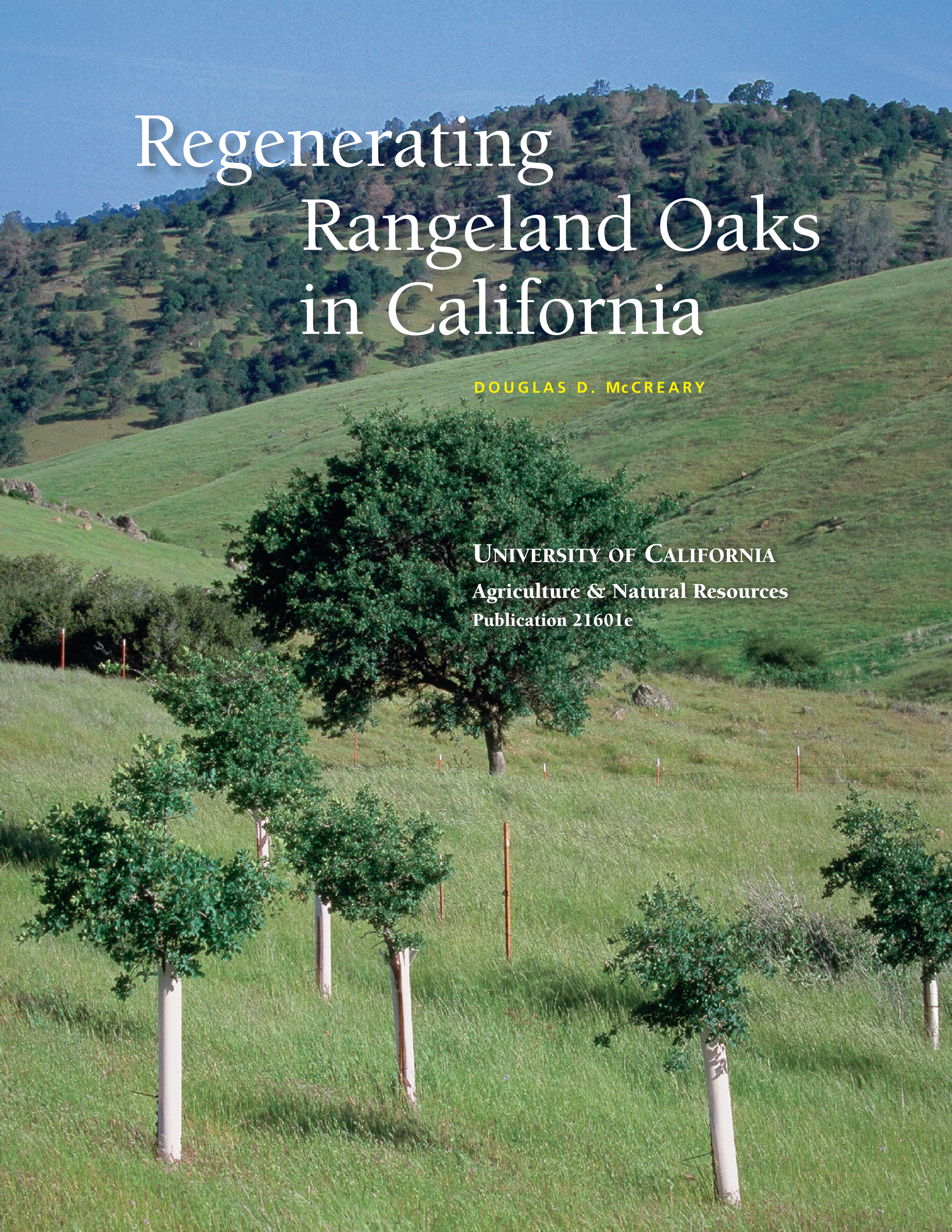

Regenerating Rangeland Oaks in California

DOUGLAS D. McCREARY

UNIVERSITY OF CALIFORNIA
Agriculture & Natural Resources
Publication 21601e

University of California
Agriculture & Natural Resources
Publication 21601e

Regenerating Rangeland Oaks in California

DOUGLAS D. McCREARY
University of California
Sierra Foothill Research and Extension Center

FOR INFORMATION ABOUT THIS AND OTHER PUBLICATIONS, CONTACT

University of California Agriculture and Natural Resources
Communication Services
6701 San Pablo Avenue, 2nd Floor
Oakland, California 94608-1239

Telephone 1-800-994-8849
(510) 642-2431
FAX (510) 643-5470
E-mail: danrcs@ucdavis.edu
http://anrcatalog.ucdavis.edu

An electronic version of this publication is available on the ANR Communication Services Web site at http://anrcatalog.ucdavis.edu.

Publication 21601e
ISBN-13: 978-1-60107-669-4

UC PEER REVIEWED

This publication has been anonymously peer reviews for technical accuracy by University of California scientists and other qualified professionals. This review process was managed by the ANR Associate Editor for Natural Resources.

web-09/09-AS/WJC/CR

Contents

Acknowledgments

I wrote most of this manual while I was on sabbatical in southern England at the British Forestry Commission Research Station at Alice Holt Lodge. I want to express my deep gratitude to all of the people there who made me feel at home and provided an environment conducive to learning, writing, and enjoyment. My primary host was Gary Kerr, a silviculturalist who not only provided general assistance and support during my stay but also reviewed early drafts of this document and offered many valuable comments and suggestions. Other scientists at the Research Station, including Peter Gosling, Richard Jinks, and Ralph Harmer, also reviewed individual chapters and helped make early versions of the manuscript much more readable and scientifically sound.

Another person who deserves special mention is Jerry Tecklin, a colleague of mine with the University of California Integrated Hardwood Range Management Program and collaborator on most of the oak regeneration research I have been involved with. Generally, when the term “we” is used in this document, it refers to work that Jerry and I have done together at the Sierra Foothill Research and Extension Center. Jerry has not only been instrumental in helping to design and carry out many of the studies cited in the text, but he also reviewed this whole manuscript at least twice and offered numerous helpful suggestions and editing comments.

There were also several anonymous reviewers recruited by Mel George, the Associate Editor for Natural Resources at the University of California Division of Agriculture and Natural Resources Communication Services, whose suggestions were very helpful and contributed to a more concise and readable document. My thanks to them and to Mel for their help. Thanks also to Laurie Lippitt, Mike Evans, and Julie Hooper for providing the information necessary to write the nursery case histories. Finally, I would like to thank the staff of Communication Services for putting this manual together, including design, layout, photography, and copyediting.

Introduction

For millennia, oaks have graced the valleys, hills, and mountains of California. The state has a rich and diverse assortment of *Quercus* species, which range in appearance from majestic solitary valley oaks (*Quercus lobata* Nee), with enormous trunks and massive canopies, to small, shrublike, huckleberry oaks (*Quercus vaccinifolia* Kellogg) that never grow more than a few feet tall. For many residents and nonresidents alike, golden-brown hills dotted with gnarled oak trees epitomize the California landscape, and native oaks symbolize values we hold dear—strength, beauty, adaptability, and longevity. The deep and endearing value of oaks in the psyche of the early settlers is clearly seen by a glimpse at any state map, where so many city and landmark names include *oak* or the Spanish equivalents *encina* and *roble*. To California's native peoples, oaks were even more revered and figured prominently in their world view and spiritual beliefs. Among other things, oaks were the source of *acorn*, a staple food source of many tribes.

The value of oaks goes well beyond their stature and beauty and how people view them. Oaks and oak woodlands are home to a rich and diverse assortment of wildlife. More than half of the 662 species of terrestrial vertebrates in California utilize oak woodlands at some time during the year, and the food and shelter provided are essential to their survival. Oaks are also critical in protecting watersheds and ensuring the quality of water resources. The majority of the state's water is stored as snowpack in high-elevation mountains before flowing through oak woodlands in rivers that support fisheries, farms, and cities. Oak trees anchor the soil, preventing erosion and sedimentation.

But not all is well with California's oaks and oak woodlands. In addition to adverse impacts from firewood harvesting, agricultural conversions, intensive grazing, and residential and commercial development, there has been concern for a number of years that several oak species are not regenerating well in portions of the state. These species grow primarily in the foothills of the Sierra, Coastal, and Transverse mountain ranges, regions that are commonly referred to as hardwood rangelands. As a result of concern about poor regeneration, there has been a concerted effort to develop successful techniques for the artificial regeneration of the rangeland oak species. Research has addressed a wide array of subjects, including acorn collection, storage, and handling; seedling propagation methods; and techniques for planting, protecting, and maintaining seedlings in the field. There has been a great deal of research on this subject in the last decade, and we have come a long way in understanding how to grow and plant rangeland oaks. Nevertheless, the results of this research have been largely fragmented and dispersed in a wide range of documents, including homeowner brochures, internal reports, and scientific publications in rather obscure journals.

This manual attempts to bring together the information available on artificially regenerating rangeland oaks in California. The manual's primary purpose is to provide a resource for restorationists, hardwood rangeland managers, and others involved in oak propagation and planting projects so that their efforts are based on the latest scientific information available and are, ultimately, more successful. I also hope that this document will be of interest to others not directly involved in regenerating oaks but who maintain a deep, personal interest in the ecology and management of *Quercus* species.

Organization *of* this Manual

This manual is divided into four chapters. The first chapter deals with the subject of poor natural regeneration of native California oaks and identifies the oak species that appear to be regenerating poorly and the conditions under which this problem seems most acute. It also describes a number of theories that have been proposed to explain why regeneration appears to be less successful today than in the past.

The second chapter focuses on acorns and provides an overview of acorn physiology, as well as a discussion of the suspected causes for the large variability in the size of acorn crops from year to year. This chapter also describes how to collect and store acorns and the recommended procedures for sorting and testing them. There is a brief discussion of genetic variability and the importance of maintaining local seed sources. Finally, information is presented on how, when, and where to sow acorns and the pros and cons of directly planting acorns in the field versus planting seedlings that have been raised in nurseries.

The third chapter discusses oak seedling propagation. Some of the more common methods of growing seedlings are presented, including case studies of three nurseries that have been producing California oaks in containers for well over a decade. The possibility of vegetatively propagating oaks is also discussed, as are the potential benefits of inoculating oak seedlings with mycorrhizae. This chapter is designed to provide a broad overview of production techniques; readers contemplating growing oaks on any large scale are advised to obtain further information from other sources, including those nurseries listed in the appendixes.

The fourth and longest chapter addresses the general subject of planting, protecting, and maintaining oak seedlings in the field. This encompasses how to select planting sites and actually plant seedlings, as well as how to overcome the two main obstacles to successfully establishing oaks: controlling competing vegetation and preventing damage to acorns and young plants by animals. A considerable amount of discussion is devoted to treeshelters since studies at the University of California Sierra Foothill Research and Extension Center (SFREC) show that these devices are particularly useful for artificially regenerating oaks, both in terms of stimulating seedling growth and preventing damage from a wide range of animals. This chapter concludes with a discussion of other practices that may enhance regeneration success, including augering planting holes, fertilizing, irrigating and shading seedlings, and top pruning.

Each of the last three chapters also contains side bars that are intended to summarize the important points covered and provide practical guides for artificially regenerating California's rangeland oaks. Following a brief conclusion are the appendixes, which are included to provide additional resources and information to assist in better understanding oak regeneration and embarking on programs to grow or plant oaks.

Finally, there is a list of all of the references cited in this manual. The main focus of the references has been to identify research conducted in California on native oak species, and most specifically, on blue oak (*Quercus douglasii* Hook. & Arn.) and valley oak. In several instances, however, relevant research from other parts of the United States and the world is also identified. It is important to point out here that the problem of poor oak regeneration, and efforts to overcome it, is not unique to California. Concerns about oak management in the Middle Ages led to forest ordinances in France—including planting programs—designed to ensure the establishment of oaks. And in the Eastern United States, concerns about oak regeneration go back to the early 1800s. There is, therefore, a large amount of literature and information on this general subject from outside of California. For those who are interested, several general references about oaks and oak regeneration both inside and outside of California are listed in the bibliography, including conference proceedings, books, and software. These references provide readers with a starting point for delving deeper into topics of interest.

It is also important to mention here that, while this manual attempts to be comprehensive and include information from throughout the state, and even from other parts of the world, much of it is based on research conducted over the past 12 years at the University of California Sierra Foothill Research and Extension Center (SFREC), located 15 miles northeast of Marysville, California. I have been very fortunate to be housed at the SFREC and, since it is located in a fairly typical oak woodland, it has proved an ideal location to carry out oak regeneration research. However, while the SFREC is representative of large areas of oak woodlands in the state, it is clearly unlike many other places where oaks grow. Consequently, the results and recommendations contained within this manual should certainly be applied to other situations cautiously. The principal characteristics of the SFREC are listed in table 1. As can be seen, the average annual rainfall is 28 inches (71 cm), which is considerably more than many areas farther south. Supplemental irrigation was not necessary in the studies described, but this may not be the case in areas of lower rainfall. Also, we report on results of trials where we have planted oaks in pastures grazed by cattle. Again, our planting areas are only moderately grazed, and in places where grazing intensity is greater, some of the procedures we recommend may be much less effective.

In spite of these limitations, it is hoped that this manual will be helpful and will, ultimately, promote the long-term conservation of oaks in California. That is the basic goal of the University of California Integrated Hardwood Range Management Program, as well as the goal of all our oak regeneration research and of this document.

Table 1. Characteristics of the University of California Sierra Foothill Research and Extension Center

Location	15 miles (24 km) northeast of Marysville, California, in rolling to steep foothills
Elevation	220–2,020 ft (67–616 m); most oak regeneration research plots are at approximately 600 ft (183 m)
Primary vegetation	oak woodlands and annual grass rangelands; primary woody species: blue oak, interior live oak (*Quercus wislizeni* A. DC.), valley oak, foothill pine (*Pinus sabiniana*)
Soils	generally rocky clay loams; primary series: Auburn, Argonaut, Las Posas, Wyman, Sobrante
Climate	Mediterranean climate zone with hot, dry summers and mild, rainy winters
Average annual rainfall	28 in (71 cm); range: 9–44 in (23–112 cm)
Temperatures	average year-round: 60°F (16°C); summer maximum mean: 90°F (32°C); winter monthly minimum: 40°F (4°C)
Historical use	cattle grazing

1

The Natural Regeneration of California Oaks

Since the turn of the century, there have been reports that certain species of hardwoods in California, including oaks, were not regenerating adequately (Jepson 1910). More recent assessments have also reported that several oak species do not seem to have sufficient recruitment to sustain populations. Describing the oaks in the foothill woodland of Carmel Valley, White (1966) stated that "a prevailing characteristic…is the lack of reproduction…with very few seedlings." Bartolome, Muick, and McClaran (1987) also concluded that "current establishment [throughout California] appears insufficient to maintain current stand structure for some sites." And Swiecki and Bernhardt (1998) reported that, at 13 of 15 blue oak locations evaluated throughout the state, "...sapling recruitment is inadequate to offset recent losses in blue oak density and canopy cover."

These regeneration assessments have relied on inventories of the size-class distribution of oaks, generally classifying the plants into three broad categories: seedlings, saplings, and mature trees. While the definitions of these classes have varied, there has been a consistent trend of finding fewer saplings or intermediate-sized trees than seedlings or mature trees (fig. 1). For instance, Phillips et al. (1997) assessed numbers of four size classes of blue oaks in different rainfall zones and reported fewer sapling- and pole-sized trees than seedlings or mature trees in all rainfall zones. It is important to note, however, that the trend of poor regeneration has only been observed in 4 of California's 22 native oak species, and patterns have varied greatly from place to place.

For these species, a general pattern of inadequate sapling recruitment has emerged in some locations. Since saplings are the trees that must be recruited into the mature size class when the older trees die, there is worry that, if these trends continue, current population densities will decline. Some areas that have historically been oak woodlands may therefore convert to other vegetation types, such as brushfields or grasslands. Generally, this regeneration problem is further exacerbated by land management practices that directly remove trees (firewood harvesting, clearing associated with construction, agricultural conversions, etc.), as well as by activities, such as intensive year-round grazing, heavy vehicle use, or yearly burning, that may create conditions in which it is much more difficult for oak seedlings to become established or grow.

However, not all assessments of existing oak stand structures have concluded that oaks are declining.

Figure 1. This mature oak stand at the SFREC has few oak saplings.

Holtzman and Allen-Diaz (1991) conducted a study that revisited vegetation plots charted in the 1920s and 1930s as part of a statewide effort to map vegetation (Wieslander 1935). They found that, in most plots originally containing blue oaks, there was an increase in the basal area of blue oaks, as well as an increase in the number of trees present. There was a decrease in the largest size class of trees, but this was offset by increases in other size classes. Davis, Brown, and Buyan (1995) also conducted an assessment of the cover and density of blue oak woodlands throughout the blue oak's current range to determine changes between 1940 and 1988. While they found many sites where woody cover had decreased, these were more than offset by sites where cover had increased. They concluded that there was little evidence of landscape-level or large-scale patterns of change. Both of these studies suggest that, in the time periods evaluated, the stands examined were sustaining themselves with sufficient recruitment to replace mortality.

Another approach to evaluating whether there are fewer or more oaks today than there were in the past utilizes pollen analysis. Pollen from oak flowers can be identified hundreds or even thousands of years after dispersal. The amount of pollen produced by a given species or genus is thought to correlate positively with the density of those plants present at the time of dispersal. In some lake beds, a pollen record can be determined by examining extracted layers of sediment. Deeper levels of this layer correspond to periods further in the past. By sampling varying depths of these lake beds and analyzing the pollen present, it is possible to estimate the abundance of oaks in different eras. Byrne, Edlund, and Mensing (1991) and Mensing (1998) evaluated sediment cores from lake beds in California and developed pollen diagrams for various species, including oaks. They concluded that, 5,000 to 10,000 years ago, the number of oaks in the Sierra Nevada Mountains increased, most likely as a result of climatic warming. In the last 500 years, however, the density of oaks has been fairly constant, except for the last 120 years. During this recent period, the density of oaks (primarily *Quercus agrifolia* Nee in the Santa Barbara coastal region studied) again increased and the authors of the studies hypothesize that this may have resulted from reduced burning by Native Americans and changes in grazing and woodcutting practices associated with intensified land use during the mid-nineteenth century.

There is obviously some disagreement about the severity of the regeneration problem and whether inventory assessments reflect real changes in population dynamics or merely natural fluctuations in the levels of recruitment that are normal. It also seems that recruitment levels can vary widely among oak species, from location to location within the state, and even over small distances within stands. As will be pointed out below, there appears to be no single cause for poor regeneration at all locations but rather many different factors that can affect recruitment success at different locations.

Oak Species with Poor Regeneration Rates

The three California oak species that are commonly reported to have regeneration problems are blue oak, valley oak, and Engelmann oak (*Quercus engelmannii* Greene) (Muick and Bartolome 1987; Bolsinger 1988), which are all deciduous white oaks. Blue and valley oaks are widely distributed and endemic to the state, while Engelmann oak has a narrower distribution range, growing only in the southern part of California and extending into Baja California, Mexico (Griffin and Critchfield 1972). In addition to these three species, coast live oak may also have insufficient recruitment to maintain existing stand structures in certain areas (Muick and Bartolome 1986; Bolsinger 1988).

It is common in stands of all of these species to find adequate numbers of seedlings and mature trees but a shortage of saplings or intermediate-sized trees. And while there are locations in the ranges of each of these species where regeneration is insufficient to sustain populations, there are also areas where regeneration appears to be adequate (fig. 2). As a result of this wide range in apparent ability to regenerate successfully, there have been efforts to correlate regeneration with both site and climatic factors, as well as with management history, to determine what is causing success and failure (Davis, Brown, and Buyan 1995; Muick and Bartolome 1987; Swiecki, Bernhardt, and Drake 1997a, 1997b; Lang 1988). While no universal reason for poor regeneration has been identified, several possible causes have been proposed.

Causes of Poor Regeneration

Introduction of Mediterranean Annuals

One widespread theory about why oaks are having more trouble regenerating today than 200 to 300 years ago claims that the change in vegetation, from predominantly perennial bunch grasses to introduced Mediterranean annual grasses and taprooted annual forbs, has created environmental conditions that make it much more difficult for oaks to establish successfully (Welker and Menke 1987). Mediterranean annuals, including bromes, ryes, oats, and filaree, are believed to have spread widely in California during the eighteenth and nineteenth centuries with the advent of widespread grazing (Heady 1977). A detailed study of the flora at the University of California Hastings Natural History Reservation in Carmel Valley reports that introduced annual grasses are now the dominant species in grasslands and in the understory of oak foothill woodlands (Knops, Griffin, and Royalty 1995). This spread of Mediterranean annuals seems to coincide roughly with the decline in oak regeneration, suggesting a possible cause and effect relationship.

Figure 2. This hillside has good blue oak regeneration and a wide range of size classes.

Competition for Soil Moisture. The probable reason why rangeland oaks may have more difficulty regenerating in an environment dominated by annuals is that annuals often deplete soil moisture at more rapid rates than perennials, especially in the early spring when acorns are sending down their roots. Danielson and

Halvorson (1991) compared the growth of valley oaks in proximity to either an alien annual grass or a native perennial and found that seedlings near the annuals grew slower. They concluded that "the introduction of alien annual grasses has reduced valley oak seedling growth and survivorship by limiting soil moisture availability." Gordon et al. (1989) also evaluated competition between blue oak seedlings and several introduced annuals and stated that "competition for soil water with introduced annual species contributes to the increased rate of blue oak seedling mortality observed in woodland systems in California." In contrast, a study that evaluated the competition for soil water between blue oak seedlings and a native perennial bunch grass concluded that "densities of *Elymus glaucus* lower than 50 plants per square meter [5/ft^2]could allow survival and successful establishment of blue oak in understories, and are of relevance to patterns of natural regeneration" (Koukoura and Menke 1995). Finally, Welker and Menke (1990) found that the ability of blue oak seedlings to survive was related to the rate at which water stress developed. Rapid soil moisture depletion rates, which would be expected in oak-annual grass communities, were much more damaging than the gradual depletion rates expected for seedlings growing among perennial grasses.

Livestock Grazing

Livestock grazing is also believed to be a cause of poor rangeland oak regeneration. This theory is supported by the rough coincidence of changing patterns of oak regeneration and widespread introduction and spread of livestock into the state during the Mission Period (Pavlik et al. 1991), beginning in the late seventeenth century. The direct evidence that livestock contribute to reduced regeneration is that both cattle and sheep browse oak seedlings, as well as consume acorns. At the University of California Sierra Foothill Research and Extension Center (SFREC), for instance, it is easy to find small oak seedlings that have been heavily browsed or trampled by cattle. A study there found that saplings were much more likely to occur in nongrazed plots than in currently grazed plots (Swiecki, Bernhardt, and Drake 1997a). Heavy grazing, especially over many years, can also indirectly affect oak recruitment because it increases soil compaction and reduces organic matter, both of which can make it more difficult for oak roots to penetrate downward and obtain moisture (Welker and Menke 1987).

