Abiotic Disorders of Landscape Plants
A Diagnostic Guide

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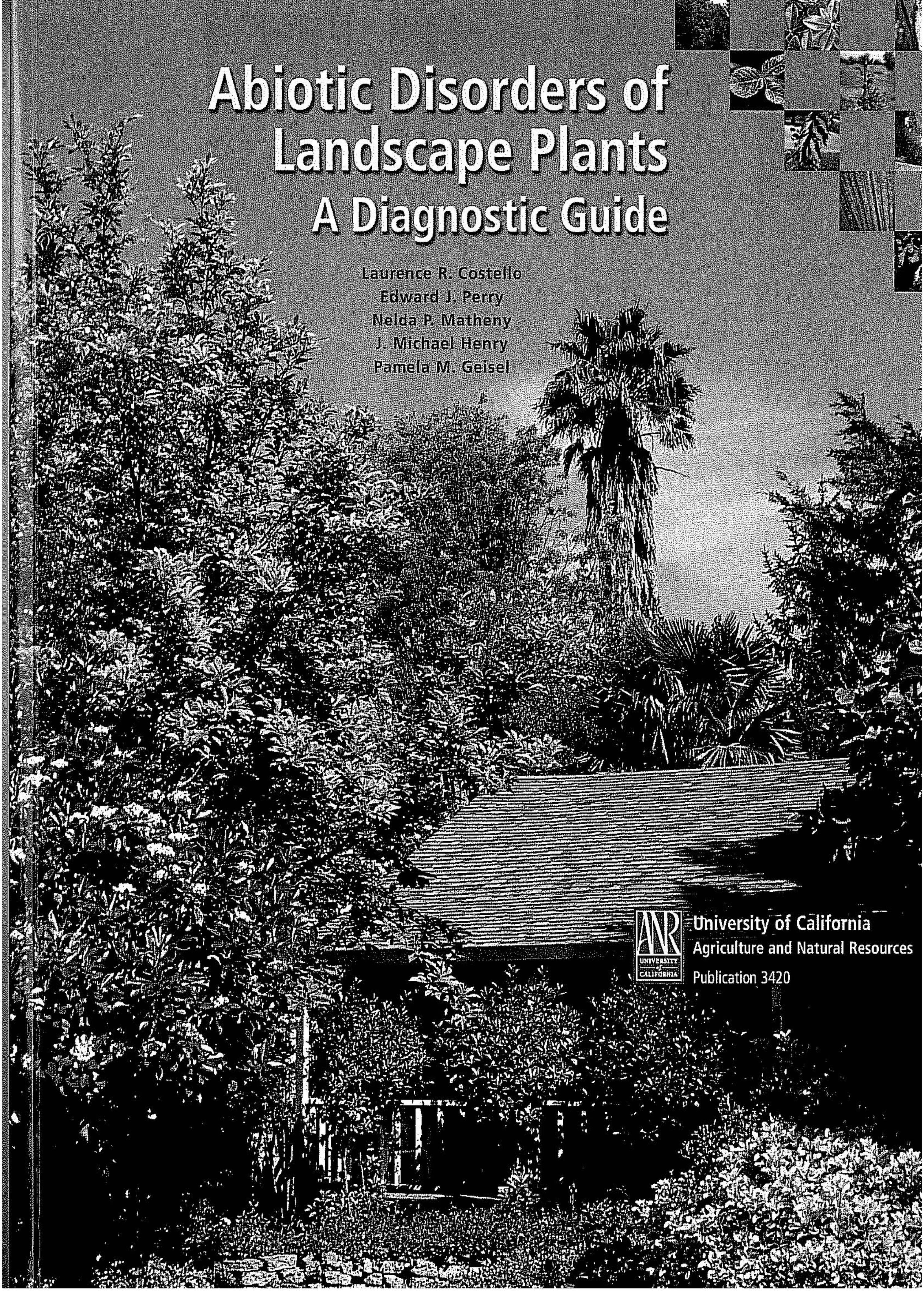

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TABLE 2.1. Soil sampling depths

Type of plant	Rooting depth		Depth at which to sample*	
	in	cm	in	cm
deep-rooted (trees and shrubs)	0–48	0–120	0–12 12–24 24–48	0–30 30–60 60–120
shallow-rooted (shrubs and groundcovers†)	0–18	0–46	0–6 6–12 12–18	0–15 15–30 30–46

Source: Harris, Clark, and Matheny 1999.

Notes:

*In raised beds or planters, sample the full depth of the container or bed.

†For groundcovers, sample at 0 to 6 inches (0–15 cm) and 6 to 18 inches (15–46 cm)

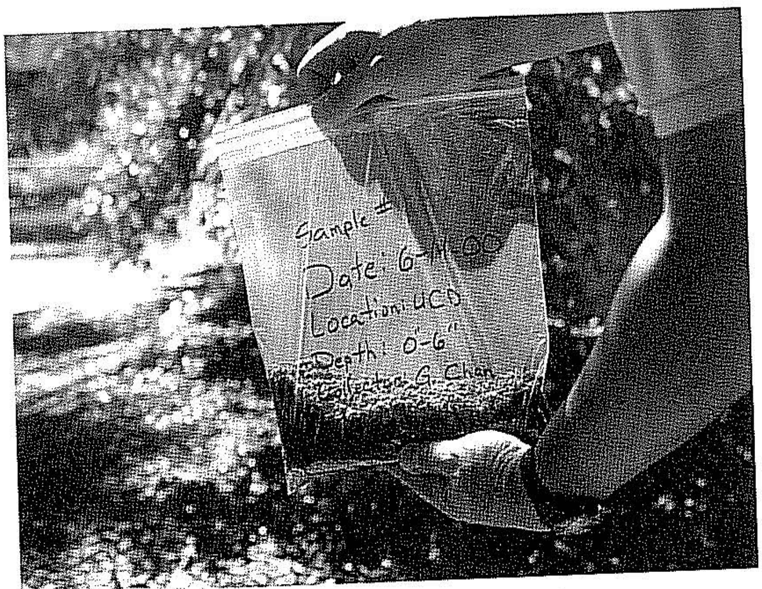

Figure 2.6. Place composite soil samples in a labeled sampling bag.

waterproof paper or plastic bags. Carefully label each sample on the outside of the bag (fig. 2.6).

Laboratory Analysis

Which analysis to request depends on which problems you suspect (see table 2.2). For example, to evaluate the level of salt in the soil, request an analysis of total soluble salts; for suspected sodic soil conditions, request salinity-alkalinity tests, which include the sodium adsorption ratio (SAR) or the exchangeable sodium percentage (ESP), which are determined from concentrations of sodium (Na), calcium (Ca), and magnesium (Mg).

Soil physical properties, including texture, bulk density, organic matter content and moisture release characteristics, depth, profile characteristics, and percolation, may need to be evaluated in order to diagnose abiotic disorders such as aeration deficits or water deficits (see table 2.3). Although soil texture can be assessed in the field, laboratory analysis is more reliable. Bulk density laboratory analysis requires a sample of specific volume (see Lichter and Costello 1994); contact a testing laboratory for instructions. Be careful not to compact samples when using a field core sampling tube. Organic matter content and moisture release characteristics should be determined by a laboratory. Depth, profile characteristics, and percolation can be determined in the field.

Results and Recommendations

Laboratories that specialize in horticultural or agricultural analyses can provide useful interpretations of results and recommendations to correct problems. Give the laboratory all pertinent information, including plant type, species, soil conditions, and relevant cultural practices, to help them customize their recommendations for your particular problem. For guidelines for interpretation of results, see table 5.6, p. 87.

Water Testing

The quality of irrigation water, whether groundwater, surface water, or recycled water, can be variable. Plants may be injured when poor-quality water is used. High concentrations of dissolved elements in irrigation water can lead to salt injury, specific ion toxicity, sodic soil conditions, and micronutrient deficiencies. Specific analyses must be conducted to diagnose particular disorders (table 2.3).

Collecting Samples

Samples must be representative of the water used to irrigate plants. Let the water run for a minute from the hose or irrigation system before collecting the sample. Collect samples in clean plastic bottles (fig. 2.7). Wash or rinse the bottles at least three times

CHAPTER 5

Specific Abiotic Disorders

Symptoms, Causes, Look-Alike Disorders, Diagnosis, Sensitive and Tolerant Species, and Remedies

WATER DEFICIT (WATER STRESS, DROUGHT, DEHYDRATION)

Almost every aspect of plant growth and development can be affected by a water deficit, including a plant's anatomy, morphology, physiology, and biochemistry. Deficits occur when water loss exceeds supply, that is, when transpiration is greater than water uptake.

Symptoms

Water deficit symptoms range from slow growth to death of the whole plant. The level of injury depends on the severity and duration of the deficit and the sensitivity or tolerance of the plant. Symptoms can be grouped into two categories: those associated with acute water deficits, and those associated with chronic deficits. Acute deficits are short-lived (hours to days), while chronic deficits last from a few days to several months. Both can cause injury symptoms that range from mild to severe.

Acute Deficit

When water loss increases substantially over a short period, or when water supply declines rapidly, plant tissues become dehy-

Figure 5.1. Wilt is an early symptom of water deficit. Leaves and shoots of periwinkle *(Vinca major)* have lost turgidity due to warm air temperatures and dry soil conditions (A). Wilting leaves of European hackberry *(Celtis australis)* during a hot summer day are indicative of a water deficit (B).

drated. Initially, leaves and shoots of many species wilt (fig. 5.1). Some species may wilt during the warmest part of the day but rehydrate in the evening (incipient wilt) (fig. 5.2). As fiber content increases during the growing season, leaves and shoots are less prone to wilt.

