Soil Aeration and Tree Health: Correlating Soil Oxygen Measurements With the Decline of Established Oaks[1]

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Abstract: Field measurements of oxygen concentration and oxygen diffusion rate (ODR) indicate that ODR is a more reliable indicator of problem sites. In a landscaped area where oak trees are declining, ODR in the upper part of the soil profile ranged between 0.1-0.2 µg O_2cm^2/minute (where µg = micrograms, and O_2 = oxygen) for weeks at a time. In laboratory experiments, we have found low oxygen levels to inhibit oak root growth, and to predispose cork oak roots to extensive colonization by *Phytophthora cinnamomi.* Work is continuing to better define stress thresholds, and the effectiveness of aeration management practices in alleviating root stress.

Trees grown in urban settings are often subjected to environmental stresses. These stresses may result from water deficit, temperature extremes, mineral deficiency or excess, air pollution, defoliation, or poor root aeration. Trees exposed to mild levels of stress may exhibit symptoms such as early fall color and leaf drop, while those exposed to more extreme levels may exhibit symptoms of progressive canopy thinning, limb dieback, and eventual death (Houston 1985). Stress is important not only because of its direct, negative effect on tree vigor, but also because reduced vigor can increase tree susceptibility to pathogenic organisms. For example, oak root fungus *(Armillaria mellea)* has often been reported to be most serious as a pathogen of trees weakened by physiological stress (Rishbeth, 1983). Thus, even when stresses are transient or sublethal, trees may still be severely damaged.

Poor root aeration is one form of stress that is particularly important in urban and park settings. Roots require a continual supply of oxygen, which moves from the above-ground atmosphere to the below-ground atmosphere through soil pores. Several factors which commonly occur in urban and park settings can interfere with this process. One is the movement of soil that typically occurs during construction and landscaping operations. Because oxygen enters soil largely by diffusion, the highest concentrations are near the surface, and they decrease with increasing depth (Kozlowski 1985). Thus, adding backfill soil around trees can suddenly and seriously reduce oxygen levels in deeper parts of the soil profile. Likewise, soil compaction can interfere with oxygen movement into soil because of the loss of macropore space. The large pores in a well- structured soil are important avenues of gas exchange, and they are lost when soils are compacted to high bulk densities. A third factor which commonly limits root aeration is high soil moisture, resulting from excessive irrigation or poor drainage. When soil pores are filled with water, oxygen cannot enter the profile, and the small amounts dissolved in water are rapidly depleted at sites of high metabolic activity.

While species differ, roots generally function best at oxygen levels above 10 percent (Kozlowski 1985). At lower concentrations, roots will cease growth and lose their selective permeability. Key metabolic pathways are modified and cellular metabolites may accumulate to toxic levels. Toxic effects are attributed to accumulation of toxic byproducts of anerobic respiration (Levitt 1980): lactate, pyruvate, and ethanol. Thus, the degree of root injury is proportional to the degree of stress. However, this generalization may not be true if root pathogens are present. Oak Root Fungus, *Armillaria mellea* may colonize root tissues killed by oxygen stress, and from that food base, invade healthier portions of the root system (Wargo 1981). Likewise, accumulation of ethanol in roots may stimulate attack by *Armillaria* (Wargo and Montgomery 1983). In both cases, the resulting damage to the root system is far greater than oxygen stress alone would cause, and could result in tree death.

There are other examples where the effects of oxygen stress are more damaging to roots when pathogens are present. For example, early references to the decline and death of avocados in flooded soils attributed the problem to "water injury," "melanorhiza," "apoplexy," or "asphyxiation." However, research showed that two to three year-old seedlings were not sensitive to flooding per se, and could tolerate up to nine days of continuous flooding with no obvious root damage. But if *Phytophthora cinnamomi* was present, flooding for as little as two days yielded severe root rot. Likewise, safflower roots continuously exposed to 0.5 percent oxygen were damaged only when treatments lasted 48 hours or more (Heritage and Duniway 1985). However, in the presence of *Phytophthora cryptogea,* exposure times as brief as six hours resulted in severe root infection. Well-aerated roots had only minimal infection, indicating that oxygen stress had rendered otherwise resistant tissues susceptible to attack. While brief oxygen stress caused no visible root damage in the absence of *Phytophthora,* there clearly were physiological changes which interfered with normal host defense mechanisms. Thus, oxygen stress may be important even at levels which would not cause direct root injury.

