Nonspecific root decline in Douglas-fir trees due to urban soils syndrome

Peter Torres
Oregon State University
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Acknowledgments

This paper is dedicated to Dr. Everett Hansen, to my graduate committee members Dr. Greg Filip and Dr. Jeff Stone, and to others who taught me about forest pathology.

Also dedicated to Dr. R.G. Pawsey, who, in a discussion about the effects of wind on the forest, expressed dismay that in one and a half days' discussion, no one had brought up the subject of root diseases (Palmer, 1968).

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Abstract

Urban soils syndrome, the deterioration of soil at developed sites, acts as a primary disease agent, causing root system necrosis by physical damage to root tissue. This condition predisposes Douglas-fir trees to attack by fungal pathogens, including *Armillaria ostoyae*, brown rotters like *Phaeolus schweinitzii*, and a variety of minor pathogens. When colonized by minor pathogens, or when damaged by edaphic factors alone, the resulting diseased condition is a non-specific root decline. This paper examines the soil conditions that contribute to root disorders. The role of minor pathogens is explored. Nonspecific root decline is difficult to detect, for many affected trees appear nonsymptomatic until they uproot in a windstorm. Sampling techniques are discussed, and a hazard rating system is proposed to help with detection.

Introduction

Urban soils syndrome is the deterioration of soil from human impact at developed sites. When a rooting zone is involved, this condition predisposes Douglas-fir trees to attack by the fungal pathogens, *Phaeolus schweinitzii, Armillaria ostoyae,* and a variety of minor pathogens. Soil deterioration also acts as a primary disease agent, causing root system necrosis by physical damage to root tissue. The resulting root decline in Douglas-fir trees has become ubiquitous in developed sites in the Pacific Northwest. Many affected trees appear nonsymptomatic until they uproot in a windstorm, but the presence of root disease should be predictable with a systematic hazard rating index.

A nonspecific root disease is more difficult to detect than strong-pathogen root diseases, because the cause cannot be attributed to a single organism (see Figure 1). When soil is damaged due to compaction, the original root system deteriorates and is replaced by a shallow adventitious root system. A soil that facilitates root penetration, but harbors strong pathogens, will also result in a shallow-rooted host (Sutton, 1980). In either case, as the original supporting roots decay, affected trees become unstable.

In contrast to more natural, or undisturbed soils, the term "urban soil" describes a soil with some or all of these characteristics, (Craul, 1994):

- Horizontal and vertical variation are easily recognizable.
- Soil structure has been modified, resulting in compaction.
- Bare soil has a hydrophobic surface crust.
- Soil reaction is elevated (alkaline).
- Drainage and aeration are restricted.

- Soil organism population is modified.
- Nutrient cycling is interrupted.
- Artificial materials and contaminants are present.
- Soil temperature regimes are highly modified.

Root decline due to urban soils syndrome probably affects all tree species, but only Douglas-fir is treated in this paper. Douglas-fir root systems can be predisposed to root decline in natural habitats without human impact, but this paper deals with urban areas. Nonspecific root decline is not a new disease, but it is poorly described, usually ignored, and increasing at an alarming rate. Windthrow resulting from the failure of affected root systems is blamed on a variety of other factors, some partially correct, some entirely wrong.

Relying on relevant literature, this paper will briefly review some important root diseases of Douglas-fir in the Pacific Northwest. A discussion of the Douglas-fir root system and a review of soil properties will follow. Root decline due to urban soils syndrome will be described, using a synthesis of relevant information and field observations. Because of the problems inherent in sampling for this disease, a program of data accumulation and analysis is proposed, one that should help to identify trees at risk by the construction of a site hazard rating.

Aggressive Pathogens

Coast Douglas-fir trees *(Pseudotsuga menziesii* var. *menziesii*) are susceptible to Armillaria root disease, laminated root rot, and Schweinitzii root and butt rot. The former two readily kill trees, and in a rural forest are often detected by symptomatic trees in root disease centers. Spatial and temporal patterns help in diagnosis, but an urban infrastructure usually disrupts these patterns. There are many other root diseases of Douglas-fir, including black stain root disease (*Leptographium* *wageneri*) and annosus root and butt rot *(Heterobasidion annosum*), but these are uncommon in the northern Willamette Valley, the area of interest.

It is a common practice to rely on a collection of symptoms collectively known as fading crown to detect root disease in conifers. This is a cumulative result of:

- chlorosis,
- reduced leader and branch tip growth,
- needle stunting,
- progressive thinning from needle loss,
- decline of the crown from top to bottom and from branch tips inward, and
- distress cone crops.

Reliance on these symptoms in developed sites is ill-advised, for once trees do exhibit crown symptoms, a significant amount of root material is already decayed. Filip (1986) found that diseased trees exhibit crown symptoms only after the root systems reach an advanced stage of deterioration. Trees can become susceptible to windthrow (or windsnap) before becoming symptomatic. To complicate matters, the symptoms can be caused by other agents, including ozone pollution, foliage disease, nutrient deficiencies, lack of mycorrhizae, and defoliation by insects, so a fading crown is not always an indicator of root disease.

Armillaria ostoyae

Armillaria root disease, caused by the basidiomycete *Armillaria ostoyae,* is an aggressive, tree-killing disease on Douglas-fir trees east of the Cascades, usually less aggressive on the west side. Trees infected with this pathogen, whether living or dead, should be considered hazardous (Harvey & Hessburg, 1992). In older trees, the fungus advances slowly through the inner bark of roots, and is sometimes stopped by phytoalexins, which are defensive chemicals. Decay can continue in the sapwood and heartwood, weakening the tree structurally, and predisposing it to windthrow (Scharpf, 1993). In the field, Armillaria root disease can best be diagnosed by mycelial fans beneath the bark of roots and butts. Characteristic mushrooms, basal resinosis (Douglas-fir is a species with resin canals), and black rhizomorphs in the soil or beneath bark are also indicators.

A. ostoyae can live quiescently in root lesions, where it facilitates entry of *P. schweinitzii*. It can occur concomitantly with Schweinitzii root and butt rot, laminated root rot, and with black stain and annosus root diseases (Shaw & Kile, 1991). Host resistance improves with longevity in forest trees, so mortality by Armillaria root disease decreases with age. In contrast, root disease due to urban soils syndrome causes greater mortality with age, as the soil continues to deteriorate, and inocula from weaker pathogens build up annually.

An aggressive pathogen like *Armillaria ostoyae* can infect without wounds or anatomical points of weakness. Wounds to root tissue resulting from wind-induced movement, stones, insect damage, and rootlets killed by excessive moisture, probably serve as easy infection courts, and facilitate infection by other root pathogens as well.

Phellinus weirii

Laminated root rot, caused by the basidiomycete *Phellinus weirii*, is a major disturbance agent in natural forests of northwest Oregon. *P. weirii* kills the inner bark of the roots and root crown and causes a laminated decay of wood in the roots and lower bole. Red-brown stain, pitted decay, and delamination of infected wood are symptoms. The presence of ectotophic mycelium or resupinate fruiting bodies on roots provides more positive identification. A handlens or microscope will reveal setal hyphae.

As with other root diseases, adventitious roots sprout where the larger roots have deteriorated. This helps to explain why crown symptoms are not reliable indicators. In one study, crown symptoms were undetectable in twenty-seven out of twenty-eight Douglas-fir trees infected by *P. weirii*, although measurable growth loss had occurred in most (Thies, 1983). Like the fading crown, growth loss can be complicated by many factors other than root disease, including drought, deficiency in nutrients or micronutrients, weather extremes, defoliation, and age. Alternatively, good growth rates can be caused by artificial irrigation, fertilization, and southern exposure, even when substantial disease is present.

***Phaeolus schweinitzii* and similar brown rotters**

Decay due to Schweinitzii root and butt rot is prevalent in developed sites, and long ago was considered "by far the most serious butt rot of conifers in the United States," (Boyce, 1948). One reason it is common in developed sites is the ubiquitous wounding of the butt and root crown during construction activities, for the fungus commonly infects a tree through basal wounds (Wagener, 1963). The most reliable way to diagnose this parasitic disease is by the characteristic conk produced on or near the base of the tree (Filip, Kanaskie & Campbell, 1995). Crown symptoms are rare, unless Armillaria colonization and bark beetle infestation follow (Hadfield, Goheen, Filip, Schmitt & Harvey, 1986).

P. schweinitzii causes a brown cubical decay of the roots and butt, which weakens the structural integrity and anchorage of the root system. Unlike the white rotters, which have enzymes that break down both cellulose and lignin, brown rot fungi selectively remove cellulose and hemicellulose. The decay residue consists mostly of lignin, which is brittle, brown, and crumbly. This residue typically contracts into cubical chunks, with either hardened resin or mycelium in the shrinkage cracks. Brown rot fungi occur primarily on conifer wood. Although the brown rotters make up less than 10% of all wood decaying fungi, their stable lignin residue is a major organic constituent of soils in Pacific Northwest forests (Parks & Shaw, 1996).

P. schweinitzii can spread from one tree to another as mycelium growing through soil litter, and possibly by root contacts. Consequently, *P. schweinitzii* can spread in pockets like other primary pathogens, rather than appearing sporadically throughout a stand (Strong, 1941). Childs (1937) found the same mycelium in three wind-thrown larches, separated by 20 to 30 feet. This modus operandi was confirmed in slash pine plantations (Blakeslee & Oak, 1980). The fungus enters through root tips and is confined to root interiors, which it stains red. In Douglas-fir, when the root ends rot, swollen stubs form, and adventitious roots sprout. The fungus can also infect a tree by the growth of mycelium through the soil (Barrett & Greig, 1983). *P. schweinitzii* is present in forest soils as a saprophyte, feeding as mycelium and resting as chlamydospores. The source of these forms is seeding by basidiospores (Dewey, Barrett, Vose & Lamb, 1984).

P. schweinitzii does not always form classic root disease centers. In a rigorous laboratory study, Childs (1937) found that neighboring conspecific hosts were usually infected by different mycelia. Childs stated that the large number of different mycelia isolated precluded the possibility that infection was initiated by vegetative spread alone, supporting the thesis of seeding by basidiospores. This work was bolstered by Barrett & Uscuplic (1971), who found that individual trees were colonized by a certain mycelium not normally found in any other tree, even when adjacent. The variation in fungal behavior should caution us to temper any preconceived notions when dealing with this, or any other root pathogen. Such variability is in addition to the great range of symptoms expressed by different host species and individual trees.