Figure 5.2. On warm summer days, leaves of poor man's rhododendron *(Impatiens oliveri)* wilt even when soil moisture is plentiful. This is called *incipient wilt.*

Figure 5.3. Marginal necrosis is a common symptom of water deficit, as seen on these sawleaf zelkova *(Zelkova serrata)* leaves.

If a water deficit continues, tissues may dehydrate to the point of becoming necrotic. Leaf necrosis may be expressed as a marginal burn, tip burn, or as irregular areas of dehydration in the leaf blade (fig. 5.3). Often, rapid dehydration causes the leaves to turn reddish brown, with distinct borders between hydrated and dehydrated tissue (fig. 5.4). In some species, extensive leaf drop may occur (fig. 5.5). If an acute water deficit is severe, the whole plant may die.

Chronic Deficit

Chronic water deficit causes slow growth or stops growth altogether. This symptom is frequently difficult to identify, however, since long-term observation of the species and the individual plant is needed. Comparing plants of similar age in similar growing conditions is usually required to assess a growth rate decline (fig. 5.6).

In addition to reduced growth rate, leaf size is often reduced on water-stressed plants (fig. 5.7). Leaf color may be less intense (e.g., change from deep green to

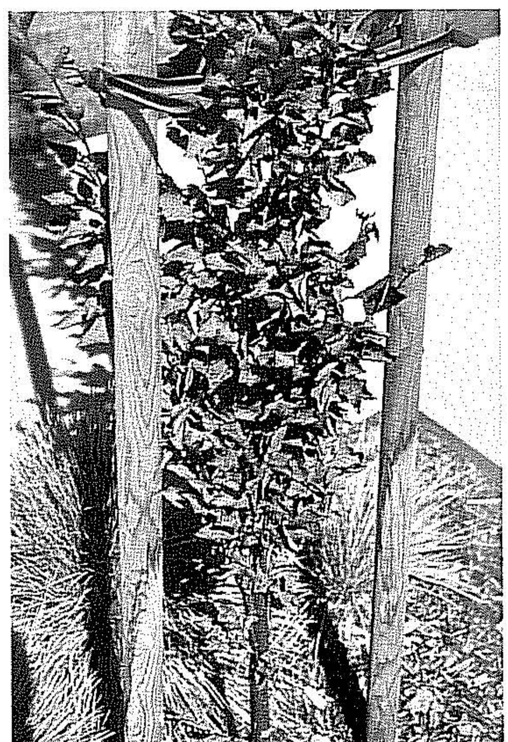

Figure 5.4. Acute water deficit may cause red-brown necrosis (with distinct margins) on the leaves of many species.

gray-green or blue-green), and certain species drop leaves prematurely, such as tulip tree (*Liriodendron tulipifera*) and southern magnolia (*Magnolia grandiflora*). The foliage of deciduous species may show fall colors much earlier than normal (fig. 5.8).

Moderately severe prolonged water stress causes shoot and branch dieback (fig. 5.9) and, in some cases, bark cracking and trunk bleeding. Chronically water-stressed plants often have low pest resistance, and secondary injury from insects or pathogens is common in some species. For

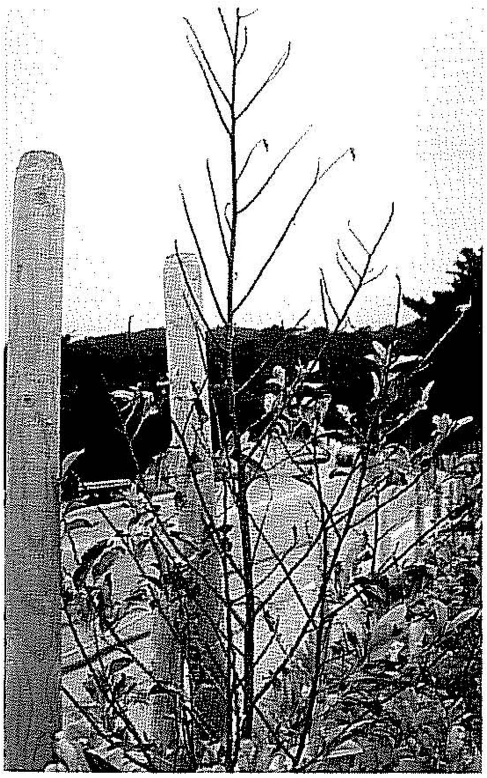

Figure 5.5. If a water deficit is severe, leaf drop and branch dieback will be evident in sensitive species.

Figure 5.6. Chronic water deficit may be expressed as a reduction in growth. These chrysanthemum plants *(Chrysanthemum morifolium)* were watered (left to right) every 10 days, 4 days, every day, and twice a day. Plants receiving lesser amounts of water produced less growth.

Figure 5.7. Knowing typical leaf size and color helps diagnose water deficit injury. Water-stressed foliage of coast redwood *(Sequoia sempervirens)* exhibits small needles and a dull green color (two shoots on left) when compared to foliage of a well-irrigated plant (right).

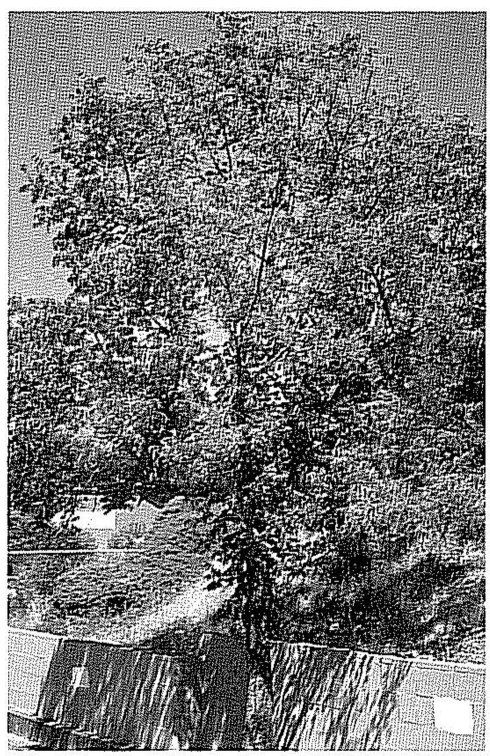

Figure 5.8. Water deficits may lead to early fall color in deciduous species. This Chinese pistache *(Pistache chinensis)* is showing fall color in August. The tree is located in a nonirrigated site with high evaporative potential.

example, bark beetle injury in Monterey pine (*Pinus radiata*) is common when trees in warm summer areas are inadequately irrigated (fig. 5.10).

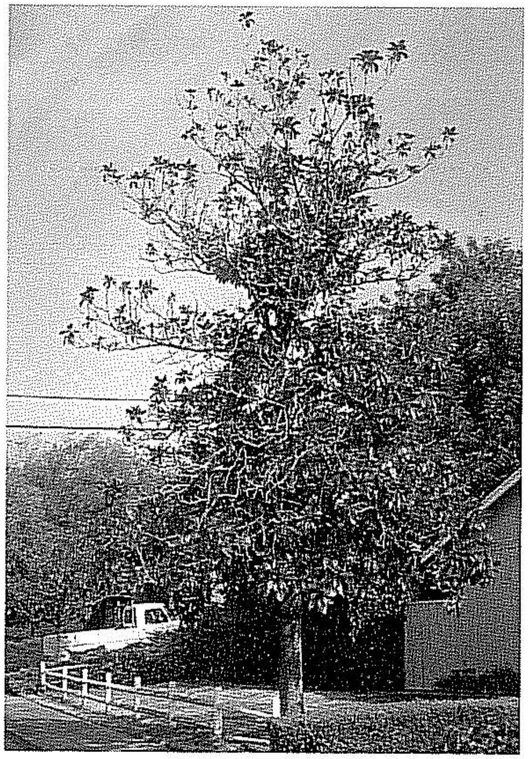

Figure 5.9. Prolonged water deficit causes branch dieback in certain species. Canopy thinning and branch dieback occurred in this southern magnolia *(Magnolia grandiflora)* when turf irrigation was discontinued.

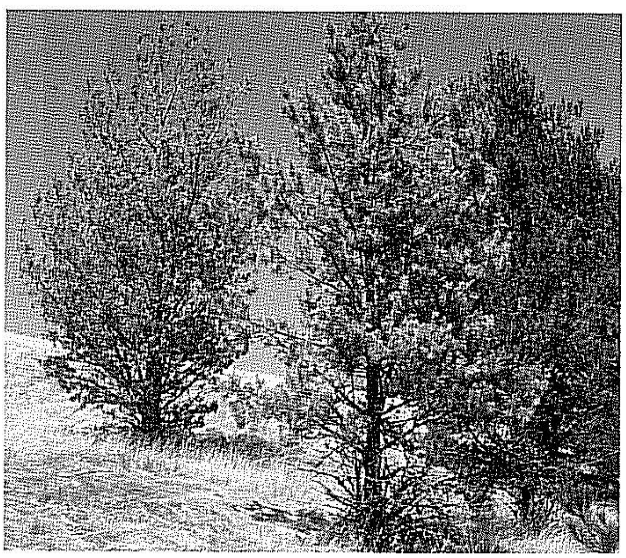

Figure 5.10. When water-stressed, Monterey pine *(Pinus radiata)* is highly susceptible to injury from bark beetles. The trees shown on left were not irrigated in the summer months and were killed by California five-spined engraver beetle *(Ips paraconfusus)*.

