances [e.g. 1 m (3.3 ft)] there is no mulch effect upon air temperature (144).

Living mulches such as turf release water vapor through evapotranspiration and reduce surface temperatures by evaporative cooling (89), though they use more soil water than non-living mulches. Interestingly, the soil temperature beneath turf was shown to be higher than that below mulch (23), perhaps because soil beneath turf was drier and thus less protected against high temperatures. Heat-reflecting mulches are sometimes useful, especially in improving fruit maturation (48); for most urban or managed landscapes, however, this is probably not a priority.

Increased soil nutrition. Living and organic mulches can increase, decrease, or have no effect upon nutrient levels depending upon mulch type, soil chemistry, and particular nutrients of interest. As living and organic mulches decompose under appropriate water and temperature levels, nutrients are released into the soil and become available for root uptake or microbial use. Generally, green and animal manures used as mulch supply nutrients at higher rates than other mulch choices (such as straw, bark and wood chips) and often perform better than inorganic fertilizers (3, 31, 100, 116). While immediately available nutrients are sometimes desirable for a landscape, it is important to note that overapplication of these materials can lead to excess mineral availability, causing damage to plants, soil organisms, and nearby watersheds. Therefore, nutrient-rich mulches should be applied sparingly and may be most effective as part of a mulch layer.

While living mulches often compete for nutrients as well as water, this characteristic can be valuable on landscapes where fertility is too high. Fast-growing plant materials will reduce soil nutrient levels (94) as can microbial activity in low-fertility organic mulches. This has been helpful in restoration of ecosystems with naturally low fertility, allowing native plants to compete more effectively with invasive species (145). Low nutrient mulches such as uncomposted bark or straw were found to decrease nitrogen levels of soil water while not impacting plant nutrition (95), thus reducing watershed pollution.

While mulches with relatively high nitrogen content often result in higher yields (127), low nitrogen mulches can also increase soil fertility and plant nutrition. For example, straw (125), sawdust (5) and bark (99) mulches have been shown to increase nutrient levels in soil and/or foliage. Likewise, mulches of husks were most effective in increasing available soil nutrients compared to grasses and leaf-litter (114), which presumably would have higher nitrogen levels.

Reduction of salt and pesticide contamination. Many landscapes experience salinity stress besides those found near marine coastlines. Arid landscapes in particular are often highly saline as evaporating water leaves behind salt crusts. Irrigation water in arid environments and improperly treated greywater (domestic, non-sewage waste water) can also contain high levels of salts from fertilizers, detergents and other chemical sources. Container plants that are over-fertilized will likewise experience increasing levels of salts.

Because mulches reduce evaporation, more water is left in the soil and salts are diluted. Furthermore, organic mulches can reduce the effect of salt toxicity on plant growth (3, 69, 142) or actively accelerate soil desalinization (29). Plastic mulches are not effective in this regard (123), probably because they are not able to bind ions as organic materials can. Organic mulches can also help degrade pesticides and other contaminants (45, 117), presumably by providing increasing microbial populations that degrade pesticides.

Increased binding of heavy metals. Organic as well as living mulches can be effective in removing heavy metals from landscape and garden soils. Common urban contaminants such as lead and cadmium can be removed from the soil solution by mulched leaves of eucalyptus (*Eucalyptus* spp.*)*, pine, poplar (*Populus spp.)*, and arborvitae (*Thuja* spp.) (106). Likewise, a mixture of compost and woodchips was found to decontaminate forest soils by complexing copper into a less toxic form (63).

Improved plant establishment and growth. Mulches are used globally to enhance establishment of many woody and herbaceous species. There are hundreds of controlled studies demonstrating that mulches improve seed germination and seedling survival, enhance root establishment and transplant survival, and increase overall plant performance when compared to unmulched controls. Practically, this translates to healthier trees and shrubs requiring less maintenance and chemical application.

A. Improved seed germination and seedling survival. Kacinski (62) demonstrated that mulching planting pits with manure or sawdust improved oak (*Quercus* spp.) seedling survival compared to unmulched pits and surface plantings. Since then, numerous studies have found mulch to enhance seed germination and seedling survival.

Seedling emergence and survival presents a management conundrum: we want to encourage desirable plants yet prevent weeds from establishing. Unfortunately, mulches do not distinguish between weeds and desirable plants. For this reason, many mulches are not appropriate for annual flower beds and vegetable gardens. On the other hand, these same mulches are excellent choices for repelling weed colonization.

Success in this respect may be determined by mulch depth and/or seedling maturity. Deeper mulches are associated with improved weed control and are not the best choices for areas that are to be seeded rather than planted, especially if the species of interest have small seeds. Broadcast seeding on a restoration site was successful when a thin mulch layer was applied post-seeding, but significantly reduced when the mulch depth was doubled or when mulch was applied before seeding (103). Organic mulch may be a better choice for seed germination than gravel (90), which in deeper layers can prevent seedling emergence (137). Once seedlings have emerged, mulches are associated with improved seedling performance under both nursery (88, 128) and field (92) conditions.

B. Enhanced root establishment and transplant survival. Numerous studies have demonstrated that improved water retention and reduced weed growth are correlated with increased root growth and exploration by desirable plants (39, 138). Mulches allow roots of trees and shrubs to extend and establish far beyond the trunk compared to bare soil (17, 134) and thus become increasingly stabilized.

Mulch choice is important in determining how well roots will explore the underlying soil. Root development and density was greatest under organic mulches compared to that under plastic (39), bare soil (134) or living mulches (50). In contrast, sheet and film mulches that act as barriers to water and air movement will encourage root growth on top of the mulch (4), which can eventually injure desirable plants when and if the sheet mulch is removed. In another study (58), plastic mulches used with a fertilizer treatment led to increased mortality of transplanted materials.

Roots tend to grow into organic mulch layers (134–135), but by and large these are fine roots whose presence is transient. Generally, these roots exploit water and nutrient resources in mulch until conditions become unfavorable (e.g. when much begins to dry in the summer). These roots die back and new feeder roots appear where resources are more available. In any case, it does not appear to injure the plant to have roots exploring the mulch layer. However, roots will also colonize landscape fabrics and if these materials are eventually removed they could cause extensive damage to fine root systems. This is one reason not to use landscape fabrics around woody plants.

If roots can establish successfully, then plant survival is more likely. Thus, use of landscape mulches have been shown to decrease mortality of new transplants even in harsh environments such as mine tailings (91, 139), saline soils (3, 123) and subarctic systems (58). Enhanced survival through mulching has been seen in nursery and field production (76, 79, 92), silvipasture systems (108), forest plantations (31, 46, 59), and restoration sites (18, 145). Competitive cover crops such as turf will increase mortality of transplants (31).

C. Increased overall plant growth performance. As early as 1942, researchers found that mulched trees grew 67% better than those grown on bare soil (56). Many others since then have shown similar improvements in growth of trees, shrubs, and other plant materials in field and nursery conditions (6, 15, 19, 42–43, 50, 99, 112, 114, 116). Specifically, increases in plant height (6, 18, 73, 76, 91, 102, 108, 115), stem or trunk diameter (6, 31, 50, 91, 107, 108, 115), leaf size and/or number (26, 31, 76, 91, 99), and flower, fruit and/or seed production (99, 127, 131) have all been reported as a result of mulching with appropriate materials.