West of the Cascades, *P. schweinitzii* is much less virulent than *P. weirii* on Douglas-fir. In general, *P. schweinitzii* probably attacks trees that have been predisposed to infection by unfavorable soil conditions (Barrett & Greig, 1985). In one survey, Schweinitzii root and butt rot was confined to trees in areas with poor subsoil drainage and alkaline soil reaction (Anonymous, 1941). Although these predisposing agents are abiotic, weak pathogens are commonly associated with such environmentally stressed trees (Tattar, 1990). Although *P. schweinitzii* is not in the same virulence class as *P. weirii* or *A. ostoyae*, it is far more aggressive than minor pathogens like the root tip pruners, because *P. schweinitzii* colonizes the drier interior wood of the roots and butt.

In Europe, *P. schweinitzii*, *Sparassis crispa*, and *Calocera viscosa* have been found to cause similar brown rots in living roots of Douglas-fir. The rot in all three diseases proceeds in the central wood of the roots (Siepman, 1983). Pawsey found that decay caused by *S. crispa (radicata)* and *Polyporus stipticus* was regularly being mistaken for decay caused by *P. schweinitzii*. The three pathogens produce a similar cubical brown rot, originating in the central stem (Pawsey, 1971). In Europe, *S. radicata* and *P. schweinitzii* sometimes occur in the same tree (Martin & Gilbertson, 1978). Both fungi can spread underground from root to root, and both elicit a strong turpentine smell. Neither *S. crispa, P. stipticus,* nor *C. viscosa* are discussed in recent literature in the Pacific Northwest, but *S. radicata* has been reported (by Weir) to occur here (Martin & Gilbertson, 1978). If these fungi are present in Douglas-fir hosts in northwest Oregon today, they could easily be mistaken for *P. schweinitzii* in the field.

Root anatomy

There are four regions in a growing root. These can be considered as distinct anatomical features when the root is studied as a static structure, or as temporal gradients when the root is considered as a growing organ. The root cap is the terminal feature, and is maintained by a continuous division of cells, the root cap initials. Functions of the root cap include protection of the apical meristem, the release of mucilaginous exudates, penetration of soil, and the perception of a gravitational stimulus. Loss of the root cap has been shown to disrupt geotropism, but not elongation (Sutton, 1980).

The meristematic region is where cell division takes place, and it grades into the cell elongation region that propels the root cap through the soil. The region of differentiation and maturation follows, where the undifferentiated cells become epidermis, cortex, and stele. Cortex is the tissue within the epidermis and surrounding the central vascular area. Stele is the central vascular tissue, made up of pericycle from which lateral roots originate, xylem, and phloem. The epidermis produces root hairs, which are ephemeral, quickly destroyed by lignification and suberization. Lignification is the build-up of lignin, and suberization is the addition of suberin, a waxy, impermeable coating.

In a healthy tree root, water is absorbed by unlignified and unsuberized tissue, no more than 20 cm behind the root cap. These absorbing root tips make up less than 1% of the total root surface area. Mycorrhizae can increase this by another 6% (Ruark, Mader & Tattar, 1982).

Root elongation is reduced or halted by environmental stress, including drought, low temperature, low oxygen availability, and high carbon dioxide concentrations. When elongation stops, the entire root system becomes suberized and stalls in the soil. Although suberin is impervious to water, suberized roots can absorb water and nutrients at wounds, lenticels, and breaks around branch roots. Some water is even absorbed by dead roots (Gadgil, 1971).

The rhizosphere, or root surface zone, is the radius of soil that surrounds the absorbing root surfaces. Influenced by root exudates, this is the site of interaction between soil microorganisms and the plant. Rhizosphere radius can vary from several millimeters in clay soils, up to one centimeter in sandy soils.

Roots could elongate throughout the year if nothing limited growth. However, in the Willamette Valley, low temperatures and lack of sunlight slow growth in the winter. Reduced moisture limits growth in the summer, due not only to the lack of water available for plant chemistry, but also to the hardening and increased impedance of clay-textured soils that are low in humus.

Adventitious roots

Adventitious roots develop from callus tissue on decayed woody roots. They grow, in response to injury, from preformed or induced root primordia that would not have produced root tissue in normal development. These adventitious roots are often able to supply adequate water to a tree with a deteriorated root system (Harris, 1992), (Thies & Sturrock, 1995).

A profusion of adventitious roots can provide enough nutrition to keep a canopy looking vigorous even when all of the structural roots have decayed. In turn, adventitious roots receive enough photosynthate to continually renew after shedding. This problem is exacerbated in landscaped settings by the application of irrigation water and nitrogen fertilizer, which enable the growth process to continue even with a severely reduced root system (Dunster, 1996). In such a case, a mature Douglas-fir tree of over one-hundred feet can maintain a vigorous canopy while subsisting on a shallow root plate extending two meters or less from the root crown (personal observation). Periodic annual increment (PAI) will not be affected and crown symptoms will not be present in a tree with root disease if the tree produces an adventitious root system that receives adequate water and nutrients (Bloomberg & Reynolds, 1985).

Root Morphology

In a survey of uprooted trees in England, Douglas-fir was described as a shallow-rooted species with a wide to very wide root plate (Gasson & Cutler, 1990). Actually, this species has the genetic potential to be a deep-rooted tree with a taproot, and branched, buttressed, descending laterals (Hepting, 1971). The genetic potential is adjusted by primary pathogen populations, by edaphic limitations, and by physiologic health. Populations of facultative parasites digest root tissues that have weakened for other reasons.

Plate-like root systems are characteristic of Douglas-fir when the soils are shallow or have a high water table (McMinn, 1963). Shallow clays and hardpan layers cause roots to spread faster and farther than deep, easily penetrated soils (Shaw & Eav, 1993). Trees planted in compacted soils produce a shallow root system with more adventitious roots, and they fail to produce a tap root. The same morphology changes occur with roots growing in uncompacted soils with reduced oxygen (Gilman, Leone & Flower, 1987). Reduced oxygen can be due to waterlogging, soil compaction, or an impervious surface crust.

Helliwell (1989) considered the root plate a normal, ubiquitous, and distinctive part of root morphology. Helliwell defined it as the area of soil upon which the tree bears, limited to a radius of about two meters around the tree. This root plate resists tilting by compression at the leeward side of the plate, by vertical roots tying the plate to deeper soils, and by lateral roots extending into surrounding soil.

The root plate, or root ball, of windthrown trees is the mass of soil and roots that come up out of the ground. The rooting zone, however, usually extends many meters beyond this plate. The extent of the root plate is determined by many factors, including tree genetics, penetrability and fertility of the surrounding ground, and the presence of root pathogens (Gibbs & Greig, 1990).

The four common causes for uprooting in trees are the loss of soil strength, a shallow root system, decayed or severed roots, and abnormally high winds. The belief that trees exposed to a prevailing wind are at greatest risk for windthrow is prevalent. Actually, after ridge tops, the greatest hazard is on the lee slopes of bell-shaped hills. Trees in this position are blown over by turbulence caused from a vortex wake that detaches from the hill and attacks the trees on the leeward side. Trees on the lee side are most vulnerable because root systems and tree shapes form in response to the prevailing winds (Robertson, 1987). Catastrophically high winds, of course, can topple or break the strongest tree in the most fertile soil.

Cutler surveyed trees that blew down in the 1987 windstorm in England and found that less than 3% of these had taproots. It was suggested that trees transplanted from open ground nurseries or containers usually lose their tap roots (Cutler, Gasson & Farmer, 1990). Gasson sampled five wind-thrown Douglas-fir trees, and reported that Douglas-fir is a shallow-rooted species with laterals and droppers, or simply lateral root systems with a very wide root plate (Gasson & Cutler, 1990). Actually, blowdowns constitute a self-selecting sample, and trees with taproots are likely to be windfirm. In catastrophic winds, a windfirm tree is more likely to break off above ground.

McMinn (1963) used hydraulic excavation to expose young Douglas-fir tree roots. This revealed a simple taproot with a few main laterals. As trees aged, the taproot was supplemented by branches from primary laterals. In trees on slopes with inclined root stocks, the primary root (taproot) had apparently diverted to a horizontal course. In vigorous trees, one or more roots took over its task and penetrated vertically anyway. All of the ten or more older trees that McMinn examined had vertical roots within the central, deep root system. In older dominant trees the lower soil profiles were permeated with roots from the taproot, its branches, and adjacent descending laterals.

Eis (1974), using hydraulic excavation, examined six Douglas-fir root systems. These had a single, well-developed tap root that grew rapidly during the first few years. The permanent root system morphology was apparently established by the tenth year. On shallow, rocky soil, the tap root either aborted or was indistinguishable from the laterals.

Large diameter oblique roots included the primary laterals from the first growing season, and second order laterals. These structural elements had the primary function of anchoring the tree. They penetrated as deep as soil conditions allowed, stopping at hardpan, water table, or rock. These structural elements occurred in all trees, sites and soil conditions in the study, regardless of wind exposure. They did not have many fine, absorbing roots. Stability in wind was due to the great weight of soil exploited by the oblique laterals (Eis, 1974).

Sinkers, which are vertical roots descending from laterals, were found, but were not ubiquitous. The sinkers terminated in fine, fibrous roots. Horizontal elements, which were long, rope-like laterals, were concentrated in the top several centimeters of soil, and were infrequent below 30 cm. Eis found that the diameter of the root system was about 75% of mature tree height. The final depth of root penetration was similar in dominant, codominant, and intermediate trees. Dominants had a more symmetrical root system with more laterals (Eis, 1974).

Hermann (1977) found that the horizontal extent of the root system correlated closely with the shape of the crown. This included lopsided lateral development. Smith (1964) used the average branch length to estimate the extent of root spread. The ratio of root spread to crown spread varied from 1.1 for open-grown Douglas-fir trees, to 0.9 for forest-grown trees. Smith estimated that only 20% of the volume of soil available to roots was actually occupied by roots at a given time.

For forest trees, the majority of roots are within the upper 50 cm, and absorbing roots are in the top 20 cm (Hermann, 1977). Under conditions of high rainfall, compacted soil, or poor drainage, roots may be extremely shallow- in the top few centimeters only (Helliwell, 1989). It is obvious that depth restriction will foster more root contact between trees, facilitating the transmission of infectious root diseases from tree to tree. Lacking depth, a root system will exploit laterally, because a root system is opportunistic.

Soil and Compaction

Soil compaction is the decrease in porosity and increase in bulk density, where bulk density is the weight of a unit volume of oven-dry soil. This weight includes the pore volume as well as the solid material, but excludes soil water (Allmaras, Kraft & Miller, 1988). A degree of compaction, or firming, is a basic growth requirement, and ensures soil contact with the roots. In this paper, "compaction" refers to a state greater than firming. An excessive degree of compaction has deleterious effects (see Figure 2).

Soil strength is the resistance of a soil, in a particular condition, to an applied force. The "particular condition" is a function of water content, bulk density, and soil texture. Texture refers to the grain size and shape and determines the average pore size. The smaller the pore size, the greater the soil strength, or resistance to penetration, at a given bulk density. Too much compaction impedes root penetration through the soil. As compaction increases, bulk density and the soil strength, or resistance to further compaction, also increase. Bulk density and soil strength are both used as measures of soil compaction.