Causes

Often a combination of conditions or multiple factors contribute to water stress. Plant water deficits can be caused by conditions that

- limit the supply and availability of water in the soil (soil and water factors)
- affect water loss from plants (aboveground factors)
- affect a plant's capacity to absorb or retain water (plant factors)

Soil and Water Factors

Soil moisture levels are rarely optimal. Even in irrigated landscapes, inadequate water supply and availability frequently contribute to water deficits (fig. 5.11). Water supply to the root zone can be limited in a number of ways:

- Below-normal rainfall. California's weather pattern of wet winters and dry summers creates a prolonged period of low soil moisture. In years when rainfall is below normal, nonirrigated plants may

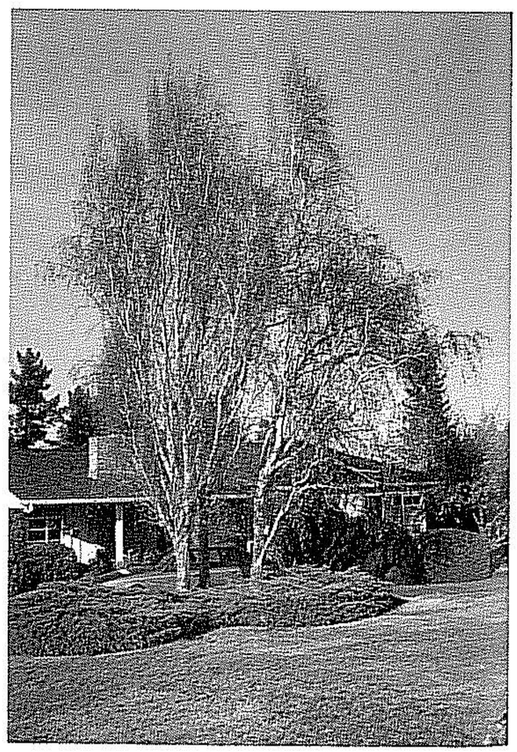

Figure 5.11. Water deficits are often caused by inadequate irrigation. These European white birch *(Betula pendula)* experienced severe water deficit and dieback when turf irrigation was discontinued. Note that junipers (*Juniperus* spp.) growing next to the birch are not showing similar symptoms.

deplete the supply of available water before it is replenished in the fall.

- Irrigation system design and function. Typical problems with irrigation systems include poor design (inadequate coverage, low water pressure) and poor function (broken valves, timer, heads, etc.).
- Irrigation scheduling. Typical problems include insufficient water volume or frequency and an application rate that is much greater than the infiltration rate, causing runoff.
- Low infiltration rate. Even when adequate quantities of water are applied, sufficient water may not infiltrate the plant root zone. The infiltration rate can be inherently low (e.g., in fine-textured soils), or it can be reduced by compaction, poor soil structure, slopes, surface barriers (hardscape or heavy organic mulch layers), and fill soils.

Water availability in the root zone can be limited when

- a small volume of water (per unit of soil volume) is retained in the soil. This often occurs in soils with low water-holding capacity (sand, loamy sand, and container soils) and in hydrophobic soils.
- the volume of soil in the root zone is small compared to the plant canopy. Soils that often have small root zone volumes include container soils, shallow soils, compacted soils, and soils limited by infrastructure elements (e.g., retaining walls, foundations, roadways, utility boxes, etc.).

To determine whether supply or availability are contributing to plant water deficits, assess the soil physical properties (texture, structure, depth, and bulk density) and, in irrigated landscapes, evaluate the irrigation system design and operation.

Aboveground Conditions

Environmental factors such as light intensity, wind, temperature, relative humidity, and aspect determine the evaporative potential of a site. Plants in sites with high evaporative potential are more likely to suffer water deficits than those in sites with low evaporative potential (fig. 5.12). For example, an isolated tree exposed to full sun in a windy parking lot is more likely to experience water deficits than a tree of the same species planted close to other trees and protected from wind.

Plant Factors

Although any plant can be injured by a water deficit, certain species are more sensitive than others. Plants from temperate zones (e.g., maple and horsechestnut) have a higher potential for injury than species from xeric (dry) zones such as century plant (*Agave* spp.) and mesquite (*Prosopis* spp.). Adaptations to control water loss or enhance absorption potential are found in species that are regularly exposed to water deficits. These adaptations include extensive root systems, small leathery leaves, and gray-green leaf color. Species without such adaptations are prone to injury, such as ferns, azalea (*Rhododendron* spp.), and hydrangea (*Hydrangea macrophylla*) (see

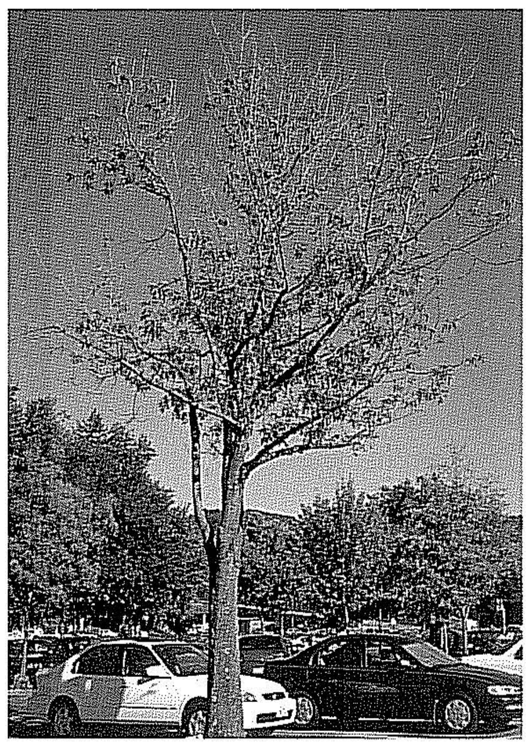

Figure 5.12. Trees planted in sites with high evaporative potential and limited soil volume are particularly prone to water deficit. Reflected light and heat from cars and pavement, restricted soil volume, and no irrigation have contributed to severe water deficit in this ash (*Fraxinus* sp.).

"Sensitive and Tolerant Species," p. 58).

Plants with limited root development, such as young plants and newly planted container stock, are also prone to water stress (fig. 5.13). Ball-and-burlap stock and bareroot stock may also have root development limitations that increase their sensitivity to water stress. Trees or large shrubs that have lost roots during transplanting are also prone to stress (fig. 5.14). In addition, plants growing in suboptimal conditions (e.g., flooded sites, compacted soils) are likely to have a reduced capacity for water absorption.

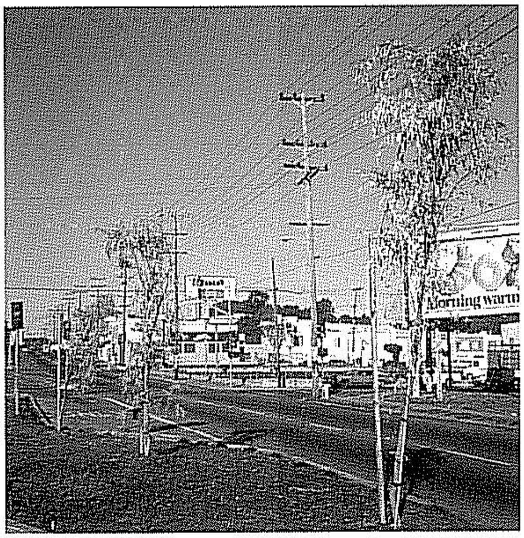

Figure 5.13. Newly planted container stock is prone to water deficit. Limited amounts of water held in the root ball can be lost rapidly under high evaporative conditions. These trees were not irrigated as frequently as needed to avoid water deficit.

Plants that have large leaf areas relative to the soil volume their roots occupy are likely to experience water deficits. For example, large plants in small containers have a much higher potential to suffer water stress than small plants in large containers (fig. 5.15).

Plants that have sustained root injury have a high potential for water stress. Root cutting that occurs during construction or utility line installation frequently leads to water stress symptoms (fig. 5.16).

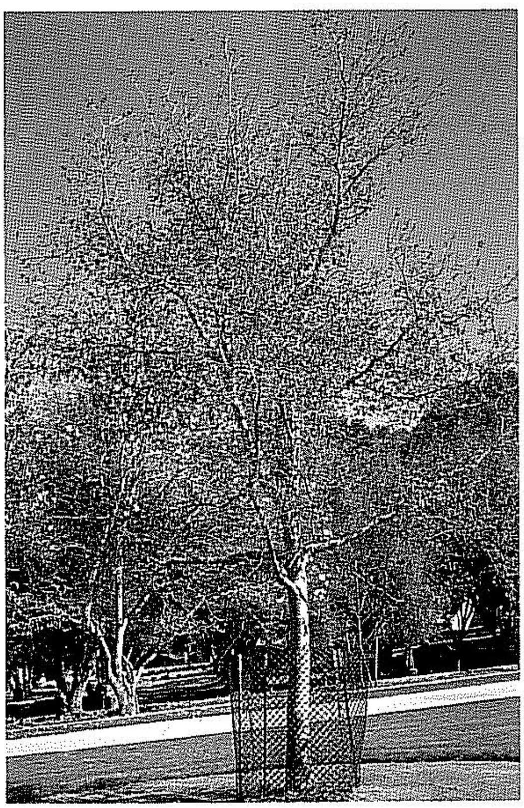

Figure 5.14. Plants that have had roots cut (intentionally or unintentionally) are subject to water deficit. This coast live oak *(Quercus agrifolia)* was transplanted from another site. In the process, much of the root system was cut, and water deficit followed. Symptoms include extensive leaf drop and branch dieback.