There may be other factors inhibiting oak regeneration, as well, so that livestock removal alone may have little impact. In a statewide oak regeneration assessment, Muick and Bartolome (1986) reported that the presence or absence of livestock was not sufficient to explain the pattern of oak regeneration. And Griffin (1973) stated that "experiences in nongrazing areas, such as the Hastings Natural History Reservation, suggest that even without cows, sapling valley oaks may be scarce."

Increased Rodent Populations

A consequence of the change in range vegetation from predominantly perennials to annuals is a change in the number and types of seeds present. It is possible that this change in flora has been accompanied by changes in certain rodent populations that feed primarily on the seeds of the introduced annuals. Since several species of rodents eat acorns and oak roots, higher populations of these animals could cause sufficient damage (see **Animals that Damage Acorns and Seedlings** in chapter 4) to inhibit regeneration in certain locations. Unfortunately, no one was counting gophers, squirrels, or voles two centuries ago, so it is hard to know whether their populations and impacts on oak regeneration have dramatically changed since then.

Changing Fire Frequencies

Another theory for poor regeneration concerns fire. Historical fire frequency rates in foothill woodlands are different today than they were in presettlement times when there was little effort to put out naturally occurring fires (Lewis 1993). In addition, Native Americans regularly burned oak woodlands to keep areas open for hunting, stimulate the sprouting of plants used for various products, facilitate acorn collection, and reduce populations of several insects that damage acorns (McCarthy 1993).

While there was a period of even higher fire frequency around the middle of the nineteenth century (Mensing 1991), and burning by ranchers was relatively common up until the early part of the twentieth century, fire frequencies in the last 60 years have greatly decreased as a result of intensive fire suppression activities (McClaran and Bartolome 1989). This has caused an increase in brush and a buildup of fuels in some understories, especially in the denser woodlands of the Sierra Foothills. Since foothill oaks evolved with, and are adapted to, fire, the change in fire regimes may have adversely affected oak regeneration. Because postfire sprout growth can be rapid, fires in the past may have contributed to oak establishment and continuation (Plumb and McDonald 1981; McClaran and Bartolome

1989). Also, fuel buildup as a result of fire suppression may have created conditions unfavorable for recruitment (Mensing 1992).

There is little evidence to support the theory that changes in fire frequencies have influenced oak regeneration. White (1966) concluded that fire probably played hardly any role in modifying the structure or composition of foothill woodlands in a study area in the Carmel Valley since stands unburned for at least 25 years showed no greater or lesser density of oak seedlings than in recently burned stands. Allen-Diaz and Bartolome (1992) also reported that prescribed burning at the University of California Hopland Field Station in Mendocino County did not affect blue oak seedling recruitment. And Swiecki and Bernhardt (1999), examining the effects of a wildfire on blue and valley oak seedlings, could find no growth or survival advantage associated with burning.

Changing Climate

Global climate change, and specifically a warming trend in California, has also been hypothesized as a factor influencing regeneration success. According to this hypothesis, populations at the edge of some oak species distribution ranges may no longer be able to regenerate and survive because they have not adapted to changed climatic conditions (Bayer, Schrom, and Schwan 1999). Thus, blue oak in the hotter and drier portions of its range may have more difficulty regenerating than in areas where conditions are less harsh. To date, there has been no research to verify this hypothesis.

The Pulse Theory of Regeneration

Finally, it is possible that the apparent shortage of oak saplings may not really signal a regeneration problem but only a lull in natural recruitment levels that happen in spurts or pulses. These pulses may only happen when a rare combination of events, such as low grazing and browsing pressures, good acorn years, and wet winters, occur simultaneously (Griffin 1973). Good regeneration may only take place once or twice a century because the necessary events occur simultaneously so rarely. For very long-lived species, such as oaks, however, these infrequent pulses may be perfectly adequate to sustain populations.

At present, there is not much evidence to support this theory, since studies evaluating the ages of blue oak (Kertis et al. 1993; McClaran 1986; Mensing 1991; White 1966) tend to indicate that seedling recruitment occurs irregularly, but continuously, over long intervals, rather than during short, distinct periods of simultaneous establishment. A significant exception to this pattern, however, is in stands where most of the trees have originated at the same time following fire or cutting (see **Stump Sprouting as a Mechanism of Natural Regeneration**, below).

Is There a Regeneration Problem?

Regardless of the cause of the problem, owners and managers of hardwood rangelands need to evaluate their oak stands to determine if there is adequate recruitment for maintaining stand density or if steps need to be taken to establish new trees. Figure 3 shows a decision key (Lang 1988) to assess oak regeneration. Regeneration is not a problem if there are enough seedlings and saplings present to replace the trees that are expected to die. Neither is there a problem (at least for 20 to 30 years) if the canopy is at the desired level, all overstory trees are healthy, and existing management practices do not adversely affect them. There is a problem, however, if seedlings and saplings are scarce or if a higher stand density is desired.

A Model for Oak Regeneration

Recently, Swiecki and Bernhardt (1998) have argued that blue oak recruitment is often naturally dependent on advanced regeneration and commonly occurs when gaps are created in stands, allowing sufficient light to reach the ground. Advanced regeneration consists of seedlings originating from acorns that are able to survive under the shade of mature trees, but remain small and stunted because of competition and environmental limitations, forming a "seedling bank" for future growth. When a tree falls down, for instance, and suddenly opens up the area in which the seedlings are growing, they receive much more light and have access to greater amounts of moisture and nutrients. They are then able to grow more rapidly and become saplings. However, grazing by livestock or wildlife can reduce the reproductive potential of blue oak by damaging or killing advanced regeneration through repeated browsing that depletes or eliminates the seedling bank over time. Grazing can also suppress the vertical height growth of released seedlings that are shorter than the browse line. Under current grazing management, even when gaps are created, there may simply not be enough seedlings in many locations to respond to new openings.

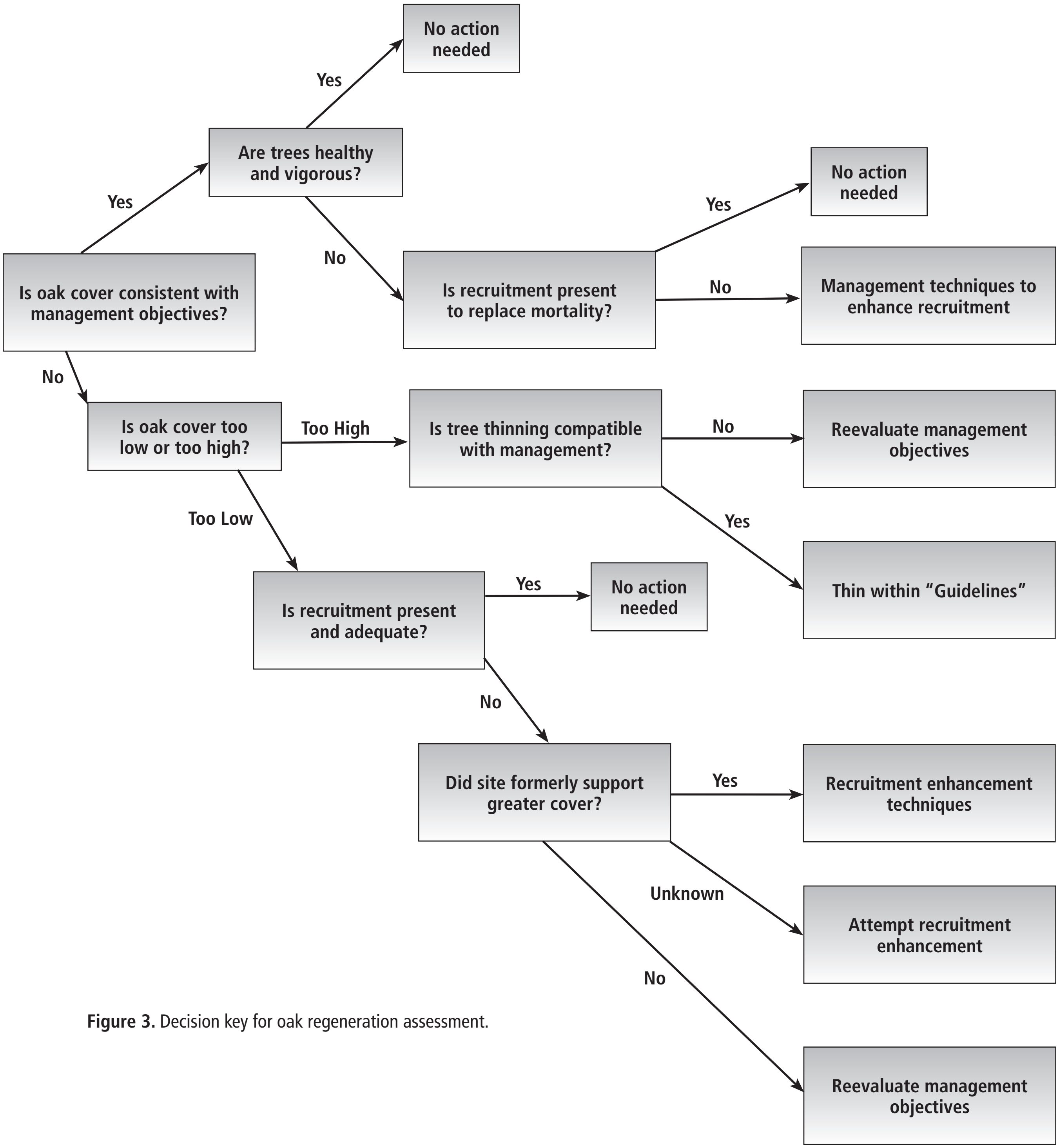

Figure 3. Decision key for oak regeneration assessment.

Stump Sprouting as a Mechanism of Natural Regeneration

There is no doubt that many of the oak trees that are alive today originated from sprouts that grew from a stump after the top was killed by fire or felling. Most stump-origin trees are easily recognized because they have multiple stems. The number of stems tends to decline with age, and older trees often have two or three main trunks. In areas where fire destroyed the stand, or where all of the oaks were cut down at the same time, most of the trees have several stems, and tree-ring studies reveal that many originated simultaneously (McClaran and Bartolome 1989; Mensing 1988).

The ability of oaks to sprout from their base following death of the aboveground portion of the tree varies by species, size of the individual tree, and environmental conditions at the site. Generally, sprouting is greater for evergreen or live oaks than for deciduous oaks; for smaller diameter stumps; and for trees growing in moister environments. While blue oak is commonly thought of as a weak sprouter compared to tan oak and California black oak (McDonald 1990), Standiford et al. (1996) found that 54 percent of blue oaks sampled in a study in the northern Sacramento Valley sprouted, even though many stumps had originally been treated with herbicides to prevent regrowth. In another large blue oak sprouting study at five sites throughout the state, almost two-thirds of the harvested trees sprouted within 2 years of harvest (McCreary et al. 1991). In general, the smaller stumps tended to sprout more, but this study detected no differences in sprouting among the four seasons of harvest, in contrast to Longhurst (1956) who reported higher sprouting for blue oaks harvested in winter.

The 1991 sprouting study also compared stumps that were protected from livestock and deer browsing to unprotected stumps. We recently assessed all trees in this study 10 years after harvest and found that protection had a tremendous effect. While the number of protected stumps that had at least one living sprout was initially higher than it was for unprotected stumps, these differences increased greatly over time. Between 1989 and 1997 the percent of protected stumps with living sprouts went down from 67 to 54 percent. Over the same interval, the percent for unprotected stumps diminished from 59 to 14 percent. Clearly the ability of sprouts to survive over time was greatly influenced by browsing.

It is not clear how many times oak stumps can sprout—several perhaps, but certainly not indefinitely. Therefore, even if sprouting is vigorous and nearly 100 percent, it will eventually be necessary for at least a portion of replacement trees to come from acorns if the stand is to be sustained over the long run.

2

Acorn Collection, Storage, and Planting

Acorns, the fruit of oak trees, contain a single seed. Compared to the seeds of most woody plants, acorns are large and contain a considerable amount of stored food. This helps ensure that they have sufficient energy to grow a large root system before producing shoots, leaves, and the photosynthetic apparatus necessary to manufacture food and become self-sufficient. This can be a great advantage in Mediterranean climates where early root development can be vital since it allows plants to more quickly reach deeper soil horizons where more moisture is available. However, there are also disadvantages of acorns compared to the seeds of some other woody plants. They are recalcitrant and cannot be dried or frozen to prolong storage. This creates problems because it means that acorns deteriorate rapidly and generally cannot be stored for more than one season. Because acorn crops tend to fluctuate from year to year, the inability to store acorns for very long periods means that planting efforts are largely dependent on current crops, which cannot be predicted with accuracy.

The *Quercus* genus can be divided into two main subgenera: the white oaks (section *Quercus*, formerly called *Lepidobalanus*) and the red or black oaks (section *Lobatae*, often known as *Erythrobalanus*) (Sternberg 1996). While there is also an intermediate group in California (section *Protobalanous*), it will not be discussed here. These subgenera have basic differences in wood structure, leaf morphology, and bark characteristics, as well as in acorn physiology. The length of time it takes from pollination and fertilization to acorn maturity is different for white and black oaks. Acorns from white oaks usually require only one year to mature, while those from black oaks (coast live oak is an exception) generally need 2 years.

Flowers on California oaks become visible in the spring, about the time the deciduous oaks are producing a new crop of leaves; both male and female flowers occur on the same tree. The male flowers, or catkins, produce clouds of pollen that are carried by wind to the female flowers, which are small and inconspicuously located in the angle between a new leaf and twig (Keator 1998). The appearance of abundant flowers, however, does not guarantee a large acorn crop (Cecich 1993). For most oak species, acorns mature and fall to the ground in the late summer and early fall. At higher elevations, this can be delayed, and weather conditions can also influence the ripening and falling dates.

Variable Acorn Crops

It has long been known that acorn production varies significantly from year to year (Sudworth 1908; Jepson 1910). In years with good acorn crops, large individual trees can have many thousands of acorns, while, in bad years, it can be difficult to find a single acorn on the same tree, or even on most of the trees in a stand or in a region. Masting cycles have been reported to vary greatly among the California oaks species examined, with good mast years occurring every 2 to 6 years.

There have been several inventories of acorn production on native California oaks. In 1977, the California Department of Fish and Game began assessing annual acorn production from 360 blue oak trees at the Dye Creek Ranch in Tehama County (McKibben and Graves 1987). They found that, in addition to highly variable annual acorn production patterns, there were certain trees in stands that were consistently better or worse producers than others. Even in heavy acorn years, about a quarter of the sampled trees had few or no acorns.

Weather As a Factor

For nearly two decades, Walt Koenig and others at the University of California Hastings Natural History Reservation in Carmel Valley have also evaluated the acorn production of several species of native California oaks, including blue and valley oak (Koenig et al. 1991; Koenig et al. 1996; Koenig et al. 1999; Koenig and Knops 1995; Koenig and Knops 1997). They have been particularly interested in finding trends in production patterns in California that are related to environmental variables that may explain why acorn crops are much larger in some years. The closest correlation they have found is related to weather at the time of flowering. When conditions are dry and warm at flowering, crop sizes for blue and valley oak tend to be larger compared to years when it is cold and wet during the same period (Koenig et al. 1996). Since acorns are wind pollinated, dry and warm conditions seem to favor pollination and subsequent acorn production. Interestingly, because some oak species, such as California black oak (*Quercus kelloggii* Newb.) and interior live oak (*Quercus wislizeni* A. DC.), require 2 years from flowering to acorn production and others, such as blue oak and valley oak, require only 1 year, it follows that production patterns between 1- and 2-year species could be very different, while trends within these groups should be similar. To date, these studies have found high synchrony throughout California within the 1-year species, but less for those requiring 2 years (Koenig et al. 1999).

Geographic Synchrony

This research has also evaluated whether or not there is geographic synchrony within individual species, that is, when acorn crops are good for blue oaks in the northern Sacramento Valley, are they also likely to be good along the central California coast or even farther south? Preliminary evidence suggests that there is widespread geographic synchrony, possibly on a statewide scale, among some of the 1-year species (especially blue oak), but much less synchrony among the 2-year species (Koenig et al. 1999).

Collecting Acorns

Timing

Acorns should be collected shortly after they are physiologically mature. While there are various indicators, such as moisture content, levels of carbohydrate, and acorn color, that have been used to predict ripeness for oak species in other parts of the country (Bonner and Vozzo 1987), the easiest and best characteristic we have found for blue and valley species is the ease with which acorns can be dislodged from the acorn cupule or cap. When acorns are ripe, they can be easily removed from the cap by gentle twisting. If they are not ripe, the caps are difficult to remove and some of the fleshy meat may be torn off the acorn and stay attached to the cap when separated. Because immature acorns cannot be ripened artificially after picking (Bonner 1979), acorns should not be collected until they are ripe. For blue oak, McCreary and Koukoura (1990) found that viable acorns could be collected over a fairly wide interval, extending from late August until mid October. Generally, acorns should be collected a few weeks after the first ones begin to drop. The early fallers often contain a large percent that are diseased or damaged by insects (Swiecki, Bernhardt, and Arnold 1991) and should be avoided.

Sensitivity to Drying

After collection, acorns are especially sensitive to drying, and their ability to germinate can decrease rapidly with even small losses in moisture content. McCreary and Koukoura (1990) found that even a 10 percent reduction in fresh weight of mature acorns resulted in nearly a 50 percent decrease in germination, and all acorns that lost 25 percent or more of their moisture

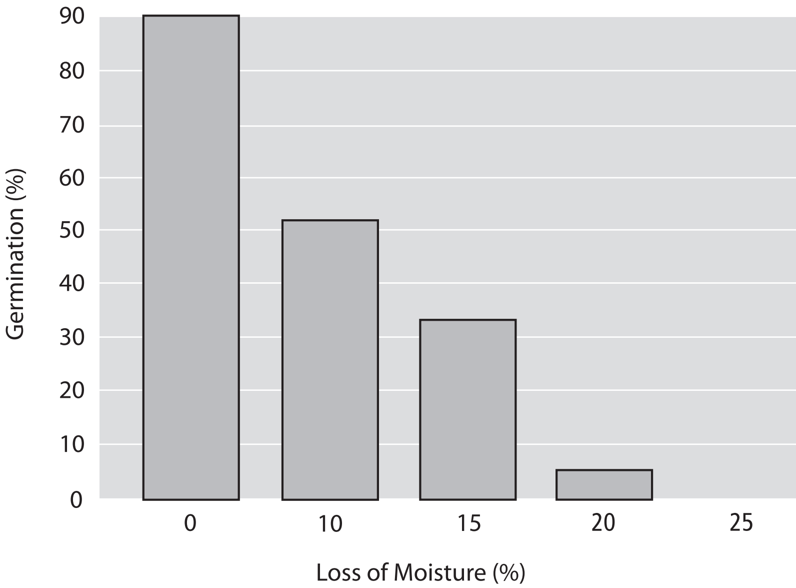

Figure 4. Acorn germination decreases with moisture loss.

failed to germinate (fig. 4). Because acorns can dry rapidly in the late summer and early fall when they drop to the ground, it is better to collect them directly from tree branches. Other researchers have reported that tree-collected acorns (fig. 5) have better germination than those collected from the ground (Teclaw and Isebrands 1986) and that damage ratings for ground-collected acorns are higher (Swiecki, Bernhardt, and Arnold 1991). On the ground, acorns can be rapidly consumed by animals. Sometimes, however, it can be impossible to collect directly from branches that are too high to reach. In these instances it is best to come back to collect acorns from the ground several times so that none remains exposed for long periods. If acorns have partially dried out, it may be possible to improve their quality by rehydrating them. Gosling (1989) found that the germination capacity of English oak (*Quercus robur* L.) acorns that had lost moisture could be improved by resoaking them for 48 hours prior to storage. However, it is best not to allow acorns to dry out in the first place.

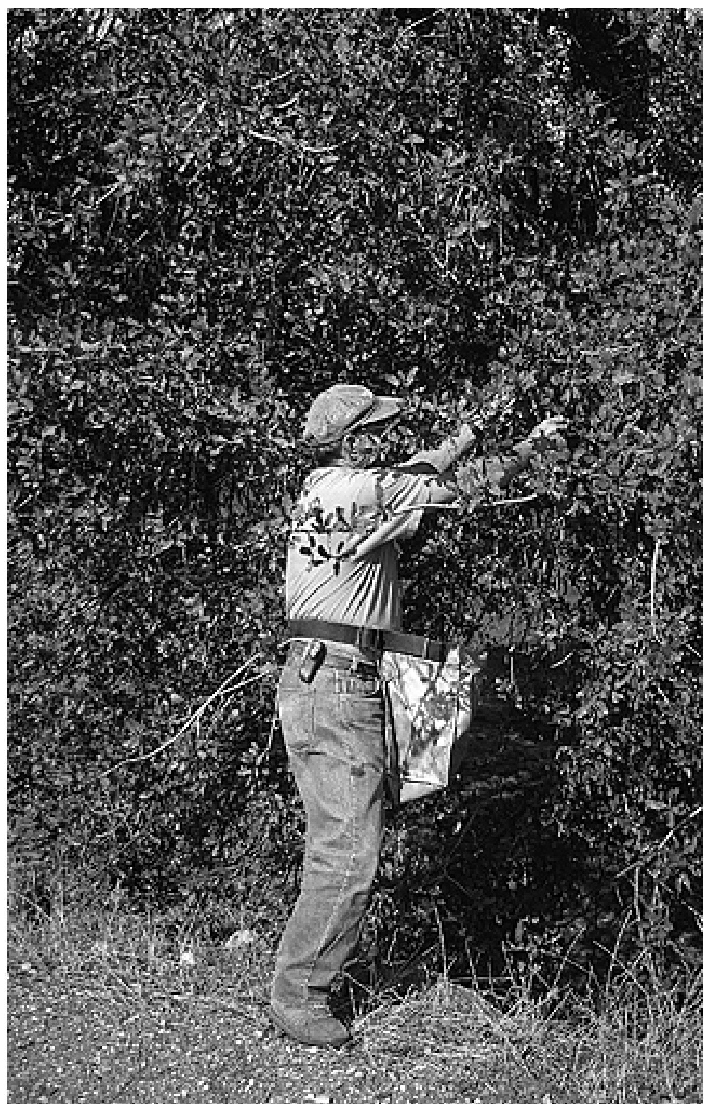

Figure 5. Using a waist bag frees both hands to collect acorns from branches.