An ideal soil has a texture with equal parts of sand, silt, and clay, with 3% to 15% humus (decomposed organic matter). Sand and gravel soils offer a root system less support than clay soils, which are stronger. However, a high clay content can increase root susceptibility to pathogens through impedance, which is the mechanical restriction of root production (Paine & Baker, 1993). A strong clay soil offers more support to an underdeveloped or deteriorated root system than do sandy soils. However, when clay soils are waterlogged, strength diminishes dramatically. A compromised root system, soil with a high percentage of clay, and sudden saturation are ingredients for whole-tree failure.

Organic matter improves soil structure and reduces compaction. With coarse soils of sand or gravel that lack a clay component, humus is the sole source of nutrients, ion exchange, water retention, and resistance to compaction.

Daddow & Warrington (1983) developed a textural triangle to predict the bulk density that limits growth in different soil textures at field capacity. Field capacity is the amount of water remaining in the pores after water has drained out of a saturated soil in response to gravity (Harris, 1992). At capacities near saturation, soil aeration becomes limiting. At capacities near the permanent wilting point, water becomes the limiting growth factor. Coder developed a table of eight soil textures, ranging from clay to sand, and the limiting bulk densities for each (Coder, 1995).

Root penetration of soil is achieved by the root tips entering pores and elongating, and by moving particles aside by radial expansion (Alberty, Pellett & Taylor, 1984). Heilman (1981) found that impedance of root penetration increased linearly with bulk density. The restriction of vertical root penetration stimulated shallower growth, with a concurrent loss of geotropism. Restriction can be due to mechanical impedance, anaerobic conditions, or waterlogging.

Heilman's study, like many others, dealt with the effects of soil compaction on seedling establishment. Although there are similarities, the effect of compaction on the fine roots of established trees is not wholly addressed by studies of seedlings. Very few fine roots of seedlings are suberized, but most fine roots in a mature tree are suberized (Vogt et al., 1993). With seedlings, growth is primary, and the differentiation into protective tissues and chemicals is secondary to growth processes. Much of the information about the effect of soil compaction on plant roots comes from other fields. Information on the compaction of agricultural soils, nursery soils, and forest soils is relevant to compaction of soils in the urban forest, but the differences must be noted. The properties and behavior of different plants' roots have much in common, but the scope of inference from observations must be considered carefully.

Any action that compresses a soil will decrease the volume by eliminating pore space and the air and water within these pores. An ideal soil has 50% of its volume as pore space, which is created and maintained by the microfauna, arthropods, and worms (Perry, 1989). Air, water, roots, and minerals can easily penetrate such a material. Compression occurs with the rearrangement of soil-particle assemblies. For example, plate-like particles of clay minerals become aligned. As pore space decreases, the continuity of pores is disrupted, and the movement of gases, water, and roots is impeded. Beneficial microorganisms that inhabit fertile soil lose the microcavities they normally colonize.

Penetrometers

The penetrometer reading is called a cone index. It integrates the mechanical properties that affect root penetration, including soil water content, bulk density, and cohesive and frictional forces in the soil. It involves shear, compressive strength, tensile strength, and soil-metal friction. A penetrometer measurement shares some parameters with dry bulk density and with soil cohesion, but the measurement always varies with moisture content. As the soil becomes drier, compression becomes more important, and the penetration force describes bulk density. As soil becomes wetter, shear, which is a measure of cohesion, becomes more important. At some intermediate moisture content, compression and shear play equal roles. Using bulk density as a diagnostic test eliminates the moisture parameter altogether, so some information is lost.

Although soil-metal friction does not mimic root friction, the index, when taken in context by calibration, can predict the ability of a root to penetrate soil. One use for penetrometer measurements is to predict the moisture content needed for roots to penetrate a soil. Another is to compare different soils at the same moisture content for resistance to penetration. Whatever the penetrometer reading is used for, the moisture percent in the soil at the time of reading must be recorded for meaningful comparisons.

The absolute resistance is lower for roots than for penetrometer cones. This is due to roots' ability to expand radially, and to minimize friction with the lubricating action of exudates. Penetrometer cones penetrate by soil deformation around the tip. This measurement of resistance gives a good estimate of relative soil strength. When the parameters of moisture and particle size and type (texture) are included, the measurement can be used to predict root impedance.

When analyzed graphically, plant response to soil compaction is parabolic, indicating an interaction of factors. This implies that a single parameter will have different effects on root growth at different levels of the other soil parameters. For example, root elongation will respond differently in a clay soil vs. a sandy soil at the same bulk density as moisture increases. Interactions among factors affecting soil compaction can be accounted for by using multiple correlation and regression (Rosenberg, 1964).

The greatest limitation to penetrometer use is the inability to compare testing episodes when soils are at different moisture contents. This applies both to a single site at different times, and to different sites. For a one-time, objective diagnosis of a soil compaction level, the soil should be near field capacity, for this is when roots are most likely to be growing. An alternative is to measure the soil moisture and the penetrometer cone index, and adjust the compaction reading along a regression line. Because of the infinite variation in the percentages of sand, silt, clay, and humus, building the regression line would be a major research project. It is possible that Daddow's textural triangle or Coder's texture table could be integrated with moisture percent, the cone index, and a field analysis of soil texture, to estimate what the compaction rating would be at field capacity.

One manufacturer (Dickey-john, 1987) supplies two cone tips with its penetrometer. It is common practice to use the larger cone to measure resistance in wet soils, and the smaller cone to measure resistance in dry soils. This is a less precise alternative, but easily done in the field.

There is general agreement in the literature regarding maximum safe compaction values. Greacen & Sands (1980) reported 2500 kPa (363 lb/in^2) as the critical value for plant growth. Mulqueen, Stafford & Tanner (1977) found that a cone index of 2000 kPa (290 lb/in^2) approximates the limiting value to root penetration and elongation. Atwell (1993) found that levels of mechanical impedance above 2000 kPa (290 lb/in^2) lowered the total root length and elongation rate by up to 50%. The Dickey-john Corp. (1987) gives 300 psi (2068 kPa) as the maximum compaction value for successful root growth.

Soil atmosphere

To grow and develop, roots require a minimum amount of oxygen for aerobic respiration (Wedenroth, 1993). The diffusion of oxygen into the soil, and of carbon dioxide and other gaseous products of metabolism out of the soil, steadily declines as bulk density and soil moisture content increase. Oxygen depletion in the soil, which is considered to be any value less than 15%, promotes anaerobic respiration in roots. In this condition, roots are unable to absorb water and nutrients, and cease to elongate (Greenly & Rakow, 1995). The elevation of carbon dioxide pressure can change the internal pH of cells to toxic levels. In addition to compaction, backfilling around trees can have this effect. Increasing the depth of fill material can reduce the oxygen content below that needed to oxidize organic compounds. The result is a build up of toxic aldehydes (Ruark, Mader & Tattar, 1982).

A slow rate of oxygen diffusion to roots causes a stressful condition that predisposes roots to successful pathogen challenges (MacDonald, Costello & Berger, 1993). Physiologic effects of poor aeration and impedance are exacerbated by these root pathogens. This has been demonstrated with some agricultural plants (Drew & Lynch, 1980). As root metabolism continues by fermentation, some of the nitrogen-containing hydrocarbons that result stimulate pathogen activity (Allmaras, Kraft & Miller, 1988). Increased impedance brings about more ethylene synthesis, radial swelling of cortical cells, and accumulation of osmotic solutes in the root apices (Atwell, 1993). These changes make a root more susceptible to pathogens, including weak pathogens like *Rhizoctonia* and *Pythium*, especially when the protective tissues are breached by abrasion, increasing the supply of exudates available to activate spores.

Stressed roots become more susceptible to exopathogens as well. When neither a parasitic pathogen, nor physiogenic causes can be found to explain a diseased condition, an exopathogen should be suspected. An exopathogen does not parasitize the suscept, but creates a diseased condition in the roots by toxins released into the rhizosphere (Woltz, 1978). Injury to a plant by the release of the chemical juglone from black walnut roots is an example, in which the walnut tree is an unusually large exopathogen.

Development, including agriculture, can impair the deepest, most fertile soils. Surface activity can induce compaction in subsurface layers by collapsing the macropores. A hard surface layer can develop by the cementing of fine organic matter. In addition to foot traffic, the impact of rain causes crusting. In a study of campsites, Legg & Schneider (1977) found that once the surface litter was depleted, such a surface formed quickly. This reduced infiltration of water and exchange of gases. Soil strength, soil atmosphere, soil moisture, and the genetic control of the root system are all important parameters for root system characteristics, but there are others. For a complete treatment, the soil temperature, pH, nutrient status, mycorrhizae, photosynthesis, and reproductive growth stage should also be considered (McMichael & Quisenberry, 1993). See Figure 3.

Fluctuations in the water table can result in the periodic dieback of roots by waterlogging when the soil water rises above field capacity for too long. Gadgil (1971) deliberately waterlogged Douglas-fir seedlings for two weeks, causing the young root tips to change in color from white, which indicated good health, to a purplish black. After four weeks the root tips were black, and the mycorrhizae were brown, the color changes coinciding with the gradual death of the fungal mantle and the root cortex. (Like other members of the family Pinaceae, Douglas-fir roots are ectomycorrhizal). Waterlogging the soil of Douglas-fir seedlings for two weeks adversely affected root physiology, but even after sixteen weeks, the roots tested by Gadgil were not entirely dead. Some air exchange can occur inside the root, and there is a certain amount of dissolved air in water.

Although waterlogging can be deadly, periodic saturation of pore space by water is desirable, for it flushes gases out of the soil pores. As the soil dries to field capacity, air re-enters the pore system, ventilating the soil. Gases also move through the soil by diffusion, and by mass movement due to diurnal temperature change.

Wounding and exposure of roots often occurs with soil compaction. The mechanical wounding of root tissues facilitates infection by facultative parasites. Defects resulting from wounds can extend into the root crown, and columns of discoloration and decay from various wounds can coalesce in the stem. Although root tissue might continue to generate, roots can gradually become hollow and weakened. Wound fungi can cause the rooting zone to shrink and anchorage to weaken, although much more slowly than the aggressive pathogens (Sharon, 1980).

The growth vs. differentiation model

The growth vs. differentiation balance (GDB) model of plant resource allocation states that the production of defensive compounds occurs when growth (cell division and enlargement) slows or ceases. When there are no limiting nutrients or environmental factors, growth predominates within the plant. When moderate environmental stresses limit growth, but are not severe enough to stop photosynthesis entirely, carbohydrates from photosynthesis accumulate, and carbon compounds are allocated to the defensive infrastructure (Herms & Mattson, 1992).