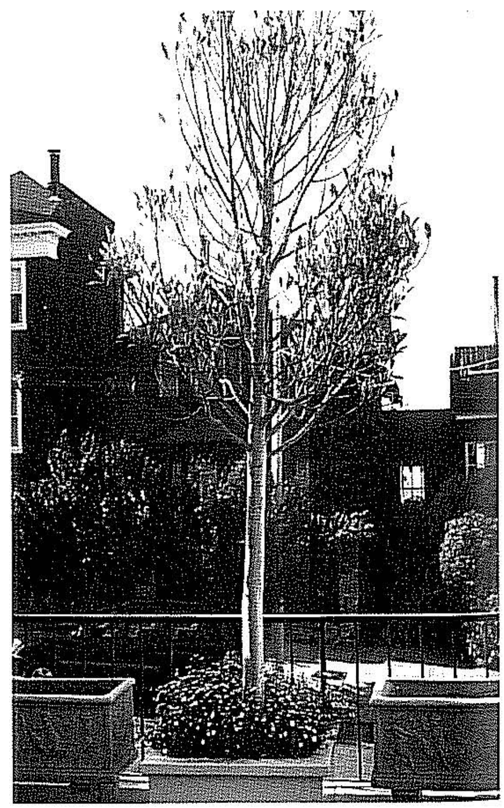

Figure 5.15. Plants growing in containers are commonly subject to water deficit due to restricted soil volume and low water-holding capacity. Water deficit symptoms in this relatively large Indian laurel fig *(Ficus microcarpa)* are typical of many plants in containers.

Look-Alike Disorders

Although injury from water deficit can be distinctive, it can also be confused with a number of other disorders. This is particularly the case with chronic water deficit. Look-alike disorders include

- salt injury
- aeration deficit
- specific ion toxicity (particularly chloride and boron)
- gas injury
- sunburn
- wind
- herbicide injury (particularly contact herbicides and nonselective materials)
- root disease and vascular wilt pathogens (e.g., *Phytophthora* spp., *Verticillium dahliae*, *Fusarium* spp., *Ophiostoma ulmi*, and *Erwinia amylovora*)
- insect injury (bark beetles, borers, root weevils)
- wildlife injury (gophers, voles, squirrels, deer, mice)
- mechanical injury (to root or trunk tissues)

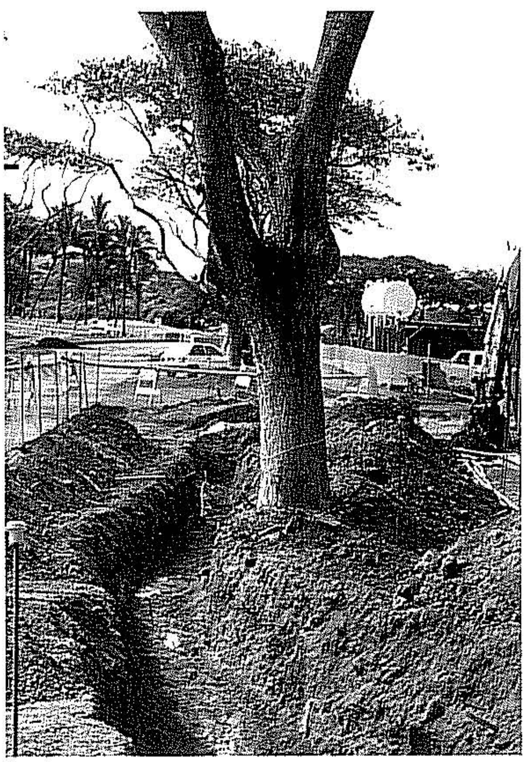

Figure 5.16. Construction activities can have severe impacts on established trees. Trenching next to this tree removed many roots, and water deficit injury is likely to follow.

Species that naturally shed leaves earlier than other species, such as honey locust (*Gleditsia triacanthos*) and California buckeye (*Aesculus californica*) may be mistakenly diagnosed as being injured by water stress. In addition, deciduous species that retain leaves into the winter (e.g., pin oak, *Quercus palustris*) may appear to be water-stressed (see chapter 4).

Diagnosis

Visual assessment and specialized diagnostic instruments can be used to assess water deficits.

Visual Assessment

Plant factors

- Identify the plant. Is the species sensitive to water deficit?
- Consider all symptoms and determine whether they are consistent with acute or chronic water stress.
- Check the condition of nearby plants. Do they show similar injury symptoms? Are they the same species?
- Evaluate plant growth (measure the annual growth increment). Considering site conditions and plant age, is growth normal for the species?
- Consider the plant history. Have there been impacts that may affect plant water uptake (e.g., root cutting, soil compaction)? Look for new features such as lights, sidewalks, utility boxes, swimming pools, etc.

Site factors

- Evaluate the soil. Is it dry, compacted, or shallow? Are there barriers to water infiltration on the surface (concrete, asphalt, fill soil, etc.)? Are the plants on a slope?
- Check the irrigation system. Is it operating properly? Is the irrigation schedule adequate? Is the coverage sufficient? Is water getting into the root zone?
- Consider the evaporative potential of the site. Is it windy, hot, or dry (low humidity)? Is there reflected light? Is the exposure south, west, or southwest?

Diagnostic Instruments

Plant water status

Leaf or stem water potential can be measured using a pressure chamber (fig. 5.17). The chamber measures tension levels in xylem sap. High tension measurements indicate water stress. Tension levels vary among species, however, and baseline data on normal and critical tensions (indicating water stress) are needed to interpret readings. Although used mainly in the past for research, this instrument has been adapted for field use.

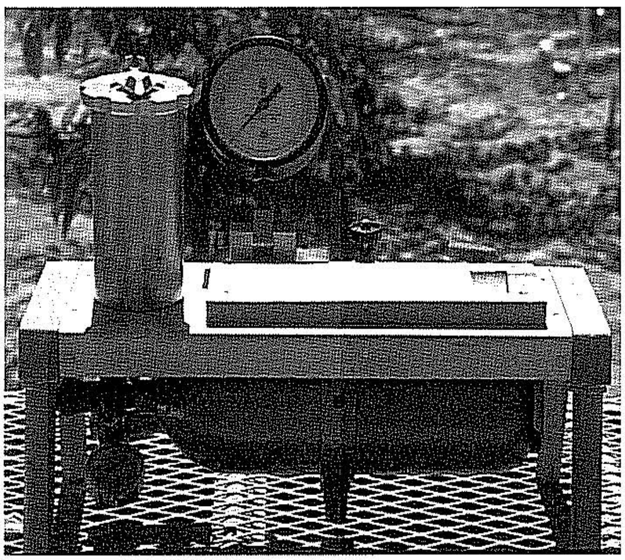

Figure 5.17. Water deficits can be assessed by measuring leaf or stem water potential using a pressure chamber. Previously used for research, this instrument has been modified for use in the field.

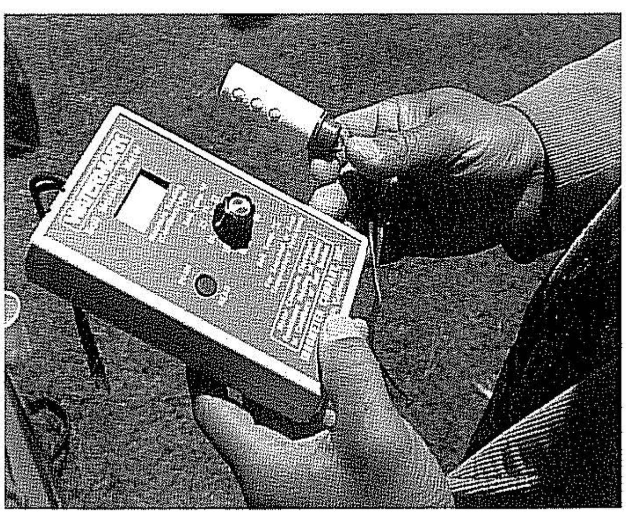

Figure 5.18. Soil moisture level can be assessed by measuring matric potential with electrical resistance sensors. The sensor is buried in the soil, and resistance is read using a hand-held digital meter.

Soil water status

Soil moisture status can be assessed by measuring soil matric potential using gypsum blocks and tensiometers (fig. 5.18). To properly interpret readings, it is necessary to understand the moisture release characteristics for the soil. For example, sands and container soils can be dry at relatively low tensiometer readings, while equivalent readings in clay indicate a well-hydrated condition.

Sensitive and Tolerant Species

Species selection is an important way to prevent water deficit injury (table 5.1; fig. 5.19). Many plant manuals provide information on the relative water needs of landscape species. An extensive list of species and irrigation-need evaluations is presented in *A Guide to Estimating the Irrigation Water Needs of Landscape Plantings in California* (Costello and Jones 2000).

Remedies

Before developing a plan for remediation, accurately identify the cause of the water deficit. Remedies should take into consideration whether the cause is related to the soil, plant, irrigation, or site.