Several practices are currently being used in the landscape and tree care industries to improve aeration in landscape soils. These include high pressure water injection (Hamilton 1984), augered aeration holes filled with porous materials (Hamilton

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[1] Presented at the Symposium on Oak Woodlands and Hardwood Rangeland Management, October 31 - November 2, 1990, Davis, California.

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1985), soil aeration pipe systems for transport of gasses through overlying fill soils or pavements (Harris 1983), and paving blocks used as substitutes for less porous materials such as asphalt or concrete. These practices have been used for many years with widely varying reports of success. Whether any of these methods significantly improve soil aeration problems leading to direct root injury, or indirect injury through the activity of pathogens, has not been critically studied.

This paper reports on the principal objectives of this research project: to determine the minimum soil oxygen concentrations which must be maintained for optimum root health in landscape trees, and to evaluate the effectiveness of various management practices in maintaining desired oxygen levels.

MATERIALS AND METHODS

Soil Oxygen Measurements Around Established Trees

Measurements of soil aeration status have been done at several field locations. At each location, we installed three replicate monitoring sites. Within each monitoring site, we installed a tensiometer, a gas sampling tube, and five platinum microelectrodes to each of three depths: 6 inches, 12 inches and 36 inches. Soil matric potentials and ODR values were measured daily over intervals of two weeks, and gas samples were extracted for chromatographic analysis at four to five day intervals. After two weeks, all ODR microelectrodes were removed and replaced with clean electrodes. The replacement electrodes were inserted into the same holes, but were pushed 1-2 cm deeper in the soil. Daily monitoring was then resumed for an additional 2 weeks. At the end of the O_2 monitoring period, undisturbed soil cores were collected from each depth from all monitoring sites. A portion of each soil core was submitted for particle size analysis, with the remainder used for determination of dewatering characteristics (between 0-300 mb matric potential) and bulk density.

Six trees at three different locations were selected for study based on tree condition and site features. The first location was a turf area beneath and between the canopy of two closely spaced and severely declining coast live oaks. The turf was irrigated approximately three times weekly. The second location was also a turf area under two cork oaks, one declining and one healthy. The two trees were spaced approximately 60 feet apart and were evaluated separately. The third location was a planting strip where a row of mature cork oaks were growing between the curb and sidewalk. Two healthy trees in the row were selected. Turf in the planting strip is irrigated, but the area outside the sidewalk is nonirrigated.

Effect of Oxygen on Root Growth and Disease Susceptibility

The effects of low oxygen concentration on root growth were studied in three species of oak: Valley oak, *Quercus lobata,* Cork oak, *Quercus suber* and Blue oak, *Quercus douglasii.* These species are believed to differ in their tolerance of low oxygen, with valley oak considered most tolerant and blue oak least tolerant. We have studied oxygen/root growth interactions using 1-2-month-old seedlings of each species, on the asumption that root tips of young seedlings would respond similarly to hypoxia (low oxygen) as those of mature trees.

Germinated acorns with 10 cm radicles were transplanted to mini-rhizotrons fitted with a removable plate surface. Root growth was encouraged along this plate by keeping the containers at a slant. After 10 days the plate was removed and root tracings were made on acetate sheets. The rhizotrons then were incubated in one of three air-tight chambers, each purged with a gas mixture of nitrogen and compressed air yielding a specific oxygen concentration. Oxygen levels between 0 percent (pure nitrogen) and 21 percent (air) were tested. Following a five day incubation period, rhizotrons were removed and the roots retraced. Treatment effects were determined by calculating the amount of root growth which occurred during the various oxygen treatments as a function of total root growth. A root growth value of 50 percent would indicate that one half of the total growth occurred during incubation in the oxygen chamber.