Acorns can also be knocked to the ground from tree branches using long plastic or bamboo poles. However, it is essential to do this when the acorns are ripe. If done too early, acorns do not dislodge from the caps and remain on the tree. If too late, acorns have already fallen and may have deteriorated or been lost to animals. We have gathered acorns this way for blue oaks using tarps placed under the limbs to collect acorns as they fall (fig. 6). But many acorns knocked from the tree this way still have their caps, which must be removed prior to storage. Care should be taken not to beat the branches too forcefully so that tender new growth and even older shoots do not fall.

Sorting Acorns

Any collection of acorns contains individuals of varying quality and potential to germinate. If acorns are collected directly from the tree branches and obviously hollow or damaged acorns are discarded as they are picked, the percentage of viable acorns collected is very high, and it is generally not necessary to sort them further. But acorns collected from the ground usually have a much higher incidence of damage, and the quality of the seed lot can be improved considerably by sorting. The easiest, least expensive, and fastest sorting method is the float test. Acorns are dumped into a sufficiently large container filled with water. They are then stirred and left for several hours to either settle to the bottom, or float to the top. "Floaters" are discarded, and "sinkers" are retained. Studies have evaluated the float test for various collections of northern red oak (*Quercus rubra* L.) and found that it works reasonably well for culling damaged or insect-infested acorns (Gribko and Jones 1997; Teclaw and Isebrands 1986). The float test identifies those acorns that are hollow or damaged inside. For example, if an acorn has been infested by weevils, and a large part of the cotyledons (the white, fleshy material that provides energy and nutrition for early seedling growth) has been consumed, it will likely float.

Similarly, if acorns have been exposed on the ground for some time before collection and have desiccated and shrunk, there might be an internal air pocket that causes them to float. Finally, some acorns drop from the tree before becoming fully developed. These will also float. While the float test is inexpensive and easy, it is not 100 percent foolproof. In large seed lots, there are always some floaters that will germinate, and some sinkers that do not. Gribko and Jones (1997) reported that the float method was much better at identifying damaged, rather than sound, northern red oak acorns. That is, most of the damaged acorns floated, but many sound acorns failed to sink. However, in heavy production years, acorns are plentiful and discarding some sound acorns is probably not important. But when acorns are very scarce, it is important to retain each acorn that might germinate, so the float test may not be helpful.

Another method of sorting acorns is to select them according to size. This is fairly easy to do, and there have been reports for some oak species that larger acorns perform better (Korstian 1927) or produce larger seedlings (Matsuda and McBride 1986). A trial to evaluate the effect of acorn size on blue oak seedling performance was conducted at the Sierra Foothill Research and Extension

Figure 6. Long poles can be used to knock ripe acorns onto tarps.

Center between 1987 and 1989 (Tecklin and McCreary 1991). Results indicated that larger acorns did, in fact, produce larger seedlings, including both larger roots and larger shoots. However, after 2 years there were no significant differences in field survival between seedlings grown from acorns of different sizes.

Stratification

Dormancy in seeds can be defined as a state that prevents germination under environmental conditions that would otherwise be favorable for growth (Olson 1974). To overcome or break dormancy and stimulate subsequent germination, some seeds need a period of cold, wet conditions. Plants have evolved this delaying tactic to ensure that they do not germinate before seasonal changes make survival of the plant likely. Thus, even though there may be a week of spring-like weather in late January, these seeds will not germinate because they have not yet been naturally exposed to the necessary period of winter-like conditions. Over the long run, this is advantageous in environments where frosts following unseasonable warm spells are likely because early germination could prove lethal to the new shoot.

White Oaks

As noted previously, the *Quercus* genus can be divided into two main subgenera: white and black oaks. White oaks in California have little or no embryo dormancy. This means that they do not have to be exposed to any special environmental conditions and are ready to germinate soon after they have been gathered. Anyone who has collected valley or blue oak acorns and stored them in the refrigerator for any length of time can testify to the fact that these acorns begin germinating within a few weeks or months, even in such a cold environment. If left long enough, the acorns can form a tangled mass of elongated radicles. It can be difficult to plant (and sometimes even to separate) such acorns, but research in the southern United States suggests that it is not essential to keep the radicles intact. Bonner (1982) found that breaking radicles prior to sowing in a nursery did not adversely affect seedling production for any of the three oak species he tested. At the University of California Sierra Foothill Research and Extension Center (SFREC), we also found that when long radicles of blue oak were cut back to a .4-inch (1-cm) length, they grew as well as acorns with intact radicles (McCreary 1996). However, when the radicles were cut all the way back to the acorn, the acorns failed to produce shoots.

Black Oaks

Acorns from this group generally have embryo dormancy although it is variable, and there can be differences in dormancy even within species (Bonner and Vozzo 1987). After collection, black oak acorns need stratification, a period of artificial, winter-like conditions that helps break dormancy and allows the acorns to germinate. According to Olson (1974), stratification for oaks "should be in moist, well-drained sand, sand and peat, or similar material for 30 to 90 days at a temperature of 32° to 41°F [0° to 5°C]." We have found that it is also possible to provide stratification for black oak acorns in California by soaking the acorns for 24 hours and then putting them in a refrigerator (but not a freezer) for 30 to 90 days, though precautions must be taken to ensure that acorns do not dry out.

Our experience with black oaks in California has been limited to California black oak (*Quercus kelloggii* Newb.), interior live oak (*Quercus wislizeni* A. DC.), and coast live oak. All of these species have germinated in storage without stratification, indicating that they do not have particularly strong dormancy or stratification requirements. Matsuda and McBride (1989b) evaluated germination of seven California oak species and found that there were fast and slow germinators, with white oaks generally in the former, and black oaks in the latter group. Longer stratification periods increased the rapidity of germination after sowing for all of these species. However, even some black oak acorns not receiving stratification eventually germinated. For tree seeds in general, stratification tends to make germination more even, reducing the interval between early and late germinators. It also widens the range of conditions over which seeds can subsequently germinate. Both of these effects can be helpful when sowing acorns in a greenhouse or nursery where it is desirable to produce seedlings of uniform size.

Storing Acorns

After collection, acorns should be stored in a refrigerator or cooler preferably at a temperature just above freezing (between 33.8° and 37.4°F [1° and 3°C]). They should be placed in plastic bags that act as moisture barriers but allow some gaseous exchange. Prior to storage, the acorn caps should be removed. Because acorns continue to respire during storage, some gas exchange with the atmosphere is necessary and airtight storage containers should be avoided. It is therefore recommended that plastic bags be kept partially open at the top so that the moisture that tends to condense on the insides of the bags can evaporate and does not accumulate. Nevertheless, it is important to regularly check acorns to make sure they are not drying out.

Keeping acorns cool during storage serves several functions. First, it tends to slow respiration, which utilizes energy and can deplete carbohydrate reserves. Second, it slows the tendency for sprouting which is especially common for white oaks. And third, refrigeration tends to reduce the incidence of harmful microorganisms that can damage or kill acorns. To further retard molds, some restorationists suggest treating acorns before storage or placing fungicides inside storage bags. Bush and Thompson (1990) recommend rinsing acorns in a solution of ½ cup (118 mL) household bleach per 1 gallon (3.8 L) of cool water to kill harmful fungi. To prevent disease problems, Adams et al. (1991) dusted acorns with the fungicide Captan prior to storage. We have generally found that treating acorns prior to storage is not necessary as long as acorns are stored at the temperatures and conditions described above, and as long as they are not stored for extended periods of time. However, if molds on acorns during storage become so extensive that the radicles become discolored and slimy, it is best to discard them.

There are also several insects that can damage acorns (see **Animals that Damage Acorns and Seedlings** in chapter 4), but most damage occurs before collection. Moreover, it is difficult to kill these insects once they are inside the acorns without damaging the acorns themselves.

White oaks cannot generally be stored for more than a single season, but some researchers have reported that acorns from certain black oak species can be stored for at least 3 years (Bonner 1973). However, little research on prolonged storage has been conducted for California species. We have kept both California black oak and interior live oak acorns in a refrigerator for more than a single season but have observed that the number that subsequently germinate drops dramatically, such that only a few acorns remained viable into the second year.

Testing Acorn Quality

There may be instances when it is important to accurately determine acorn quality. Such information may be valuable before proceeding with a large-scale collection, or to assess whether temporary storage or handling procedures have been detrimental. Seed tests are also important for nurseries that need to calculate sowing densities. The most accurate measure of potential acorn performance is to incubate a representative sample of intact acorns under environmental conditions that bring about germination. Standard conditions recommended by the Association of Official Seed Analysts (AOSA 1993) for conducting germination tests on acorns are a day temperature of 86°F (30°C) and a night temperature of 68°F (20°C), with an 8-hour photoperiod (length of daily light interval). It is also critical that the acorns be placed on a moist medium, such as sand, sand and peat, or vermiculite, and not be allowed to dry during the test. These tests provide an estimate of germination percentage. Unfortunately, germination tests on the intact acorns of many oak species can take 2 months or more to complete, and this is often too long to wait. One way to speed tests is to partially dissect the acorns before sowing them. Cutting acorns in half (discarding the cap end) and peeling away the pericarp (acorn skin) can reduce the germination time to about 3 to 4 weeks. However, even this is frequently too long. Consequently, a number of more rapid viability tests have been developed and may be of use in special situations.

Recommended Acorn Collection and Storage Procedures

- Collect acorns in the fall, several weeks after the first ones have started to drop and when those remaining on the tree can be easily dislodged from the acorn cap by gentle twisting.
- If possible, collect acorns directly from the branches of trees, rather than from the ground.
- If acorns are collected from the ground, place them in a bucket of water for several hours, and discard floaters.
- Stratify acorns from the black oak group by soaking them in water for 24 hours and then storing them in a cooler or refrigerator (33.8° to 37.4°F [1° to 3°C]) for 30 to 90 days before sowing.
- Store acorns in a cooler or refrigerator in loosely sealed plastic bags, but do not store acorns from the white oak group for more than 1 or 2 months before planting to ensure greatest viability.
- If acorns start to germinate during storage, remove and plant them as soon as possible.
- If mold develops during storage, and acorns and radicles are discolored and slimy, discard acorns.

A viability test identifies those seeds that are alive, but that does not necessarily mean that they are capable of germinating. Bonner and Vozzo (1987) describe three options for quick viability tests. The first, simplest, oldest, crudest, and probably best technique is a cutting test. In this test, a sample of acorns are cut in half and those with clean, firm, and healthy-looking cotyledons are considered viable. Those that are entirely empty or in which the embryo appears undeveloped, shriveled, moldy, or insect-damaged are not viable.

Another method of testing is X-radiography. This is a quick and nondestructive technique for identifying empty and damaged fruits and seeds of most species. Unfortunately, for acorns it can be difficult to interpret because the high moisture content of live acorns renders the X-ray images opaque.

Finally, there is the tetrazolium test. This relies on the premise that only living cells have the enzymes capable of converting a colorless solution of tetrazolium salt into a colored precipitate. Although this test has been widely applied to the seeds of a large number of species, it is only moderately successful for acorns (Bonner 1984). This is probably because acorns contain secondary compounds that interfere with the staining reaction.

Genetic Considerations

Genetic Differences within Oak Species

Restoration is defined as bringing something back to a former or normal condition. For restoration, therefore, only a given species of oak should be planted in areas where it naturally grows or grew in the past. But even within an oak species, the source of the acorns must be considered. Both blue oak and valley oak are widely distributed species in California, ranging in latitude over much of the length of the state and in elevation from near sea level to 5,600 feet (1,700 m) for valley oak (Griffin and Critchfield 1972), and to over 4,500 feet (1,400 m) for blue oak (McDonald 1990). Clearly, there is a very wide range of environments in which different populations within these species grow. For instance, blue oak grows on Santa Cruz and Santa Catalina Islands, as well as at lower to middle elevations in the northern Sierra Nevada. While the coastal environment is generally temperate and mild, growing seasons in Northern California are shorter, and frosts commonly occur in late spring. If acorns collected from coastal trees were planted in the north, they may grow quite well for a number of years. But in the life span of an oak tree (which can be 200 to 300 years), it is likely there will be an environmental extreme that they are not genetically adapted to. A serious freeze in late spring, for instance, could seriously damage or kill a tree from a coastal source, while local trees may suffer few negative effects.

Although there has not been a lot of research on the genetics of native California oaks, Rice, Richards, and Matzner (1997) found evidence for local adaptation of blue oak populations collected at the University of California Sierra Foothill Research and Extension Center and at the University of California Hopland Research and Extension Center. However, Riggs, Millar, and Delany (1991) found only relatively small genetic differences within valley and blue oak populations using biochemical assay techniques and could detect no geographic pattern in variation in these biochemical markers.

Genetic Contamination

Another potential problem of moving oaks from one locale to another is genetic contamination. Oaks are wind pollinated and require pollen from male flowers to pollinate and fertilize female flowers. If pollen-producing trees are from off-site locations and contain genetic traits poorly adapted to the area where they are growing, there is a risk that they could introduce these ill-adapted traits into the population via newly produced acorns. While there certainly is debate over how serious a threat this is for oaks as well as for other species, it makes sense to avoid this potential danger when possible. It is, therefore, recommended that acorns be collected as near to the planting site as possible. Furthermore, to ensure adequate genetic variability within the local population, Lippitt (1992) recommends collecting acorns from at least 15 trees at any given site.

Timing of Acorn Planting

As mentioned above, blue and valley oak acorns generally ripen in late summer to mid fall. However, at this time soils can still be extremely dry because the first heavy, fall rains may not have occurred. While even fairly dry soils can have relatively high humidities under the surface, these soils can also be extremely hard, and, even if acorns do germinate, root penetration is likely difficult. We, therefore, recommend that acorns are only directly planted in the field after there has been sufficient rainfall to soak the soil at least several inches down. But how soon after these rains should acorns be planted? In a trial at the University of California Sierra Foothill Research and Extension Center with blue and valley oaks, we compared field performances of acorns sown at monthly intervals for 5 months starting in early November

(McCreary 1990a). Acorns for each species were collected from single trees in early October and were stored in the refrigerator for intervals ranging from 1 to 5 months before planting. We then recorded emergence date, total emergence, first- and second-year heights and diameters, and survival of seedlings in the field. There were profound and consistent effects of acorn planting date, with better performance for those that were sown earlier. They tended to emerge earlier, have higher survival, and grow more. While early emergence might increase the risk of frost damage, we have never observed such damage at SFREC. Sowing acorns on the last date in early March was particularly harmful since the seedlings seemed to get such a late start that they apparently were not able to grow a very large root system before the summer dry period. Based on these results, we recommend that blue and valley oak acorns be planted early in the season, as soon as possible after the soil is sufficiently wet. As a rule of thumb, planting should take place no later than the end of January, and even this may be too late in areas with less rainfall and shorter winters.

How to Sow Acorns

Planting Depth

When directly sowing acorns in the field, it is important to bury them since the likelihood of depredation, as well as desiccation damage, is much greater for exposed rather than buried acorns. In a study with blue, valley, and coast live oaks, Griffin (1971) found that burying acorns did not eliminate rodent damage but did reduce losses. And Borchert et al. (1989) reported that recruitment of buried blue oak acorns was twice that of surface-sown ones. We generally sow acorns ½ to 1 inch (1.0 to 2.5 cm) deep, but in some situations it may be better to plant them deeper. In an area where rodents were a threat, Tietje et al. (1991) found that, in general, emergence was better for blue oak and valley oak acorns planted 2 inches (5 cm) in the ground because shallower plantings (½ in [1 cm]) had much higher depredation, while deeper plantings (4 in [10 cm]) made it too difficult for shoots to grow up through to the soil surface. However, if acorn depredation is not a serious concern, shallower plantings are generally preferred.

Recommended Methods for Sowing Acorns of Rangeland Oaks in the Field

- Sow acorns in the fall and early winter, as soon as soil has been moistened several inches down.
- If possible, pregerminate acorns before planting and outplant when radicles are ¼ inch to ½ inch (½ to 1 cm) long.
- Cover acorns with ½ to 1 inch (1 to 2 ½ cm) of soil.
- If acorn depredation is suspected as a serious problem (high populations of rodents are present), plant deeper, up to 2 inches (5 cm).
- If acorns begin to germinate during storage, outplant as soon as possible with the radicle pointing down. Use a screwdriver or pencil to make a hole in the soil for the radicle.
- If radicles become too long, tangled, and unwieldy to permit planting, clip them back to ½ inch (1 cm) and outplant.
- If acorn planting spots have aboveground protection (treeshelters), and acorns have not been pregerminated, plant two or three acorns per planting spot and thin to the best seedling after 1 year. (See chapter 4.)
- Keep planting spots free of weeds for at least 3 years after planting. (See chapter 4.)

Pregermination

We have found that by pregerminating acorns before field planting, more than 90 percent will initially grow. Pregerminating acorns is easily done by filling pie pans or other shallow dishes with moist vermiculite, sand, or peat. Acorns are then placed on their sides and gently pressed into the medium (fig. 7). It is important that the material stay moist, but not overly saturated, while the acorns are germinating. The trays can be placed at room temperature on a table, windowsill, or bench for observation. Blue oaks generally begin germinating in 1 to 2 weeks, as evidenced by a white tip, or radicle, protruding from the pointed end of the acorn. They are then ready to outplant. When planting pregerminated acorns with developed radicles, use a pencil, screwdriver, or other pointed object to make a hole in the soil and carefully position the acorn in the hole with the radicle pointing downward. Acorns can then be covered as described above.

Figure 7. Place acorns in trays of moist vermiculite for easy pregermination.

Multiple Seeding

When directly planting acorns, it is a good idea either to sow those that you are sure will germinate or several at each planting spot to ensure germination of at least one individual. Some restorationists feel it is important to plant two or three acorns per planting spot (Bush and Thompson 1989). This is particularly important if planting spots are protected with cages or tubes because such planting requires considerable expense and effort. Since acorns are generally easy to obtain, multiple seeding is far less expensive than replanting. However, multiple seedlings should eventually be thinned to the single best plant, which is not always easy to do inside of tubes. This can be time consuming and expensive, and, if acorn quality is extremely good and expected germination rates are above 90 percent, it is probably not necessary to sow more than one acorn per spot.

Acorn Orientation

Some researchers have questioned how acorns should be oriented when planted. Both the shoot and the root emerge from the pointed end of the acorn, so whether they are planted point up or point down may subsequently affect how seedlings grow. McDonald (1978) reported the results of a field test that compared point up vs. point down plantings of tanoak acorns *(Lithocarpus densiflorus),* a species closely related to *Quercus*. He found that planting point up resulted in earlier and more complete emergence. A study with northern red oak, however, found that, while planting position (point up, point down, or sideways) had no statistically significant effect on seedling survival and growth, acorns lying sideways had the highest average survival (Trencia 1996). In our research trials at SFREC, we have opted to plant acorns horizontally, and this has proven quite effective.

Acorns or Seedlings?

The choice of whether to plant acorns or seedlings depends on a host of factors including availability of suitable planting material and conditions at the planting site. Sometimes it is difficult to obtain seedlings from local sources. Only by collecting acorns yourself can you be sure that your planting will be adapted to local conditions. However, if large numbers of acorn-eating rodents, such as mice or ground squirrels *(Spermophilus beecheyi),* are present, it can be difficult and costly to successfully establish oaks by direct seeding. In these situations, the best solution may be to plant seedlings.

We have conducted several trials to compare the field performance of acorns and seedlings from the same seed source. In one study, we detected very little difference between blue oak seedlings that originated as directly sown acorns and those that were grown for 4 months in containers and then transplanted. Both had over 90 percent survival, and, after 5 years, there were no significant differences in height (McCreary and Tecklin 2001). This is consistent with a previous blue oak trial at the SFREC (McCreary 1996) in which these two stock types were also compared. In the 1996 trial, however, acorns had far greater growth than 1-year-old seedlings planted at the same time. It is important to note that both of these trials were conducted in highly controlled environments, and in less intensively managed wildland settings, transplants might perform better.

Because it is easier and less expensive to directly plant acorns, this method may be preferable in many situations. However, if direct sowing is used, it is important that steps be taken to ensure that acorn depredation will not be a problem since this can negate any benefits that might otherwise be realized. Our plots were kept fairly weed free, and, therefore, there were not many rodents, which are attracted to locations where weed cover is dense (see **Animals that Damage Acorns and Seedlings** in chapter 4).

3

Propagating Rangeland Oak Seedlings

Until a decade ago, there were relatively few native oaks produced for artificial regeneration in California, mainly because there was little demand. Historically, most California oak species have not been considered desirable landscape plants, partly because they had a reputation for growing slowly. Also, few seedlings were commercially grown because oaks in California have never been considered important timber trees. The lack of commercial importance also meant that there was almost no research carried out on how to grow oaks, either in containers or in bareroot nurseries. While such research has been extensive for commercially important eastern oak species, such as northern red oak (Johnson 1988; Ruehle and Kormanik 1986; Thompson and Schultz 1995), in California the propagation methods used have evolved from the growers' experiences and have been based largely on trial and error.

The last decade has seen a significant increase in demand for, and production of, oak seedlings. Oak seedling quality has also improved over the same period, reflecting improvements in nursery husbandry. Nurseries, such as Tree of Life in San Juan Capistrano, Circuit Rider in Windsor, and the California Department of Forestry and Fire Protection L. A. Moran Reforestation Center in Davis, have now been growing oaks for many years. Below are some general comments about propagation methods for container-grown oak seedlings, followed by case histories summarizing production methods used by these three nurseries. For further information about container production practices, consult one of the nurseries listed in appendix A.

Seedling Production in Containers

The vast majority of native oaks produced in California are grown in containers, which range in size from a few cubic inches to large boxes of many cubic feet. In general, oak seedlings tend to put a large amount of energy into producing a taproot with a carrot-like configuration. Seedlings can, therefore, quickly become pot-bound in small containers, meaning the volume of seedling roots produced can exceed the growing space in the container. Planting such stock can result in poor subsequent field performance or even death. It is, therefore, important not to grow seedlings in containers that are too small. Some nurseries start oaks in small sleeves called "liners"

Preparing Potting Mix

Combine the following:

5 ft^3 course peat moss

5 ft^3 course vermiculite

4 ft^3 fir bark (1/8- to 1/4-inch size)

1 lb lime

2 lb slow-release fertilizer granules

or in flats, and then transplant the seedlings to larger containers as they become bigger. In general, better quality oak seedlings are produced in narrower, deeper containers, rather than in wide, shallow containers. For this reason, a common container for raising oaks is a "treepot," with dimensions of approximately 4 by 4 by 14 inches (10 by 10 by 36 cm) although large-scale production is often started and completed in liners or small containers called "plant bands."

Preventing the Formation of Deformed Roots

Oak taproots generally reach the bottom of a container before the shoots emerge from the soil surface. Once at the bottom, these roots tend to circle around unless they are checked or prevented from growing. Such root circling creates a plant that is poorly adapted to growing in the field. Deformed roots can persist for years and even decades after field planting and can cause poor tree growth and lack of stability.