The best mulches for overall plant performance are organic materials, consistently rated as the best or second best in comparative field trials. Tested mulches include rapid decomposers such as grass clippings, leaves, and compost (50, 99, 107, 115, 127), moderate decomposers including paper (102), hay and straw (26, 73, 108, 131), and other crop residues (6, 76, 115) and slow decomposers, especially bark and woody chips (31, 50, 99, 102). The exceptions to this trend are almost exclusively found in annual crop production research, where slow decomposers such as bark can create nutritional problems for fast-growing species with limited root mass (26).

Gravel and stone are generally not as effective as organic mulches (6, 108, 112, 115) in optimizing plant performance. Sheet mulches can also produce disappointing results (73, 112). Not surprisingly, competitive ground covers such as turf grasses result in reduced growth (107, 131) even compared to bare soil conditions (31, 65).

Reduction of disease. Physically, mulches will reduce splashing of rain or irrigation water, which can carry spores of disease organisms up to the stems or leaves of susceptible species. Additionally, the populations of beneficial microbes that colonize many mulch materials can reduce soil pathogens either through direct competition for resources or through chemical inhibition. Regardless of the mechanism involved, disease reduction is an important benefit of many mulches.

Researchers have long suspected that mulches play complex roles in disease prevention and recovery. Spaulding and Hansbrough (119) found the ‘retention of a normal layer of fallen dead needles under the trees … will help the trees to resume normal growth’ after suffering needle blight. Part of the complexity is that mulches can act indirectly and/or directly to prevent disease establishment. This relationship was explored by Downer et al. (32) who identified both short- and long-term effects of mulching on the incidence of *Phytophthora* root rot. Indirect effects are both short- and long-term and include increased soil moisture, soil temperature moderation, improved soil nutrition, and improved soil aggregation and drainage. Thus, mulches maintain an optimal soil environment, which in turn supports healthy plants that are less susceptible to opportunistic pathogens (130).

Mulches can combat disease organisms directly as well. Researchers have found that Western red cedar (*Thuja plicata*) heartwood contains thujaplicin, a water-soluble tropolone not only inhibitory to various bacteria and fungi, but with antitumor activity as well. This antimicrobial activity is probably responsible for the rot-resistant nature of cedar wood. In addition to plant-derived antibiotics, healthy organic mulches may also contain a variety of soil microbes that can exert biological control over pathogens, either through resource competition or enzymatic degradation (24). Many microbes produce cellulase enzymes that attack the cell wall of pathogens such as cinnamon fungus (*Phytophthora cinnamomi*) (32). Mulching soils to encourage populations of indigenous, beneficial soil microbes will increase the effectiveness of biological control in managing disease (38). This may explain why organic mulches such as straw (11) and wood chips (26) are more effective in suppressing disease than landscape fabric and black polyethylene, respectively.

Some mulches, however, can increase the incidence of disease by exacerbating already poor soil conditions (e.g. using a plastic mulch). Sawdust was implicated as a likely medium for shoestring root rot (*Armillaria mellea*) when used as a garden mulch in 1948 (77). Bacterial soft rot (*Erwinia carotovora*) was significantly greater in plants grown with a black polyethylene mulch than with bark or wood chips (26). Therefore, selecting an appropriate mulch is crucial as part of an IPM program.

Reduction of weeds. Mulching as a means for landscape weed control is highly effective, though the mechanism(s) responsible for control are not completely understood for all mulch types. Mulches can effectively be used in nursery production as well as in the field; Wilen et al. (136) found a 92% reduction in weeds of container plants that were mulched rather than left bare. Nearly all mulches reduce light, which will stress existing weeds and prevent the germination of many weed species, especially those with small seeds. A comparison of 15 mulch types showed that all significantly reduced weed growth as compared to bare soil, but there were no differences between types tested (122). The physical barrier created by other mulches can prevent weeds from emerging, though this effect is temporary and disappears as mulches decompose. Certain organic mulches, especially wood chips, may control weeds chemically through the leaching of allelopathic chemicals naturally occurring in the wood. Additionally, the protected soil habitat created by the use of mulches can increase beneficial organisms that prey upon weeds or eat their seeds.

Living mulches can reduce weed problems through both competition for resources and allelopathy. Ideally, cover crops and ground covers suppress weed seed germination and establishment while having little effect on desirable plants. This ideal is realized in situations where ground covers occupy a different niche than the desirable plants (e.g. trees and large shrubs whose roots are typically deeper than ground covers) (52). If ground covers are too much like other plants in the landscape, such as low-growing herbaceous perennials, then they may compete more directly for limited resources like water, nutrients and sunlight.

Although they can be highly effective in immediately eliminating weeds, plastic films and landscape fabrics should not be used as a long-term approach of weed control in landscapes. White and green plastics do not eliminate photosynthetic radiation, thus allowing weeds to continue to grow underneath; darker mulch colors will eliminate these wavelengths and prevent weed growth (57). Regardless of mulch color, eventually, weeds will colonize soil above these mulches and some weeds can pierce and grow through plastic films (57). Replacement of plastics and fabrics is not only time-consuming and expensive but also damages the roots of desirable plants that invariably will grow through and over these mulches (4).

In general, inorganic and organic mulches are most effective in weed control when applied at sufficient depth (51) and are least susceptible to compaction (37). Inorganic mulches such as gravel will prevent weed growth if the layers are at least 4 cm (1.5 in) deep (137). Because inorganic mulches do create otherwise optimal conditions (i.e. adequate soil moisture and moderated temperature), the absence of light in these deeper mulches is probably responsible for the lack of germination of weed seeds that require light for germination.

Organic mulches are variable in their weed-controlling abilities. Nutrient-rich, finely textured materials like compost are not satisfactory mulches for weed control (75, 79, 95). Instead, they act as a fertile base and potential seed bank for establishment of new weeds or enhancement of perennial weeds. Weed seeds that settle on top of organic mulches are more likely to germinate, especially if the mulch layers are thin (meaning seedling roots can more quickly reach the underlying soil. Applying two, rather than one organic mulch layer results in significantly less seed germination (103).

Organic mulches that are coarse, applied in thicker layers, and/or less nutrient-rich are more effective in controlling weeds — sometimes even better than herbicides (18, 44). Locally-derived residues from crops (26, 76, 93, 95) and forest products (19, 26, 37, 46, 57, 95) have all proved effective in reducing weed success in a variety of agricultural and landscape situations, especially in uncomposted form (95). While some studies recommend the use of sawdust for weed control on forest lands (5, 131) or in container production (90), others have noted that thick layers of sawdust can be impermeable to gas and water movement (120). This material might best be used in situations where soils are less frequently compacted by vehicular or foot traffic: not urban landscapes.

Reduced pesticide use. Mulches reduce plant stress and susceptibility to pests. This important function means that plants will be more resistant to weed invasion and opportunistic pests and pathogens, which leads to reduced use of herbicides, insecticides, and fungicides. Reduction in unnecessary chemicals not only saves money but also preserves the health of beneficial insects, bacteria, fungi, and other soil organisms that might otherwise be negatively affected.

Aesthetic improvement. Mulches can be beautiful as well as functional; though this is not a scientifically measurable aspect, the fact remains that aesthetics will influence mulch choices and usage. Many mulches, such as ground covers or tumbled glass, can add to a landscape's design elements while protecting soil. Visually distinctive mulches can be used to control foot traffic by directing pedestrians through a landscape, which both protects sensitive root zones and adds a design element. Some mulches add other sensory elements in addition to visual interest: smooth rock and soft ground covers invite touching, while fragrant ground covers and fresh organic mulch add enjoyable scents to the landscape. The aesthetic appeal of mulches is critical to their acceptance by consumers, who may otherwise perceive mulches as 'messy' and prefer the appearance of bare soil.