The effect of oxygen treatment on susceptibility to *Phytophthora* infection was determined by inoculating individual roots of cork oak seedlings with zoospores of *Phytophthora cinnamomi.* Inoculations were done at root tips.

RESULTS

Soil Oxygen Measurements Around Established Trees

ODR did not vary with soil matric potential in a consistent manner. In the irrigated turf area (location 1), the soil profile remained quite wet. Matric tensions at 12 inches and 36 inches remained fairly constant at 18 and 22 centibars, respectively (fig.1). In the upper 6 inches, matric tensions fluctuated with irrigation episodes, but generally never exceeded 25 centibar. Within the 15 to 25 centibars range, ODR values ranged from 0.1 to 0.8 for the three depths. Surprisingly, higher ODR values were found in the lower depths (12 inches and 36 inches). Further analysis suggests that low ODR values in the 6 inch depth reflected soil compaction as a limiting factor, rather than matric tension. At the 12 inch to 36 inch depths, where bulk densities were low (1.27-1.30 g/cm^3) and a large proportion of

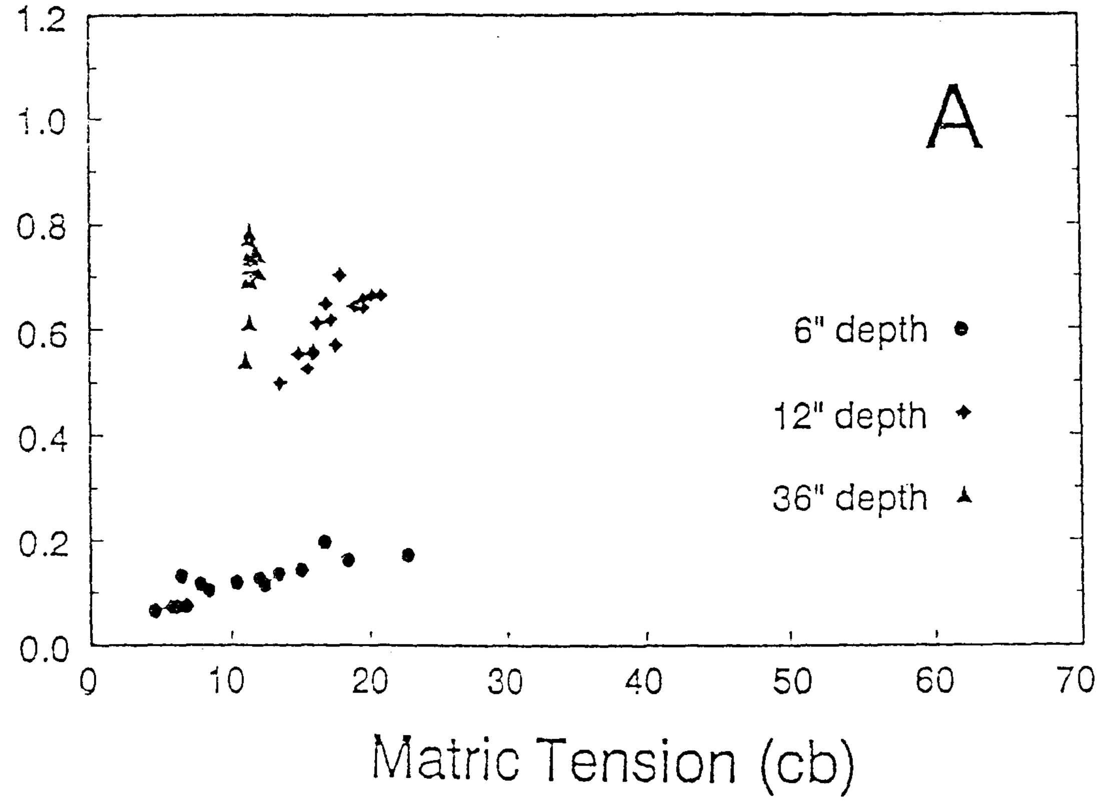

Figure 1—Oxygen diffusion rates (µg 02/=2/min) at three depths in a sandy loam soil, with corresponding matric potential values. Measurements taken under two declining coast live oak trees in Davis, California. ODR values less than 0.3 have been found to impair root function of many species (cb=centibars).

soil pores are drained at 18-22 centibars, ODR values ranged between 0.5 to 0.8 µg/0_2/cm^2/min.