Soil

- Assess soil physical properties to determine whether they are limiting factors. Improve the soil condition that limits water availability or supply. Cultivate to reduce compaction, amend to increase water-holding capacity, treat hydrophobic soils with a wetting agent, increase soil volume where limited, or improve infiltration rate (e.g., by using a hollow-tine aerator).
- Add mulch to the soil surface to improve soil structure, decrease evaporation, and reduce competition from weeds.

Irrigation

- Correct irrigation system malfunctions (timer, valves, heads, etc.).
- Improve system uniformity. Conduct a "can test" to evaluate water distribution over the irrigated area (see Pittenger 2002, p. 73).

TABLE 5.1. Water needs of selected landscape plants

Scientific name	Common name
High water needs	
Acer palmatum	Japanese maple
Alnus spp.	alder
Betula spp.	birch
Fuchsia spp.	fuchsia
Hydrangea macrophylla	hydrangea
Impatiens spp.	impatiens
various genera	ferns
Low water needs	
Acacia spp.	acacia
Arbutus menziesii	madrone
Arctostaphylos spp.	manzanita
Nerium oleander	oleander
Olea europaea	olive
Pinus canariensis	Canary Island pine
Pinus halepensis	Aleppo pine
Pinus sabiniana	digger pine
Prosopis spp.	mesquite
Quercus agrifolia	coast live oak
Quercus douglasii	blue oak
Quercus wislizenii	interior live oak
various genera	iceplant
various genera	palms

- Adjust the irrigation schedule to supply the amount of water the plants need. Develop a water budget.
- Provide sufficient water to thoroughly wet the soil in the root zone (deep irrigation, drip, hand-watering, etc.).
- Match the water application rate with the infiltration rate of soil.
- Adapt the irrigation system and schedule for plants on slopes. For example, use short run times and repeat cycles.

Plant

- Select species that are appropriate for the site and environmental conditions. Group species with similar water needs in an irrigation zone (hydrozone).
- Irrigate at a level and frequency appropriate for the plants in a hydrozone.
- Improve root zone conditions that have impaired the function of the root system (e.g., improve drainage in saturated or flooded soils).

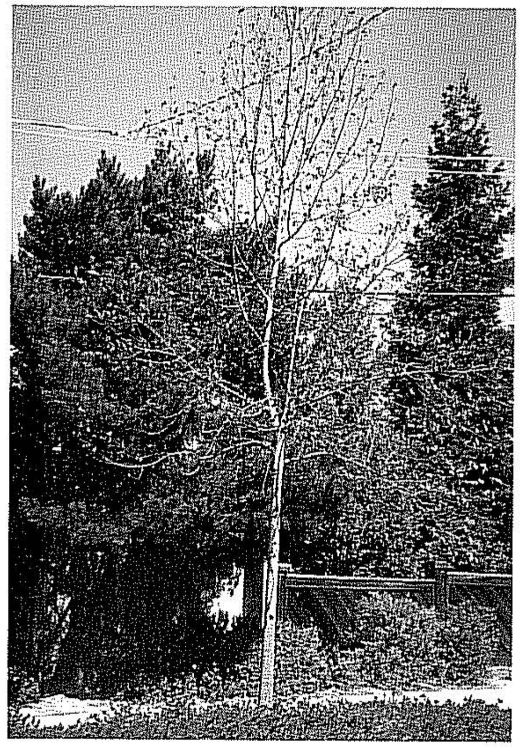

Figure 5.19. Species with dissimilar water needs should not be planted in the same irrigation zone. Here, a tulip tree (*Liriodendron tulipifera*) planted in manzanita (*Arctostaphylos* sp.) groundcover became severely water-stressed.

- Avoid injuring root systems during construction activities. Do not trench across root systems; use excavation techniques that avoid root cutting (e.g., hydro-excavation or pneumatic excavation).
- Provide sufficient root space for plants. Do not overplant an area with limited soil volume.

Site

- Evaluate the site to determine what is increasing the evaporative potential. Modify the site environment to reduce the evaporative potential (e.g., add shade, increase humidity, protect from wind, reduce light reflection, reduce heat inputs).
- Select species that are well adapted to the site.
- Adjust the irrigation to match the evaporative potential of the site.

Aeration Deficit (Poor Aeration, Anoxia, Oxygen Deprivation, Oxygen Stress, Wet Feet)

Plant roots require an adequate supply of oxygen for growth and development. Insufficient supply or availability of oxygen causes aeration deficits and limits root function. Root respiration is usually the first plant process to be restricted, followed by disruptions in metabolism, nutrient uptake, water absorption, and photosynthesis. Aeration deficits commonly occur in irrigated landscapes.

Symptoms

Aeration deficits can produce a range of symptoms from slow growth to death of the whole plant. The severity of the symptoms depends on species tolerance or sensitivity, severity and duration of the aeration deficit, and the initial health or condition of the plant. As with water deficits, aeration deficits can be acute or chronic.

Figure 5.20. Acute aeration deficit can cause whole-plant death. Excess irrigation and poor drainage excluded oxygen in the root zone of this newly planted photinia *(Photinia fraseri)*. Symptoms include leaf necrosis, branch dieback, root discoloration, blackening of soil, and foul odor.

Acute Deficit

When oxygen supply or availability is below a critical level for a short time (hours to days), an acute deficit occurs. Symptoms include wilting, extensive leaf drop, and, in some cases, death of the whole plant (fig. 5.20). Roots suffocate and no longer absorb nutrients or water. Frequently, they appear discolored and water-soaked (fig. 5.21; see also fig. 3.26, p. 29). In some species, wood tissues in the stem or trunk may become discolored.

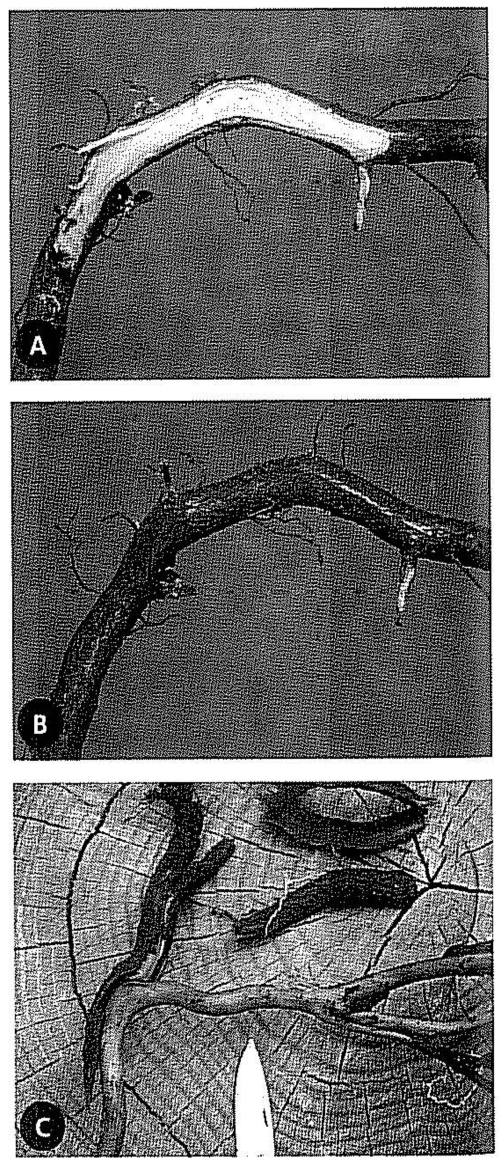

Figure 5.21. Healthy roots appear white and turgid (A), and the bark is firm and intact (B). Roots injured by an aeration deficit can appear discolored and water-soaked, and bark can lift off easily (C).

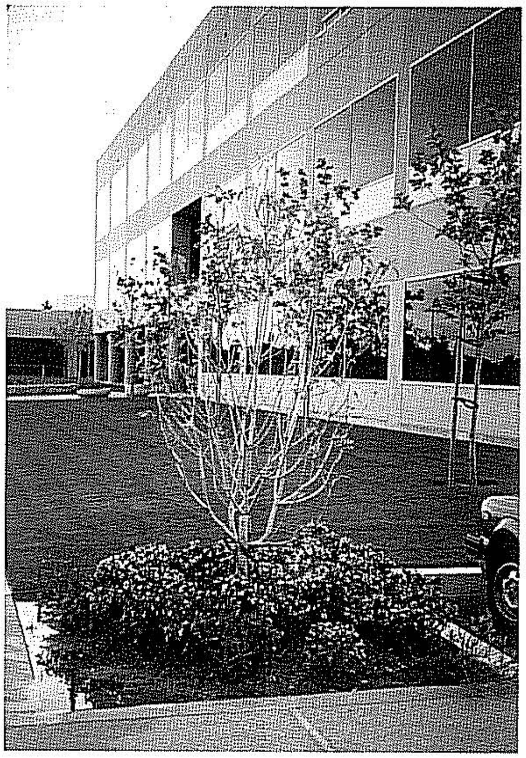

Figure 5.22. Slow growth, canopy thinning, and chlorosis in this Victorian box *(Pittosporum undulatum)* were caused by an aeration deficit. The aeration deficit resulted from excess irrigation and poor drainage. Previously, several India hawthorn *(Rhaphiolepis indica)* planted at the base of the Victorian box were killed by the aeration deficit.

Plants exposed to acute aeration deficits are more susceptible to root disease. Frequently, pathogens such as *Phytophthora cinnamomi* (water mold root rot) or *Armillaria mellea* (oak root fungus) infect roots and cause further injury.