Economic value. For any landscape management practice to become widely adopted its economic viability must be established. Many decades of research has demonstrated that mulching improves crop production. Far fewer studies have addressed the economic impacts in urban landscapes and so it is difficult to make detailed economic arguments based solely on tangible costs and benefits.

Over 40 years ago Hunt (59) found that 'the increase in survival of mulched plants more than compensated for the extra cost.' Likewise, Brantseg (14) found that retaining logging slash increased increment size of new tree seedlings and thus the economic value of replanted pine forests. Not all mulches result in defensible cost:benefit ratios. Paper, plastic discs and black polyethylene mulches all failed to improve survival and growth for several tree species, causing the researcher to recommend against their use for economic reasons (70). Furthermore, the synthetic mats and films tend to be the most expensive choice (111, 141).

Cost savings have been more specifically identified by others and include reduced use of pesticides (21, 46) or other weed control methods (46). Utilizing locally-produced woody debris as a production mulch was described as 'a useful and affordable tool' with low external input for restoring damaged land, improving crop tree growth, and increasing farmer income (91). In a more urban application, brush mulch was found to be 'applied easily and economically' during revegetation of roadsides (104).

Locally available materials continue to be good economic choices. An early study (131) recommended timber harvest residue as a mulch over peat materials based on both cost and performance. Another study which compared several different mulches found unprocessed bark from regional sawmills to have the greatest cost:benefit ratio as long as the cost did not exceed \$2.75 per m^3 (\$2.10 per yd^3) (102). In tropical regions, paddy straw mulch is routinely used and one study found it to have the highest benefit:cost ratio (93).

Mulch Problems — Real and Perceived

Acidification. Organic mulches such as wood chips and bark are thought by some to be soil acidifiers. No scientific research supports this, and in fact studies refute this perception. One study found neither pine bark nor pine needles had any affect on soil pH (51). A second report (60) found bare soil to be more acidic than soil covered by inorganic mulch, and that shredded bark and wood chips were least acidifying of all treatments. Similarly, a year-long study found that the soils under organic mulches were either more alkaline or not affected by mulch treatment (100).

It's likely that in artificial conditions, such as nursery production, that woody materials do have an acidifying effect when they are used as part of a potting medium. Release of phenolic acids is one stage of the decomposition of woody material, and if this material comprises the bulk of medium then acidification is likely to occur. In a field situation, however, where the woody material is used as a mulch (and not worked into the soil), any acidification will be localized within the mulch layer and have little effect on the vast underlying soil environment below. Thus, soil acidification due to mulching with woody plant material is unlikely to occur under real world conditions.

Allelopathy. Allelopathy is the inhibition of seed germination and growth of plants through the release of chemicals and apparently plays a large part in the weed-controlling behavior of many organic and living mulches. A few growth-inhibiting substances have been isolated and identified, including the classic example of juglone (and juglonic acid) which is produced in all parts of black walnut (*Juglans nigra*). Juglone can injure or kill seedlings and shallowly rooted plants, though it apparently has little effect on established plants (54). In laboratory tests, allelopathic activity of a compound is usually confirmed by inhibition of seed germination (34) rather than how it affects mature plant materials. Other well-studied, plant-derived natural pesticides, such as those within the *Thuja* species described earlier, have no demonstrated negative effect upon plant materials.

Seeds and seedlings, whether weeds or desirable species, are most sensitive to mulch suppression as they do not have the extensive root systems of established plants. Mulches made of pine, eucalyptus, and acacia (*Acacia* spp.) were able to suppress germination of several common weed species as were water extracts of these materials, supporting an allelopathic function (110). Grasses may be less affected than dicot weed species (110), and this may help explain the apparently contradictory evidence demonstrating that eucalyptus leaf mulch has no effect on rice seed germination (*Oryza* is a monocot genus) (71).

It is unlikely that any properly applied landscape mulch will have allelopathic effects on established landscape plants, but is most likely to injure newly planted or shallowly rooted plants in the landscape. For such plantings, a short period of composting and correct application of woody mulch will prevent damage.

Competition. As mentioned earlier, living mulches can be competitive with landscape plants for water, nutrients, and space. Bedford and Pickering (1919) were perhaps the first to document both the interference of grasses with tree growth, as well as its subsequent recovery upon grass removal (9). Turf and other grasses are very competitive (9, 47), especially during plant establishment (65, 139). Thus, turf grass must be kept away from newly installed shrubs and trees and can easily be replaced with an organic mulch. These 'tree skirts' allow rapid root establishment without competition from turf roots (Fig. 1).

Chemical contamination. As with composts, woody mulch quality is influenced by the source of materials. Mulches created from branches and tree trimmings often contain a diversity of leaves, wood, and bark, which contributes to a highly functional mulch. In contrast, woody mulch made from wood recovered from construction and demolition debris can contain pressure-treated lumber. In one Florida study, 18 of 22 samples collected from debris processing facilities contained arsenic (from chromated copper arsenate-treated wood) at concentrations greater than the state's allowable levels (129). Similarly, mill wastes that contained formaldehyde and other wood processing residues reduced survival of tree seedlings when used as a mulch (85).

Disease. Mulches made from diseased plant materials can contain those pathogens. For this reason, many mulches are composted (55) or otherwise treated at temperatures that kill the pathogens along with other harmless or beneficial organisms. Therefore, many commercially available organic mulches are relatively sterile.

While mulches made from diseased wood can contain viable populations of pathogens such as honey locust canker (*Thyronectria austro-americana*) (64), few examples of disease transference exist in the literature. Wood chips made from infected maple trees and used as a mulch failed to spread *Verticillium* spp. to healthy trees (28). Likewise, a wood chip mulch containing the shoestring root rot pathogen did not exhibit disease transmission, perhaps because the organism

Fig. 1. Tree skirt of coarse arborist wood chips creates a competitor-free zone to allow root establishment in turf.

dried out rapidly (98). Finally, a six-year study of diseased woody mulches found no transmission of either butt rot (*Armillaria gallica*) or canker (*Botryosphaeria ribis*) pathogens to common landscape tree species (61). The only evidence of disease transmission occurred when foliage from Austrian pines (*Pinus nigra*) infected with tip blight (*Sphaeropsis sapinea*) was used as a mulch around healthy saplings of the same species (61). No trees from other species were affected, and the author acknowledges that Austrian pines are particularly susceptible to this pathogen. It is not surprising that so few examples of mulched-mediated disease transmission have been documented. The pathogen of interest must be present in such a way as to fit the epidemiology of the disease cycle; simply existing in a mulch source is not enough.

While disease transmission from mulch to tree is unlikely, there is greater probability of infection if backfill soil is amended with wood chips. A researcher working with rhododendron (*Rhododendron* spp.) lost plant material to *Phytophthora* root rot after amending the soil with 33% composted wood chips (97). A similar transmittal of verticillium wilt (*Verticillium dahliae*) was seen when infected wood chips were used as part of a potting mix (41). Not only is this a poor practice for installing woody plants, it also casts doubt on the efficacy of composting to eliminate pathogens.