Air Pruning. Many container production systems employ air pruning to thwart root circling. As the seedling roots grow to the bottom of the container, they are exposed to air. This is accomplished by using open-ended containers that are placed on screens or mesh to prevent the soil from falling out while still exposing roots that reach the bottom. Since the air is dry, and roots need moisture, the root tips stop growing. This, in turn, causes the production of lateral branch roots farther up the main root, creating a much more fibrous root system. This type of air pruning is used at the California Department of Forestry L. A. Moran Reforestation Center with excellent results (Lippitt 1992).

Chemical Pruning. There are also commercially available copper compounds that can be painted on the interior of containers. These compounds arrest the growth of root tips (Regan, Landis, and Green 1993). When roots come in contact with these chemicals, they are pruned, causing further root branching and development of a more fibrous root system.

Planting Medium

Oak seedlings grow well in a variety of potting mixes. According to Schettler and Smith (1980), "nearly any reasonable planting medium can be used with good results as long as it is well-drained."

Fertilizing

Container seedlings generally need to be fertilized within a few weeks after sowing. Fertilizer can be provided in irrigation water or in slow-release fertilizers incorporated into the soil mix. A fertilization regime that has been used successfully is adding 20-20-20 at 100 parts per million of nitrogen in irrigation water, plus micronutrients.

When to Transplant

Most container seedlings are grown for a year or two before transplanting to the field. In some cases, however, the time in the container can be considerably longer as plants are repeatedly transplanted to increasingly larger containers in order to produce large-sized (and very expensive) landscape plants. At SFREC, we have experimented with a shorter production schedule. We collected acorns in October, sowed them in outdoor shadehouses at the California Department of Forestry Nursery in Davis in December, and then planted the young seedlings back at the University of California Sierra Foothill Research and Extension Center in late March. While these seedlings appeared quite fleshy and tender at the time of outplanting, they performed well in the field (McCreary 1996). In fact, in this trial they were superior to 1-year-old container stock in terms of survival and growth. Obviously, it is far less expensive to produce a 4-month-old seedling than one grown for a full year, so this stock type may be suitable in some situations.

Growing Your Own Seedlings

Germination

It is possible to grow your own oak seedlings without sophisticated greenhouses or other equipment. Acorns are easy to collect and germinate, and the requirements for small seedlings are relatively modest. Pregerminate acorns in shallow trays to make sure that all of the acorns that are planted are viable and ready to grow.

Containers and Potting Mix

As previously discussed, tall, narrow containers are preferable to short, wide ones. We have had good success with small milk-carton-like boxes that are open at both ends. These are available in a variety of sizes (see appendix A), and a size of 2 by 2 by 10 inches (5 by 5 by 26 cm) seems particularly well suited to growing oak seedlings. These containers are wide enough to lay acorns flat for planting, and tall enough to allow good root development. For growing large numbers of seedlings, the potting mix described in the box on page 20 has worked well. But for growing fewer than two hundred seedlings, it is probably easiest to buy commercially available potting mixes in ¾-cubic-foot bags. Course mixes that have better drainage are preferable to finely textured ones.

To prevent the potting mix from falling out of the open-ended containers, we place a single sheet of newspaper in the bottom of the rack. These decompose about the time the roots reach the base of the containers, but by that time, there is little risk of the soil falling away. Racks should not be placed on a solid surface, but should be elevated slightly or placed on screen, narrow strips of wood, or mesh.

Containers can be kept indoors or outdoors; but if outdoors, the seedlings must be protected from severe freezes. It may also be necessary to make sure that birds or rodents do not remove acorns. While the roots start to grow right away, it may take several months for the shoots to emerge. As noted above, we have found that 4-month-old blue oak seedlings grown this way (sown in containers in December and field planted in March) have performed well in the field, as long as they are irrigated at the time of planting. But since the seedlings are fairly tender and fleshy, they need to be handled and planted carefully.

Recommended Procedures for Growing Oak Seedlings in Containers

- Grow oak seedlings in tall and narrow, rather than short and wide, containers.
- Select appropriate container sizes and transplant seedlings to larger-sized containers before seedlings become "pot-bound."
- Use containers that promote the pruning of root tips at the bottom.
- Use a coarse, well-drained, potting mix; keep it moist, but not saturated, and make sure it does not dry out during warm weather.
- Ensure seedlings have adequate nutrition by incorporating a slow-release fertilizer into the potting mix or using a balanced, liquid fertilizer in irrigation water.

Other Ways to Grow Oak Seedlings

There are also other ways to grow oak seedlings. A video and manual produced by the University of California Cooperative Extension in Calaveras County, *Oak Tree Project,* (Churches and Mitchell 1990) describes a program to collect acorns and grow seedlings, targeting school and community groups.

Nursery Case Histories Involving Container-Grown Seedlings

Circuit Rider Productions

Circuit Rider Productions is a nonprofit service corporation dedicated to the enhancement of environmental and human resources. Since 1978 they have operated a native plant nursery where they produce plants for restoration and revegetation projects, specializing in site-specific liner stock. From the beginning, they have grown a number of California oak species, including valley, blue, California black, coast live, canyon live (*Quercus chrysolepis* Liebm.), interior live, and Oregon white oaks (*Quercus garryana* Douglas ex Hook.).

Container Types. Many are grown in tapered plastic tubes called "super cells" (1½ inches [4 cm]in diameter and approximately 10 inches [26 cm] deep). These tubes have ribs on the internal walls that help direct roots downward, resulting in air pruning and preventing root circling. Other containers that are used at

Circuit Rider Productions include deepots (2 in [5 cm] in diameter and 10 in [26 cm] deep) and treepots (4 by 4 by 14 in [10 by 10 by 36 cm]). The containers are filled with a well-drained growing medium and are regularly irrigated during the dry season to ensure that the growing medium stays moist, but not saturated. A slow-release fertilizer is incorporated into the potting mix prior to sowing, and liquid fertilizer is added during the growing season. Oaks grown in super cells develop an 8-inch (21-cm) root and a shoot that is about 4 to 8 inches (10 to 21 cm) tall, and they are ready for field planting the fall following container planting. These seedlings are particularly suited for planting in remote areas because they are lightweight and easy to transport. Seedlings in deepots are also grown for a single season, while those in treepots are transplanted into larger containers and require 2 years to reach the desired size.

Acorn Collection and Storage. Acorns sown by Circuit Rider are generally collected close to the future planting site within the same watershed to ensure adaptation to local conditions. Collection sites are tracked by accession numbers and, for the more common oak species, collections are made at 20 to 25 different sites for a given year in Northern and Central California. Circuit Riders usually harvest acorns directly from trees, either by picking them from branches or by knocking them to the ground with poles. After discarding obviously defective acorns and sorting them by flotation, acorns are placed in small to medium resealable polyethylene bags containing a moist medium consisting of vermiculite or perlite, or a combination of the two. Acorns are mixed with a high volume of medium to maintain high acorn moisture during storage. The bags are then placed in a refrigerator at 40°F (4.4°C) until sowing in containers. If radicles become long and tangled during storage, they are trimmed prior to sowing. When planting in containers, acorns are sown with the pointed tip buried halfway at an angle of approximately 45 degrees and placed in a shadehouse to germinate. They are kept in partial shade during the summer to ensure that the containers don't dry out too quickly.

Tree of Life Nursery

The Tree of Life Nursery has been producing native California plants for more than two decades and claims to be the largest supplier of native plants in the state. Their grounds, located in San Juan Capistrano, include 30 acres of growing area with both shadehouses and greenhouses, and they maintain laboratory facilities for the propagation and testing of mycorrhizal plants and inoculum. They grow a wide variety of native oak species, including blue, valley, coast live, California black, canyon live, island (*Quercus tomentella* Engelm.), scrub (*Quercus berberidifolia* Liebm.), coastal scrub (*Quercus dumosa* Nutt.), and Engelmann oak. They are particularly well known for growing Engelmann oak seedlings since the nursery is located within the very narrow range of this species, and they have worked closely with conservation groups focusing on Engelmann oak restoration.

Acorn Storage and Sowing. The Tree of Life Nursery collects acorns from a variety of collection areas for most species, and records identifying the location of the seed source are maintained. Acorns are then put in water, with floaters discarded and sinkers placed in lugs or flats containing moist peat moss. After germination, radicles are pinched off, the acorns are sown in super cells, and the seedlings are grown for one growing season. Nursery manager Mike Evans feels that root pinching is beneficial since it promotes the early development of a more fibrous root system and improves the ratio of roots to shoots. The potting mix consists of 80 percent organic amendments, including bark products and peat, and 20 percent inorganic components, consisting of perlite, vermiculite, and sand. A slow-release, 18-6-12 fertilizer is incorporated into the potting mix prior to planting, and the seedlings are generally inoculated with an endomy-corrhizal fungi, VAM 80. This fungi is thought to enhance the ability of seedlings to take up nutrients following outplanting, thereby improving field performance.

Transplanting. After one growing season, seedlings are either sold or transplanted into larger containers. Many are planted in 1-gallon containers that promote the development of a much deeper root system, resulting in better growth and survival after outplanting. After 1 year in this size, some oak seedlings are sold, while the remainder are transplanted into 5-gallon containers. After one additional growing season, seedlings are either sold or transplanted to 15-gallon pots, the largest size grown by the nursery. At each stage of transplanting, excess roots are trimmed off prior to moving the seedlings to larger containers. Generally, the smaller seedling sizes are destined for revegetation plantings, while the larger sizes are for landscaping projects.

California Department of Forestry L. A. Moran Reforestation Center

The L. A. Moran Reforestation Center in Davis is the only container nursery operated by the California Department of Forestry and Fire Protection (CDF). Its primary mission is to sell tree and shrub seedlings to the public. While, historically, the main focus of the nursery has been to produce and sell commercial conifer species, there has been increased emphasis in recent years on growing native plants for restoration purposes. The nursery has produced native oak seedlings since 1987. Their primary species are blue and valley oaks, with lesser quantities of California black, coast live, canyon live, interior live, Engelmann, and Oregon white oaks. However, the species grown and number of seedlings produced depend largely on the availability of acorns, and during poor acorn years, the number of seedlings of a given oak species may be restricted. The nursery produces an average of approximately 5,000 oak seedlings annually and as many as 10,000 additional seedlings as contract requests.

Acorn Processing. CDF is particularly concerned with identifying the sources of all their acorns and only distributing seedlings from acorns that have been collected relatively near the planting area. Acorns are generally collected directly from the tree branches or knocked off trees with poles. They are upgraded by discarding obviously cracked or damaged ones, including those with multiple bore holes and uneven coloration. The CDF nursery then X-rays the seed lot, which provides an additional indication of quality. If the quality is good, no further treatment is done. If there are many empty acorns, the CDF nursery uses an air separator to cull them. After sorting, acorns are stored in plastic bags that are left slightly open at the top and refrigerated at 35°F (1.7°C) until planting.

Sowing. To prevent deterioration and premature germination, acorns are generally sown in early winter, preferably by mid-December. They are sown one per container on their side and covered with about ½ inch (1 cm) of coarse vermiculite. The containers are foil-covered, paper, plant sleeves that are 2½ by 2¼ by 12 inches (6 by 6 by 31 cm) and are open at the bottom to promote air pruning of the roots. A well-drained potting medium containing peat, bark, perlite, and vermiculite is used and a slow-release fertilizer is incorporated into the mix to promote the breakdown of the bark and to encourage initial root growth. Perlite is used as a top dressing to decrease drying. Following sowing, the containers are moved directly into a shadehouse where the acorns germinate. When germination appears complete, the empty containers are removed and the remainder consolidated. Regular irrigations from an overhead system usually commence in the spring and are designed to provide deep thorough soakings, with seedlings drying between each irrigation. A balanced fertilizer is added through irrigation water, but rates are kept low. The following winter, the seedlings are sized, graded, and made available for sale.

Bareroot Seedling Production

Few bareroot oak seedlings are produced in the state. However, the California Department of Forestry and Fire Protection Nursery at Magalia began growing and selling a limited number to the public about 10 years ago. To determine which cultural practices are most effective for bareroot production of blue oak seedlings, a study was initiated at the nursery in 1987 to compare several root pruning (drawing a blade through the soil 8 to 10 inches [21 to 26 cm] deep to cut off deep roots) and sowing treatments (Krelle and McCreary 1992).

Root Pruning

Undercutting roots is common in the production of commercially important oak species such as northern red oak in the East and Midwest (Johnson 1988). Results from the Magalia study indicated that it was essential to prune seedling roots in order to produce acceptable plants. If the roots were unpruned while in the nursery bed, they grew so deep that it was impos-

Recommended Procedures for Growing, Lifting, and Storing Rangeland Oak Seedlings in Bareroot Nurseries

- Sow acorns in nursery beds by the end of January at a density of no more than 12 to 14 per square foot (129 to 151/m²).
- Undercut seedling roots in both May and August to inhibit taproot development and promote a fibrous root system.
- Lift seedlings no later than early February and place in cold storage, making sure roots stay moist.
- Store seedlings for up to 2 months, but avoid extended storage for late-lifted stock (see chapter 4).

Figure 8. These bareroot seedlings were field-planted in 1989, and many are now over 10 feet (3 m) tall.

sible to "lift," or remove, them from the nursery beds without damaging them. However, the timing of the pruning was critical. If pruning was done too early, before the roots had grown down at least 8 inches (21 cm), then it had little or no effect on root form. If pruning occurred too late in the season, after seedlings had produced fairly thick, deep, carrot-like roots, then so much of the roots were lost during pruning that the seedlings were severely damaged, and, in many cases, died.

Based on the results of these experiments, nursery manager Bill Krelle opted for both an early (May) and a late (August) pruning treatment to produce the best blue oak seedlings, with the second pruning approximately 2 inches (5 cm) deeper than the first. This study also found that seedlings from a late fall or midwinter sowing performed much better than those from an early spring sowing since late sowing apparently delayed germination and resulted in greatly reduced growth. In this trial, seedlings were grown for a single season at a density of 12 to 14 per square foot (129 to 151/m^2), though much lower bed densities are common for growing northern red oak (Schultz and Thompson 1997).

Lifting Dates and Storage

The 1987 Magalia study also evaluated different lifting dates and seedling storage treatments and found that bareroot blue oak seedlings could be lifted over a fairly wide interval, extending from early December to early February, without seriously affecting seedling quality. They could also be cold-stored for up to 2 months without damage, as long as the roots were not allowed to dry out. Seedlings from this trial (McCreary and Tecklin 1994b) have now been growing at the University of California Sierra Foothill Research and Extension Center for 10 years, and many are 10 to 15 feet (3.0 to 4.6 m) tall with basal diameters exceeding 2 inches (5 cm) (fig. 8).

Recommended Procedures for Vegetative Propagation

Vegetative propagation may be a desirable alternative to growing seedlings in containers or in bareroot nurseries because it offers the opportunity to produce uniform, genetically superior plants selected for traits such as disease or drought resistance. Another advantage is that this production method does not depend on acorns. As noted previously, acorns do not store well, and because acorn crops are so variable, restoration planning can be very difficult and seedlings unavailable when needed.

At present, however, no vegetatively propagated oak seedlings are commercially produced in California. Even for important eastern species, such as northern red oak, commercial vegetative propagation is uncommon, though there has been considerable research on it. The most widely tested method of vegetative propagation for oaks is with the use of rooted cuttings. While it is generally recognized that oaks are more difficult to root than many other woody species, it can be done. Most of the successes are attributed to combinations of using cuttings from young plants and providing growth regulators, moisture, and shade (Davis 1970; Zaczek, Heuser, and Steiner 1997). Isebrands and Crow (1985) successfully rooted softwood cuttings of 3-week-old northern red oak in a greenhouse, and Drew and Dirr (1989) found that cuttings from younger flushes (a period of stem elongation) rooted better than those from older flushes. Morgan (1979) also reported that the younger the oak, the greater the rooting success. In almost all trials, cuttings were treated with the hormone indoyl butyric acid (IBA) to stimulate rooting.

In vitro plantlet regeneration of several oak species has also been reported. Shoot cultures of English oak have been established and multiplied using original material from both juvenile seedlings and stump sprouts from mature trees (Vieitez, San-Jose, and Vieitez 1985). However, this approach is difficult and expensive, and it is unlikely that California oaks produced in this manner will be available in the near future.

Mycorrhizal Inoculation

Inoculating oak seedlings with mycorrhizal fungi has been reported to improve field performance after outplanting (Garrett et al. 1979; Anderson, Clark, and Marx 1983; Ruehle 1984; Dixon et al. 1981). This improvement is attributed to an increased capacity of the root system to take up moisture and nutrients. On sites in California where oaks were cleared decades ago and have remained treeless since, a lack of mycorrhizal inoculum could be a factor inhibiting natural oak regeneration. While a number of mycorrhizal species can be found in oak woodlands, there has been little evidence that artificially inoculating California oak seedlings, either before or after planting, significantly improves growth and survival. At the University of California Sierra Foothill Research and Extension Center, we compared valley oak seedlings inoculated with the broad spectrum and commercially available *Pisolithus tinctorius* mycorrhizae to uninoculated controls but could detect no subsequent improvement in field performance after outplanting.

However, in a trial that incorporated litter from under Engelmann oak trees (and presumably inoculum of native mycorrhizae) into planting spots with Engelmann oak seedlings and acorns, significant increases in a number of growth variables were reported (Scott and Pratini 1997). While it could not be proven definitively that mycorrhizae from the native soil conferred a growth advantage, it was concluded that this was likely. Berman and Bledsoe (1998) also added soils from valley oak riparian areas to growth media for valley oak seedlings grown in a greenhouse and found that the percent mycorrhizal infection and mycorrhizal diversity on the seedlings were increased more by transfer of oak forest and woodland soil than agricultural field soil. While the benefits of mycorrhizal inoculation for native California oak seedlings are not yet well documented, the Tree of Life Nursery regularly inoculates their oak seedlings, and its staff believes it confers a significant benefit after outplanting.

4

Seedling Planting, Maintenance, and Protection

Regeneration research in California during the past 12 years has indicated that successful oak establishment is dependent upon proper planting, maintenance, and protection. The greatest barriers to success are weed competition and animal damage. Regard-less of how well acorns are collected and processed or how well seedlings are grown and planted, if competing vegetation is not controlled and acorns and seedlings are not protected from damaging animals, chances for success are slim. Below are discussions of techniques and practices that can greatly enhance the prospects that outplanted acorns and seedlings will grow into saplings and trees.

Planting Rangeland Oak Seedlings

When to Plant Seedlings

As with date of sowing acorns directly in the field, the planting date for seedlings can influence subsequent field performance. The greatest problems arise from planting seedlings too late in the season. For blue and valley oaks, March is usually too late, and it is preferable for seedlings to be planted by the end of January. Bareroot blue oak seedlings lifted on several dates and stored for varying intervals performed well as long as they were not planted after early March (McCreary and Tecklin 1994b), and 1-year-old container seedlings planted in mid-December tended to grow more than those planted 6 or 12 weeks later (McCreary and Tecklin 1993b). In environments with low average annual rainfall and early onsets of spring and summer, these planting dates should be moved up even earlier.

Because both blue and valley oaks are able to grow roots during winter, early planting allows them to develop well-established root systems while the soil is still moist. In the Mediterranean climate of California, having such a root system is critical because there might be little or no rain for nearly 6 months, and the soil, especially near the surface, can become exceedingly dry. Seedlings planted late in the season may simply not have sufficient time to develop an adequate root system before soil conditions preclude further growth. It should be mentioned, however, that we have successfully planted seedlings of the 4-month-old stock type described in **Seedling Production in Containers** (see chapter 3) in March and even April. But, in all instances, the seedlings have been thoroughly watered at time of planting to ensure sufficient soil moisture for initial root growth.

How to Plant Seedlings

There are standard procedures for planting conifer seedlings (Schubert, Adams, and Richey 1975), and these apply to oaks as well. First, the seedlings should be maintained properly prior to planting, so that they are not injured. Seedling roots are particularly vulnerable and should not be allowed to dry out, heat up, or freeze, and care should be taken to make sure seedlings are not physically damaged by rough handling. It is also important to plant seedlings at the proper depth so that the ground line at planting is roughly similar to the seedling's ground line when it was growing in its container or bareroot nursery bed (fig. 9). The planting hole should be deep enough so that the roots do not turn up ("J-rooting") at the bottom of the hole. Finally, the soil should be suitably moist, not frozen, and any air pockets in the ground adjacent to the roots should be eliminated by gently compacting the soil, or irrigating thoroughly around the seedling immediately after planting.

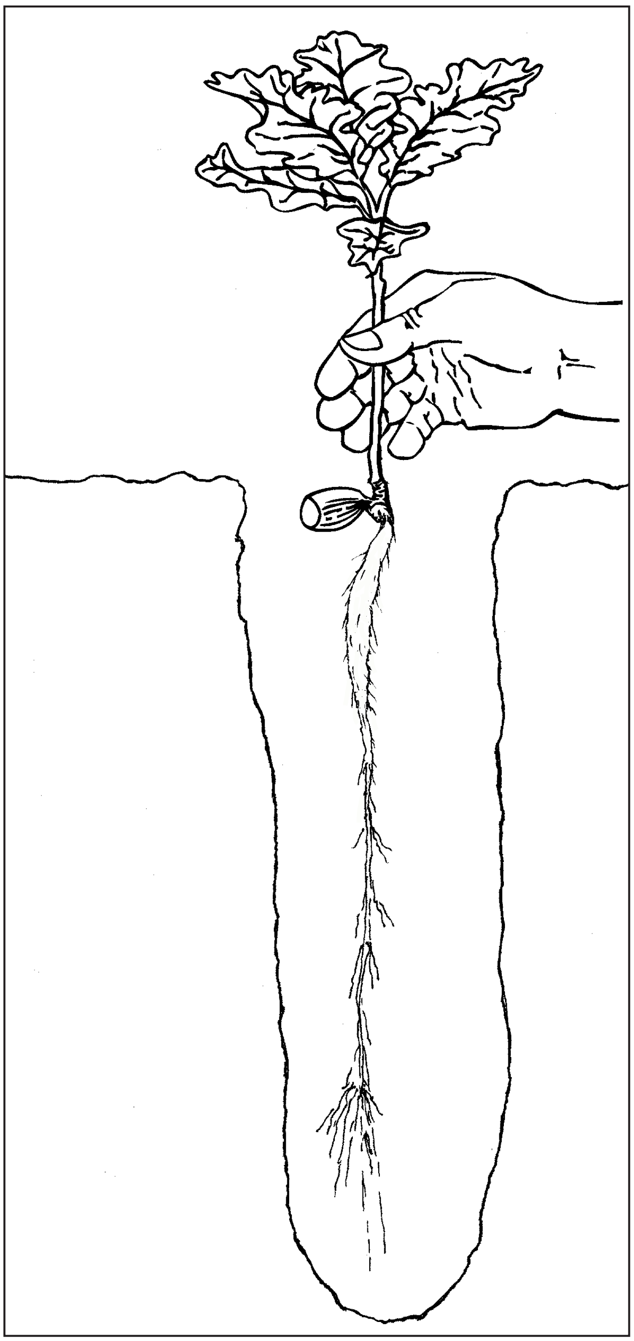

Figure 9. It is important to maintain the same ground line when outplanting oak seedlings.