Similar results were found during preliminary studies at another location. Matric tension in the 6 inch layer increased from 0 to 40 cb and ODR sharply increased from 0.2 to 1.0 µg/cm^2/min. However, over the same matric potential range, ODR values in the 12 inch layer never rose above 0.2. Soil core analysis showed that soil in the 12 inch layer was compacted and only a small percent of its pores would drain at these matric potentials.

Although differences in ODR could be detected at different locations, corresponding differences in oxygen concentration were not found. Oxygen levels remained around 15 to 18 percent at all locations, depths, and sampling times. ODR seems to be a more sensitive indicator of reduced 0_2 availability in soil than measurements of gaseons 0_2 concentration. As a result, we are now basing our field and laboratory experiments on ODR measurements rather than 0_2 percent.

In comparing ODR measurements taken from the rootzone of declining and healthy oak trees (fig. 2), depressed ODR values in the 6 inch zone were the only measurements that correlated with decline. In general, ODR values less than 0.2 inhibit root function, and less than 0.3 impairs root function in most species (Stolzy and others 1964). Both declining trees were found to have ODR values less than 0.3 in the 6 inch zone. Where values were greater than 0.3 in the 6 inch zone, tree health was good. High and low ODR values in the 12 inch or 36 inch zone were found in both healthy and declining trees. This suggests that shallow root activity may be an important factor in tree health and vigor. We will examine other sites to determine whether there is any consistency in this association.