Many landscape pathogens are both opportunistic and pervasive in the soil environment. *Armillaria* spp., for instance, are widespread in many soils as a decomposer but can become pathogenic under unhealthy soil conditions. Healthy soil communities, on the other hand, have diverse fungal and bacterial species, many of which are symbiotic partners of plant root systems. These beneficial species can outcompete pathogens as long as soil conditions remain optimal for root growth. When soils become compacted and anaerobic, plants decline and become susceptible to opportunistic pathogenic microbes — always present but inactive in healthy soils.

Given the distance between wood chip mulch and plant roots, it's doubtful that pathogens would travel far under healthy soil conditions. Fresh wood chips have been used as a mulch in other long-term studies without any report of disease transmission (43, 95). It does, however, point out the importance of keeping wood chip mulches away from the trunks of trees and shrubs as moist trunk conditions are at risk of pathogen infection. In addition, only unprocessed wood should be used in making wood chips. Mulches derived from shipping pallets and other wood packing materials, especially if uncomposted, could introduce exotic plant pathogens (64).

Though they do not qualify as disease organisms, other fungal species should be mentioned as possible nuisances in woody mulches. The artillery fungus (*Sphaerobolus stellatus*) can be found on landscape mulches where it can propel sticky spore masses onto the sides of nearby light-colored cars and houses (13, 55). Spent mushroom compost has recently been identified as an antagonist to this fungus (25) and might be a wise choice as a mulch component in affected landscapes. The colorfully named 'dog vomit fungus' (*Fuligo septica*) — actually a slime mold — creates a bright yellow mass on woody mulches. This is not a pathogenic species but may be of questionable aesthetic value.

Flammability. Though there are documented incidences of spontaneous combustion of yard wastes (16), in general wood-based mulches are not flammable. A recent comparison of 13 landscape mulches (121) found rubber mulch to be the most flammable, followed by fine textured organic mulches (dried pine needles, straw, shredded bark), coarse textured organic mulches (chipped wood, bark nuggets, cocoa shells), mulches with higher water content (composted yard waste and sod), and finally brick chips (which never ignited). These comparisons should be carefully considered when mulching in regions where there is significant fire danger.

Nitrogen deficiency. A common misconception about woody mulches is that they impose a nutrient deficiency upon plant materials. This is based on the fact that woody mulches have a high C:N ratio and nitrogen will be 'tied up' by microbes during the decomposition process. Furthermore, woody materials that are used as amendments incorporated into soil or potting mixes will create zones of nitrogen deficiency, which is visualized by spindly, chlorotic growth of plants in these zones.

Experimental research reveals that neither nitrogen immobilization nor growth suppression occurs as a result of using woody materials for mulch (51, 100). To the contrary, many studies have demonstrated that woody mulch materials actually increase nutrient levels in soils and/or associated plant foliage (5, 99, 114, 125). A zone of nitrogen deficiency exists at the mulch/soil interface (Chalker-Scott, unpublished data), possibly inhibiting weed seed germination while having no influence upon established plant roots below the soil surface. For this reason, it is inadvisable to use high C:N mulches in annual beds or vegetable gardens where the plants of interest do not have deep root systems.

Pests. Many organic mulches, especially those based on wood products, have an undeserved reputation as 'pest magnets.' In fact, many of these wood-based mulches are not attractive to pest insects but are actually insect repellent. *Salvia* spp., pine needles, and cedar shavings were found to repel fire ants (*Solenopsis invicta*) under laboratory conditions (1). *Thuja* species have developed a number of chemical weapons against pests including thujone, one of several essential oils found in arborvitae foliage and that of other non-*Thuja* species. Best known for its ability to repel clothes moths, thujone and other foliar terpenes also repel, inhibit, or kill cockroaches (Blattodea), termites (Isoptera), carpet beetles (Dermestidae), Argentine ants (*Iridomyrmex humilis*), and odorous house ants (*Tapinoma sessile*).

A common concern is whether wood-based mulches are attractive to termites. There have been specific studies targeting this question with sometimes surprising results. One recent study (74) compared subterranean termite (*Reticulitermes virginicus*) activity underneath both organic (bark and wood) and inorganic (gravel) mulches. The greatest termite activity was found beneath the gravel mulch. Not only were the wood and bark mulches unappealing to termites, but when fed a diet of these materials in the lab they suffered increased mortality. These results are partially explained by an earlier study (35), which found that termites preferred mulches with higher nitrogen and phosphorus content. Martin and Poultney (76) confirm this in a study demonstrating termite partiality for banana mulch, a relatively nutrient-rich material. Therefore, in regions where subterranean termites are potential pests, organic mulches should be selected that are low in nutrients.

Research upon the ability of mulch to exacerbate or control other pest insects and nematodes is sparser and more variable, so it is not easy to draw generalizations. Dry-surfaced mulches, such as gravel or wood chips, are recommended as deterrents to ticks (*Ixodes scapularis*) that carry Lyme disease (78); other insects (beneficial or otherwise) may likewise be discouraged. Black plastic and landscape fabric may reduce certain pest species in the short term (33, 83), but their long-term negative impacts on soil and plant health are so significant that their perpetual use in a landscape cannot be recommended. In general, any mulch which increases the general health of the soil environment will undoubtedly enhance the diversity of beneficial microbes and insects in the landscape (124).

Mulches are variable in their ability to attract or repel mammalian pests as well. Some materials may naturally repel herbivorous mammals by virtue of their thorns or odors (20) or texture (125), while others may attract undesirable pests, especially rodents, who can use dense ground covers or sheet-type mulches for shelter (40, 86, 113).

Weed contamination. Mulches lacking pedigrees can be carriers of weed seeds and other undesirable plant parts. While controlled research on this problem is lacking, anecdotal evidence suggests that improperly treated crop residues and composts as well as bark mulches are often carriers of weed seed. Woody mulches may contain invasive species associated with tree materials that are chipped. Many of these species, such as English ivy (*Hedera helix*), can easily grow from seed or regenerate vegetatively, thus colonizing landscapes. If it is not possible to document the mulch source, it might be prudent to use it on a small area of the landscape and monitor it for problems before using it more widely.

A successful mulch must be deep enough to suppress weeds and promote healthy soils and plants: research has demonstrated that weed control is directly linked to mulch depth (81), as is enhanced plant performance (42). As mentioned earlier, coarse materials are more effective in this regard as their depth will not have the negative impacts found with fine-textured materials.

A review of the research on coarse organic mulches and weed control reveals that shallow mulch layers will promote weed growth (67) and/or require additional weed control measures (144). Coarse organic mulches applied at depths of 7.6 cm (3 in) or less are most likely to fall into this category. On the other hand, mulches applied at 10 cm (4 in) (36) or 15 cm (6 in) (57) were effective in weed control.

Other considerations. In addition to the objective science that should be used to guide landscape management decisions, there are other factors to consider. Perhaps most important are those that affect the sustainability of not only the local landscape but global ecosystems as well. While this literature review has focused directly on plant and soil criteria associated with landscape mulches, other important environmental issues may well play a role in the ultimate choice of landscape mulch materials. Such issues as environmental degradation associated with acquisition of some mulching materials, use of invasive species as ground covers, nutrient overload from overuse of organic mulches, and toxic leachates from some synthetic mulches, must also be considered.