There are a variety of tools that can be used to make holes prior to planting, including shovels, power augers, tiling spades, hoedads, and clamshell-type post-hole diggers. We have used the latter extensively at the University of California Sierra Foothill Research and Extension Center and have found that holes can be excavated fairly rapidly, as long as the soil is sufficiently moist and the ground is not too rocky or compacted. An additional benefit of post-hole diggers, compared with tools that create a slit in the ground, is that the holes created allow the root to initially have much more of a three dimensional configuration, which can be especially important when planting container seedlings that have a plug of soil and roots. Digging a hole with a post-hole digger also facilitates placement of fertilizer at the appropriate depth.

Auger Planting

Many of the hardwood rangelands in California have been grazed continuously for the past two centuries, compacting the soil in many locations. There are also areas underlaid with natural hard pack. Hard, compacted sites can make it difficult for oak roots, especially those of shallow-planted acorns, to penetrate downward. Augering planting spots (fig. 10) can greatly reduce the bulk density of the soil and make it much easier for the oak roots to grow downward. At SFREC, we evaluated three depths of augering (1, 2, and 3 ft [30, 60, and 90 cm]) and found that, compared to unaugered controls, all three depths improved the growth of surviving blue oak seedlings planted from acorns (McCreary 1995). However, we also found that the 3-foot augering had a negative side effect. In spite of efforts to compact the soil that we placed back in the holes for these deep-augered holes, the holes tended to subside several inches after the first heavy rains. In several instances, this caused acorns to become exposed, resulting in higher acorn depredation, probably from mice. As a consequence, overall mortality for this treatment was higher.

Figure 10. Tractor-mounted augers can be used to break through compacted soil.

We could also detect little difference between the three augering depths tested. We attributed this to the fact that most of the compaction was in the upper foot of the soil, and as long as this area was broken up, the oak roots had little trouble growing deeper. We therefore recommend either augering compacted soils prior to planting or excavating holes with a shovel or post-hole digger, but only to the depth required to penetrate the bottom of the compacted layer. It is important to auger well in advance of planting either acorns or seedlings so that the soil can settle thoroughly with natural rainfall. Finally, in wet, heavy soils, augering can result in a slick, smooth surface on the inside of the hole created. This can make it difficult for the oak roots to penetrate, and even slow water percolation so that the holes act like a pot. If holes become glazed from augering, use a shovel or tiling spade to rough up the sides of the hole before planting.

Selecting Microsites for Planting

Many areas targeted for oak regeneration contain a range of possible planting locations, or microsites, for individual seedlings. Even over short geographical distances, conditions at these planting sites can vary greatly. Some may be adjacent to rocks, logs, or stumps that provide natural protection and reduce direct solar radiation. Others may be close to gullies, swales, or even springs where soil moisture is greater. Still others may be far from obvious animal populations, as evidenced by gopher mounds or ground squirrel tunnels that can pose a threat to seedlings planted nearby. Finally, there is some evidence that certain shrubs may act as nurse plants for blue and valley oaks and promote establishment of seedlings planted near them (Callaway 1992). Because resources for plant restoration projects are generally limited, and it is too expensive to plant everywhere, it makes sense to choose microsites where seedlings will have the best chance to survive and grow. These may be difficult to determine, but insight can often be gained by looking at nearby areas where oaks are present and observing patterns where trees have become established naturally. In oak woodlands, south-facing, exposed ridges are generally less likely to have oaks than are north-facing slopes or drainages because soil conditions are much drier on southern aspects. And in grazed areas, oaks that have survived can often be found in locations that present some natural barrier to livestock and deer, such as rock outcrops. Mimicking such patterns in artificial regeneration efforts and choosing sites that afford some natural protection or better environmental conditions can often enhance success rates.

Planting Patterns

The number of acorns or seedlings to plant in a given area depends on how many oak trees are desired to grow there, as well as on attrition. Unfortunately, it is difficult to predict how many trees will be produced from plantings because a host of factors, including weather, animals, and competing vegetation, can influence survival. But following the steps described below on weed and animal control will help minimize mortality. Using these methods, it is not unreasonable to expect 70 to 80 percent, or higher, survival in many locales after the first 2 years.

The growth rates of seedlings also vary depending on species, site, and intensity of management. To predict the canopy cover after a given number of years, all of these factors need to be considered. A model of blue oak growth based upon the initial 10-year growth of a planting in 1987 (McCreary 1991) and stand structure models for this species developed by Standiford (1997) found that, under a high level of management (weed control for 3 years, protection from animals, fertilization), the canopy cover after 30 years would be 29 percent with 400 seedlings planted per acre (988/ha). With less intensive management (1 year of weed control, no protection), canopy cover over the same interval would be expected to be approximately 13 percent.

When planting, consider spacing seedlings or acorns in a naturalistic manner rather than in straight rows, using surrounding stands of oaks as a model. Also consider planting in small clumps or clusters, with some open areas between the clumps. Planting trees in clusters rather than with relatively uniform spacing can break up the landscape and provide more horizontal diversity of vegetation, which may benefit a wider range of wildlife.

Recommended Procedures for Planting Rangeland Oaks

- Plant oak seedlings early in the growing season, soon after the first fall rains have saturated the soil; do not plant after early March unless irrigation is planned.
- Make sure seedlings are not frozen, allowed to dry out, or physically damaged before, during, or after planting.
- Plant seedlings at proper depth, making sure they are not J-rooted, and eliminate air pockets in soil adjacent to seedling roots.
- In hard, compacted soils, break up soil (using a shovel, auger, or post-hole digger) through the compacted zone prior to planting to promote deeper rooting. If planting holes are augered, make sure the sides of the holes are not glazed.
- Select microsites for planting that afford some natural protection and provide the most favorable growing conditions.
- Plant in a natural pattern, avoiding straight, evenly spaced rows.

Weed Competition

How Weeds Impact Oak Seedlings

Competition for Soil Moisture. The primary effect of competing vegetation on both planted and natural oak seedlings is a reduction in soil moisture available for uptake. In the Mediterranean climate of California, where there is often little precipitation from April to October, a lack of moisture in the soil can limit growth and affect survival. Because all plants growing in an area compete for the same limited amount of water, more competition means less moisture available for oak seedlings (fig. 11). Eliminating this competition by the methods described in this section means greater access to moisture and a greater chance for growth and survival for oak seedlings.

Drought Resistance. Oak seedlings in California have evolved a number of mechanisms to deal with limited moisture in the dry part of the year (Rundel 1980). Germinating acorns tend to produce large and deep root systems before they start to grow a shoot. As mentioned above, this growth pattern allows oak seedlings to reach deeper soil where more moisture is available longer. In a 1986 report, Matsuda and McBride found that during the first growing season, 73 percent of the dry weight of blue oak was allocated to belowground material. They also found that California oaks showed much greater root elongation and smaller leaf area to root weight ratios than Japanese oak species. Their conclusion was that the extensive root systems and small leaf areas of California oaks help seedlings survive under dry conditions (1989b). Momen et al. (1994) evaluated the water relations of planted and natural blue oak seedlings and concluded that they also "resist drought by osmotic adjustment, particularly when seedling water stress progresses slowly because of lack of severe, belowground competition from grasses." Under extremely

Figure 11. Natural, or volunteer, oak seedlings often face severe competition from dense annual plants.

Figure 12. Oak seedlings typically grow a deep taproot with relatively little lateral root branching.

harsh conditions, oak seedlings can also grow very slowly. Phillips et al. (1997) found that more than 10 percent of blue oak seedlings less than 1 foot (31 cm) tall in portions of the southern Sierra Nevada Foothills were more than 25 years old, even though there was no evidence of browsing.

Taproots. Most oaks initially produce a primary taproot and relatively little side branching (fig. 12). But do nursery production systems that prune this initial taproot, and, therefore, prevent normal root development, predispose seedlings to slow growth or even death after outplanting? We have tried to answer this question by observing roots of both planted and natural, or "volunteer," oak seedlings, as well by monitoring the root growth of acorns planted in root observation boxes. Our experience suggests that the initial taproot configuration may not last long in nature and is probably not critical for regeneration success. Roots growing downward in soil may encounter rocks or other impenetrable objects. Soil microorganisms can also attack the root tips. The result is the development of several taproots at the point of injury or obstruction. These multiple roots continue growing downward and appear to function similarly to single taproots. In one study, we planted pregerminated, blue oak acorns that had intact radicles (and were, therefore, presumably predisposed to a single taproot configuration) alongside acorns that had radicles severed at approximately ½ inch (1 cm) to promote the development of multiple taproots. While this treatment clearly affected root morphology, we could detect no subsequent effect on field growth or survival (McCreary 1996). Koukoura and Menke (1994) found that pinching the roots of blue oak seedlings resulted in faster root growth but did not affect total root length and dry mass.

Competition for Nutrients and Light. In addition to vying for a limited amount of soil moisture, forbs and grasses also compete with oak seedlings for nutrients and light. Although these factors are generally not as important as moisture competition, in certain instances, such competition can severely impact oak seedlings.

Recommended Weed Control Procedures

- Select method of weed control (herbicides, physical weed removal, or mulching) based on environmental, fiscal, and philosophical considerations.
- Maintain a weed-free circle that is 4 feet (1.2 m) in diameter around individual seedlings or acorns for at least 2 to 3 years after planting; if using herbicides to control weeds, remove weeds in circle with a diameter of 6 feet (1.8 m).
- Initiate annual weed control by early spring to ensure that weeds do not become established and deplete soil moisture before oak roots can penetrate downward.
- Visit planting sites at least twice annually to remove both early- and late-season weeds and weeds that may have grown through mulch.
- If using postemergent herbicides, make sure that chemicals do not come in contact with foliage or the expanding buds of seedlings.
- After weed control is discontinued, visit plantings regularly to make sure vole populations and damage to seedlings have not increased. If increases are observed, remove thatch.

For example, regardless of moisture availability, small oak seedlings growing in dense competition with forbs and grasses may simply not receive sufficient light for growth.

Secondary Effects of Weeds

In addition to their primary competitive impacts, the undesirable dense growth of annual grasses and other exotics we call *weeds* can also have significant effects on oak seedlings by providing a favorable habitat for animals that can damage them. For instance, large amounts of dead annual grasses, or thatch, can provide an ideal habitat for voles or meadow mice *(Microtus californicus)*. The fecundity of these animals is high, and populations can increase dramatically when weeds are neither grazed nor artificially controlled. The result can be serious damage to oak seedlings. At the University of California Sierra Foothill Research and Extension Center, we have observed oak saplings that are 8 feet (2.4 m) tall and girdled half way up the stem when weed control was discontinued and thatch levels rose, providing ideal vole habitat (see **Length of Time for Weed Control**, below). Removing weeds even in relatively small areas around seedlings can greatly reduce vole damage (Davies and Pepper 1989; Tecklin and McCreary 1993).

Grasshopper herbivory is also affected by the amount of herbaceous vegetation in proximity to seedlings. We have successfully reduced grasshopper damage to blue and valley oaks by spraying herbicides and mowing grassy areas inside planting zones, thus reducing late-season green weeds that are attractive for grasshoppers. This usually requires treatment of the entire planting area (as well as a perimeter), rather than treating small areas around individual seedlings since grasshoppers can readily fly short distances from treated to untreated areas.

Weed Control

As indicated above, controlling weeds around planted acorns or seedlings is essential because direct weed competition and the habitat created by weeds can make it very difficult for oak seedlings to survive and grow. Studies have repeatedly shown that weed control can greatly enhance the field performance of blue and valley oaks (Adams et al. 1992; Adams, Sands, and McHenry 1997; McCreary and Tecklin 1997). There are a variety of methods that can be used to eradicate weeds. The actual procedure or technique chosen may depend on many variables, including equipment or materials available, oak species planted (deciduous or evergreen), and even a grower's philosophical orientation. For instance, some people prefer not to use herbicides of any sort because of concerns about health and environmental contamination. Whichever methods are chosen, weed control greatly improves the chances for the success of oak plantings.

Herbicides. These are generally the cheapest, easiest, and most effective method of eliminating weeds. While herbicides are routinely used in California around oak seedlings, there have been no large-scale trials to determine which chemicals are most effective for which weed species and soil types and which cause the least injury to nontarget plants. The most common chemical currently used is probably glyphosate. This is a broad-spectrum, postemergent herbicide that kills grasses and forbs. It is considered to be safer than many herbicides and carries a “caution” rating on the label, meaning that it is an unrestricted chemical. It breaks down rapidly and has no residual activity in the soil. It should not be sprayed on the foliage of oak leaves, however, especially the new growth and initial shoots emerging from planted acorns, because glyphosate might seriously damage or kill seedlings.

We have sprayed glyphosate directly over the tops of deciduous oaks in the winter when they have no leaves, but, even in this situation, a small percentage of seedlings demonstrated signs of herbicide injury. Seedlings appear to be more vulnerable to this type of damage when buds are swelling in the early spring. Even when seedlings are dormant, it is safest to avoid chemical contact with twigs or buds. For very small seedlings, individual plants can be covered with anything from paper cups to 1-gallon or larger containers. Alternatively, spray can be applied directionally away from plants, but it is important that the air be still so there is little chance of drift onto the seedlings. It is also possible to protect small- to medium-sized seedlings by placing a section of stovepipe over them (fig. 13) while spraying, being careful not to allow any drift to enter the open top. Pieces of cardboard or a similar shield can also be used to protect one side of a plant, rotating the cardboard around to the opposite side when spraying weeds on that side, as long as the side that has had contact with the herbicide does not touch the seedlings.

Spraying glyphosate early in the spring is advantageous from a soil moisture point of view because killing competing plants when they are small and have not yet seriously depleted soil moisture means that there will be more water available for the oak seedlings. However, one problem with foliage-active (as opposed to soil-active or pre-emergent) herbicides, such as glyphosate, is that they only affect the plants that are present when the chemical is applied. On California rangelands, there are many annual plants, mainly from the family Asteraceae, such as yellow starthistle *(Centaurea solstitialis),* that usually germinate quite late in the season and are not present during early-season applications. As a result, there can be a whole new contingent of plants competing with oak seedlings by late spring. If left untreated, these plants can create serious competition problems. We, therefore, recommend an additional weed treatment in May to eliminate these late-germinating plants.

Physical Weed Removal. Several years ago, we initiated an experiment to compare various sizes of weed-free areas around young blue oak seedlings (McCreary and Tecklin 1997). Weed removal was provided by using a hoe to scrape the surface vegetation, leaving only bare soil (fig. 14). This treatment was applied in early spring and not only removed weeds that were currently growing, but greatly reduced the seed bank in the upper inch or so of soil. This essentially eliminated competition in the early part of the growing season. Unfortunately, later in the spring, numerous weeds returned and a repeat scalping was necessary to keep the areas bare. All scalping treatments resulted in significantly better field performance than the control, and the larger the weed-free circles, the greater the subsequent seedling growth. However, it was extremely difficult and time consuming to scalp a 6-foot (1.8-m) diameter circle around each seedling. Scalping also becomes even more difficult in rocky or dry soil. Therefore, we can only recommend scalping when it is done on a small scale.

Figure 13. A stovepipe can be placed over oak seedlings to protect them while spraying weeds with postemergent herbicides.

We have also eliminated weeds around oaks late in the season using lawn mowers and weed-eaters. These treatments are not generally recommended because they only remove the top of the plants without killing them. If done early in the growing season, the plants will grow back rapidly and this treatment has little effect. It may even cause an increase in soil moisture loss as vigorous new growth following mowing, especially of grasses, can increase water use (Williamson 1992). However, if mowing is done in early or mid summer when most annuals have stopped growing and have turned brown, it can improve access and remove some of the habitat favorable to damaging animals, such as voles. In these conditions, the plants are not competing seriously with oak seedlings (except, perhaps, for light), but they are still providing habitat. Cutting weeds back may, therefore, reduce the potential for future animal damage. Cultivation is another technique for eliminating weeds but generally requires large equipment and multiple applications.

Figure 14. A hoe was used to remove ground vegetation from around this planted seedling, resulting in better field performance.

Figure 15. Organic mulches, such as bark chips, can effectively suppress weeds and reduce surface evaporation.

Mulches. There are a variety of organic and inorganic materials that can be used as mulches around young oaks. All of these materials tend to suppress weeds by physically covering them, thereby eliminating the light necessary for photosynthesis and growth. Organic materials include straw, wood chips, and compost (fig. 15). Plastic products are also commonly used, including those that are opaque but porous, allowing moisture to pass through but keeping light out. Mulches also conserve soil moisture by reducing evaporation from the soil surface, resulting in more moisture for the oak seedlings. Organic mulches can, over the long term, improve soil structure. As mulching materials break down and are incorporated into the soil, they tend to reduce soil bulk density, increase percolation, and improve the nutritional status of the soil.

It may be difficult to effectively suppress dense weeds that are already on-site using mulch alone unless the weeds are dealt with first. In these instances, it is often necessary to physically remove weeds before mulching, or to spray herbicides before putting the mulch in place, which reduces the likelihood that weeds will subsequently grow up through the mulch.

A study evaluating a variety of mulches, including black plastic, paper, and hay, on four oak species in the southern United States found that all of these materials positively affected growth for all species studied (Adams 1997). Adams, Sands, and McHenry (1997) compared impervious and porous plastic mulches on outplanted blue oak seedlings at the University of California's Hopland and Sierra Research and Extension Centers and found that both types of mulches significantly improved performance. Bernhardt and Swiecki (1991) also evaluated both organic mulch and polypropylene landscape fabric on valley oak plantings and found that both significantly increased growth. Circuit Rider Productions recommends installing a 3-foot-by-3-foot (91-by-91-cm) square of woven polypropylene fabric, secured with 6-inch (15-cm), heavy-gauge wire staples, around plantings to lessen competition for moisture and nutrients (Bush and Thompson 1990).

A problem with all mulches is that they do not last forever. Plastics tend to become brittle and photodegrade, while organic materials gradually decompose. Over time, weeds tend to grow through holes in the plastic or through shallow places in the organic mulch. For maximum benefit, these weeds should be regularly removed. In general, mulches are more expensive than herbicides and often require considerable upkeep and maintenance. As such, they are probably best suited for small plantings that can be managed intensively.

Area of Treatment. We have found that from a practical standpoint, circles with diameters of 4 feet (1.2 m) around individual seedlings are a good compromise between ease of application and effectiveness. While we found that even larger circles (6 ft [1.8 m]) promoted slightly greater growth (McCreary and Tecklin 1997), larger weed-free areas are considerably more difficult and expensive to provide (except with herbicides) and do not appear to be worth the extra effort and expense.

Length of Time for Weed Control. Determining when seedlings are fully established and need no further protection or maintenance involves site-specific judgments. It is, therefore, difficult to make generalizations about how long areas around oak plantings should be kept weed-free. This depends on the severity of the competition, the environmental conditions at the site, the growth rate of the seedlings, and the potential for animal damage once the weed control ceases. While we generally recommend a minimum of 2 to 3 years of weed control after planting, in some cases this may not be long enough. Although this interval may be adequate from a soil-moisture standpoint, it may not be adequate from an animal-damage standpoint unless other steps are taken to protect oak seedlings from animal damage (see **Treeshelters**, below).

Animal Damage and Control

Those involved in oak restoration projects know that there are many animals that eat or otherwise damage acorns and small oak seedlings. Damage from animals is not limited to artificially generated seedlings. An examination of natural seedlings often reveals shoot browsing, bark stripping, defoliation, and root clipping. Sometimes it seems remarkable that any oak seedlings are able to survive given the overabundance of damaging factors they must contend with in order to grow into trees.

Animals That Damage Acorns and Seedlings

Livestock. Both sheep and cattle browse young oak seedlings. In addition, both animals eagerly seek out acorns on the ground. The severity of browsing damage to young oak seedlings is related to the intensity of grazing (fig. 16). In pastures that are used rarely and for relatively short intervals, some oak seedlings may escape damage, especially if there is an abundance of other plants to eat. In intensively grazed pastures,

Figure 16. Cattle often graze in oak woodlands and can inhibit both natural and artificial regeneration.

Figure 17. Oak seedlings can be stunted from the repeated browsing of deer and cattle.

unprotected oak seedlings have little chance of escaping injury. Repeated browsing can keep plants stunted for years, even decades (fig. 17).

In addition to browsing young oaks and eating acorns, large-hoofed animals, such as cattle, can also cause damage to small oaks by trampling them. Hall et al. (1992) found that, in confined pastures, trampling damage from cattle accounted for nearly 15 percent of total damage to blue oak seedlings. This same study also evaluated the extent of damage to planted oak seedlings at different times of the year. Not surprisingly, browsing damage was greatest for deciduous blue oaks in the spring and summer when the plants were fully leafed out and other green vegetation was scarce, and was least in the winter when seedlings were bare. The timing and intensity of grazing can, therefore, influence the extent of damage to unprotected oaks in grazed pastures.

Deer. A common species of deer on hardwood rangelands in California is mule deer *(Odocoileus hemionus Californicus)*. The extent of their herbivory on both natural and planted oak seedlings varies greatly by site. In areas where deer are migratory and only pass through briefly at certain times of the year, damage will likely be minor. While annoying, such damage may be acceptable and not require protection. Such is the case at the University of California Sierra Foothill Research and Extension Center, where oak shoots are occasionally clipped off. However, in areas with resident deer herds, damage can be far greater (fig. 18). At the University of California Hopland Research and Extension Center in Mendocino County, deer browsing from a resident population precludes any successful attempt at artificially regenerating oaks without effective protection from these animals. Even oak stump sprouts there are clipped back to the trunk soon after they emerge.

In certain areas, repeated browsing can create bushlike plants that survive for decades. Griffin (1971) reported that it can take more than 20 years in a favorable habitat for coast live oak seedlings to grow above the reach of deer. At the Hastings Reserve in Carmel, White (1966) reported that only 12 percent of 154 oak seedlings were unbrowsed by deer and concluded that deer may be an important factor limiting seedling establishment (fig.19).

Rodents. Several rodents can seriously hamper oak restoration efforts. In a study evaluating various factors affecting survivorship of blue oak, Davis et al. (1991) stated that rodents were the most important predators of both acorns and seedlings. In blue and valley oak plantings at SFREC, the animals that have been the most troublesome are meadow mice, or voles (Tecklin and McCreary 1993), which thrive there in a dense cover of ground vegetation (fig. 20).