Because the primary (growth) and secondary (differentiation) metabolic pathways share common chemical precursors and intermediates, the energy cost of switching back and forth between growth and differentiation is low. Chemical and morphological changes in the differentiation phase include lignification and thickening of cell walls, and the production of substances such as gums and resins (Lorio, 1988). A tree that is forced to maintain the growth processes becomes more susceptible to disease and insect attack, because preformed resin, tannins, pisatin, and other allelochemicals are not being produced (Herms & Mattson, 1992).

In the Willamette Valley, Douglas-fir and similar species are adapted to summer drought, but irrigation and nitrogen fertilization can force the growth cycle to continue through the dry summer. Under the GDB model, such growth occurs at the expense of the chemical differentiation phase. I would expect to find a larger ratio of early wood (growth) to late wood (differentiation) in a tree with forced growth than in a tree with normal seasonal balance. A forced tree does not shift its metabolism from the growth processes of cell division and enlargement to differentiation, where the build-up and maintenance of the constitutive and induced defense reactions occur, in a timely manner.

Minor pathogens

It is difficult to determine the effect of the minor pathogens because combinations produce disease complexes, and distinctive disease symptoms are often lacking. Affected roots are rapidly colonized by saprophytes, and quickly decompose in the soil. Opportunistic pathogens are easily masked when a more aggressive parasite is also present. It is unlikely that disease complexes resulting from combinations of opportunists are even noticed. Most of these minor pathogens can survive as soil saprophytes. Typically, under conditions that foster a strong host, they are unable to penetrate and disrupt the vascular system, and can only infect seedlings.

Salt (1979) defines the minor pathogen as a "saprophyte or parasite damaging only meristematic cells and cortical cells and surviving in soil as a saprophyte, as resting spores or as sclerotia." Root tips and mycorrhizae are vulnerable to attack by these opportunistic fungi. According to Salt, who wrote mostly about agricultural pests, the majority of these minor pathogens are unspecialized facultative parasites and include *Pythium, Fusarium, Rhizoctonia,* and *Cylindrocarpon.* They are ubiquitous in soil, and their ability to cause disease depends upon host predisposition, and on environmental conditions.

Facultative parasites like these assume greater importance in urban environments than in natural habitats. This is because of host predisposition due to urban soils syndrome. If soil were sterile, physical damage due to compacted soil would be an abiotic disease, or plant disorder. Because facultative pathogens are ubiquitous in soil, soil deterioration leads inexorably to the decline disease, root dieback.

"Pathogen-dominant tissue-nonspecific disease" is a description for the interaction of unspecialized root parasites and seedling roots in the nursery setting (Manion, 1991). In this model, the fungus rapidly macerates root tissue, resulting in nutrient deficiency, and eventual death of the seedling. I would argue that root predisposition brought on by urban soils syndrome makes mature trees susceptible to the same disease. Obviously, preventing soil compaction and correcting soil deterioration are more important than trying to control the secondary-action organisms that cause the eventual mortality of debilitated hosts (Houston, 1984).

Bloomburg (1979) reported that, in British Columbia nurseries, more than 90% of damping-off and root rot is caused by *Fusarium oxysporum*. Craul (1993) noted that compacted, anaerobic soils enhance the growth of *Fusarium* species. *Phytophthora pseudotsugae* and other *Phytophthora* species have also been isolated from roots of Douglas-fir trees growing in nurseries (Hamm & Hansen, 1982).

Pythium species are involved with the destruction of root hairs and fine roots of forest trees. The root disease resulting is called "fine root necrosis" (Hendrix & Campbell, 1973). *Pythium* species are quickly followed by more aggressive fungi, but apparently have an advantage in soils with high moisture content and poor gas exchange. In one pathology report, *Rhizoctonia* was named as the primary cause of decline and mortality in mature Douglas-fir in southwest Washington state, with *Pythium* contributing secondary infections (Ribeiro, 1996). This makes sense in the context of nonspecific root decline in a degenerate, urban soil. Roots die from known pathogens like those mentioned above, and probably from many others that cause damage analogous to the leaf spot fungi and canker fungi in aerial plant parts. These minor pathogens are not well known, and are much harder to study than the aggressive pathogens (Huisman, 1982).

Aggressive parasitic fungi are able to enter undamaged root walls by mechanical rupturing and/or chemical dissolution of the wall. Less virulent fungi can infect only primary tissues, or secondary root tissue through wounds. It must be remembered that the distinction between primary and secondary tissues is arbitrary. There is a gradient, not a dividing line. A ubiquitous wound in roots is the rupture where lateral roots emerge from the pericycle, for this is not healed by the plant (Burstrom, 1965). The opportunistic nature and the plasticity of roots allow for the shedding of lateral roots in dry soil, with the induction of secondary lateral roots in more favorable areas (Smucker, 1993). Continuous shedding and generation of fine roots is a strategy that keeps the largest mass of absorbing roots in fertile microsites. It can also provide weak pathogens with potential infection courts.

Root tips remain active through most of the year, the exception being during summer drought (Santantonio & Hermann, 1985). Fine roots may be replaced two, three, or more times per year. Because of this turnover rate, the fine roots can constitute up to two-thirds of the annual biomass production in trees (Marshall & Waring, 1985). The rapid turnover rate of non-woody roots is due to the temperature and moisture extremes of the soil surface, and feeding by nematodes, springtails, and other soil microfauna. (Perry, 1989). The seasonal flux in root tips and unsuberized fine roots provides another source of potential infection sites.

Epidemiology

The spread of disease in Douglas-fir trees due to aggressive pathogens is different than the spread of disease caused by minor pathogens. Roots from the most vigorous trees in an infected stand are the first to contact inoculum from strong parasites like *A. ostoyae* and *P. weirii*, which survive saprophytically in roots and stumps. Pathogen challenges are successful because of pathogen virulence.

Most minor root rot fungi are facultative pathogens, and exist as spores embedded throughout the soil. Trees in all vigor classes are in constant contact with these potential inocula. Fungal propagules germinate in response to root exudates. By definition, the sphere of exudate influence is the rhizosphere, which can range from less than 1 mm to over 12 mm in radius (Huisman, 1982). Rhizosphere radius increases with coarser texture and with increased moisture. The specific exudates and propagules involved, of course, introduce further variation. As explained below, fast-growing roots are likely to escape infection by these weak pathogens, and slow-growing roots are likely to be infected.

Soil compaction, the parameter of interest here, slows the rate of root elongation by impeding root tip penetration. This is of interest because the speed at which a root tip penetrates soil determines which host tissue is encountered by germinating spores. In soil with good tilth, an elongating root can escape infection from slow-germinating pathogens that use the root tip or zone of elongation for an infection court. Huisman (1982, p.319) gives the example of a 1 mm long root tip and zone of elongation, growing at a rate of 1 cm per day. To encounter this primary tissue, a propagule would have only 1 to 3 hours to germinate after receiving an exudate signal. Germination times like this are observed with Pythiaceous fungi, successful root tip pruners. If germination took longer, by the time the penetration tube was formed, the pathogen would encounter differentiated tissue, and senesce or remain behind as an epiphyte. Huisman suggests that this is the case with *Fusarium* and *Verticillium* species, which have germination times of 6 to 10 hours, and which often form epiphytic colonies in cortical tissues.

A root tip growing in hard soil remains vulnerable to minor pathogens simply due to the relationship of root elongation time vs. spore germination time. Not all infection courts are successful, because roots can defend with phytoalexins. As successful infections in compacted soil increase, more root tissue becomes necrotic, and pathogens build up high inocula pressures. Widespread damage to root tips makes it difficult for the root system to exploit new soil, and contributes to the decline spiral of an established root system.

Environmental and parasitic stresses to roots are additive, the sum sufficient to cause injury where neither would cause injury alone, but only a slowing of growth. In other words, different elastic strains can together cause a plastic strain (Ayres, 1984). Using this terminology, any factor adversely affecting a plant is a stress upon the plant, putting the plant under strain. If that strain goes away when the stressor is removed, the strain is elastic. If the strain remains, it is a plastic strain, or injury. Multiple injuries can lead to death of the system.

Normal physiological death of the root cortex occurs when constituent cells become senescent. Facultative pathogens and saprophytes colonize these senescent cells, but are unable to penetrate secondary tissues. The minor pathogens are unable to invade living plant tissue once suberization and lignification occur. To degrade this drier, interior wood, it takes a basidiomycete. I surmise that a root system in decline from fine root necrosis has a large surface area of vulnerable secondary tissue due to the action of minor pathogens degrading the primary tissues. These many small infection courts could be exploited by the brown rotting basidiomycetes, of which *P. schweinitzii* and *Lentinus lepideus* are prime examples. This would explain the presence of brown rot decay in stumps which have no discernible wounds above ground.

There is some evidence that ectomycorrhizal fungi help control the growth of pathogens. Competition for water and nutrients, the formation of a physical barrier, and the alteration of root exudates are likely factors. The ectomycorrhizal root system of Scots pine, for example, produces monoterpenes and sesquiterpenes that inhibit the growth of aggressive pathogens like *Phytophthora cinnamomi* and *Heterobasidion annosum*. These compounds are not present in non-mycorrhizal roots

(Curl & Truelove, 1986). It should be noted that hyphae from mycorrhizal fungi do not fare well in a compacted soil (Shigo, 1991, p. 251).

Sampling

Root sampling strategy for the detection of nonsymptomatic root disease in Douglas-fir trees remains problematic. Even in the wild forest, statistically significant differences between root samples are usually lacking due to the normally high variation among samples (Watson, Kelsey & Woodtili, 1996). In one study, sampling root systems in old-growth Douglas-fir forests revealed that differences in the biomass of root systems could vary as much between conspecifics as between different hardwood and conifer species (Santantonio, Hermann & Overton, 1977). Sutton writes that intraspecific variation is so great that interspecific comparisons should probably not be made at all, and offers examples with several conifer species (Sutton, 1969). Root sampling is preferred over sampling the root crown or butt for nonspecific root decline, because when strong pathogens are lacking, signs and symptoms may never show up in the butt.

Systematic area sampling

In forest stands where there are no high-value targets nearby, systematic area sampling, in which the surveyor excavates a predetermined number of pits and analyzes them for infected roots, can be effective. Zeglan & Baker (1990) used this method to sample for *Armillaria* in lodgepole pine stands. Area excavation was the preferred method because uncertainty could be brought down to as low a value as needed. Single root excavation was found to be undesirable, because this method underestimated the number of trees infected, and overestimated the infection severity in individual trees. For example, with lodgepole pine trees known to be infected by *A. ostoyae*, single root excavation extending one meter out only proved positive in 55% of the roots sampled.