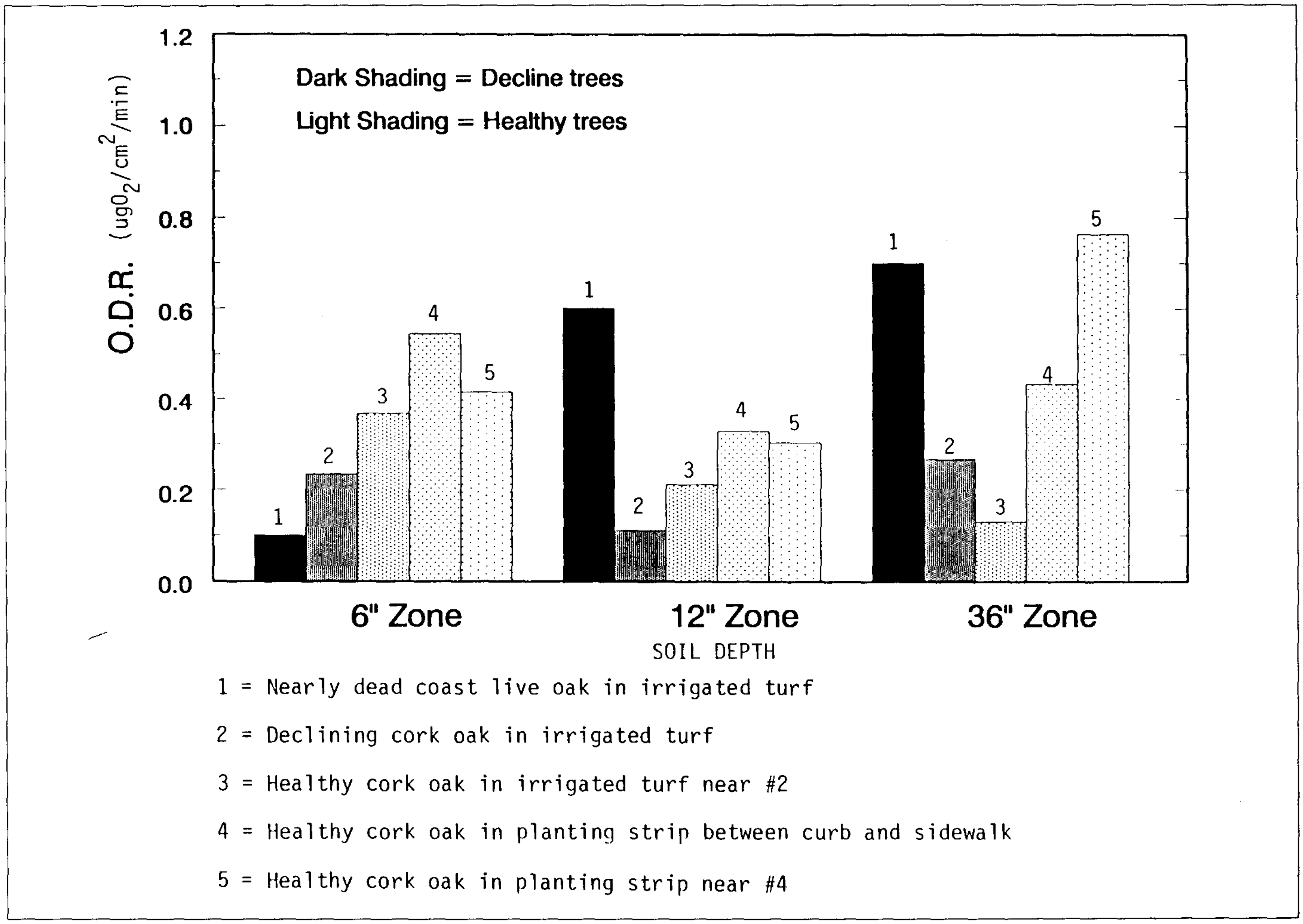

Figure 2—ODR measurements taken at 3 soil depths in the root zone of 5 oaks at different locations. Trees 1 and 2 were declining, while 3, 4, and 5 appeared healthy. Low ODR values in the 6 inch zone correlates with tree decline.

Effect of Oxygen on Root Growth and Disease Susceptibility

Root growth response to increasing oxygen could be significantly described for all species (fig. 3) using a logarithmic growth function (r^2 between 0.61 and 0.87, where r^2 = coefficient of determination). However, the relationship is least significant for blue oak ($r^2 = 0.61$). Oxygen levels at or below 4-5 percent were highly inhibitory to root growth of all three species causing > 50 percent decrease in growth as compared to that occurring at 21 percent oxygen. Other experiments indicate that blue oak is indeed most sensitive to hypoxia which supports the flood tolerance studies, but further investigation with acorns from this coming season are needed to clarify this point.

We also have measured ODR in the minirhizotrons by inserting probes to the mid-point of the profile. The soil ODR values which caused a 50-75 percent reduction in root growth were 0.3.µg $O_2/cm^2/min$. This compared to controls where ODR was 0.7-0.8 µg $O_2/cm^2/min$. Soil ODR values of 0.1 caused 75-95 percent reductions. In separate experiments, we found that vegetative growth of *Phytophthora,* was not inhibited over the same range of oxygen concentrations. Growth in pure culture continued at very low oxygen levels (near zero), and when roots were inoculated prior to exposure to low ODR, the fungus grew extensively in the stressed tissue. This was determined by excising inoculated roots and cutting them into serial segments from the point of inoculation upward toward the crown. Growth in roots exposed to ODR values of 0.1 µg $O_2/cm^2/min$ was far more extensive than in roots exposed to ODR values above 0.3 µg $O_2/cm^2/min$.