Chronic Deficit

An aeration deficit that persists over an extended period (weeks to months) is considered to be chronic. Chronic, mild deficits initially slow plant growth; shoot length and leaf size are smaller than normal. This condition may be difficult to identify, however, since knowledge of the normal growth rate for the species is needed.

As a chronic deficit continues, leaves become chlorotic, and cankers or bleeding may occur. Typically, older leaves are affected first, then younger leaves. Plants begin to look anemic, or "sick." Leaf drop and canopy thinning is common (figs. 5.22–23). Lenticels may develop on the stem, and adventitious roots may appear near the root crown. In some species, cankers may be seen on the stem or trunk, and resinous or gummy substances may exude from the cankers (fig. 5.24A). Bark may split, exposing discolored wood beneath.

In more severe cases, twigs and small shoots die, followed by death of an entire branch. Eventually, a section of the canopy is affected or the whole plant may die (fig. 5.24B–C).

Under anaerobic (no oxygen) conditions, soil and roots smell like rotten eggs because gas containing sulfur is produced. When the condition persists, the soil color may change to bluish gray or black (fig. 5.25).

As with acute deficits, plants suffering from chronic aeration deficits are more sus-

Figure 5.23. Conifers injured by aeration deficits exhibit symptoms similar to broadleaf plants: slow growth, needle drop, and chlorosis. Accumulation of water at the bottom of this slope led to the decline of Monterey pine *(Pinus radiata)*. Note that Monterey pines on the slope are not showing symptoms. All trees were the same size and age at planting.

Figure 5.24. In some species, trunk bleeding and cankers can result from aeration deficits (A). When aeration deficits are prolonged and severe, extensive canopy dieback can be found. Localized poor drainage caused an aeration deficit in the root zone of the southern magnolia *(Magnolia grandiflora)* in the foreground (B). After 2 years, the same tree was virtually dead (C). Drainage in the root zone of the healthy tree in the background was substantially better than that of the injured tree.

Figure 5.25. Blackened soil is an indication of anaerobic soil conditions.

ceptible to root disease and other plant pathogens. Infections can cause further injury, masking symptoms of the primary cause (aeration deficit).

Causes

Plant aeration deficits are caused either by critically low oxygen concentrations in the root zone or by substantial reductions in oxygen movement through the soil (oxygen diffusion rate). Oxygen concentration and diffusion rate are in turn affected by a variety of soil and plant factors.

Low Oxygen Concentration

Oxygen depletion occurs when oxygen consumption in the root zone exceeds supply. Oxygen is consumed during respiration. Roots respire as they metabolize and grow, and soil microorganisms respire as they decompose organic matter. The combined respiration of roots and microorganisms reduces oxygen concentration. Consequently, soils that have active root systems or are high in organic matter generally have higher respiration levels than those with little root activity or low organic matter.

When respiration is high and oxygen

supply becomes limited, concentrations of oxygen in the root zone can be reduced to injurious levels. Oxygen concentration in the atmosphere is approximately 21 percent. Although most plants are not injured until the oxygen concentration in the root zone declines to below 10 percent, sensitive plants may be injured at between 10 and 15 percent. As the oxygen concentration declines below 10 percent, root functions are increasingly harmed. Notably, however, certain species (e.g., rice and other flood-tolerant species) are adapted to tolerate very low levels of oxygen (less than 5 percent).

Soil temperature has an important effect on injuries caused by low oxygen concentration. Plants are generally less tolerant of low oxygen levels when the soil temperature is relatively high; they are more tolerant at lower temperatures. This is because respiration increases as temperature increases and declines as temperatures drop. Increased respiration during warmer soil temperatures reduces the oxygen concentration, making oxygen deficits more likely.

The supply of oxygen from the atmosphere to the root zone can be limited by physical barriers at or on the soil surface, such as asphalt, concrete, plastic, and surface compaction (fig. 5.26). These barriers can reduce the rate of oxygen entry into the soil.

Low Oxygen Diffusion Rate (ODR)

Oxygen moves through soils by diffusion, that is, from areas of high concentration to areas of low concentration. As oxygen is consumed by roots or microorganisms, its concentration is reduced. This establishes a concentration gradient for oxygen diffusion from the atmosphere through the soil to the respiring surface (root or microorganism). The greater the oxygen gradient, the higher the diffusion rate.

A soil oxygen diffusion rate (ODR) greater than 0.3 $\mu g/cm^2/min$ is sufficient to meet the respiratory needs of most species. As ODR declines below this level, however,

Figure 5.26. Surface materials such as concrete or asphalt are thought to cause aeration deficits by reducing the rate of oxygen movement into soils. Pavement around this blackwood acacia *(Acacia melanoxylon)* may have reduced aeration levels and contributed to its decline (A). There are many cases, however, where trees do not appear to be injured by pavements, such as these pines (*Pinus* spp.) in Tahoe City, California (B).

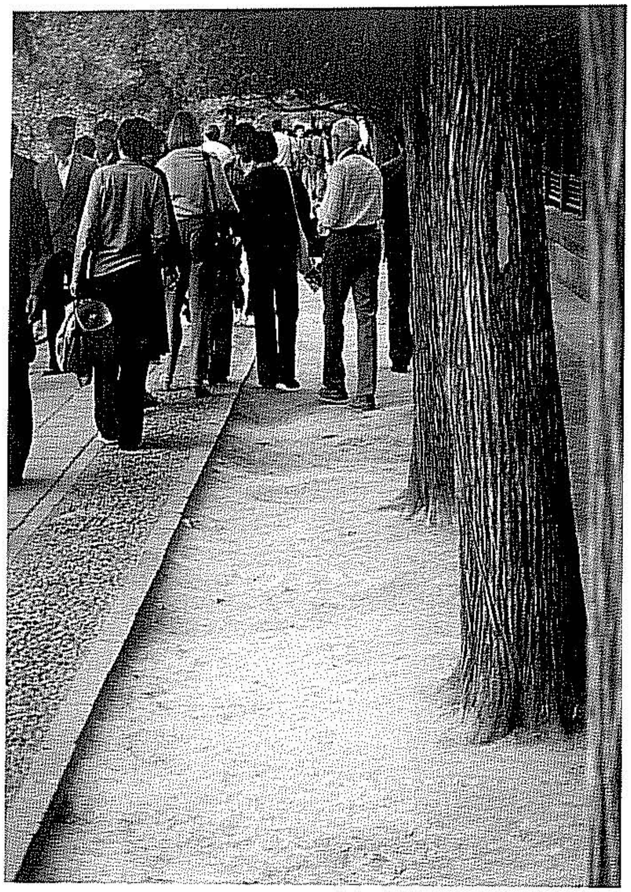

Figure 5.27. Soil compaction caused by foot traffic resulted in a reduction in air-filled pore space around these trees. This limits the oxygen diffusion rate in soils and can cause aeration deficits.

oxygen supply to root surfaces is diminished, and aeration deficits may occur: not enough oxygen is arriving at root surfaces to meet respiratory needs.

The oxygen diffusion rate is reduced by barriers along the diffusion pathway (the "air-filled pore space" in soil). This pathway is a network of pores that are large enough to be occupied by air after water drainage (macropores) that serve as channels for gas diffusion. A soil with an air-filled pore space of 10 to 12 percent (by volume) is satisfactory to meet the ODR needs of most plant species. Soils with good structure or soils with inherently large pore space (e.g., sand, loamy sand, and container soils) generally have 10 to 12 percent (or more) air-filled pore space. Soils with little air-filled pore space (e.g., fine-textured soils such as clay or poorly structured soils) are prone to low ODR levels. In addition, soils that have experienced a reduction in macropore space (e.g., by compaction) have diminished ODR (fig. 5.27). When ODR is diminished below a critical level for a species, then an aeration deficit occurs.

Water is perhaps the most common barrier to oxygen diffusion. Oxygen diffuses through water 10,000 times slower than through air. When water occupies macropore space, oxygen diffusion is reduced substantially. This occurs in flooded soils, poorly drained soils, and soils that are irrigated excessively. It is particularly a problem in soils that typically have little macropore space (e.g., clay, compacted soils, or poorly structured soils). In these soils, water occupies the space needed for gas diffusion, and oxygen cannot move to root surfaces fast enough to meet respiratory needs (fig. 5.28). As a result, an aeration deficit occurs.

Because oxygen moves from the atmosphere into the soil to the roots, barriers on the soil surface such as asphalt, concrete, fill soil, and surface compaction may reduce oxygen movement into the soil (fig. 5.29). If so, ODR decreases and aeration deficits may follow. It is not known by how much ODR is reduced by these barriers, however. Although many cases have been observed where it is believed that plants have been injured by surface barriers, there are many more cases of plants growing very well in spite of being surrounded by surface barriers (e.g., trees planted in sidewalks). This may be because most paved surfaces have many fine cracks through which gases may diffuse.

Look-Alike Disorders

Aeration deficit injury is not highly distinctive and can be confused with other disorders, such as chronic water stress, salt injury, gas injury, high light injury, nitrogen deficiency, air pollution, herbicide injury (soil-residual herbicides that cause chlorosis in older foliage), and root diseases such as water mold root rot (*Phytophthora* spp.) or oak root fungus (*Armillaria* spp.).