Literature Cited

1. Anderson, J.T., H.G. Thorvilson, and S.A. Russell. 2002. Landscape materials as repellents of red imported fire ants. Southwest Entomologist 27:155–163.

2. Anonymous. 1957. Handbook on Mulches. Brooklyn Botanical Garden Records 13:1–79.

3. Ansari, R., N.E. Marcar, A.N. Khanzada, M.U. Shirazi, and D.F. Crawford. 2001. Mulch application improves survival but not growth of *Acacia ampliceps* Maslin, *Acacia nilotica* (L.) Del. and *Conocarpus lancifolius* L. on a saline site in southern Pakistan. Intern. For. Rev. 3:158–163.

4. Appleton, B.L., J.F Derr, and B.B. Ross. 1990. The effect of various landscape weed control measures on soil moisture and temperature, and tree root growth. J. Arboriculture 16:264–268.

5. Arthur, M.A. and Y. Wang. 1999. Soil nutrients and microbial biomass following weed-control treatments in a Christmas tree plantation. J. Soil Sci. Soc. Amer. 63:629–637.

6. Balvinder, S., G.N. Gupta, and K.G. Prasad. 1988. Use of mulches in establishment and growth of tree species on dry lands. Indian Forester 114:307–316.

7. Banko, T.J. and M.A. Stefani. 1991. Effects of container medium peat content and bed surface on plant growth during capillary irrigation. J. Environ. Hort. 9:33–36.

8. Becker, O.S. and S. Becker. 1982. Vergleichsversuch von Geholzpflanzungen mit Mulchmatte (A trial on the use of mulch matting in shrub plantations). Zeitschrift fur Vegetationstechnik im Landschafts und Sportstattenbau 5:24–29.

9. Bedford, Duke of and S. Pickering. 1919. Science and Fruit Growing, Being an Account of the Results Obtained at the Woburn Experimental Fruit Farm Since Its Foundation in 1894. London, Macmillan & Co., Ltd.

10. Borst, H.L. and R. Woodburn. 1942. The effect of mulching and methods of cultivation on runoff and erosion from Muskingham silt loam. Agric. Eng. 23:19–22.

11. Bowen, K.L., B. Young, and B.K. Behe. 1995. Management of blackspot of rose in the landscape in Alabama. Plant Dis. 79:250–253.

12. Bowersox, T.W. and W.W. Ward. 1970. Black polyethylene mulch — an alternative to mechanical cultivation for establishing hybrid poplars. Tree Planters' Notes 21:21–24.

13. Brantley, E.A., D.D. Davis, and L.J. Kuhns. 2001. Influence of mulch characteristics on sporulation by the artillery fungus *Sphaerobolus stellatus*. J. Environ. Hort. 19:89–95.

14. Brantseg, A. 1962. Irrigation and twig-covering experiments in Scots Pine forests. Communicationes Instituti Forestales Fenniae 55:14 pp.

15. Buban, T., B. Helmeczi, J. Papp, E. Dorgo, L. Jakab, I. Kajati, I. Merwin, F. Polesny, W. Muller, and R.W. Olszak. 1996. IFP-compatible ground-cover management systems in a new-planted apple orchard. Organisation Internationale de Lutte Biologique et Integrée contre les Animaux et les Plantes Nuisibles: Section Régionale Ouest Paléarctique Bulletin 19:263–267.

16. Buggeln, R. and R. Rynk. 2002. Self-heating in yard trimmings: conditions leading to spontaneous combustion. Compost Sci. and Utilization 10:162–182.

17. Burgess, P.J., J.C. Nkomaula, and A.L. Medeiros-Ramos. 1997. Root distribution and water use in a four-year old silvoarable system. Agroforestry Forum 8:15–18.

18. Cahill, A., L. Chalker-Scott, and K. Ewing. 2005. Wood-chip mulch improves plant survival and establishment at no-maintenance restoration site (Washington). Ecological Restoration 23:212–213.

19. Calkins, J.B., B.T. Swanson, and D.L. Newman. 1996. Weed control strategies for field grown herbaceous perennials. J. Environ. Hort. 14:221–227.

20. Chaudhary, R.S., U.S. Patnaik, and A. Dass. 2003. Efficacy of mulches in conserving monsoonal moisture for the Rabi crops. J. Indian Soc. Soil Sci. 51:495–498.

21. Clemens, J. and R.K. Starr. 1985. Field establishment of container-grown plants. I: Effects of weed control. J. Environ. Management 21:257–261.

22. Clifford, E.D. and J.W. Massello. 1965. Mulching materials for nursery seedbeds. Tree Planters' Notes 72:18–22.

23. Cregg, B.M. and M.E. Dix. 2001. Tree moisture stress and insect damage in urban areas in relation to heat island effects. J. Arboriculture 27:8–17.

24. Crohn, D.M. and M.L. Bishop. 1999. Proximate carbon analysis for compost production and mulch use. Trans. ASAE 42:791–797.

25. Davis, D.D., L.J. Kuhns, and T.L. Harpster. 2005. Use of mushroom compost to suppress artillery fungi. J. Environ. Hort. 23:212–215.

26. Davis, J.M. 1994. Comparison of mulches for fresh-market basil production. HortScience 29:267–268.

27. Deters, M.E. 1939. Frost heaving of forest planting stock at the Kellogg reforestation tract, near Battle Creek, Michigan. Michigan Acad. Sci. 25:171–177.

28. Dochinger, L.S. 1956. New concepts of *Verticillium* wilt disease of maple. Phytopathology 46:467 (abstract).

29. Dong, B.B., H.T. Zhu, Z.K. Zhong, and G.F. Ye. 1996. Study on ecological effect of the forest land under-crop sowing and mulching of coastland soil by newly planted. Acta Agriculturae Zhejiangensis 8:154–157.

30. Donnelly, J.R. and J.B. Shane. 1986. Forest ecosystem responses to artificially induced soil compaction. I. Soil physical properties and tree diameter growth. Canadian J. For. Res. 16:750–754.

31. Downer, J. and D. Hodel. 2001. The effects of mulching on establishment of *Syagrus romanzoffiana* (Cham.) Becc., *Washingtonia robusta* H. Wendl. and *Archontophoenix cunninghamiana* (H. Wendl.) H. Wendl. & Drude in the landscape. Scientia Hortic. 87:85–92.

32. Downer, J., B. Faber, and J. Menge. 2002. Factors affecting root rot control in mulched avocado orchards. HortTechnology 12:601–605.

33. Duncan, R.A., J.J. Stapleton, and M.V. McKenry. 1992. Establishment of orchards with black polyethylene film mulching: effect on nematode and fungal pathogens, water conservation, and tree growth. J. Nematology 24:681–687.

34. Duryea, M.L., R.J. English, and L.A. Hermansen. 1999a. A comparison of landscape mulches: Chemical, allelopathic, and decomposition properties. J. Arboriculture 25:88–96.

35. Duryea, M.L., J.B. Huffman, R.J. English, and W. Osbrink. 1999b. Will subterranean termites consume landscape mulches? J. Arboriculture 25:143–149.

36. Ecological Agriculture Projects, McGill University. Mulching for weed control. http://www.eap.mcgill.ca/general/home_frames.htm.

37. Einert, A.E., R. Guidry, and H. Huneycutt. 1975. Permanent mulches for landscape plantings of dwarf crape myrtles. Amer. Nurseryman 142:9, 59, 62–65.