Acorns can also constitute a sizable portion of the diet of western gray *(Scirius griseus)* and California ground squirrels at certain times of the year (McDonald 1990), and these animals can destroy unprotected acorn plantings. Adams et al. (1987) reported that more than 5,000 blue and valley oak acorns were dug up at a planting in Madera County, presumably by ground squirrels. Deer mice (*Peromyscus* spp.) also eat acorns that are exposed or planted very shallow.

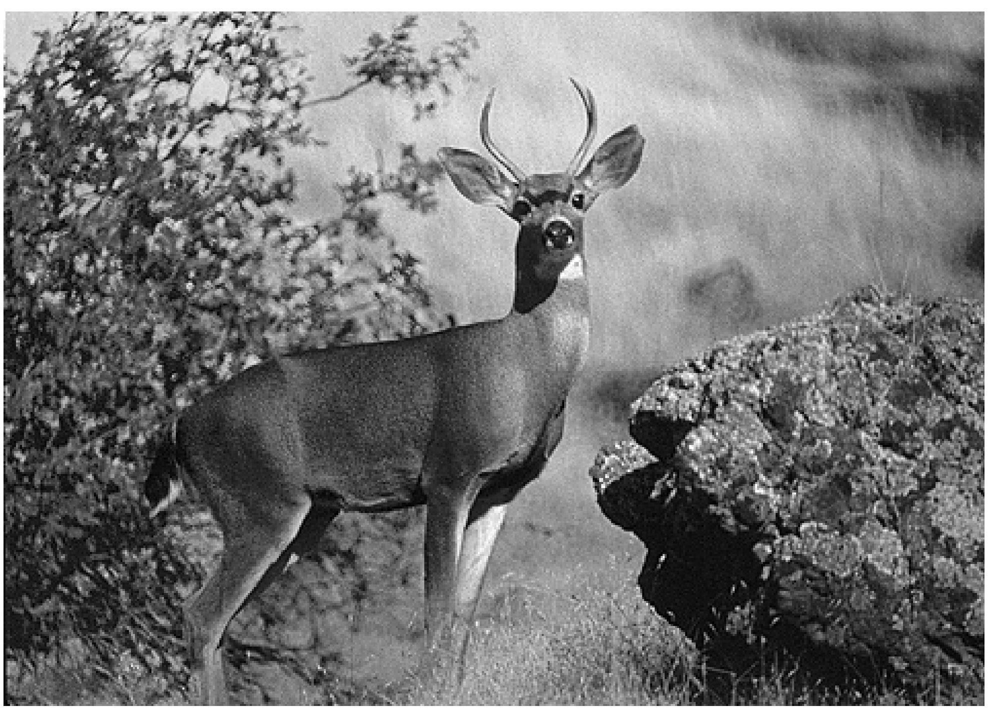

Figure 18. Many deer live among California's oaks, feeding on seedlings and other plants.

Figure 19. This oak was only able to release and elongate a dominant leader when the oak bush became so large that deer could no longer reach in and clip off shoots near the center.

Figure 20. This dense patch of dead grass and forbs, or thatch, is ideal vole habitat.

Pocket gophers *(Thomomys bottae)* constitute a serious pest in many oak plantings because they clip roots below the soil surface. In a study at the Hastings Reserve in Carmel in the early 1970s, Griffin (1971) noted that pocket gophers ate about 250 one-year-old seedlings in a woodland plot. Damage is not limited to newly planted seedlings, as gophers can kill oaks several years old, and also eat acorns (Griffin 1976). Gopher populations vary greatly by area and, in some locations, gophers are not a major concern. Where they are a problem, modifying the habitat can reduce populations and damage. However, this generally means treating entire areas and removing most or all of the surface vegetation. Gophers can also be effectively controlled by baiting with poisoned grain (see **Repellents and Baits,** below).

Insects. The primary insect damaging oak plantings at the University of California Sierra Foothill Research and Extension Center is the grasshopper, and in particular the species *Melanoplus devastator* (McCreary and Tecklin 1994a). As with many pests, populations fluctuate greatly from year to year, as well as over relatively short geographical distances. Even within the SFREC, we have observed large differences in the number of grasshoppers present within just a few hundred yards. Most commonly, populations seem to peak in late July and August. The cycle begins as eggs laid the previous fall hatch in the spring. Heavy rainfall years tend to promote the development and survival of large numbers because grasshoppers thrive in the abundant grass present in uncultivated areas. During years when populations are high, a single oak seedling can be covered with dozens of grasshoppers (fig. 21). During such outbreaks, almost all of the foliage on every unprotected seedling can be consumed. After the foliage is gone, the bark on seedlings is often stripped, and, in some cases, the seedling is completely girdled, killing the top. There are several other foliage-eating insects that also occasionally damage seedlings, but the injury is generally localized and not extensive.

The most common insect pests of California oak acorns are the filbert worm *(Melissopus latiferreanus)*

Figure 21. Grasshopper populations can explode during favorable conditions, and large numbers feed directly on oak seedlings.

and filbert weevils (*Curculio* spp.). The adults of the filbert worm lay their eggs on the surface of immature acorns, and, when the larvae hatch, they bore into the acorns. Adult filbert weevils penetrate the acorn skin or pericarp with their ovipositor and lay their eggs inside the acorns. As the larvae of both species grow, they feed on the cotyledons. Generally, the eggs are laid near the acorn cap and away from the pointed end of the acorn where the embryo is located. The larvae often emerge from the acorns during storage and accumulate in the bottom of bags or containers. Where there are multiple larvae in a single acorn, damage can be extensive. Griffin (1980) reported that over an 8-year period 21 percent of the valley acorns that dropped into collection traps were clearly nonviable due to insect damage, mainly from filbert weevils. However, even when much of the cotyledon is consumed, as long as the embryo is intact, the acorn can still germinate although there is less stored food available for initial root growth. The mature larvae usually chew their way through the shell of the acorn after the acorns drop to the ground in the fall (Brown and Eads 1965). In addition to the direct damage that larvae cause, their entrance and exit holes can also provide a site of entry for other pathogens that affect acorns (Swiecki, Bernhardt, and Arnold 1991).

A comprehensive listing of diseases and arthropods that affect native California oaks is contained in a host index database called CODA that was developed by Swiecki, Bernhardt, and Arnold (1997). CODA contains information on 45 native and cultivated oak species in California, 1,259 agents that affect these oaks, and 320 references that describe these interactions. It also contains information on 2,619 individual interactions between oaks and biotic or abiotic agents. It can be downloaded for free at http://www.phytosphere.com.

Protecting Rangeland Oaks from Animals

Without protection from animals, oak plantings often stand little chance of survival. However, the type of protection necessary depends on the type of damaging animals present. In some situations, large herbivores may be the primary species of concern, while in others, small insects may be the only threat. Below are descriptions of several general categories of animal protectors that have been used and some discussion about which animal pests they are most effective against.

Fences and Large Cages. It is estimated that over 80 percent of the hardwood rangelands in the state are privately owned (Bolsinger 1988). The primary economic use on many of these lands is livestock grazing. Because both cattle and sheep browse young oaks, it is often necessary to protect plants from them. Fences are obviously used to control livestock access to certain areas and can be built around oak plantings to keep animals out. But fences are not only costly to install and maintain, but if they exclude livestock from large areas, then these areas are removed from livestock production. If deer are a problem, higher and more costly fences are needed. Fences alone have not proven to be effective in promoting natural oak regeneration or in protecting artificial regeneration, except in small research exclosures with thorough weed control. This is because there are usually other animals, such as rodents and insects, that damage young oaks, even if livestock and deer are excluded.

However, in instances where deer and livestock are the only threats, fences may be effective. In these situations, it is important to weigh the costs of installing and maintaining fences against the costs of other types of protection. In England, the costs of fences were compared to the costs of protecting individual seedlings with treeshelters (see **Treeshelters**, below). It was concluded that if 450 trees per acre (1,112/ha) were planted, fences would only be cost-effective if more than 2 acres (0.81 ha) needed to be protected (Vickers 1999). However, this model did not consider the lost revenue from deferred grazing while fences excluded livestock.

Several types of small cages have also been used to keep livestock and deer away from individual oak seedlings or groups of seedlings. The simplest is a square exclosure, approximately 5 feet (1.5 m) per side, with metal fence posts at the corners and field fencing on the perimeter (fig. 22). This will effectively keep out livestock and deer since the protected area is too small to allow deer to jump inside. However, the cost is high, approximately $8 for four new fence posts and more for the field fencing and labor. In time, stock may also push the fencing over in efforts to reach young trees.

Figure 22. These exclosures, built with metal t posts and field fencing, effectively keep out deer and cattle.

Another type of cage using metal posts and field fencing has been described by Bernhardt and Swiecki (1991; 1997) and nicknamed a *vaca* cage (*vaca* is Spanish for *cow*). This is a circular structure approximately 4 feet (1.2 m) tall and 1½ feet (.5 m) in diameter, constructed from galvanized 12-gauge wire fencing with welded 2-by-4-inch (5-by-10-cm) mesh (fig. 23). The cage is secured to the ground with a t post and a 3-foot (.9-m) length of steel reinforcing bar. Materials costs per cage were $8 to $10 in 1997. Vaca cages are effective against deer and cattle although they do require periodic inspection and maintenance. They can be assembled and installed in about 12 minutes.

Screen Cages and the Collar-and-Screen Device. In oak regeneration studies initiated at the University of California Sierra Foothill Research and Extension Center in the late 1980s, seedlings were covered with cages made of aluminum window screen (McCreary 1989). These were constructed by cutting pieces of the screen into squares approximately 18 inches (46 cm) per side. These were then rolled into cylinders, folded closed at the top, and stapled to wooden stakes. The cylinders were placed over seedlings after field planting, and the stake was pounded into the ground (fig. 24).

These screen-cylinder cages cost about $1 each, plus labor, to construct. They were effective in preventing deer browsing, rabbit clipping, and grasshopper damage, but were worthless in pastures grazed by cattle since the ani-

Figure 23. This vaca cage costs approximately $8 to build and consists of a single t post, a 3-foot piece of rebar, and 5 feet of field fencing.

Figure 24. Tubes of aluminum window screen were initially used in oak regeneration trials at the SFREC.

Figure 25. When seedling growth reaches the top of aluminum screen cages, the screen should be opened to allow growth to progress normally.

Animals That Commonly Damage or Kill Rangeland Oak Seedlings and Recommended Seedling Protection

- Livestock, including cattle and sheep, eat oak foliage and consume acorns. In grazed pastures, seedlings must be protected, or they have little chance of growing. Fences can be used to keep livestock out of planting areas, but often other animals still damage plants. Treeshelters (see **Treeshelters**, below) secured to heavy metal posts can protect individual seedlings in moderately grazed areas.
- Deer browse seedlings and consume acorns. Damage is usually greatest when a resident herd is present. Planted areas can be fenced, or individual seedlings can be covered with treeshelters, screen cages, or seedling protection tubes.
- Voles, or meadow mice, strip bark from seedlings and saplings and can girdle and kill oaks. They thrive in dense grass or thatch, and populations can increase explosively. Damage levels can be greatly reduced by keeping the area within 2 feet (.6 m) of oaks free of vegetation.
- Pocket gophers commonly clip roots below the ground and can kill oak seedlings that are several years old. Seedling roots can be protected with hardwire cloth, aluminum window screen, or root guards, but material must degrade or be removed to ensure roots are not damaged as plants grow larger. Damage can be reduced by eliminating ground vegetation. In small areas, gophers can be effectively controlled by baiting.
- Ground squirrels clip seedlings and dig up acorns. High populations are usually evident by extensive mounds, holes, and burrows. Planting near such areas should be avoided.
- Grasshoppers eat foliage, and their damage is usually greatest in midsummer to late summer. Populations can fluctuate greatly from year to year, increasing dramatically during outbreak years. At these times, damage can be reduced by keeping the area where the oaks are planted free of ground vegetation.

mals easily knocked over and trampled them. The screens also presented another problem. As the seedlings grew taller, it was necessary to open them up, again making the tops of the seedlings vulnerable (fig. 25). If opening-up was delayed, the seedling became confined and deformed, a condition they do not soon recover from. In addition, insects and rodents could get underneath the screens if they were not buried or stapled down.

A modification of the screen cylinder method developed at the University of California, Davis, and refined by the Pacific Gas and Electric Company and Circuit Rider Productions (Bush and Thompson 1989) is the collar and screen. This consists, first, of a 1-quart (.95-L), plastic, yogurt or cottage cheese container with the bottom cut out. A square of aluminum screen is then wrapped around the plastic container and secured with wire and folded over at the top. The whole device is then placed over the seedling or direct-sown acorn with the plastic container sunk in the ground. This plastic container is believed to afford some protection against gophers (at least for shallow roots) and, if the plants are watered, creates a small, artificial reservoir. As long as plastic containers are available, this device is probably easier to assemble and less expensive than a screen cage.

Seedling Protection Tubes. Several manufacturers make seedling protection tubes from rigid plastic mesh (fig. 26). They can be purchased in lengths from 18 to 36 inches (.5 to .9 m) and are relatively inexpensive, with the 36-inch (.9-m) tubes costing about 28¢ each. They are usually secured to the ground with lath or bamboo stakes. They are not only reasonably effective in protecting against deer damage but also afford protection against rabbits. However, since the mesh is fairly wide, it is very easy for small animals, such as grasshoppers and even voles, to pass through, especially near the ground. As seedling shoots grow through the sides of the mesh (which is very common), the exposed portion is also vulnerable to browsing. Finally, these devices do not offer much protection in pastures grazed by cattle since they are easily uprooted or knocked over. Solid tubes called treeshelters were developed, in part, to overcome this limitation (see **Treeshelters**, below).

Underground Protection. As mentioned above, gophers and ground squirrels can be very troublesome in certain planting locations. In these situations, either the animals must be eliminated or the oak seedlings protected from them. Physical barriers have been successfully used to keep animals away from oak seedling roots. Plumb and Hannah (1991) reported that ¼-inch (6.5-mm) hardwire cloth buried 12 inches (31 cm) in

Figure 26. This seedling protection tube of rigid plastic mesh guards seedlings from deer and rabbits but not from grasshoppers or cattle.

the ground afforded some protection although they were concerned with the cost ($1 per seed spot) and the fact that these devices could restrict root growth as seedlings became larger. Adams and Weitkamp (1992) found that thin tubes of aluminum screening placed in the ground around seedling roots significantly reduced gopher damage. A metal mesh basket called “root guard” comes in several sizes and is designed to protect plant roots from gophers (see appendix B for source information).

Repellents and Baits. Some animals can be eliminated or controlled with poisons or baits. For gophers, probes can be used to place poisoned grain in underground tunnels. For large areas, however, this may not be practical. Also, baited areas must be regularly checked for evidence that gophers may have returned (distinctive C-shaped mounds will be present), and baiting repeated if necessary. Clearly, it is critical that no nontarget animals have access to the bait and that all pesticide labels be carefully adhered to when using any pesticide products.

The movement of grasshoppers into research plots from adjacent grassy areas can also be reduced using poisoned bait. A thin line of bait containing an insecticide can be placed around the perimeter of the oak planting area. The grasshoppers consume the bait as they move toward the plot and die before they reach the seedlings. This treatment has proven moderately effective at the University of California Sierra Foothill Research and Extension Center.

Habitat Modification. As mentioned earlier, animals require specific habitats to live and reproduce. If the habitat is significantly altered such that it is no longer suitable for their needs, the animals will leave or die. This knowledge of habitat requirements and preferences can be used to reduce or eliminate impacts from certain animals. The most effective way we have found to control voles, for instance, is to eliminate grass and forbs from an area. Even eliminating weeds in 4-foot (1.2-m) diameter circles around individual seedlings seems to provide a sufficient barrier that these animals are generally reluctant to cross, presumably because of predatory threats from hawks, owls, and other animals. Removing grasses and forbs in oak planting areas also helps to reduce grasshopper damage and has been used successfully to control pocket gophers in conifer plantations (Engeman et al. 1995).

Treeshelters

Treeshelters are individual, translucent, plastic protectors that fit over seedlings. Most are made from twin-wall polypropylene although some are made from single, flat sheets that are assembled on-site. Treeshelters were initially developed and tested in England 20 years ago (Tuley 1983; 1985). By 1984, over one million treeshelters were commercially manufactured and sold there. Although the number sold in England today is probably less, in 1991 it was estimated that annual production probably exceeds 10 million (Potter). They

Methods of Protecting Trees from Animals

- Fences and large cages are effective only if livestock and deer are the only animals of concern. Fences require a large initial investment and result in fenced areas being removed from livestock production. Fences and cages must be maintained regularly.
- Screen cylinders provide adequate short-term protection against insects, rodents, and deer but are ineffective against livestock and must be reopened once seedlings grow to the top, exposing plants.
- Seedling protection tubes are an inexpensive way to protect plants against rabbits and deer, but they are not effective against livestock, insects, or small rodents. Shoots that grow through the sides of tubes are vulnerable to browsing.
- Treeshelters have proven very effective in protecting rangeland oak seedlings from a wide range of animals and stimulating rapid, above-ground growth. They are relatively expensive but can greatly reduce the time required for seedlings to grow to sapling stage.
- Habitat modification can reduce damage from grasshoppers and some rodents, but it is ineffective for larger ranging animals, such as deer. Care must be taken to monitor the regrowth of vegetation or animals will quickly reoccupy site.

Recommended Procedures for Treeshelter Installation

- Select the size of treeshelter based on the browsing height of animals that are a threat.
- Install shelters so that they are upright and secure them to stakes using plastic ratchet clips or wire; make sure that seedlings are not damaged when shelters are secured to posts.
- Where treeshelters are used, plant in an aesthetic, “natural” arrangement rather than in regular, evenly spaced rows.
- Utilize stakes that are durable enough to last the length of time treeshelters will be in place and pound them at least 1 foot (31 cm) into the ground before planting seedlings.
- Make sure that the tops of stakes are lower than the tops of shelters to prevent access by rodents that can climb stakes and damage to seedling shoots from rubbing against stakes.
- To prevent seedling desiccation, install shelters with the base buried in the ground.
- To prevent bird access, install plastic netting over the tops of shelters.
- If treeshelters are placed in pastures grazed by livestock, secure the shelters to metal posts using wire and thread flexible wire through the top instead of using plastic netting.

are reported to not only protect seedlings from a variety of animals but also to stimulate above-ground growth. This growth stimulation seems to result from creating a mini-greenhouse inside the shelter, with elevated temperatures, humidity, and carbon dioxide concentrations. The higher relative humidity improves seedling moisture status by reducing transpiration. The treeshelters also help conserve moisture by condensing transpirational water on the tube interior. The condensation then drips back to the soil at the bottom of the shelter. Treeshelters can also make it easier to apply postemergent herbicides without risking contact of the chemical with the seedling’s foliage (Potter 1988). Finally, treeshelters can help identify where seedlings are planted, which facilitates subsequent weed control and irrigation treatments; plants are also less likely to be accidentally mown or run over. As a result of these benefits, survival and growth in treeshelters is thought to be better. A large-scale survey of 193 sites in England that were planted with various tree species over the previous 12 years using treeshelters found that 89 percent of the shelters surveyed contained a living tree (Kerr 1995).

Although treeshelters have not been used for as long or as extensively in the United States, they have been evaluated in several oak field trials in California with promising results (Costello, Peters, and Giusti 1996; McCreary 1996; McCreary and Tecklin 1997; Tecklin, Connor, and McCreary 1997). They are effective in preventing animal damage from deer, rabbits, grasshoppers, and voles. When treeshelters are buried a few inches in the ground, they also seem to provide some protection against pocket gophers, though this has not been thoroughly evaluated. Finally, treeshelters show promise for use in pastures grazed by livestock (McCreary 1997; 1999) as long as they are secured to heavy-metal fence posts (fig. 27). But clearly they are not appropriate for all plantings, and, in many cases, it may be more cost-effective to utilize other protective measures.

Treeshelter Design, Construction, and Installation

There are several manufacturers of treeshelters and two main designs. The first design consists of flat sheets that can easily be shipped and transported. Once on site, they are rolled into cylinders or assembled into square boxes and placed over seedlings. The second major type of treeshelter design is made up of cylinders of extruded tubular plastic that need no assembly. The disadvantage of solid, cylindrical treeshelters is that they are bulky and expensive to ship and transport. Consequently, they are usually more expensive. Most types of treeshelters come in a range of heights.

Staking. Shelters more than 1 foot (31 cm) tall require attachment to a stake, usually with nylon ratchet clips, while some short types can be partially buried and are self-supporting. We have found that the nylon ratchet clips are easily broken when cattle rub against shelters and posts, and, therefore, recommend securing shelters to posts with wire in grazed pastures. It is important that the material securing the shelter to the stake not be wrapped directly around the seedling since this could obviously restrict growth and cause damage as seedlings become larger. After shelter installation, the supporting stakes should be several inches below the lip of the shelter to prevent contact with and damage to the emerging tree (fig. 28).

Stakes or posts can be made of a variety of materials, including wood, metal, and fiberglass. The stakes should be durable enough to last the length of time treeshelters are in place, be resistant to warping, offer frictional resistance to any twisting movement around

Figure 27. Treeshelters have been used effectively in establishing seedlings in areas grazed by cattle.

Figure 28. The supporting stakes on treeshelters should be several inches below the top of the tube itself.

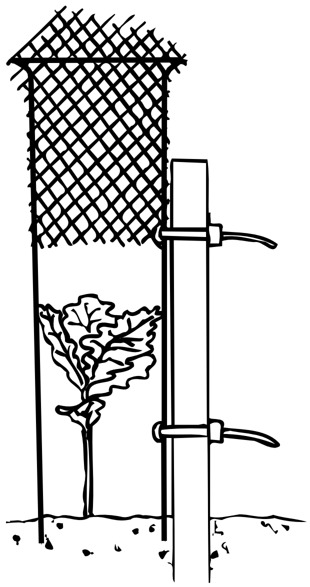

Figure 29. Treeshelters should be installed and maintained in an upright position.

Figure 30. This 13-foot giraffe tube was used to evaluate the effects of very tall treeshelters on oak seedling growth in England.

the stake, and be relatively easy to remove (Kerr 1996). We have found that oak stakes provided by manufacturers generally last 5 years, while 1-by-2-inch (2.5-by-5-cm) untreated, pine stakes can rot away below the ground after 1 or 2 years. We have also used 4-foot (1.2-m) pieces of rebar (steel-reinforcing rods) and standard metal fence posts. Both are durable and last far longer than necessary, but they generally require a post-pulling tool to take them out of the ground when the shelters are removed. It has been suggested that seedling root may grow around the metal flange at the bottom of the fence posts, causing injury to the seedling when the post is removed, but this has not yet been evaluated.