Diagnosis

Diagnosis of aeration deficit injury requires familiarity with symptoms of acute and chronic deficits and an understanding of soil conditions that may limit oxygen concentration or movement in the soil. Close visual inspection and, in some cases, measurements of soil oxygen status will be needed for accurate diagnosis. Review the symptoms of aeration deficit (above) and determine whether the plant's symptoms are consistent with them. Also:

- Check the soil moisture content. This can be done using a shovel, soil sampling tube, steel probe, or tensiometers. Is the soil very wet? Have there been large water inputs from rainfall? Is there an irrigation system? If so, what is the irrigation schedule? Is it too long or too frequent? Is there a drying period between irrigations? Are there irrigation system leaks?
- Evaluate the color and smell of the soil. Does it smell like rotten eggs? Is it a bluish gray color?
- If possible, sample the roots. Do they appear water-soaked or discolored? Do they smell like rotten eggs?
- Evaluate surface drainage patterns at the site. Is surface water being directed to the affected plants? Does water form puddles (ponding) in the area? Is water being channeled to the affected plants (e.g., from downspouts connected to a roof drainage system)?

Edema (Corky Scab, Corky Excrescence, Scab, or Scurf)

Edema (or oedema) is the growth of small, raised, corky outgrowths resembling lenticels on the underside of leaves. It is often seen in camellia *(Camellia japonica* and *C. sasanqua)*, hibiscus (*Hibiscus* spp.), ivy (*Hedera* spp.), privet (*Ligustrum* spp.) and yew (*Taxus* spp.). Edema may be caused by aeration deficits; it typically develops in plants growing in waterlogged soils, especially when transpiration is reduced, such as during cloudy weather. Edema also develops under conditions of exceptionally high humidity, such as in greenhouses. The wartlike growths usually have a corky texture and are light brown or rust-colored (fig. 5.30). They may occur in small groups or cover large areas of a leaf. The upper surfaces of leaves with edema are normal in size and texture but are often chlorotic. The corky eruptions may be mistaken for rust diseases caused by fungi.

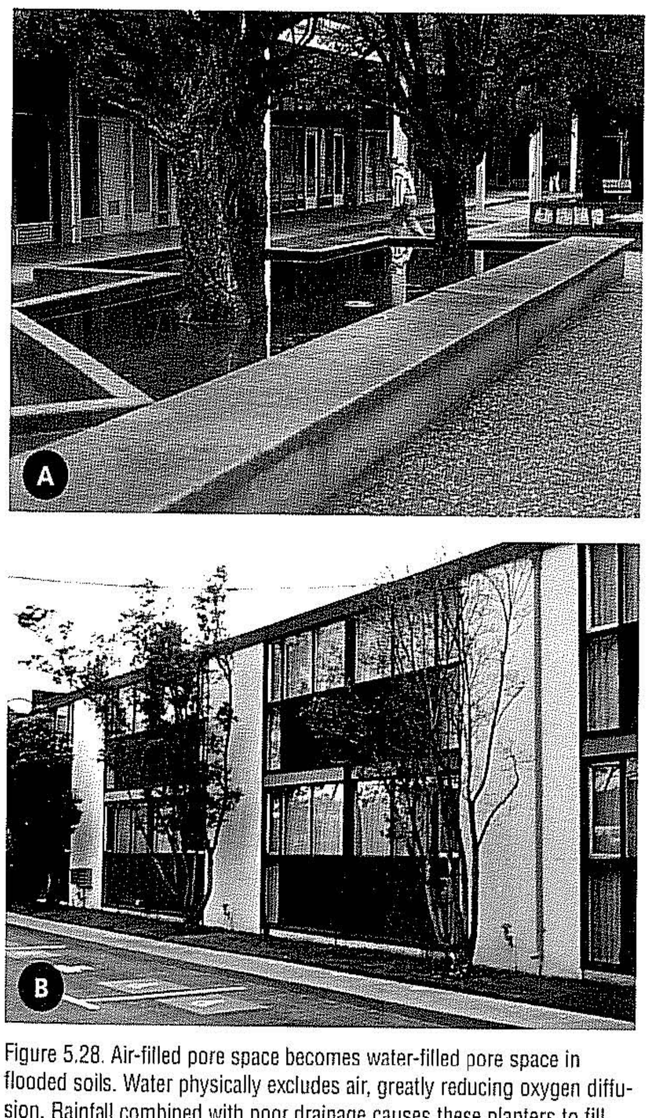

Figure 5.28. Air-filled pore space becomes water-filled pore space in flooded soils. Water physically excludes air, greatly reducing oxygen diffusion. Rainfall combined with poor drainage causes these planters to fill with water leading to an aeration deficit and decline of cork oak *(Quercus suber)* (A). Water delivered from the downspout likely contributed to an aeration deficit and subsequent decline of this evergreen pittosporum *(Pittosporum crassifolium)* (B).

Figure 5.29. Fill soil may contribute to aeration deficits and plant injury. The decline of this Aleppo pine *(Pinus halepensis)* was attributed to an aeration deficit caused by the placement of approximately 2 feet (0.6 m) of fill around its base (A). The fill soil covered the trunk flare (B).

- Evaluate the soil's internal drainage. Are there barriers to internal drainage such as hardpan? Is there a perched water table near the surface? Are there tidal water effects at the location? Are there subterranean barriers such as utility boxes, basements, transit lines, or sewer lines? Is the soil fine-textured or poorly structured (i.e., does it have a low capacity for internal drainage)? Is the sodium content of the soil high?
- Check the bulk density of the soil. If compaction has occurred, bulk density will be above a critical level for the soil texture class. Use a field-core-sampling tool or use the volume excavation technique (see Lichter and Costello 1994). Is bulk density at or above a critical level (for values, see Harris, Clark, and Matheny 1999)?
- Determine whether the surface grade of the soil has been changed. Look for indications that fill soil has been added on top of field soil around affected plants. For trees, look for a root flare (buttress roots) at the base of the trunk. If a root flare is not present (i.e., if the trunk arises from the ground like a pole), it is likely that fill soil has been added (fig. 5.31).
- Look for surface barriers. Is concrete, asphalt, or other hardscape present near the affected plants? Are the barriers sealed such that water or air may not be able to enter the soil? Have they recently been installed? How much of the root zone has been covered?
- Evaluate soil organic matter content. Is it very high (greater than 20 percent)? Is the organic matter composed of slowly decomposing materials (e.g., wood chips) or quickly decomposing materials (e.g., leaves)?
- Evaluate the oxygen diffusion rate and/or the oxygen concentration. Although it is possible to measure the oxygen status of the soil, there are practical limitations. Measuring ODR requires equipment that has not been adapted for diagnostic use. The equipment is useful for research, but general field use would require substan-

tial time, skill, and expense. Equipment to measure oxygen concentration is available, but variation in quality does exist. Follow established protocols for taking oxygen measurements. Remember that an ODR deficit may occur even when the oxygen concentration is satisfactory.

Sensitive and Tolerant Species

Although lists of aeration-deficit sensitive and tolerant species are not available, lists of flooding-sensitive species have been developed (table 5.2). It is possible that species sensitive to flooding are also sensitive to other types of aeration deficits (e.g., reduction in oxygen diffusion rate caused by changes in grade), but this has not been established. Consequently, the species that are sensitive to or tolerant of flooding listed here should not necessarily be considered as sensitive or tolerant to other types of aeration deficits.

Keep in mind that flood tolerance depends on the conditions to which plants have adapted. For example, after growing in drained soil, rice can be severely injured if flooded. Also, species tolerance varies with the time of the year. Dormant plants are more tolerant of low aeration conditions than actively growing plants. For example, valley oak (*Quercus lobata*) can tolerate flooding during the winter, but not during the summer.

Remedies

Identify the cause of an aeration deficit before developing a plan for remediation. Remedies are usually specific to the cause; for example, if the cause is a reduction in oxygen concentration, the remedy should focus on increasing the oxygen concentration.

Oxygen Concentration

Low oxygen concentration can be linked to organic matter content in the soil, surface barriers, and soil temperatures.

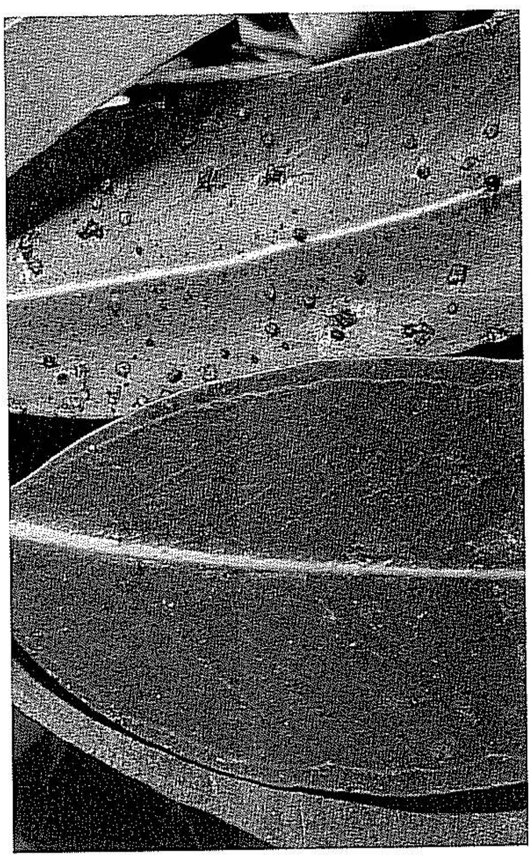

Figure 5.30. Small, raised, corky outgrowths (edema) on leaves of certain species such as this *Eucalyptus* sp. can result from a flood-induced aeration deficit.