With systematic area sampling, the surveyor performs the following steps to estimate the amount of root disease present in a stand:

1. Determine how intense a sampling is required (n=3, 5, or 8, for example).
2. Excavate the requisite number of pits (20cm x 20cm cells) in a 3 x 3 meter grid.
3. Determine how many cells contain infected roots.
4. Using an integrated table, choose the level of confidence needed.
5. Use the table to get the range of disease in the stand as a percent (i.e. 41% to 80%).

Systematic area sampling could be useful for the detection of aggressive pathogens in larger, uninterrupted urban forest stands. Due to the stochastic nature of individual Douglas-fir root systems, this method would not be useful for individual trees or for small stands. To make matters worse, many subject trees are surrounded by lawns and landscape plantings, irrigation, underground utilities, buildings, and pavement. Nonspecific root decline due to urban soils syndrome does not produce the obvious signs and symptoms characteristic of aggressive diseases like laminated root rot and Armillaria root disease.

Starch sampling

The appearance of visible symptoms in a canopy suggests that stress levels have reached the damage threshold. Roots, however, typically exhibit detectable stress before that threshold is reached. Roots have evolved to buffer changes in the soil environment so that aboveground parts are unaffected by elastic stresses.

One way to monitor root health is by the starch content. Stressed roots have a lower starch content, reflecting decreased carbohydrate reserves. The energy reserve stored in the living parenchyma cells in woody roots is essential for root defenses, and when reserves get low, opportunistic pathogens attack (Shigo, 1996).

High starch reserves in roots and in the bole are correlated with fine root growth in conifers (Vogt et al., 1993). This varies throughout the year with normal carbon allocation cycles, so the sampling date must be accounted for.

A quick way to test for starch content is to stain with an iodine solution (I_2KI). Starch stored in the parenchyma cells will turn purple when the solution is applied. The test can be made on cut roots or increment cores. This technique would be most useful for monitoring changes in individual trees over time. For comparison studies, a colorimetric chart constructed from control trees in different conditions would be required (Shigo, 1991, p. 277).

Proposal

Because conifers affected by root decline due to urban soils syndrome are typically nonsymptomatic until failure in a wind storm, it would be prudent to develop a hazard rating system based on site factors. The general objective is to develop a procedure that practitioners, including foresters, arborists, park managers, and extension agents, can use to detect nonsymptomatic Douglas-fir trees with nonspecific root decline. If we can use soil and root zone parameters as criteria to evaluate root health, then we have more diagnostic tools to work with. The goal is to identify Douglas-fir trees with root dieback by using a diagnostic procedure that is 85-90% reliable. This constitutes an indicative diagnosis (Shurtleff & Averre, 1997), and is probably the best that we can hope for with an obscure root disease.

This hazard rating procedure for root disease will begin with a visual tree assessment coupled with an evaluation of the site for disturbance factors (see Figure 4). These first steps will suggest either that no further investigation is indicated, or that soil removal, root flare drilling, and increment coring are needed. Soil sampling for compaction, moisture and humus percent, and phosphorous, nitrogen and potassium levels will help to assess soil health. In the final analysis, one of the following treatments will be recommended: no action, monitoring, or hazard mitigation. Mitigation might entail removing the tree, moving targets that are at risk, or some other, intermediate response with the subject tree, the grounds, and nearby host species.

The detection of hazard trees has received much attention in recent years, from the International Society of Arboriculture (Matheny & Clark, 1991), from the University of California (Edberg, Costello & Berry, 1993), from the British Department of the Environment (Mattheck & Breloer, 1994), and from the USDA Forest Service, among others. In a recent Forest Service study, 54% of failures in Douglas-fir trees at Pacific Northwest recreation sites were due to root collapse (Harvey & Hessburg, 1992). This is the most dangerous sort of failure, for it involves the whole tree. The information garnered from this research project will contribute towards building a Douglas-fir species profile for use in evaluating the safe useful life expectancy (SULE) of Douglas-fir on disturbed sites (see Figure 5). This species profile will be modeled on one developed for western hemlock in British Columbia (Dunster, 1996).

This study will focus on Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) in the Willamette Valley near Portland, Oregon, which is a developed area with a large rural forest interface. Along the fringes, subdivisions are being built in a landscape dominated by Douglas-fir. Outlying areas are growing as extended low-density development into the forest (Shands, 1991). The Portland city limits include 5,400 acres of natural park lands in upland mixed coniferous/deciduous forests (Lev & Houck, 1988). Much of this is forested by Douglas-fir.

When winter rains or root rots weaken root anchorage in compacted urban soils, Douglas-fir trees become susceptible to windthrow. When trees in these remnant stands topple, property damage and personal injury entail. For example, damage to Portland General Electric property due to windstorms during the winter of 1995-1996 cost an estimated sixteen million dollars (MacKenzie, 1996). Most of this damage was from uprooted Douglas-fir trees. These catastrophic wind storms exposed widespread root disease and caused many trees to topple at once rather than toppling singly over the coming years.

As an arborist practicing in the Portland, Oregon area, I have made at least a cursory inspection of fifty or more toppled Douglas-fir trees. I have noticed that nearly every exposed root system has had some decay. This includes trees in shallow clay soils that were temporarily waterlogged by flooding. (One Douglas-fir tree involved in a landslide had laminated root rot, and this condition was a contributing factor to the landslide). Excluding several laminated root rot centers in undeveloped sites, the Douglas-fir trees I have seen uproot in this urban area have involved dieback of the roots due to brown-rotting fungi. Diseased roots are typically hollowed, and blackened on the outside. They exhibit a brown, crumbly decay where the breaks occur, often surrounded by adventitious roots. We occasionally find Douglas-fir trees that have died suddenly from bark beetle infestation in Portland. It is likely that nonspecific root decline or brown rot pathogens have predisposed the trees to these bark beetle attacks.

First Objective

The first objective is to develop a hazard rating system that helps determine when intensive, invasive sampling is needed. The cities of Lake Oswego and Durham, Oregon, have city ordinances that require landowners to obtain a tree cutting permit before cutting down any tree over five inches at standard height (4 ½ feet above grade). Applications are logged, and these logs are public records.

Given the cooperation of landowners, each Douglas-fir tree to be cut down will be analyzed. One hundred sites (experimental units) will be used, no matter how many trees are involved per site, for a minimum of one hundred sampling units. The final output will be a predictive model, based on the correlation of site parameters with disease incidence. Causal inference will not be made, because this is not a controlled experiment. The procedure follows.

1. An evaluation of targets will be made based on A Photographic Guide to the Evaluation of Hazard Trees in Urban Areas (Matheny & Clark, 1991). For this study, we will always move to step two. In practice, without a target that represents economic loss, the evaluation is concluded.

2. A visual tree assessment will be made, using the VTA method (Mattheck & Breloer, 1994). See Figure 6. Crown appearance will be judged by crown class condition, using a data sheet based on the Tree Hazard Evaluation Form (Matheny & Clark, 1991).

Butt swell, wounds or scarring in exposed roots or butt, and signs of canker in bark patterns will be noted, based on the Guidelines for Log Grading Coast Douglas-fir (Lane & Woodfin, 1977), and Indicators of Cull in Western Oregon Conifers (Aho, 1982).

Fungal structures including basidiocarps, hyphal fans, and rhizomorphs in the wood or root zone will be identified.

3. Site and stand conditions. Stand information will be based on silvicultural assessment of the immediate area. The history of irrigation, fertilization, and herbicide use will be garnered by observation, and by interviewing the landowner. Site improvements within the root zone will be noted (pavement, buildings, patios, etc.) Other vegetation within the root zone, including turf, ground cover, and other trees or shrubs, will be coded and noted on the field data form. Root zone extent will be based on a radius of one foot for each inch of diameter at standard height.

4. Root crown morphology. In practice, my minimum requirement for safety with a Douglas-fir tree root system is the presence of three or more main buttress roots, with no hemisphere (contiguous 180 degrees) lacking a buttress root. If there is any indication of stress in the crown, or if the site is other than uncompacted forest, the buttress roots will be exposed to at least eighteen inches from the root crown and drilled to ensure that they are intact and uninfected near the root crown. Ideally, drilling would be done with a resistograph, but this is not yet a common tool (Mattheck & Breloer, 1994). Instead, a 5/32 inch drill bit will be used. Changing drill pressure, and the consistency and odor of the wood chips brought out by the drill can reveal decay or incipient decay.

If stained or otherwise suspicious wood is brought out, then an increment core will be taken for further analysis, including a test for strength with a fractometer (Mattheck, Breloer, Bethge, Albrecht & Zipse, 1995), and agar cultures if indicated. Blair & Driver (1977) successfully detected annosus root disease by drilling into trees with a 3/8 inch ship's auger bit, and collecting the wood chips. These were incubated and examined for the pathogen's imperfect stage. Culturing wood from drill shavings would probably not be fruitful with the weak parasites of interest here. Weak pathogens are easily masked by saprophytes as soon as the environment changes.

5. Soil and moisture conditions. Soil samples will be taken with an Oakfield soil sampler, and analyzed by the LaMotte method for soil type, N, P, K, and humus content (Tucker, 1985). Moisture content and soil pH will be measured with a Seiki soil meter. Soil compaction will be tested with a penetrometer. These variables will allow us to quantify the relative fertility of the soil, and the mechanical condition of the root zone (Lichter & Lindsey, 1994).

6. Analysis of incremental growth. One increment core per tree will be taken to a depth of six inches on the SW side at breast height. These will be stored in a clear plastic tube and labeled. Analysis

for growth trends, and for the earlywood-to-latewood ratio for the preceding ten years will be made with a dissecting microscope. Suggestion of an imbalance in the growth vs. differentiation phases will be tested as part of the hazard rating system for root disease. Cores will be compared to an increment core index that will be developed for Douglas-fir as described in Objective 2, below. In addition, each core will be tested for strength with a fractometer.

7. Root crown health. Following the removal of the tree, but before stump removal, the root crown will be cut immediately above the soil line and examined for signs and symptoms of root disease. This inspection will not reveal fine root necrosis, but is likely to reveal infection by the more aggressive brown rotters. When a stump is to be removed immediately, the cooperation of the landowner and the tree cutters will be enlisted to save a cross section nearest the root crown for this analysis.

8. Statistical analysis. The variables measured in items one through six above, will be analyzed for significant correlation with root disease.

Second objective

An increment core index for Douglas-fir will be made from samples of one hundred Douglas-fir trees. These will include fifty trees from an undisturbed rural forest site with no indication of disease or environmental strain, and fifty trees known to be root-diseased. The latter group will include ten trees in a laminated root rot center, ten trees in an Armillaria root disease center, ten trees with conks from *P. schweinitzii*, ten trees dying from waterlogging, and ten trees affected by soil compaction.

1. Increment cores will be made at standard height on the SW side, straight into the tree toward the center of the bole, to a depth of six inches.