Advantages of Solid-Construction Treeshelters. While solid-construction treeshelters are generally more expensive, they have several advantages over types that require assembly. First, once on site they are relatively easy to place over planting spots. Second, they are inherently more sturdy and, consequently, can more easily be sunk into the ground around the seedlings. This can be important since a gap between the shelter base and the ground can create a "chimney effect," resulting in more desiccating conditions inside the shelter. In the Mediterranean climate of California where moisture stress often limits establishment success, such desiccation can be lethal. Solid shelters are also less likely to be dislodged or damaged by buffeting winds or animals that rub against them. Finally, solid-design treeshelters generally require less maintenance after they are installed, less frequent return visits to make sure they remain attached to the stake, do not have weeds growing inside them, and function properly. For woodland plantings in England, Vickers (1999) estimated that the average cost of maintaining solid-construction treeshelters to original specifications for a planting density of 450 per acre (1,112/ha) would vary between $50 and $150 per acre ($124 and $372/ha).

Colors. In addition to different shapes and sizes, treeshelters also come in several colors, including beige, orange, white, and clear. Beige shelters, which are designed to blend in with surrounding vegetation, are reported to reduce light intensity by approximately 50 percent, while white shelters reduce it by approximately 30 percent (Kjelgren, Montague, and Rupp 1997). In low light situations, such as plantings under canopies, white or clear shelters may, therefore, be preferable. From an aesthetic point of view, white shelters can be unsightly, especially if seedlings are planted in evenly spaced rows, which can give the planting area the appearance of a cemetery. In general, it is recommended that beige shelters be used in open-area plantings, with seedlings planted in irregular patterns, rather than in a systematic grid. Care should be taken to install and maintain shelters in an upright position and to check them and remove weeds that may be growing inside (fig. 29).

Heights. Treeshelters come in a variety of heights, ranging from 8 inches to 6 feet (20.5 cm to 1.8 m). Some trials in England have even used treeshelters that are 13 feet (4 m) tall (Windell 1993) (fig. 30). Not surprisingly, taller shelters are more expensive. Therefore, it is generally advisable to use shelters that are only as tall as necessary to protect against animals that are a threat. For example, if voles are the only concern, shelters that are 1 foot (31 cm) in height should be adequate. For rabbits, shelters that are 2 feet (.6 m) tall can be used. We have found that for deer and cattle at the University of California Sierra Foothill Research and Extension Center, 4-foot (1.2-m) shelters are tall enough. However, both deer and cattle can clearly reach up and nip seedlings emerging from the tops of 4-foot (1.2-m) shelters, so if browsing pressures are intense (resident deer or confined livestock), it may be necessary to use shelters that are 5 or even 6 feet (1.5 or 1.8 m) tall. It is also important to keep in mind that the effective height of a treeshelter is reduced when used on steep or uneven terrain since browsing animals can stand upslope and more easily reach seedlings. While treeshelters are relatively expensive compared to some other seedling protectors, the cost in the United States has dropped considerably in the last several years. Currently a 4-foot (1.2-m), solid-construction treeshelter, without the stake, costs approximately $3.

In 1995, a treeshelter conference in Pennsylvania surveyed the current state of knowledge on treeshelters used in reforestation and ecological restoration. The proceedings were published by the U. S. Forest Service (Brissette 1996) and are a good reference. Other references include a comprehensive booklet describing the use of treeshelters in Great Britain (Potter 1991) and a general description of the use of treeshelters in the United States and elsewhere (Windell 1992). A large U. S. Forest Service research project has also compared the effectiveness of various treeshelter designs and commercial products (Windell and Haywood 1996).

Trapped Birds. A potential problem associated with treeshelters is that birds can become trapped inside. Western blue birds *(Sialia mexicana)* have been identified as one species prone to this. To reduce the possibility of this happening, some manufacturers provide plastic netting to place over the tops of shelters, creating a physical barrier (albeit fairly flimsy) to entry. Advertisements also state that these nettings prevent the entry of butterflies that can also become trapped. We recommend using these net protectors and have observed them to work reasonably well, as long as they remain in place and are not blown off.

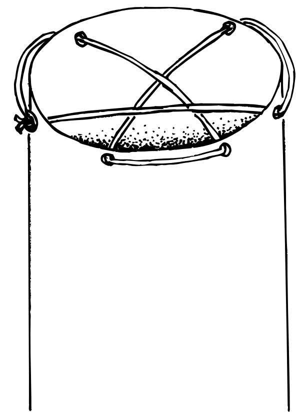

Figure 31. Flexible wire threaded through the top of a treeshelter can be substituted for netting to prevent bird entry when cattle are present.

However, where livestock are present, netting is generally not effective. Cattle invariably take the netting in their mouths, chew it up and spit it out. Where cattle are present, we recommend replacing netting with flexible wire threaded through the top of the treeshelter as described by Tecklin (1993) (fig. 31). The wire should be removed as the tree grows up and out of the shelter.

Oak Seedling Growth in Treeshelters

In addition to providing effective protection against a wide range of animals, treeshelters have also increased the growth of blue and valley oak seedlings in trials at the University of California Sierra Foothill Research and Extension Center and elsewhere (McCreary 1997; McCreary and Tecklin 1993a, 1993c; McCreary and Tecklin 1996). On average, height growth in the first 2 years tripled compared with growth of unsheltered seedlings in plots where animal damage was not a consideration (fenced and weeded). Costello, Peters, and Giusti (1996) also reported better growth for blue oak, valley oak, and coast live oak protected with treeshelters, but these differences were greatest in irrigated, rather than unirrigated plots. In two separate trials (Burger, Forister, and Kiehl 1996; Burger, Forister, and Gross 1997), it was reported that valley and coast live oak seedlings in

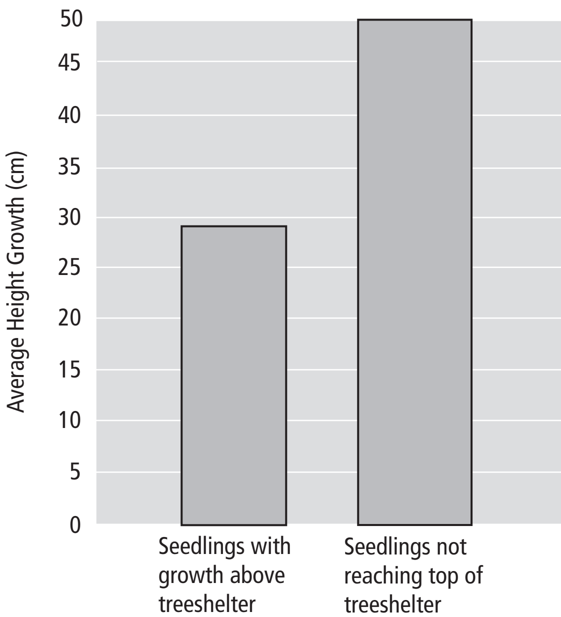

Figure 32. Annual height growth changes once a seedling grows above the top of the treeshelter.

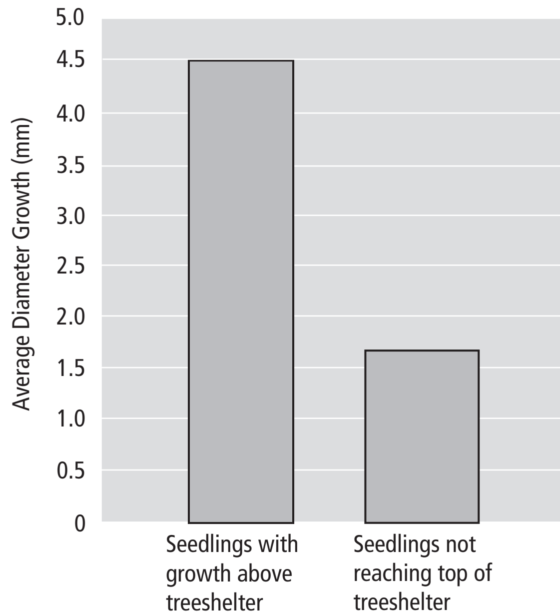

Figure 33. Annual diameter growth changes once the seedling grows above the top of the treeshelter.

treeshelters were taller compared to unsheltered seedlings during the first year of growth. After 2 years, however, they were not significantly taller.

Diameter Growth. Treeshelters do not seem to lead to an increase in the diameter growth of seedlings. In trials at the SFREC, most blue oak seedlings in treeshelters grew taller but had diameters similar to controls, resulting in seedlings inside shelters that were tall and thin. To evaluate this further, we established a trial to examine different shelter heights (2, 4, and 6 feet [.6, 1.2, and 1.8 m]). We measured the annual height and diameter growth while seedlings were still inside shelters, as well as after they had grown up and out of the tops (McCreary and Tecklin 2001). Height growth was consistently greater while seedlings were shorter than the shelters, regardless of shelter size (fig. 32). As soon as seedlings grew above the tops of the shelters, however, height growth diminished and diameter growth increased (fig. 33). As a consequence, when seedlings were below the tops of the tubes, they were tall and spindly. If the shelters had been removed at this point, the plants would almost certainly have toppled over without staking. After several years of growth above shelters, their girth increased greatly (while height growth slowed markedly), and they were larger, more robust plants than their unsheltered counterparts.

Costello, Peters, and Giusti (1996) found that when shelters were removed from three species of California oaks after 4 years, most saplings had sufficiently well-developed trunks to maintain an upright position (fig. 34). We recommend that shelters not be removed for at least 3 years after the seedlings have emerged from the tops. Treeshelters can be left in place longer, but should be removed before they restrict diameter growth (see **Treeshelter Durability and Maintenance**, below).

Burger, Forister, and Kiehl (1996), working with 10 species of landscape trees, including valley oak and coast live oak, recommended removing treeshelters as soon as young plants emerge from the tops and then staking them. They found that the benefits of shelters, in terms of accelerated growth, decreased with time. This research, however, focused on ornamental trees where greater costs of establishment—including staking—may be more easily justified. In almost all wildland planting situations, protecting oak seedlings from animals for at least 3 to 5 years is critical for success, and shelter removal before that time could result in unacceptable damage.

Effects on Roots. There is an additional concern that even though the use of treeshelters increases growth, this aboveground growth may be at the expense of the roots, resulting in plants that have a poor root to shoot

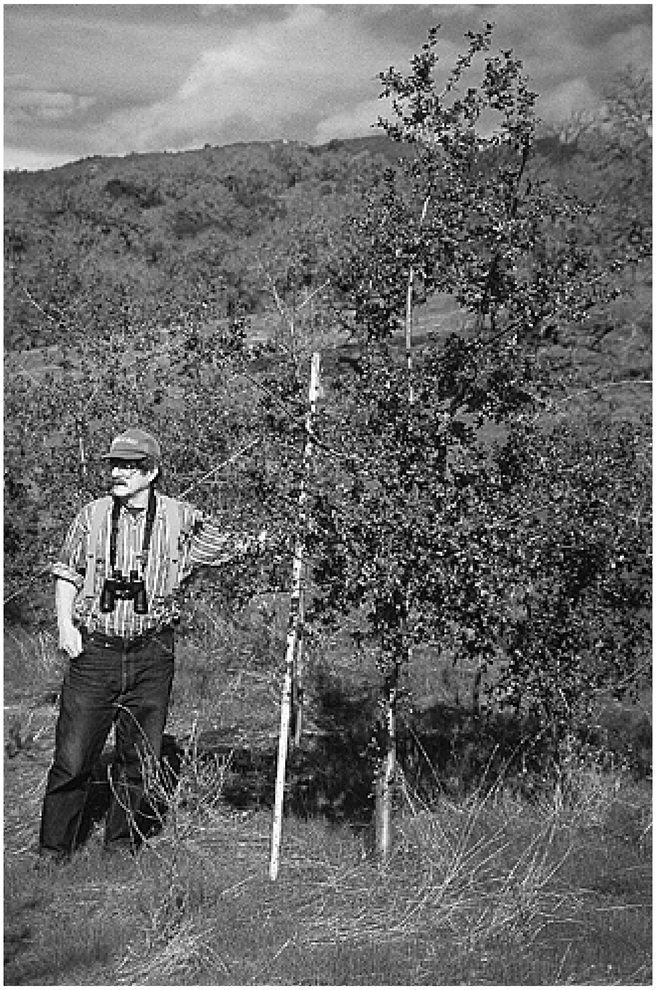

Figure 34. These seedlings were in treeshelters for 4 years. They continue to stand upright after the treeshelters are removed.

ratio. Rendle (1985) reported that treeshelters altered the distribution of dry matter in English oak, causing seedlings to have larger shoot to root ratios. Burger, Svihra, and Harris (1992) also found that oaks grown in containers had growth ratios for aboveground and belowground growth that were out of balance. Burger, Forister, and Gross (1997) further reported that after 2 years in a nursery setting, treeshelters reduced root dry mass, root to shoot ratios, total root length, and total root mass for valley oak, as well as the aboveground biomass for valley oak and coast live oak. However, these studies were of short duration, and these ratios may again change as plants grow older. Ponder (1996), for instance, found that sheltered, northern red oak seedlings, harvested 3 years after outplanting in forest openings, had both higher stem and root weights than seedlings not protected with shelters.

Treeshelters have also been effectively used to "retrofit" both natural and planted oak seedlings that are stunted (Gillespie, Rathfon, and Meyers 1996; Tecklin, Connor, and McCreary 1997; Shuler and Miller 1996). This has resulted in greatly accelerated growth. In the Tecklin trial at the SFREC, unprotected blue oak seedlings that had languished in an experiment for 2 years and averaged only 6 inches (15 cm) in height, suddenly grew vigorously when treeshelters were placed over them. After being protected for 2 years, they averaged more than 3 feet (.9 m) in height, while unprotected seedlings continued to grow slowly and averaged less than 1 foot (31 cm) tall.

Treeshelters with California Black Oak. We have also used treeshelters with California black oak, but with very different results. In a trial with this species, treeshelters did not promote accelerated height growth, and seedlings in all treatments, including uncovered controls and seedlings covered with seedling protection tubes, remained quite small, even after 3 years. Friske (1997) used treeshelters with California black oak in Yosemite National Park and, after 6 years, found that while seedlings in treeshelters were significantly taller than those in open plastic mesh, they averaged less than 2 feet (.6 m) in height. It is unclear why this oak species seems to initially grow so slowly, both with and without treeshelters.

Treeshelter Durability and Maintenance

Most shelters do not deteriorate readily. They remain intact for a number of years (for durability comparisons, see Windell and Hayward 1996) because they have stabilizing ultraviolet inhibitors added to the plastic. In early trials without stabilizers, treeshelters broke down before seedlings had grown large enough to be self-supporting. While attempts have been made to incorporate a quantity of inhibitors that will result in timely degradation (3 to 5 years), this has not been routinely successful and the treeshelters have not degraded as expected (Kerr 1992). Strobl and Wagner (1996) could detect no photodegradation of treeshelters after 5

Recommended Treeshelter Maintenance Procedures

- Visit shelters at least once each year to make sure they are upright, attached to the stake, buried in the ground, and functioning properly.
- Keep a 4-foot (1.2-m) diameter or larger circle around shelters free of weeds for at least 2 years after planting, and remove weeds that grow inside shelters.
- Replace flexible netting that has blown off shelter tops.
- Replace stakes that have rotted or broken.
- Leave shelters in place for at least 3 years after seedlings have grown out the tops, longer if shelters are still intact and are effectively protecting seedlings.
- Remove shelters if they are restricting growth or abrading seedlings; to remove solid shelters, slice down the sides with a razor or knife, being careful not to damage the seedling inside.

years. This raises the question of when treeshelters should be removed. In England, Kerr (1996) recommends removing shelters before they begin restricting the diameter growth of the saplings, or when treeshelters are abrading and severely damaging trees. Until this point, treeshelters help provide support and prevent damage from rabbits, squirrels (which are a terrible pest in England and can girdle trees by stripping bark), and deer (browsing and antler rubbing). For most California species, however, growing to this size could take a decade or more, and there may be aesthetic or environmental reasons to remove shelters earlier. However, it is important to leave shelters in place for at least 3 years after seedlings have emerged from the top.

By the time seedlings are taller than the tops of shelters, it is usually impossible to slip the solid shelters over the seedlings, but it is fairly easy to slice these shelters down the side using a razor or utility knife so they can easily be removed. It is especially important that treeshelters be split or removed before trees become so large that their diameters are as great as that of the shelters. At this point, stem deformation or even sapling death can occur. To reduce this possibility, some treeshelter manufacturers have begun incorporating a strip down the sides with a preformed weakness in the plastic. This is intended to permit the shelters to split apart when plants grow and press against the sides of the shelters. Whether or not this will work reliably is yet to be determined.

Finally, even though treeshelters have been shown to improve water relations and accelerate seedling growth, it is important to caution that they do not eliminate the need for weed control. Kerr (1996) noted that "the use of effective weed control in combination with treeshelters is very important to ensure rapid establishment of young trees." It is also important to remove weeds growing inside shelters because the favorable environment inside can lead to rapid weed growth.

Fertilization

There have been relatively few fertilization trials with native California oak plantings, and those that have been conducted have had mixed results. Adams, et al. (1987) reported a negative effect of granular, slow-release fertilizer (18-6-12) placed beneath blue and valley oak acorns and transplants at time of planting. Tappeiner and McDonald (1980), however, reported that annual fertilization with ¼ pound (113 g) per seedling of 16-20-0 enhanced survival and height growth of California black oak. McCreary (1996) also found that .74-ounce (21-gm), slow-release, fertilizer tablets (20-10-5), placed below outplanted blue oak acorns and seedlings, significantly increased both diameter and height growth. In the eastern and northern United States, fertilizers have been consistently reported to improve oak seedling performance (Johnson 1980). Differences in the California findings may be partially explained by an interaction with weed growth. In the first trial mentioned (Adams et al. 1987), weeds were not completely controlled and may have benefited more from the fertilizer than the seedlings, resulting in greater competition. In other trials, the plots were kept largely weed-free, and increased competition was not a problem. Obviously, soils can also vary tremendously in their fertility, and seedling response to fertilizers varies accordingly.

Compared with other costs associated with artificial regeneration, fertilization is inexpensive. The .74-ounce (21-gm) tablets used in the study above (McCreary 1996) cost about 5¢ each in 1993 when purchased in bulk, so even small improvements in performance were worth the costs. Since they are so inexpensive, we recommend using fertilizer tablets, placing them 3 to 4 inches (7.5 to 10 cm) below seedling roots at the time of planting.

Irrigation of Rangeland Oaks

When, Where, and How Much to Irrigate

In large-scale, wildland plantings, irrigation is generally not practical, especially if there is not an available water source near the planting area. In some settings, however, especially where cost is not as great a concern, it may be possible to water seedlings for several years after planting. Because water stress can seriously limit seedling survival and growth, irrigation can greatly improve the chances of establishment, especially on dry sites.

Effects of Different Soils. Sites and soils are very different and can have a tremendous effect on moisture-holding capacity and the availability of water for the seedlings. Plantings in deep, sandy, alluvial soils along the Sacramento River may need to be watered almost daily during the first year after planting. In the heavier, shallower soils at the University of California Sierra Foothill Research and Extension Center, however, this is not the case. We conducted a trial with newly planted valley oak seedlings at the SFREC that compared four treatments: no irrigation, 1 gallon (3.8 L) of water weekly, 1 gallon (3.8 L) every 2 weeks, and 1 gallon (3.8 L) every 4 weeks (McCreary 1990b). All 30 seedlings from each treatment in this study survived, indicating that irrigation was not necessary for establishment. After the first year, those that received any of the three irrigation treatments were significantly taller than unirrigated plants, but there were no significant differences among the three irrigated groups. This suggests that 1 gallon (3.8 L) of water every 4 weeks was sufficient during the first year in these soils and this environment.

In a study that evaluated soil moisture availability as a factor affecting valley oak establishment at The Nature Conservancy's Cosumnes River Preserve, irrigated, field-planted seedlings grew vigorously while unirrigated seedlings had greater water stress, less growth, and higher mortality (Meyer 1991). Bernhardt and Swiecki (1991) examined the value of irrigating direct-seeded valley oak and found that irrigation initially had a significant positive effect on seedling growth at two of three sites. However, irrigation was extremely expensive compared with moisture-conserving mulching treatments. Six years after planting, irrigation showed no positive effects on survival or growth, and it was observed that "irrigated seedlings generally sustained greater damage from small herbivores than did unirrigated seedlings. Damaging animals may be attracted to irrigated sites by the moist soil or increased succulence of oak tissues" (Bernhardt and Swiecki 1997).

Fertilization, Irrigation, and Top Pruning

- Place .74-ounce (21-g), slow-release fertilizer tablets (20-10-5) 3 to 4 inches (7.5 to 10 cm) below planted acorns or seedlings.
- Irrigation in many situations is not necessary if there is timely and thorough weed control.
- If irrigation is needed for establishment and the terrain is steep or percolation of water through soil is slow, construct earthen irrigation basins.
- Provide irrigation in the form of infrequent, deep irrigations rather than frequent, shallow irrigations; time irrigations to extend the rainy season.
- Always control competing vegetation, even in situations where supplemental irrigation is provided.
- Top-prune seedlings at the time of planting if they are too tall and are out of balance with root systems; prune small, liner stock back to a 6-inch (15-cm) top.

Irrigation Varies by Species. Light and Buchner (1999) found that optimum irrigation amounts varied for four oak species evaluated on California's North Coast. Providing water enhanced growth of each species, but there were levels of irrigation above which growth declined. Oregon white oak, for instance, performed best on a frequent irrigation schedule that caused blue oak growth to decline. At lower levels of irrigation, however, blue oak growth peaked, while the performance of Oregon white oak declined. They concluded that to thrive, all of the oak species evaluated (which also included California black oak and interior live oak) needed "appreciably more water than is available from rainfall alone."

Effects of Weed Control. It is important to remember that the need for irrigation is closely related to weed control. In almost all situations where there is little or no weed control, irrigated seedlings will still be under moisture stress. In fact, supplemental water can cause so much growth of competing plants that oak seedlings are adversely affected. Eliminating competing vegetation can lessen water stress and greatly reduce or even do away with the need for supplemental water. At the SFREC,

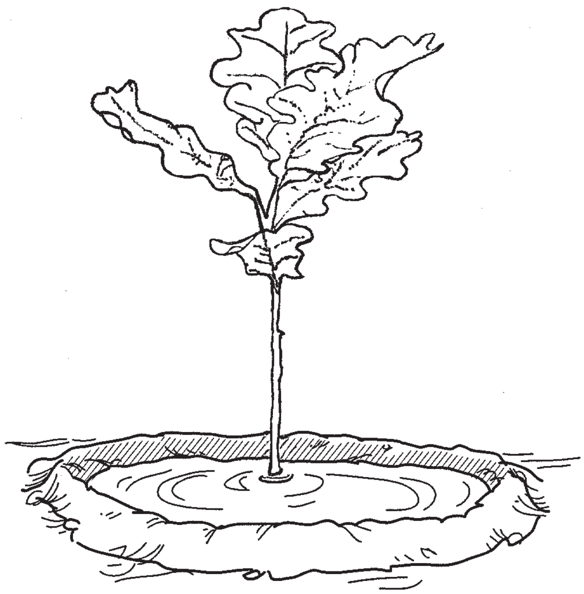

Figure 35. An earthen water basin can prevent rapid runoff of irrigation water.

which averages 28 inches (71 cm) of rainfall annually, we have concluded that supplemental irrigation is not necessary in our blue, valley, and interior live oak trials as long as we maintain areas around seedlings free of weeds for at least 2 years (preferably longer). Planting seedlings late in the season when soils are already becoming dry creates an exception. In this situation, we like to water-in seedlings to make sure that there is adequate initial moisture in the soil and air pockets are eliminated.