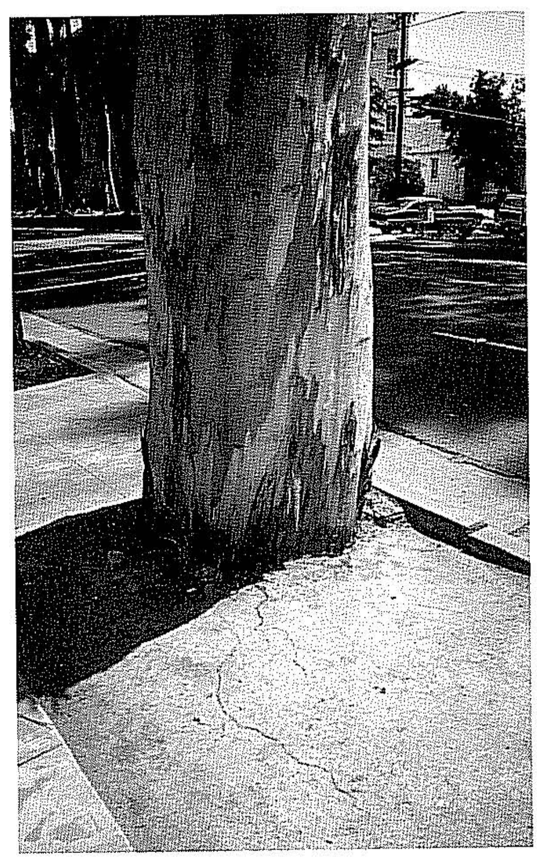

Figure 5.31. If the root crown or trunk flare is not visible, fill soil is likely to have been placed around the base of the tree.

- If organic matter content is high (increasing respiration and oxygen use), reduce inputs of organic matter.
- If surface barriers are present, consider methods to improve the entry of air into the soil, including vents, barrier-free areas, or creating openings in the barrier.
- If high soil temperatures contribute to aeration deficits, add an organic mulch to the soil surface to moderate temperatures.

TABLE 5.2. Flooding tolerance of selected landscape plants

Scientific name	Common name
Flood-sensitive species	
Acer platanoides	Norway maple
Cercis canadensis	eastern redbud
Cornus florida	flowering dogwood
Crataegus × lavallei	Carriere hawthorn
Crataegus phaenopyrum	Washington thorn
Magnolia soulangiana	saucer magnolia
Malus spp.	flowering crabapple
Picea abies	Norway spruce
Picea pungens	blue spruce
Prunus persica	peach
Prunus serotina	black cherry
Prunus subhirtella	flowering cherry
Quercus agrifolia	coast live oak
Quercus kelloggii	black oak
Quercus lobata	valley oak
Robinia psuedoacacia	black locust
Thuja occidentalis	American arborvitae
Flood-tolerant species	
Acer negundo	box elder
Acer rubrum	red maple
Alnus spp.	alder
Betula spp.	birch
Celtis occidentalis	common hackberry
Fraxinus americana	white ash
Fraxinus pennsylvanica var. *lanceolata*	green ash
Gleditsia triacanthos var. *inermis*	thornless honey locust
Juglans nigra	black walnut
Liquidambar styraciflua	American sweetgum
Metasequoia glyptostroboides	dawn redwood
Morus alba	white mulberry
Nyssa sylvatica	tupelo
Platanus occidentalis	American sycamore
Populus spp.	poplar
Quercus bicolor	swamp white oak
Quercus palustris	pin oak
Salix spp.	willow
Sequoia sempervirens	coast redwood
Taxodium distichum	bald cypress
Tilia cordata	little-leaf linden
Ulmus americana	American elm

Oxygen Diffusion Rate

The oxygen diffusion rate can be improved by increasing the air-filled porosity of the soil, reducing moisture content, or correcting surface barrier problems (see Harris, Clark, and Matheny 2003, table 7.4).

Improving air-filled porosity

Cultivation, amendments, and mulches can improve air-filled porosity (fig. 5.32).

- Cultivation of compacted soils creates macropore space. This effect may be short-lived in some cases, however, because soil particles may return to precultivation compaction levels (e.g., following irrigation or rainfall). Eliminating compaction sources (traffic, equipment, etc.) and adding organic matter helps to retain cultivation effects.
- Organic amendments such as wood chips, sawdust, and bark improve air-filled porosity. These materials retain small amounts of water relative to other organic amendments such as peat. Generally, it is recommended that these organic materials be incorporated in the root zone at a rate of 25 to 50 percent of the soil by volume. This may not be practical over large areas, however, and incorporation may cause substantial root damage to existing plants.
- Organic mulches can improve soil structure and protect against surface compaction. The breakdown products of mulches help aggregate soil particles, increasing macropore space. Decomposition rates of mulches vary, however, as does the time required for the soil structure to improve. On wet soils, mulches may prevent soil drying, however, and this may contribute to root disease.
- Radial trenching may improve aeration status in localized areas of the root zone. This practice is a "soil-replacement"

strategy: poor-quality soil is replaced with higher-quality soil (fig. 5.33). For example, highly compacted soil is replaced with soil of a much lower bulk density. In some cases, a poor-quality soil is removed, amended, and then replaced. Soils with limited or reduced air-filled porosity may be improved by this technique, but the benefit is likely to be confined only to the volume of replacement soil.

Reducing soil moisture content

In many cases, high soil moisture content is directly responsible for inadequate aeration. Soil moisture should be maintained at levels that allow for adequate plant water supply and for adequate root zone aeration. Aeration can be improved by managing irrigation properly and improving drainage.

- Reduce water inputs: adjust the irrigation schedule to reduce application amount or frequency.
- Select species tolerant of high soil moisture conditions (fig. 5.34).
- Allow soil to dry between irrigations. The use of tensiometers may be useful to monitor soil moisture status.
- Improve surface drainage to avoid areas with standing water or ponding. Use drainage ditches or French drains to channel water out of low-lying areas. Contour the soil surface to direct water away from the affected area (see Harris, Clark, and Matheny 1999, table 7-2).
- Improve internal drainage (see Harris, Clark, and Matheny 1999, table 7-2).

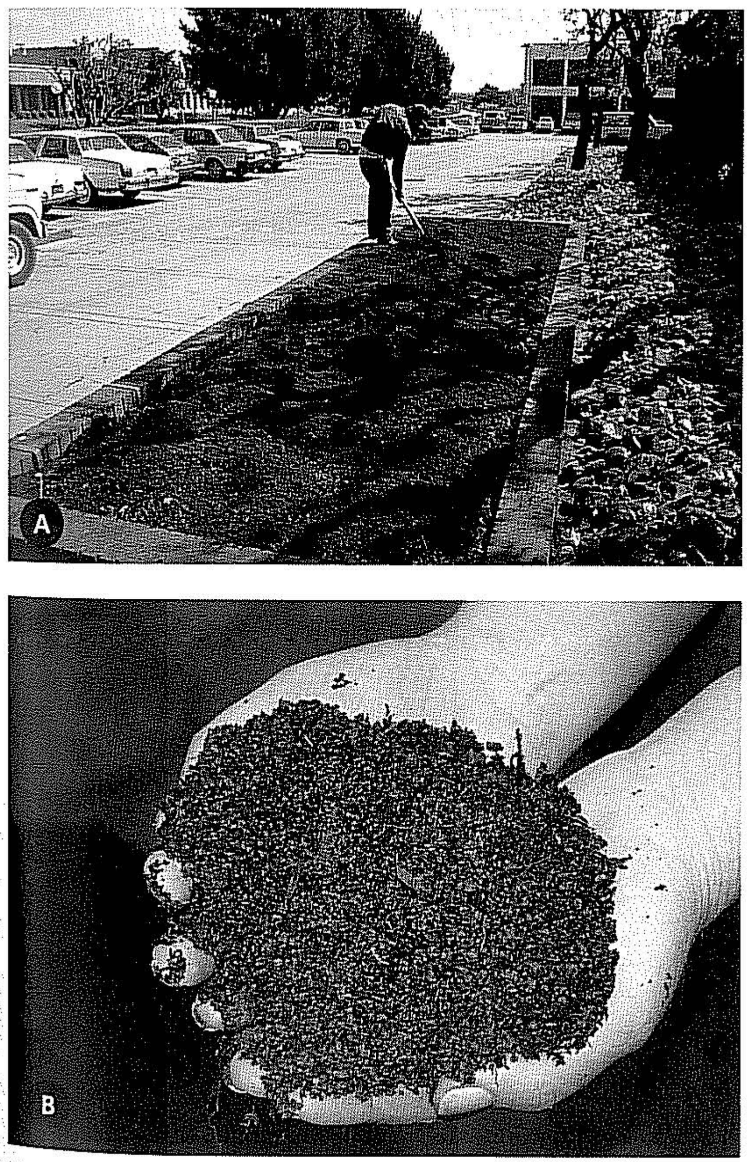

Figure 5.32. Cultivation (A) and physical amendments (B) can increase the air-filled porosity of soils.

Figure 5.33. Soil replacement using a radial trenching technique can improve aeration in localized areas of the root zone. To improve aeration in the root zone of this California black oak *(Quercus kelloggii)*, soil with low air-filled porosity is being replaced using soil with a higher air-filled porosity.