2. A statistical analysis of the earlywood-to-latewood ratio for all trees tested will be made to search for

a correlation between this ratio and root disease.

3. PAI will be measured.

Third objective

A starch index for Douglas-fir will be made using the population in the second objective, above. Cores for this will be taken from the main buttress root closest to the SW side of the tree. Correlation will be made with PAI, with the earlywood-to-latewood ratio, and with the known health condition of subject trees.

Preliminary study

A preliminary field study was made at the Olson Memorial Clinic, in Lake Oswego, Oregon, in 1996. During the storm of December 12, 1995, three large Douglas-fir trees uprooted, with ensuing property damage. The root plates were small, and the broken roots exhibited a brown cubical decay. The bark was blackened, and large roots had died back with adventitious roots sprouting from the affected areas.

Samples were taken from one uprooted tree and sent to a plant pathology clinic. This was a thirty-two inch diameter Douglas-fir tree that had roots decayed to within five feet of the bole. *P. schweinitzii* was diagnosed by visual assessment of the samples as the most likely causal factor.

In the summer of 1996 I had the opportunity to cut down seventeen Douglas-fir trees on this property, and to take samples of the root crown areas as they were exposed. Samples were taken at ground level by cutting a slice off of the stump as close to the ground as possible. Decayed areas, discolored areas, and areas where resin pockets had formed were sampled and bagged. Samples were also taken from an uprooted stump that had roots still in the ground, and from an old, decaying stump cut down in the past. Soil compaction measurements were consistently above 300 lb./in^2. Soil pH was between 6 and 7. Soil moisture was below 50%. The root zones were covered with two inches or more of bark dust, were not irrigated, and were extensively disturbed with buildings and infrastructure.

Isolations were started on both Goldfarb's agar and Nobles' media. Cultures that consisted of fast growing contaminant fungi and bacteria were discarded. Slow-growing colonies were assumed to be wood-decaying basidiomycetes. These were subcultured up to five times to develop pure cultures for identification. Colonies that appeared to be identical based on mat characteristics were grouped together, and a representative used for identification. Finally, five representative, distinct cultures remained for identification using Nobles' keys (Nobles, 1964).

The identification procedure was a process of elimination, or exclusion diagnosis, from a list of fungi known to be responsible for decay of Douglas-fir in the Pacific Northwest region. That list was based on Diseases of Pacific Coast Conifers (Scharpf, 1993). The list included the white rotters, *Heterobasidion annosum*, *Ganoderma applanatum*, *G. oregonense*, *Poria subacida*, and *Polyporus tomentosus*. Due to a negative oxidase reaction with guiacol, which was indexed with a known *H. annosum* culture, all of these white rotters were eliminated.

The remaining suspect list included the following brown rotters: *Fomitopsis cajanderi*, *Lentinus lepideus*, *Fomitopsis pinicola*, *Phaeolus schweinitzii*, *Polyporus sulphureus*, *Fomes officinalis*, and *Sparassis crispa*. Using Nobles' keys, slides prepared from each culture were compared to the list of attributes for each known fungal species.

Fomitopsis cajanderi was eliminated from the short list on the basis that:

- hyphae were not thin walled and consistently nodose-septate (code symbol 3 was lacking)
- hyphae in KOH solution and mats were not hyaline or white (code symbol 36 was lacking)
- fruit bodies had not formed (code symbol 48 was lacking).

Fomitopsis pinicola was eliminated on the basis that:

- hyphae were not thin walled and consistently nodose-septate (code symbol 3 was lacking)
- hyphae in KOH solution and mats were not hyaline or white (code symbol 36 was lacking).

Phaeolus schweinitzii was eliminated on the basis that:

- the hyphae were not thin walled and consistently simple-septate, for there were clamp connections (code symbol 6 was lacking).

Polyporus sulphureus was eliminated on the basis that

- hyphae were not thin walled and consistently simple-septate, for there were clamp connections (code symbol 6 was lacking).

Fomes officinalis was eliminated on the basis that:

- hyphae were not thin walled and consistently nodose-septate (code symbol 3 was lacking)
- there were no conidia present (code symbol 33 was lacking)
- hyphae in KOH solution and mats were not hyaline or white (code symbol 36 was lacking).

Information on ***Sparassis crispa*** was from Stalpers (Stalpers, 1978). *S. crispa* was eliminated on the basis that:

- hyphae in KOH solution and mats were not hyaline or white (code symbol 36 was lacking)
- the culture contained chlamydospores (code symbol 32 was lacking)
- hyphae remained thin-walled and undifferentiated (code symbol 7 was present)
- fruit bodies had not formed (code symbol 48 was lacking).

Lentinus lepideus was eliminated from all but one of the cultures on the basis that:

- the culture contained chlamydospores (code symbol 32 was lacking)
- hyphae in KOH solution and mats were not hyaline or white (code symbol 36 was lacking)

L. lepideus was identified as the organism in one of the cultures, originally isolated from tree number 114 at the Olson Clinic site. This tree had evidence of an old wound on one root, as well as a saw cut where a secondary leader had once grown from just above grade. According to Scharpf (1993), *L. lepideus*, or scaly cap fungus, is a mushroom-type brown heart rot. It can be found in roots as well as the upper bole, and produces typical brown rot decay. Incipient decay is a yellow stain, which becomes dark brown or black when exposed. Wood becomes cubically cracked with thin white mycelial fans in shrinkage cracks, and has an odor of turpentine. *L. lepideus* is considered a facultative parasite.

The description for decay due to *L. lepideus* is very similar to decay caused by other brown rotters, including *P. schweinitzii*, and *S. crispa*. In tree number 114, *L. lepideus* was apparently acting as a weak wound parasite. The disease it caused was visible at the root crown where the stump cut was made, and it extended up into the butt and down into the roots.

Main buttress roots on the trees that uprooted at the Olson Memorial Clinic could have been infected by *L. lepideus*, or another brown rot pathogen, gaining entry through basal or root crown wounds, and moving distally. Alternately, brown rotters might have work their way proximally from dying lateral roots towards the root crown. The below-ground infection courts could have been due to the maceration of primary root tissue by minor pathogens, and the subsequent exposure of (juvenile) secondary root tissues. In any case, a systematic approach for the prediction of failure in Douglas-fir trees due to root decline would be helpful.

Treatment for compacted soils

Vertical mulching is the process of drilling vertical channels in the soil throughout the root zone. Although a common arboricultural practice with anecdotal successes, there are no scientifically rigorous studies to support this practice as a remedy for compacted root zone soil (Kalisz, Stringer & Wells, 1994). An alternative method, the creation of holes with high pressure water jets, fared no better (Pittenger & Stamen, 1990).

The fracturing of compacted soils was originally done with dynamite, a practice no longer feasable. Fracturing with compressed air, with or without the forced injection of amendments, has not proved to be an effective treatment, although variations of this practice are as commonly used as vertical mulching. Bulk density is not lowered, and oxygen diffusion is improved only at the (usually single) fracture line. This fracture line soon recompacts (Smiley, Watson, Fraedrich & Booth, 1989). Rolf reported short-term effects in sandy loam, and deleterious effects in clay loam (Rolf, 1992).

Other remedial treatments have similar track records (Day & Bassuk, 1994). Rototilling, and subsoiling, or the plowing of soil at depth, can be useful for site preparation, but are not practical around established trees. Both spike aeration and core aeration can provide limited relief in a surface that has crusted or is covered with competing vegetation like turf. There have been good results with radial trenching, or excavating between lateral roots and replacing the soil with an amended mixture (Craul, 1994). The drawbacks include unacceptable damage to roots and surrounding property when using a backhoe, and prohibitively high labor costs when using hand tools.

Hydraulic excavation, including removal of the slurry with vacuum equipment and replacement of the original soil with compost, has yielded favorable results with a minimum of root damage (Watson, Kelsey & Woodtili, 1996). Hydraulic soil excavation requires specialized equipment and is expensive, but it is much less damaging to a root system than any other excavation method. It could be used for large-scale root sampling where a vacuum truck has access (Gross, 1995). This system might become popular for wealthy property owners with high-value trees, but treatment at the stand level does not seem likely. Whether decline in conifers like Douglas-fir can be corrected with this procedure is not known.

Prevention of soil compaction

Most ameliorative treatments for soil compaction are ineffective. Others are impractical or cost-prohibitive in the urban environment. Therefore the prevention of soil compaction is necessary. Prevention is an immediate concern around mature Douglas-fir trees, because soil deterioration and the dieback of a root system can create a dangerous condition within a few years. Other factors such as edge effects or trenching can create an immediate hazard. A newly planted tree will adapt to a compacted site by growing a shallow root plate. This may not be dangerous until the tree grows larger.

Prevention can be built into a construction project by limiting mass grading with tree protection zones. However, groundwater flow, surface absorption, and runoff can still change, and these factors must be corrected with drainage and irrigation. Selective grading is a construction technique limiting the use of compaction and slab construction, and instead building with discontinuous foundations of stem walls and piers (Lichter & Lindsey, 1994). Even with this construction system, some compaction will occur from the presence of machinery, vehicles, materials, and foot traffic. Mulching with wood chips to a depth of 15 cm or more will provide a protective surface, and fencing the root zones of trees to be preserved will minimize damage from wounding and compaction. The use of lightweight equipment, wide, low pressure tires, and the avoidance of work when soils are moist, are other key ingredients in an integrated soil preservation program.