38. Entry, J.A., C.A. Strausbaugh, and R.E. Sojka. 2005. Compost amendments decrease *Verticillium dahliae* infection on potato. Compost Sci. and Utilization 13:43–49.

39. Fausett, J.B. and C.R. Rom. 2001. The effects of transitioning a mature high-density orchard from standard herbicide ground-cover management system to organic ground-cover management systems. Arkansas Agric. Expt. Sta. Res. Series 483:33–36.

40. Ferm, A., J. Hytonen, S. Lilja, and P. Jylha. 1994. Effects of weed control on the early growth of *Betula pendula* seedlings established on an agricultural field. Scandinavian J. Forest Res. 9:347–359.

41. Foreman, G.L., D.I. Rouse, and B.D. Hudelson. 2002. Wood chip mulch as a source of *Verticillium dahliae*. Phytopathology 92:S26 (abstract).

42. Foshee, W.G., W.D. Goff, K.M. Tilt, J.D. Williams, J.S. Bannon, and J.B. Witt. 1996. Organic mulches increase growth of young pecan trees. HortScience 31:811–812.

43. Fraedrich, S.W. and D.L. Ham. 1982. Wood chip mulching around maples: effect on tree growth and soil characteristics. J. Arboriculture 8:85–89.

44. Froment, M.A., C.P. Britt, and J. Doney. 2000. Farm woodland weed control: mulches as an alternative to herbicides around newly planted oak *Quercus robur* transplants. Aspects of Applied Biology 20:81–86.

45. Gan J., Y. Zhu, C. Wilen, D. Pittenger, and D. Crowley. 2003. Effect of planting covers on herbicide persistence in landscape soils. Environ. Sci. Tech. 37:2775–2779.

46. Gardiner, E.S. and J.L. Yeiser. 1998. Converting stands of low-grade hardwoods to loblolly pine: stimulating growth and reducing costs through litter retention. Southern J. Applied For. 22:148–155.

47. Garrity, D.P. and A.R. Mercado Jr. 1994. Nitrogen fixation capacity in the component species of contour hedgerows: how important? Agroforestry Systems 27:241–258.

48. George A.P., R.J. Nissen. A. Mowat, R.J. Collins, and R. Collins. 2003. Innovative production systems for non-astringent persimmon. Acta Hortic. 601:151–157.

49. Goulet, F. 1995. Frost heaving of forest tree seedlings: a review. New Forests 9:67–94.

50. Green, T.L. and G.W. Watson. 1989. Effects of turfgrass and mulch on establishment and growth of bareroot sugar maples. J. Arboriculture 15:268–272.

51. Greenly, K. and D. Rakow. 1995. The effects of mulch type and depth on weed and tree growth. J. Arboriculture 21:225–232.

52. Griffiths, W. and T.H. Fairhurst. 2003. Implementation of best management practices in an oil palm rehabilitation project. Better Crops International 17:16–19.

53. Gupta, G.N. 1991. Effects of mulching and fertilizer application on initial development of some tree species. For. Ecol. Management 44:211–221.

54. Harris, R.W., J.R. Clark, and N.P. Matheny. 2004. Arboriculture: Integrated Management of Landscape Trees, Shrubs, and Vines, 4th edition. Prentice Hall, Inc, Upper Saddle River, NJ. 578 pages.

55. Hoitink, H.A.J. and M.S. Krause. 1999. Control of nuisance and detrimental molds (Fungi) in mulches and composts. Special Circular Ohio Agric. Res. Dev. Ctr. 165:66–69.

56. Hopp, H. and G.B. Posey. 1942. Evaluation of cork oak as a new farm tree crop in the southeastern United States. Bull. Ecol. Soc. Amer. 23:73.

57. Horowitz, M. and J.M. Thomas. 1994. Couverture du sol pour la gestion des mauvaises herbes (Soil cover for weed management), pp. 149–154. Maitrise des adventices par voie non chimique. Communications de la quatrieme conference internationale I.F.O.A.M. 2nd Edition.

58. Houle, G. and P. Babeux. 1994. Fertilizing and mulching influence on the performance of four native woody species suitable for revegetation in subarctic Quebec. Canadian J. Forest Res. 24:2342–2349.

59. Hunt, L.O. 1963. Evaluation of various mulching materials used to improve plantation survival. Tree Planters' Notes 57:19–22.

60. Iles, J.K. and M.S. Dosmann. 1999. Effect of organic and mineral mulches on soil properties and growth of 'Fairview Flame R' red maple trees. J. Arboriculture 25:163–167.

61. Jacobs, K.A. 2005. The potential of mulch to transmit three tree pathogens. J. Arboriculture 31:235–241.

62. Kacinski, N.A. 1951. Posev duba v mikroponizenija kak sredstvo borjby s zasuhoi na svetlokastanovyh pocvah (Sowing oak in micro-depressions as a means of combating drought on light chestnut soils). Pocvoved 10:585–603.

63. Kiikkila, O., J. Derome, T. Brugger, C. Uhlig, and H. Fritze. 2002. Copper mobility and toxicity of soil percolation water to bacteria in metal polluted forest soil. Plant and Soil 238:273–280.

64. Koski, R. and W.R. Jacobi. 2004. Tree pathogen survival in chipped wood mulch. J. Arboriculture 30:165–171.

65. Kraus, H.T. 1998. Effects of mulch on soil moisture and growth of desert willow. HortTechnology 8:588–590.

66. Kudinov, V.I. 1972. Sawdust instead of manure. Sadovodstvo 12:38.

67. Kuhns, L.J. 1992. Efficacy and phytotoxicity of three landscape herbicides with and without a light mulch. Proc. Northeastern Weed Sci. Soc. 46:85–89.

68. Lakatos, T., T. Buban, W. Muller, F. Polesny, C. Verheyden, and A.D. Webster. 2000. Effectiveness of different groundcover materials to preserve soil water content in a young apple orchard. Acta Hortic. 525:425–426.

69. Landis, T.D. 1988. Management of forest nursery soils dominated by calcium salts. New Forests 2:173–193.

70. Leclerc, D. 1997. Le paillage en foret (Mulching in forests). Bulletin Technique Office National des Forets 32:39–46.

71. Lillaram, N.T. and B.V.V. Rao. 1980. Leachings from eucalyptus leaves have no adverse effect on germination and growth of paddy. Current Research 9:202–203.

72. Littlefield, E.W. 1942. *Pinus thunbergii*: a successful exotic on the north Atlantic Coast. J. Forestry 40:566–573.

73. Litzow, M. and H. Pellett. 1993. Influence of mulch materials on growth of green ash. J. Arboriculture 9:7–11.

74. Long, C.E., B.L. Thorne, N.L. Breisch, and L.W. Douglass. 2001. Effect of organic and inorganic landscape mulches on subterranean termite (Isoptera: Rhinotermitidae) foraging activity. Environ. Ento. 30:832–836.

75. MacLean, R.H., J.A. Litsinger, K. Moody, A.K. Watson, and E.M. Libetario. 2003. Impact of *Gliricidia sepium* and *Cassia spectabilis* hedgerows on weeds and insect pests of upland rice. Agric. Ecosystems and Environ. 94:275–288.

76. Martin, P.J. and R. Poultney. 1992. Survival and growth of clove seedlings in Zanzibar. 1. Effects of mulching and shade crops. Tropical Agric. 69:365–373.