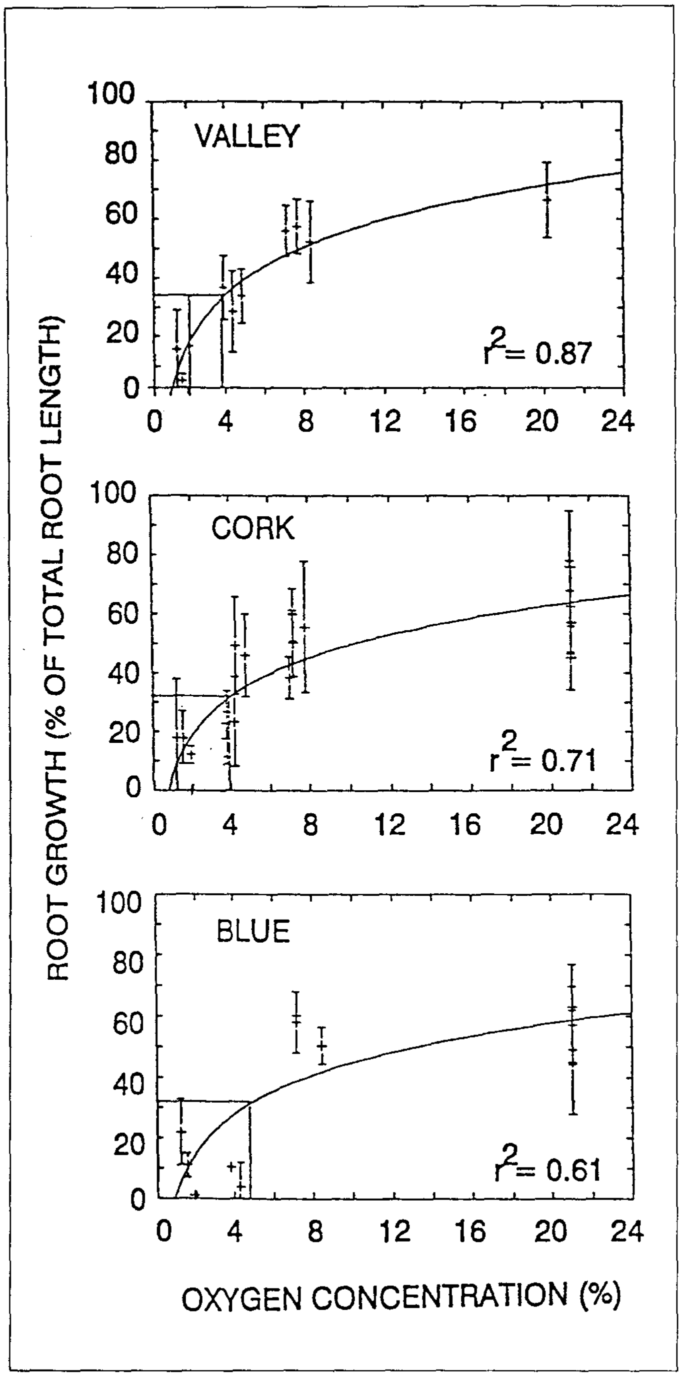

Figure 3—Effects of oxygen concentration on the root growth of three species of oak. Concentrations less than 5 pct inhibited root growth in all species.

Further Research

Research further evaluating soil compaction and moisture content effects on ODR levels is in progress. Future studies will assess other soil conditions which may affect ODR (e.g., grade changes and pavements), and field assessments of declining and healthy trees will continue. Methods used to alleviate low soil aeration conditions will be evaluated.

ACKNOWLEDGMENTS

The assistance of Terry Berger of UC Davis, and Mike and Gary Hutnick of Sta Green Tree Service, Carmichael, California is greatly appreciated.

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