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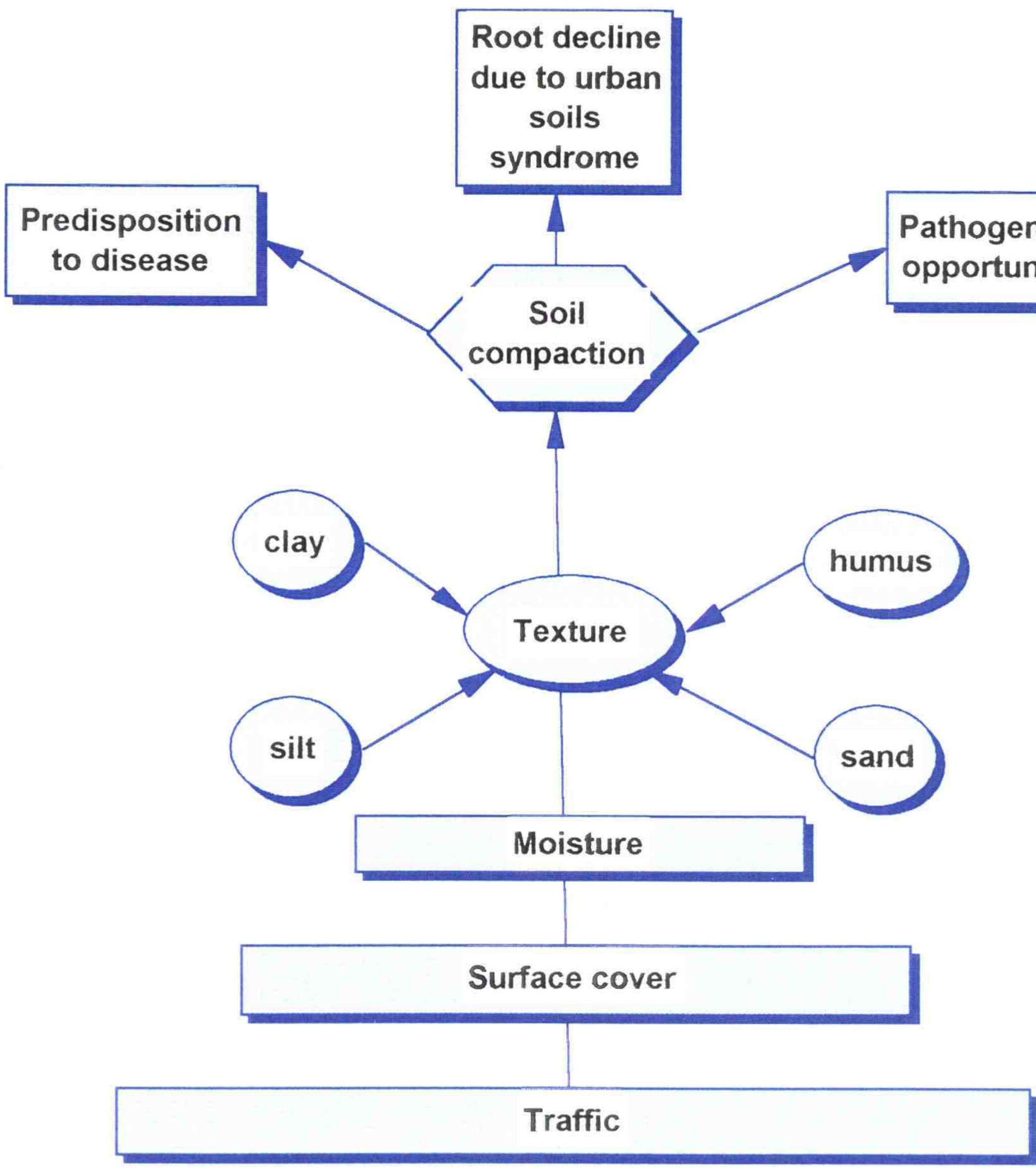

Figure 1. Elements of soil compaction

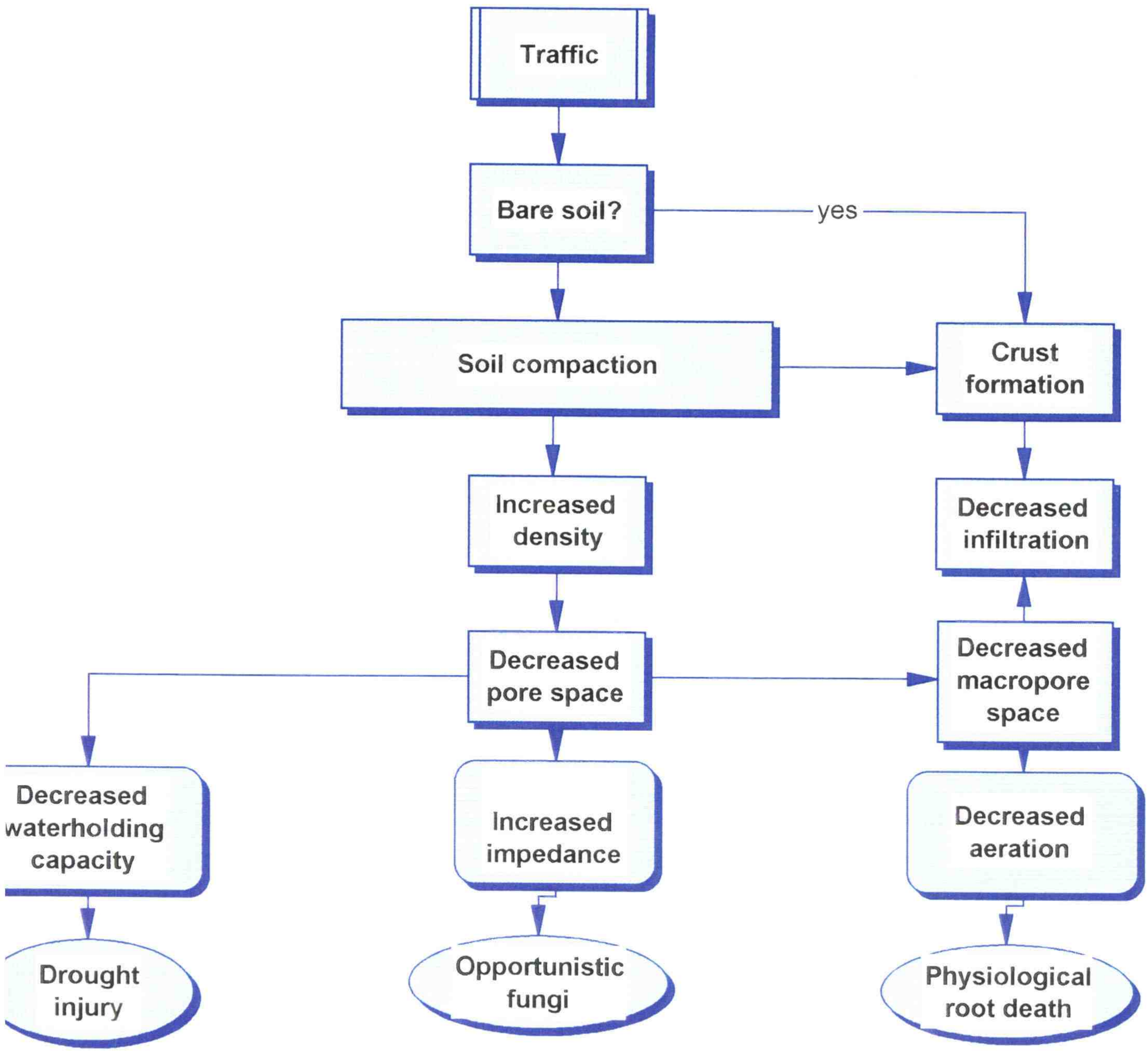

Figure 2. Traffic impact on soil and its effects. After Craul (1994)