77. Matthews, B. 1948. Report on sawdust. New Zealand Gardener 4:391–394.

78. Maupin, G.O., D. Fish, J. Zultowsky, E.G. Campos, and J. Piesman. 1991. Landscape ecology of Lyme disease in a residential area of Westchester County, New York. Amer. J. Epidemiology 133:1105–1113.

79. Maynard, A.A. 1998. Utilization of MSW compost in nursery stock production. Compost Sci. and Utilization 6:38–44.

80. McCambridge, W.F., M.J. Morris, and C.B. Edminster. 1982. Herbage production under ponderosa pine killed by the mountain pine beetle in Colorado. USDA Forest Service Rocky Mountain Forest and Range Experiment Station Research Note RM-416, 3 pp.

81. McDonald, H.G., J.M. Smith, and C.P. Britt. 1996. The effectiveness of organic mulches on weed control in farm woodlands. Aspects of Applied Biology 44:63–68.

82. McGovern, R.J., R. McSorley, and M.L. Bell. 2002. Reduction of landscape pathogens in Florida by soil solarization. Plant Dis. 86:1388–1395.

83. McKenzie, C.L., S.L. Lapointe, and L.W. Duncan. 2001. Landscape fabric as a physical barrier to neonate *Diaprepes abbreviatus* (Coleoptera: Curculionidae). Florida Entomologist 84:721–722.

84. Megahan, W.F. 1974. Deep-rooted plants for erosion control on granitic road fills in the Idaho Batholith. USDA Forest Service Research Paper, 18 pp.

85. Mengel, D.L., C.B. Davey, and D.K. Cassel. 1993. First-year survival and height-growth of red ceiba following various site preparation techniques on vertic soils in northern Colombia. New Forests 7:287–303.

86. Merwin, I.A. and W.C. Stiles. 1994. Orchard groundcover management impacts on apple tree growth and yield, and nutrient availability and uptake. J. Amer. Soc. Hort. Sci. 119:209–215.

87. Merwin, I.A., J.A. Ray, T.S. Steenhuis, and J. Boll. 1996. Groundcover management systems influence fungicide and nitrate-N concentrations in leachate and runoff from a New York apple orchard. J. Amer. Soc. Hort. Sci. 121:249–257.

88. Mishra, A.K., A.K. Bhowmik, and S.K. Banerjee. 1996. Effect of mulches on growth of tree species on fly ash. Environ. Ecol. 14:411–414.

89. Montague, T. and R. Kjelgren. 2004. Energy balance of six common landscape surfaces and the influence of surface properties on gas exchange of four containerized tree species. Scientia Hortic. 100:229–249.

90. Montano, J.M., J.T. Fisher, and D.J. Cotter. 1977. Sawdust for growing containerized forest tree seedlings. Tree Planters' Notes 28:6–9.

91. Munir, A.D., N.M. Majid, I. Abdol, and G.S. Khan. 1998. Effects of mulching on the growth of interplanted *Acacia mangium* on sandy tin-tailings in Peninsular Malaysia. Lyallpur Akhbar 65:3.

92. Naklang, K., A.M. Whitbread, Y. Konboon, D. Suriya-Arunroj, G.J. Blair, and R.D.B. Lefroy. 1999. The management of pre and post-legume crops, fertilisers and plant residues on rice yields and soil carbon in a flooded rice cropping system, pp. 51–57. *In*: A.M. Whitbread and G.J. Blair (eds.), Integrated nutrient management in farming systems in Southeast Asia and Australia: Proceedings of an International Workshop. National Agricultural Research Centre, Vientiane, Laos. April 21–22, 1999.

93. Nath, J.C. and R. Sarma. 1992. Effect of organic mulches on growth and yield of Assam lemon (*Citrus limon* Burm). Horticultural J. 5:19–23.

94. Nedwed, A. 1991. Auswirkungen unterschiedlicher Baumstreifenbehandlungen auf die Stickstoffverfugbarkeit in Apfelanlagen (Effects of different tree strip treatments on nitrogen availability in apple orchards). Mitteilungen Klosterneuburg, Rebe und Wein, Obstbau und Fruchteverwertung 41:249–256.

95. Niggli, U., F.P. Weibel, and C.A. Potter. 1988. Unkrautregulierung in einer Dauerkultur durch Bodenbedeckung mit organischen Materialien (Weed control in a perennial crop using an organic mulch). Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz 11:357–365.

96. Oliveira, M.T. and I.A. Merwin. 2001. Soil physical conditions in a New York orchard after eight years under different groundcover management systems. Plant and Soil 234:233–237.

97. Pair, J.C. 1994. Adaptability of evergreen rhododendrons to the great plains as influenced by landscape exposure. Amer. Rhododendron Soc. J. 48:69–72.

98. Perez-Sierra, A., G. Laflamme, J.A. Berube, and G. Bussieres. 2003. Preliminary study on the survival and spread of *Armillaria mellea* in mulches in gardens. Information Report Laurentian Forestry Centre, Quebec Region, Canadian Forest Service, No. LAU-X-126:436–438.

99. Pfammatter, W. and A. Dessimoz. 1997. Influence de l'irrigation et de la couverture du sol sur le developpement et le rendement de jeunes pommiers (Influence of irrigation and ground cover on development and yields of young apple trees). Revue Suisse de Viticulture, d'Arboriculture et d'Horticulture 29:301–304.

100. Pickering, J.S. and A. Shepherd. 2000. Evaluation of organic landscape mulches: composition and nutrient release characteristics. Arboricultural J. 23:175–187.

101. Pirone, P.P. 1941. Freak weather damages trees and shrubs. New Jersey Agriculture 23:3.

102. Ringe, J.M. and D.H. Graves. 1990. Mulches derived from wood: an economic comparison of two materials used to reclaim surface mines. Forest Prod. J. 40:35–38.

103. Rokich, D.P., K.W. Dixon, K. Sivasithamparam, and K.A. Meney-KA. 2002. Smoke, mulch, and seed broadcasting effects on woodland restoration in Western Australia. Restoration Ecology 10:185–194.

104. Rothwell, R.L. 1978. Erosion control on forest roads. Agriculture and Forestry Bulletin, University of Alberta 1:29–32.

105. Russell, J.C. 1939. The effect of surface cover on soil moisture losses by evaporation. Proc. Soil Sci. Soc. Amer. 4:65–70.

106. Salim, R. and R.A. El-Halawa. 2002. Efficiency of dry plant leaves (mulch) for removal of lead, cadmium and copper from aqueous solutions. Process Safety and Environ. Prot. 80:270–276.

107. Samarappuli, L. and N. Yogaratnam. 1984. Some aspects of moisture and soil conservation in rubber plantations. pp. 529–543. *In*: Proceedings of the International Rubber Conference. 75 Years of rubber research in Sri Lanka, September 1984, Colombo. Volume 1, Part 2. Rubber Research Institute of Sri Lanka: Agalawatta, Sri Lanka.

108. Samra, J.S. and S.C. Singh. 1998. Evaluation of an *Acacia nilotica* based silvipasture system on degraded land of Shivalik foothills. Indian J. Soil Conservation 26:226–233.

109. Sartz, R.S. 1963. Water yield and soil loss from soil-block lysimeters planted to small trees and other crops. USFS Research Paper LS-6, St. Paul, MN, 23 pp.

110. Schumann, A.W., K.M. Little, and N.S. Eccles. 1995. Suppression of seed germination and early seedling growth by plantation harvest residues. South African J. Plant and Soil 12:170–172.