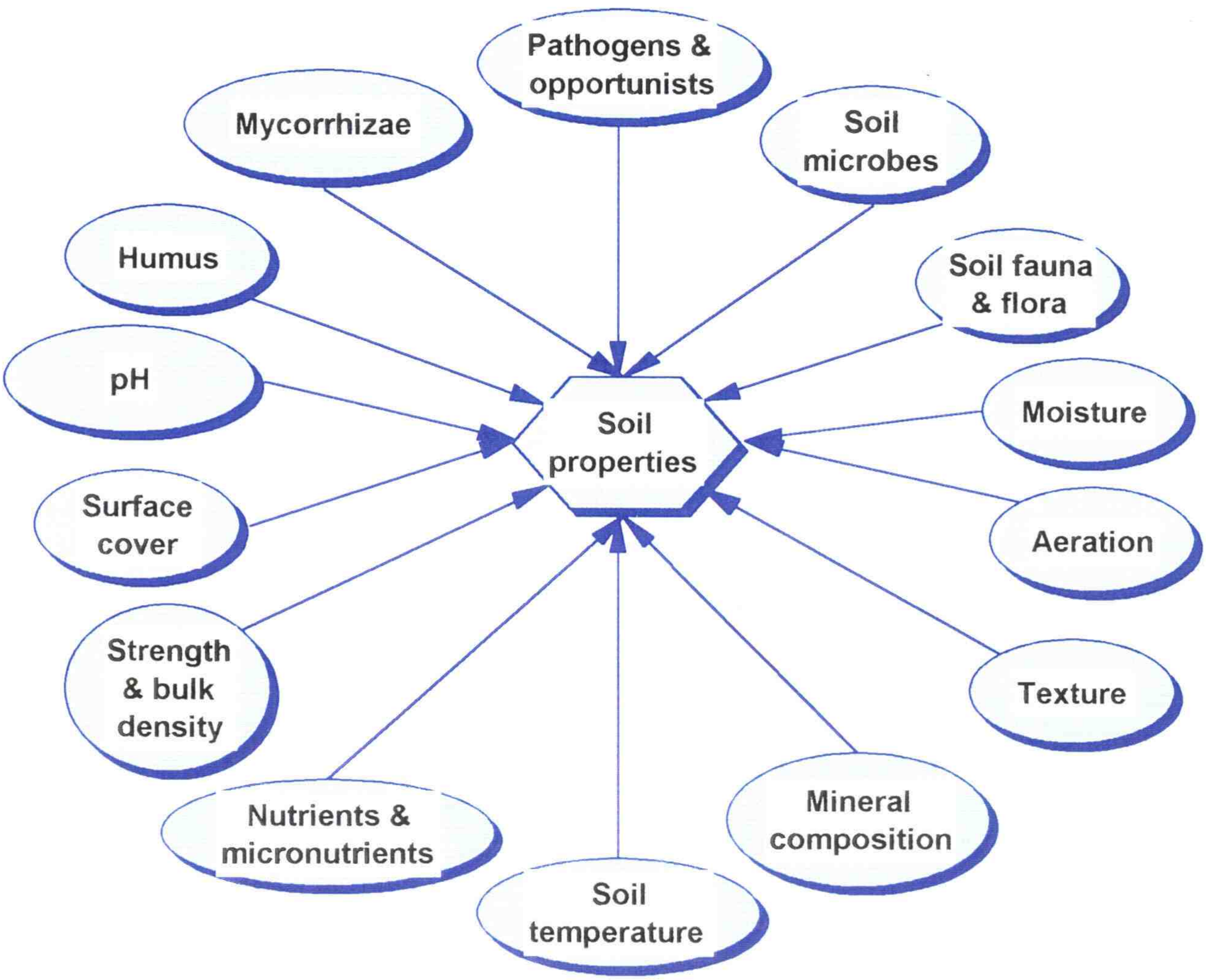

Figure 3. Soil properties to include in a site hazard rating index

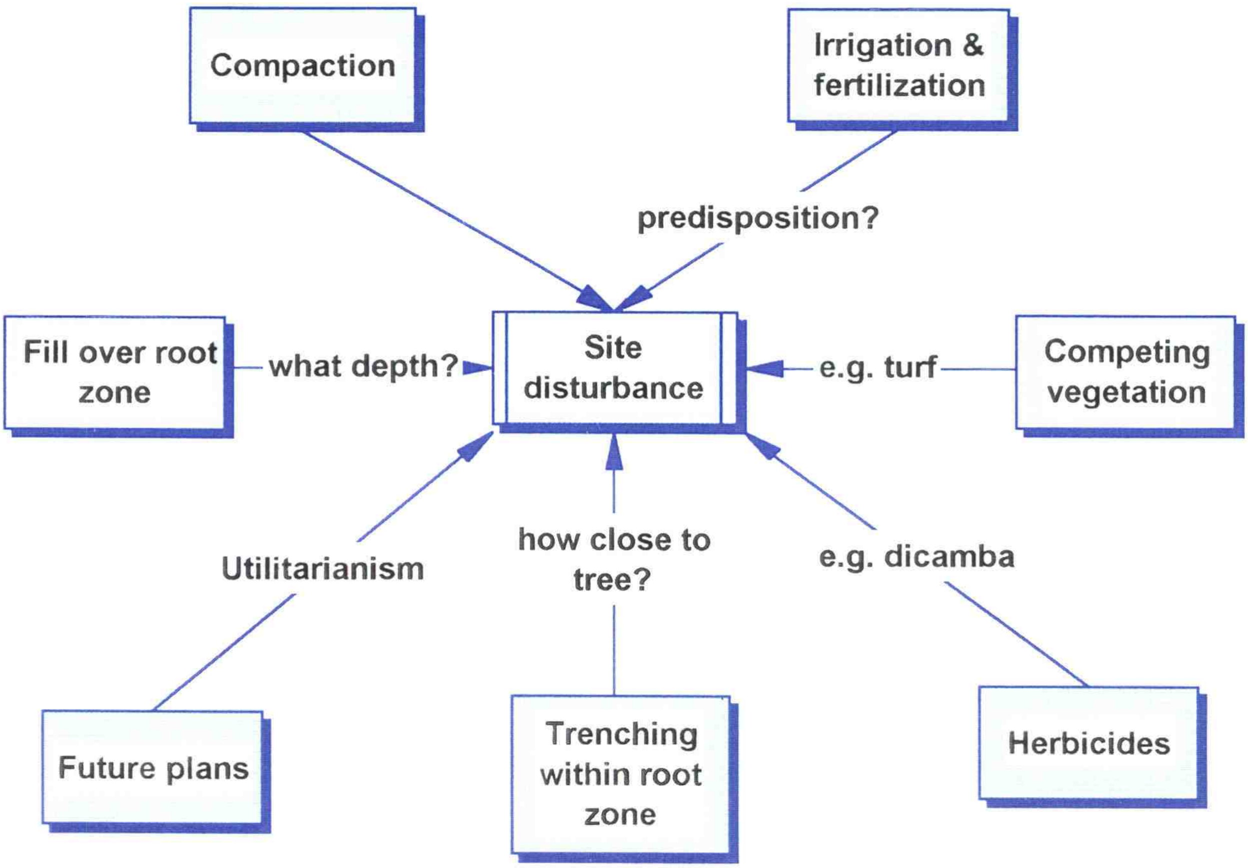

Figure 4. Disturbance factors to include in a site hazard rating index

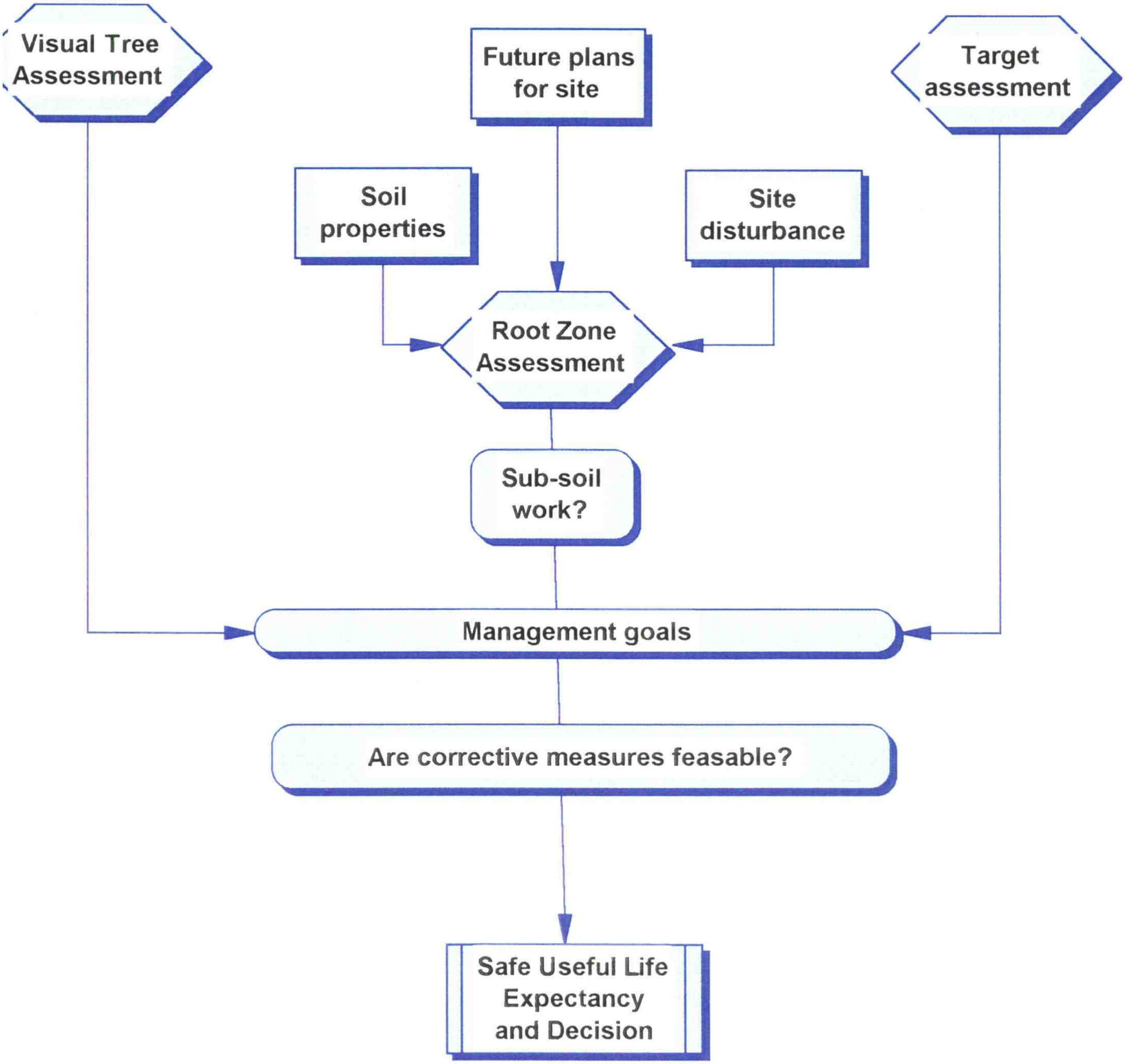

Figure 5. Evaluating the safe useful life expectancy for Douglas-fir trees

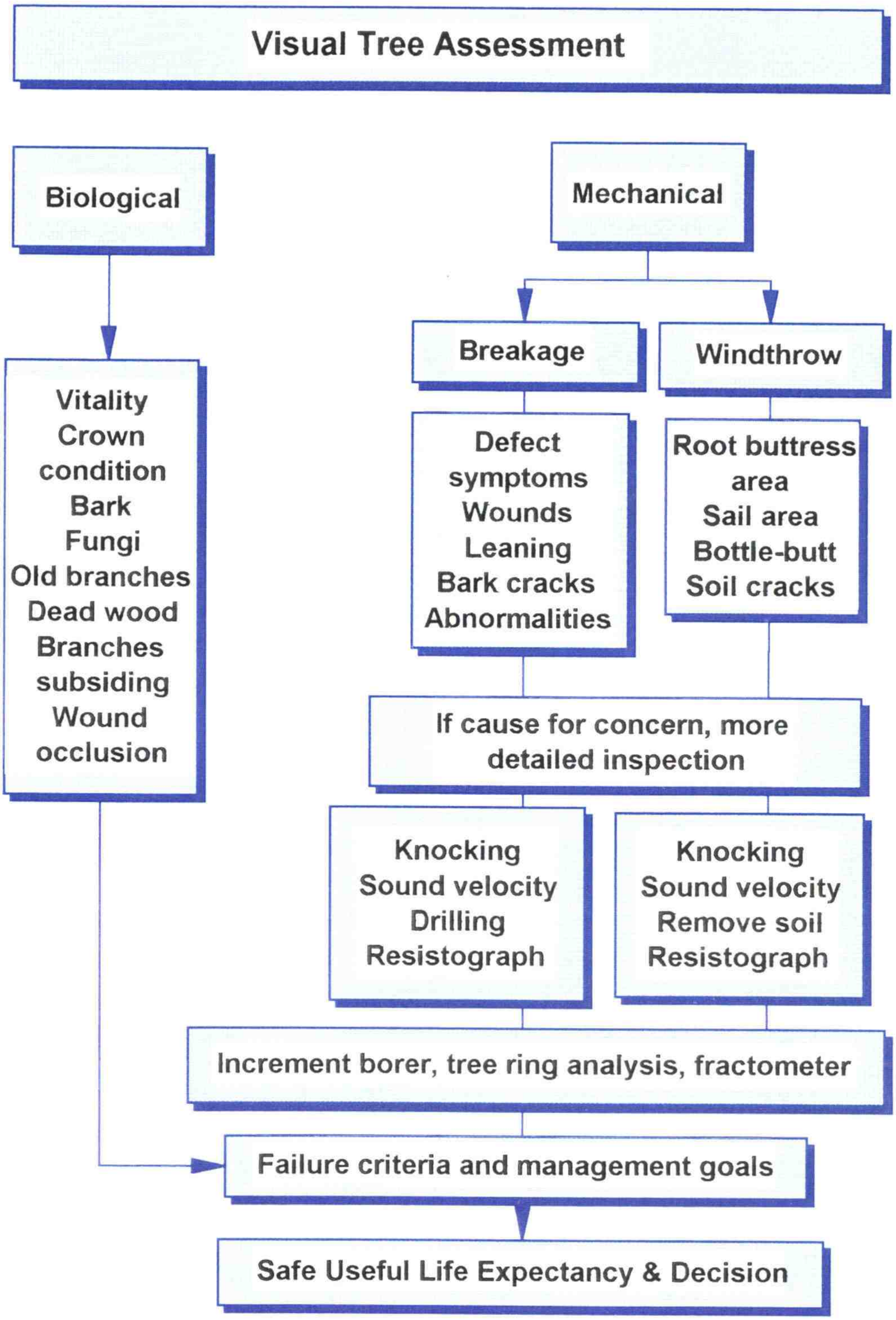

Figure 6. Visual Tree Assessment (VTA). After Mattheck & Breloer (1994).