111. Schwan, T. 1993. The effects of organic and inorganic mulches on black spruce seedlings in seed orchards: (first year results). Northeast Science and Technology Technical Report, Ontario, Canada, No. TR-013.

112. Seckler, D.W. and K.G. Tejwani. 1983. Effect of sand and gravel mulching on moisture conservation for tree saplings. J. Tree Sci. 2:20–23.

113. Siipilehto, J. 2001. Effect of weed control with fibre mulches and herbicides on the initial development of spruce, birch and aspen seedlings on abandoned farmland. Silva Fennica 35:403–414.

114. Singh, A.K. and R.B. Singh. 1999. Effect of mulches on nutrient uptake of *Albizia procera* and subsequent nutrient enrichment of coal mine overburden. J. Tropical For. Sci. 11:345–355.

115. Singh, A.K. and S. Saggar. 1997. Effectiveness of mulches and organic moisture retainer on growth of *Dalbergia sissoo* in a highly degraded land. Indian Agriculturist 41:209–216.

116. Singh, S.B., K. Pramod, K.G. Prasad, and P. Kumar. 1991. Response of *Eucalyptus* to organic manure mulch and fertilizer sources of nitrogen and phosphorus. Van Vigyan 29:200–207.

117. Smith, L.J. and W.A. Skroch. 1995. Turf herbicide injury to landscape trees as influenced by mulch. J. Environ. Hort. 13:60–63.

118. Smith, M.W. 2000. Cultivar and mulch affect cold injury of young pecan trees. J. Amer. Pomology Soc. 54:29–33.

119. Spaulding, P. and J.R. Hansbrough. 1943. The needle blight of Eastern white pine. USDA Bureau of Plant Industry, 2 pp.

120. Stenn, H. 2005. Woody mulch research review, professional users and product availability surveys. Seattle Public Utilities, Seattle, WA.

121. Steward, L.G., T.D. Sydnor, and B. Bishop. 2003. The ease of ignition of 13 landscape mulches. J. Arboriculture 29:317–321.

122. Stinson, J.M., G.H. Brinen, D.B. McConnell, and R.J. Black. 1990. Evaluation of landscape mulches. Proc. Florida State Hort. Soc. 103:372–377.

123. Sun, D., G. Dickinson, and A. Bragg. 1994. The establishment of Eucalyptus camaldulensis on a tropical saline site in north Queensland, Australia. Agriculture, Ecosystems and Environment 48:1–8.

124. Sunderland, K. and F. Samu. 2000. Effects of agricultural diversification on the abundance, distribution, and pest control potential of spiders: A review. Entomologia Experimentalis et Applicata 95:1–13.

125. Szwedo, J. and M. Maszczyk. 2000. Effects of straw-mulching of tree rows on some soil characteristics, mineral nutrient uptake and cropping of sour cherry trees. J. Fruit and Ornamental Plant Res. 8:147–153.

126. Tanavud, C., P. Kheowvongsri, C. Yongchalermchai, W. Leowarin, O. Densrisereekul, A. Bennui, J. Murase, and M. Kimura. 2001. Effects of land use patterns on soil and water quality in Khlong U-Taphao Basin. Thai J. Agric. Sci. 34:15–31.

127. Tilander, Y. and M. Bonzi. 1997. Water and nutrient conservation through the use of agroforestry mulches, and sorghum yield response. Plant and Soil 197:219–232.

128. Tisserat, N. and J.E. Kuntz. 1984. Root deterioration of black walnut seedlings during overwinter storage in Wisconsin. Tree Planters' Notes 35:31–35.

129. Townsend, T.G., G.H. Solo, T. Tolaymat, and K. Stook-K. 2003. Impact of chromated copper arsenate (CCA) in wood mulch. Science of the Total Environment 309:173–185.

130. Turchetti, T., G. Maresi, D. Nitti, A. Guidotti, and G. Miccinesi. 2003. Il mal dell'inchiostro nel Mugello (Fi): danni ed approcci di difesa (Chestnut ink disease in the Mugello area: damage and control). Monti e Boschi 54:22–26.

131. van Nierop, E.T. and D.P White. 1958. Evaluation of several organic mulching materials on a sandy loam forest nursery soil. J. Forestry 56:23–27.

132. Walker, R.F. and S.B. McLaughlin. 1989. Black polyethylene mulch improves growth of plantation-grown loblolly pine and yellow-poplar. New Forests 3:265–274.

133. Walsh, B.D., S. Salmins, D.J. Buszard, and A.F. MacKenzie. 1996. Impact of soil management systems on organic dwarf apple orchards and soil aggregate stability, bulk density, temperature and water content. Canadian J. Soil Sci. 76:203–209.

134. Watson, G.W. 1988. Organic mulch and grass competition influence tree root development. J. Arboriculture 14:200–203.

135. Watson, G.W. and G. Kupkowski. 1991. Effects of a deep layer of mulch on the soil environment and tree root growth. J. Arboriculture 17:242–245.

136. Wilen, C.A , U.K. Schuch, and C.L. Elmore 1999. Mulches and subirrigation control weeds in container production. J. Environ. Hort. 17:174–180.

137. Winkel, V.K., J.C. Medrano, C. Stanley, and M.D. Walo. 1995. Effects of gravel mulch on emergence of galleta grass seedlings. General Technical Report Intermountain Research Station, USDA Forest Service INT-GTR-315:130–134.

138. Wood, C.B., T.J. Smalley, M. Rieger, and D.E. Radcliffe. 1994. Growth and drought tolerance of *Viburnum plicatum* var. *tomentosum* 'Mariesii' in pine bark-amended soil. J. Amer. Soc. Hort. Sci. 119:687–692.

139. Woods, F.W., R.L. Hay, and G.H. Irwin. 1979. Summer planting on strip mines successful. Tree Planters' Notes 30:22–23.

140. Yasnobu, Y. 1974. Studies on cold injury in Japanese Chestnut trees. VI. Cold injury to the trunk and branches and the use of 2,3,5-triphenyltetrazolium chloride [TTC] in assessing cold injury in phloem tissues. Bull. Kanagawa Horticultural Expt. Sta. 22:34–41.

141. Yi, F.L., C.Y. Yu, and S.Z. Chen. 1987. Techniques for tree planting mulched with polyethylene films in semi-dry rocky areas. Forest Sci. and Technology Linye Keji Tongxun 12:7–10.

142. Yobterik, A.C. and V.R. Timmer. 1994. Nitrogen mineralization of agroforestry tree mulches under saline soil conditions. *In*: R.B. Bryan (ed.), Advances in Geoecology 27:181–194.

143. Zajicek, J.M. and J.L. Heilman. Transpiration by crape myrtle cultivars surrounded by mulch, soil, and turfgrass surfaces. HortScience 26:1207–1210.

144. Zaragoza, C., S. Moya, and G. Martinez. 1995. Efectos de las coberturas organicas a base de cortezas de pino y restos de poda en un huerto de frutales (Effects of mulches based on pine bark and pruning residues in a fruit orchard), pp. 283–290. Proc. 1995 Congress Spanish Weed Sci. Soc., Huesca, Spain.

145. Zink, T.A. and M.F. Allen. 1998. The effects of organic amendments on the restoration of a disturbed coastal sage scrub habitat. Restoration Ecol. 6:52–58.