Earthen Basins. In many oak plantings that are irrigated, earthen basins are constructed around individual seedlings to form a reservoir that can hold several gallons of water (Bush and Thompson 1989). This is especially important in heavier soils where percolation can be slow and on slopes where irrigation water would run off too rapidly. With a basin, a large quantity of water can be added and then left to soak in gradually. Generally, these basins are 1 to 2 feet (30 to 61 cm) wide, with sides that are several inches tall (fig. 35). They need to be reasonably level, however, or water will drain out of them when they are filled. Basins have an added advantage of capturing greater quantities of rainfall, so even without irrigation, the soil moisture conditions in the rooting zone should be improved. Basins can be difficult and time consuming to construct, especially in hard, compacted, or rocky soil. This adds to the cost of planting and must be considered along with the benefits expected. In drier regions, and especially where plants will be irrigated occasionally, basin construction is probably a good investment. We generally do not use them at the SFREC since we have found that irrigation is not necessary, as long there is good weed control. At a planting in Walnut Creek, however, basins were essential because plantings were on steep slopes. Without basins, irrigation at this site would have been ineffective.

Potential Risks of Disease with Summer Irrigation

It is well recognized that summer irrigation around native California oaks can prove deadly, since diseases such as oak root fungus *(Armillaria mellea)* and crown rot *(Phytophthora cinnamomi)* proliferate where it is warm and wet, conditions which normally do not occur in the Mediterranean climate of the state (Raabe 1980). Irrigation around mature oak trees, which have evolved in conditions where summer rainfall is rare, should be avoided. Consult any arborist and you will hear horror stories of magnificent oak trees lost to disease after a homeowner put in a lawn beneath them and began watering. But, while there has not been much research on the summer irrigation of oak seedlings, it appears that small seedlings are less sensitive to diseases from warm and moist soils. Also, the benefits of summer irrigation can outweigh the risks for seedlings that are under substantial moisture stress. To reduce potential risks from watering, it is recommended that irrigation be deep and infrequent rather than often and shallow. If only several waterings are planned, it is better to time them to extend the normal rainy season into late spring rather than provide water in the middle of summer.

Superabsorbants

There are a variety of soil amendments on the market that claim to reduce moisture stress on plants. Many of these are superabsorbant hydrogels, polymers that absorb and retain several hundred times their own weight in water. Theoretically, they improve water relations by binding water when it is available and then slowly releasing it. These materials do not create any new water, but they can influence moisture availability over time. While the effectiveness of these materials is debated, it is hard to imagine a situation where they would be particularly useful for wildland oak plantings. First and foremost, it would be prohibitively expensive to mix these materials into the soil where the oaks are to be planted. A variation of these materials are containers similar to milk cartons that contain a polymer gel. These are placed in the ground next to planted seedlings. The material inside the 1-pint (.47-L) or 1-quart (.95-L) container is supposed to slowly release moisture to the target plant over a period of several months. We did a small field trial evaluating blue oaks with and without these containers and could find no benefit.

Shading Oak Seedlings

Blue oak has been characterized as highly intolerant of shade (Sudworth 1908), and it has been reported that blue oak saplings do not survive under dense shade (Swiecki and Bernhardt 1998). However, there is some evidence that providing artificial shade may improve field performance of planted blue oak in certain situations. Muick (1991) compared the response of directly-sown blue oak acorns in full sunlight and 50 percent shade and found that shade improved both emergence and survival. Artificial shade provided by placing commercially available "shadecards" on the south side of seedlings has been reported to improve Douglas fir survival in some situations (Helgerson 1990), and shade may offer some benefit for oaks on dry exposed sites, although the gains are likely to be small. We used black plastic shadecards in one study with blue oaks at the University of California Sierra Foothill Research and Extension Center but found that seedlings quickly grew above them. We could detect no improvement in survival or growth (McCreary 1989) from this treatment and have not used shadecards since.

Top Pruning Oak Seedlings

Studies outside of California have indicated that there are benefits from top pruning oak seedlings, both before and after lifting from bareroot nurseries (South 1996; Johnson 1984) or just after outplanting (Adams 1984). This is done to create plants of uniform size with more favorable shoot to root ratios. In California there has been no research on top pruning oaks in nurseries. At SFREC, we did a trial to test whether top pruning after field planting would be beneficial (McCreary and Tecklin 1993b). One-year-old blue oak seedlings in containers were top pruned at the time of field planting and compared with both large and small, unpruned controls. After two growing seasons, top pruned seedlings had significantly greater height and caliper increments than the other seedling types, suggesting that seedlings with large tops should be top pruned before or just after field planting to enhance performance.

Appendix A

Nurseries That Sell Oak Seedlings and Saplings

Below is a list of some of the wholesale and retail nurseries in California that produce native oaks in various sizes, ranging from seedlings in liners to specimen trees. The species of oaks grown at each nursery are not identified since this depends on several factors, such as acorn availability and demand, and can vary from year to year. Please contact the nursery for a current list of species and stock sizes available.

All Seasons Nursery
McKnew Enterprises
P. O. Box 2128
Elk Grove, CA 95759
916-689-0902
http://www.growtube.com

Arrowhead Growers
990 Rutherford Cross Road
P. O. Box 398
Rutherford, CA 94573
707-963-5800

Bitterroot Restoration Inc.
55 Sierra College Boulevard
Lincoln, CA 95648
916-434-9695

Blue Oak Nursery
2731 Mountain Oak Lane
Rescue, CA 95672
530-677-2111

Calaveras Nursery
1622 Highway 12
Valley Springs, CA 95252
209-772-1823

California Conservation Corps
Napa Satellite Center
P. O. Box 7199
Napa, CA 94558
707-253-7783

California Department of Forestry and Fire Protection
L. A. Moran Reforestation Center
P. O. Box 1590
Davis, CA 95617
530-753-2441

California Flora Nursery
2990 Somers Street
P. O. Box 3
Fulton, CA 95439
707-528-8813

Circuit Rider Productions, Inc.
Native Plant Nursery
9619 Old Redwood Highway
Windsor, CA 95492
707-838-6641

Cornflower Farms
P. O. Box 896
Elk Grove, CA 95759
916-689-1015

Drought Resistant Nursery
850 Park Avenue
Monterey, CA 93940
831-375-2120

Elkhorn Native Plant Nursery
P. O. Box 270
Moss Landing, CA 95039
831-763-1207

Freshwater Farms
5851 Myrtle Avenue
Eureka, CA 95503
800-200-8969

J. M. Oak Tree Nursery
430 La Lata Place
Buellton, CA 93427
805-688-5563 *(by appointment only)*

King Island Wholesale Nursery
8458 West Eight Mile Road
Stockton, CA 95219
209-957-6212

Las Pilitas Nursery
3232 Las Pilitas Road
Santa Margarita, CA 93453
805-438-5992
http://www.laspilitas.com

Matsuda Nursery
8501 Jackson Road
Sacramento, CA 95826
916-381-1625

Native Oak Nursery
45 Webb Road
Watsonville, CA 95076
831-728-8662

Native Revival Nursery
8022 Soquel Drive
Aptos, CA 95003
831-684-1811

Native Sons Wholesale Nursery
379 West El Campo Road
Arroyo Grande, CA 93420
805-481-5996

North Coast Native Nursery
P. O. Box 744
Petaluma, CA 94953
707-769-1213

Specialty Oaks Inc.
12552 Highway 29
Lower Lake, CA 95457
707-995-2275
http://www.specialtyoaks.com

Tree of Life Wholesale Nursery
P. O. Box 736
San Juan Capistrano, CA 92693
949-728-0685

Village Nurseries
1589 North Main Street
Orange, CA 92867
800-542-0209

Yerba Buena Nursery
19500 Skyline Boulevard
Woodside, CA 94062
650-851-1668

Appendix B

Sources of Materials for Oak Regeneration Projects

TREESHELTERS AND SEEDLING PROTECTION TUBES

All Seasons Nursery
McKnew Enterprises
P. O. Box 2128
Elk Grove, CA 95759
916-689-0902
http://www.growtube.com

Treegard—Albert F. Kubiske
3825 Highridge Road
Madison, WI 53704
608-837-9093

Terra Tech
International Reforestation Suppliers
2635 West 7th Place
Eugene, OR 97402
800-321-1037
503-345-0597

American Forestry Technology, Inc.
100 North 500 West
West Lafayette, IN 47906
765-583-3311

Tree Pro
3180 West 250 North
West Lafayette, IN 47906
800-875-8071
http://www.treepro.com

Tree Sentry Treeshelters
P. O. Box 607
Perrysburg, OH 43552
419-874-6950

Treessentials Company
2371 Waters Drive
Mendota Heights, MN 55120-1163
800-248-8239

ROOT GUARD

Digger's Product Development, Inc.
P. O. Box 1551
Soquel, CA 95073-2531
831-462-6095

CONTAINERS

Stuewe & Sons, Inc.
2290 Southeast Kiger Island Drive
Corvallis, OR 97333
800-553-5331
http://www.stuewe.com

Monarch Manufacturing
13154 County Road 140
Salida, CO 81201
800-284-0390
http://www.monarchmfg.com

Spencer-Lemaire Industries Limited
11406—119th Street
Edmonton, Alberta
Canada T5G 2X6
800-668-8530

SHADECARDS

Terra Tech
International Reforestation Suppliers
2635 West 7th Place
Eugene, OR 97402
800-321-1037
503-345-0597

MULCH MATS

Treessentials Company
2371 Waters Drive
Mendota Heights, MN 55120-1163
800-248-8239

References

Adams, J. C. 1984. Severe top-pruning improves water oak seedling growth. In Third biennial southern silvicultural research conference. USDA Forest Service Gen. Tech. Rep. SO-54. 1–3.

———. 1997. Mulching improves early growth of four oak species in plantation establishment. *Southern Journal of Applied Forestry* 21(1):44–46.

Adams, T. Jr., and W. H. Weitkamp. 1992. Gophers love oaks—to death. *California Agriculture* 46(5):27–29.

Adams, T. Jr., P. B. Sands, and W. B. McHenry. 1997. Weed control improves survival of transplanted blue oak. *California Agriculture* 51(5):26–30.

Adams, T. Jr., P. B. Sands, W. H. Weitkamp, and N. K. McDougald. 1991. Blue and valley oak seedling establishment on California's hardwood rangelands. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 41–47.

———. 1992. Oak seedling establishment on California rangelands. *Journal of Range Management* 45(1):93–98.

Adams, T. Jr., P. B. Sands, W. H. Weitkamp, N. K. McDougald, and J. W. Bartolome. 1987. Enemies of white oak regeneration in California. In T. R. Plumb and N. H. Pillsbury, tech. coords., Proceedings of the symposium on multiple-use management of California's hardwood resources, November 12–14, 1986, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-100. 459–462.

Allen-Diaz, B. H., and J. W. Bartolome. 1992. Survival of *Quercus douglasii* (Fagaceae) seedlings under the influence of fire and grazing. *Madroño* 39:47–53.

Anderson, L. M., A. L. Clark, and D. H. Marx. 1983. Growth of oak seedlings with specific ectomycorrhizae in urban stress environments. *Journal of Arboriculture* 9(6):156–159.

AOSA. 1993. Rules for testing seeds. *Journal of Seed Technology* 16(3):84.

Bartolome, J. W., P. C. Muick, and M. P. McClaran. 1987. Natural regeneration of California hardwoods. In T. R. Plumb and N. H. Pillsbury, tech. coords., Proceedings of the symposium on multiple-use management of California's hardwood resources, November 12–14, 1986, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-100. 26–31.

Bayer, R., D. Schrom, and J. Schwan. 1999. Global climate change and California oaks. In D. D. McCreary, ed., Proceedings of the second conference of the International Oak Society. San Marino, CA: International Oak Society. 154–165.

Berman, J. T., and C. S. Bledsoe. 1998. Soil transfers from valley oak (*Quercus lobata* Nee) stands increase ectomycorrhizal diversity and alter root and shoot growth on valley oak seedlings. *Mycorrhiza* 7:223–225.

Bernhardt, E. A., and T. J. Swiecki. 1991. Minimum input techniques for valley oak restocking. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 2–8.

———. 1997. Effects of cultural inputs on survival and growth of direct seeded and naturally occurring valley oak seedlings on hardwood rangelands. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 301–311.

Bolsinger, C. L. 1988. The hardwoods of California's timberlands, woodlands and savannas. USDA Forest Service Resour. Bull. PNW-148.

Bonner, F. T. 1973. Storing red oak acorns. *Tree Planters' Notes* 24(3):12–13.

———. 1979. Fruit maturation in hardwoods. In Proceedings, seed collection workshop, May 16–18, 1979, Macon, GA. USDA Forest Service Tech. Publ. SA-TP8. 6–10.

———. 1982. The effect of damaged radicles of pre-sprouted acorns on seedling production. *Tree Planters' Notes* 33(4):13–15.

———. 1984. Testing for seed quality in southern oaks. USDA Forest Service Res. Note SO-306.

Bonner , F. T., and J. A. Vozzo. 1987. Seed biology and technology of *Quercus*. USDA Forest Service Gen. Tech. Rep. SO-66.

Borchert, M. I., F. W. Davis, J. Michaelson, and L. D. Oyler. 1989. Interactions of factors affecting seedling recruitment of blue oak *(Quercus douglasii)* in California. *Ecology* 70:389–404.

Brissette, J. C., ed. 1996. Proceedings of the tree shelter conference, June 20–22, 1995, Harrisburg, PA. USDA Forest Service Gen. Tech. Rep. NE-221.

Brown, L. R., and C. O. Eads. 1965. A technical study of insects affecting the oak tree in Southern California. California Agricultural Experiment Station Bulletin 810.

Burger, D. W., G. W. Forister, and R. Gross. 1997. Short- and long-term effects of treeshelters on root and stem growth of ornamental trees. *Journal of Arboriculture* 23(2):49–56.

Burger, D. W., G. W. Forister, and P. A. Kiehl. 1996. Height, caliper growth, and biomass response of ten shade tree species to treeshelters. *Journal of Arboriculture* 22(4):161–165.

Burger, D. W., P. Svihra, and R. Harris. 1992. Treeshelter use in producing container grown trees. *HortScience* 27(1):30–32.

Bush, L., and R. Thompson. 1989. Acorn to oak: A guide to planting and establishing native oaks. Windsor, CA: Circuit Rider Productions.

———. 1990. Growing natives: Planting oaks. *Fremontia* 18(3):105–107.

Byrne, R., E. Edlund, and S. Mensing. 1991. Holocene changes in the distribution and abundance of oaks in California. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 182–188.

Callaway, R. M. 1992. Effect of shrubs on recruitment of *Quercus douglasii* and *Quercus lobata* in California. *Ecology* 73(6):2118–2128.

Cecich, R. A. 1993. Flowering and oak regeneration. In Symposium proceedings: Oak regeneration: Serious problems, practical recommendations, Sept. 8–10, 1992, Knoxville, TN. USDA Forest Service Gen. Tech. Rep. SE-84. 79–95.

Churches, K. R., and J. Mitchell. 1990. Oak tree project. San Andreas, CA: University of California Cooperative Extension.

Costello, L. R., A. Peters, and G. A. Giusti. 1996. An evaluation of treeshelter effects on plant survival and growth in a Mediterranean climate. *Journal of Arboriculture* 22(1):1–9.

Danielson, K. C., and W. H. Halvorson. 1991. Valley oak seedling growth associated with selected grass species. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 9–15.

Davies, R. J., and H. W. Pepper. 1989. The influence of small plastic guards, tree-shelters, and weed control on damage to young broadleafed trees by field voles *Microtus agrestis*. *Journal of Environmental Management* 28:117–125.

Davis, E. A. 1970. Propagation of shrub live oak from cuttings. *Botanical Gazette* 131(1): 55–61.

Davis, F. W., M. Borchert, L. E. Harvey, and J. C. Michaelson. 1991. Factors affecting seedling survivorship of blue oak (*Quercus douglasii* H. & A.) in Central California. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 81–86.

Davis, F. W., R. W. Brown, and B. Buyan. 1995. Vegetation change in blue oak and blue oak/foothill pine woodland. Report to the California Department of Forestry and Fire Protection Strategic Planning Program.

Dixon, R. K., H. E. Garrett, G. S. Cox, P. S. Johnson, and I. L. Sander. 1981. Container- and nursery-grown black oak seedlings inoculated with *Pisolithus tinctorius*: Growth and ectomycorrhizal development following outplanting on an Ozark clearcut. *Canadian Journal of Forest Research* 11(3):492–496.

Drew, J. J. III, and M. A. Dirr. 1989. Propagation of *Quercus* L. species by cuttings. *Journal of Environmental Horticulture* 7(3):115–117.

Engeman, R. M., V. G. Barnes, R. M. Anthony, and H. W. Krupa. 1995. Vegetation management for reducing mortality of ponderosa pine seedlings from *Thomomys* spp. *Crop Protection* 14(6):505–508.

Friske, S. L. 1997. A California black oak restoration project in Yosemite Valley, Yosemite National Park. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 281–288.

Garrett, H. E., G. S. Cox, R. K. Dixon, and G. M. Wright. 1979. Mycorrhizae and the artificial regeneration potential of oak. In Proceedings, regenerating oaks in upland hardwood forests, Feb. 22–23, 1979, 82–90. W. Lafayette, IN: Purdue University.

Gillespie, A. R., R. Rathfon, and R. K. Meyers. 1996. Rehabilitating a young northern red oak planting with tree shelters. *Northern Journal of Applied Forestry* 13(1): 24–29.

Gordon, D. R., J. M. Welker, J. M. Menke, and K. J. Rice. 1989. Competition for soil water between annual plants and blue oak (*Quercus douglasii)* seedlings. *Oecologia* 79(4):533–541.

Gosling, P. G. 1989. The effect of drying *Quercus robur* acorns to different moisture contents, followed by storage, either with or without imbibition. *Forestry* 62(1):41–50.

Gribko, L. S., and W. E. Jones. 1997. Test of the float method for assessing northern red oak acorn condition. *Tree Planters' Notes* 46(4):143–147.

Griffin, J. R. 1971. Oak regeneration in the upper Carmel Valley, California. *Ecology* 52:862–868.

———. 1973. Valley oaks—the end of an era? *Fremontia* 1(1):5–9.

———. 1976. Regeneration in *Quercus lobata* savannas, Santa Lucia Mountains, California. *The American Midland Naturalist* 95(2):422–435.

———. 1980 Animal damage to valley oak acorns and seedlings, Carmel Valley, California. In T. R. Plumb, tech. coord., Proceedings of the symposium on the ecology, management and utilization of California oaks, June 26–28, 1979, Claremont, CA. USDA Forest Service Gen. Tech. Rep. PSW-44. 242–245.

Griffin, J. R., and W. B. Critchfield. 1972. The distribution of forest trees in California. USDA Forest Service Res. Pap. PSW-82.

Hall, L. M., M. R. George, D. D. McCreary, and T. Adams, Jr. 1992. Effects of cattle grazing on blue oak seedling damage and survival. *Journal of Range Management* 45(5):503–506.

Heady, H. F. 1977. Valley grassland. In M. G. Barbour and J. Major, eds., Terrestrial vegetation of California. 383–415. New York: Wiley.

Helgerson, O. T. 1990. Effects of alternate types of microsite shade on survival of planted Douglas-fir in southwest Oregon. *New Forests* 3:327–332.

Holtzman, B. A., and B. H. Allen-Diaz. 1991. Vegetation change in blue oak woodlands in California. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 189–193.

Isebrands, J. G., and T. R. Crow. 1985. Techniques for rooting juvenile softwood cuttings of northern red oak. In J. O. Dawson and K. O. Majerus, eds., Proceedings, fifth central hardwood forest conference, April 15–17, 1985. 228–233. Urbana-Champaign: University of Illinois.

Jepson, W. L. 1910. The silva of California: University of California memoirs. Berkeley, CA: University of California.

Johnson, P. S. 1980. Response to fertilization of five oak species eight years after planting. *Tree Planters' Notes* 31(1):9–10.

———. 1984. Responses of planted northern red oak to three overstory treatments. *Canadian Journal of Forest Research* 14:536–542.

———. 1988. Undercutting alters root morphology and improves field performance of northern red oak. In Proceedings, 10th North American forest biology workshop, July 10–22, 1988, 316–323. Vancouver.

Keator, G. 1998. The life of an oak. Berkeley, CA: Heyday Books; Oakland, CA: California Oak Foundation.

Kerr, G. 1992. To remove or not?: Treeshelter question. *Forestry and British Timber*, December, 1992, 18–20.

———. 1995. The use of treeshelters: 1992 Survey. Forestry Commission Technical Paper 11. Edinburgh: Forestry Commission.

———. 1996. The history, development and use of treeshelters in Britain. In J. C. Brissette, ed., Proceedings of the tree shelter conference, June 20–22, 1995, Harrisburg, Pennsylvania. USDA Forest Service Gen. Tech. Rep. NE-221. 1–4.

Kertis, J. A., R. Gross, D. L. Peterson, R. B. Standiford, and D. D. McCreary. 1993. Growth trends of blue oak (*Quercus douglasii)* in California. *Canadian Journal of Forest Research* 23:1720–1724.

Kjelgren, R., D. T. Montague, and L. A. Rupp. 1997. Establishment of treeshelters II: Effect of shelter color on gas exchange and hardiness. *HortScience* 32(7):1284–1287.

Knops, J. M. H., J. R. Griffin, and A. C. Royalty. 1995. Introduced and native plants of the Hastings Reservation, Central Coastal California: A comparison. *Biological Conservation* 71(2):115–123.

Koenig, W. D., and J. M. H. Knops. 1995. Why do oaks produce boom-and-bust seed crops? *California Agriculture* 49(5):7–12.

———. 1997. Patterns of geographic synchrony in growth and reproduction of oaks within California and beyond. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 109–116.

Koenig, W. D., W. J. Carmen, M. T. Stanback, and R. L. Mumme. 1991. Determinants of acorn productivity among five species of oaks in Central Coastal California. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech Rep. PSW-126. 136–142.

Koenig, W. D., J. M. H. Knops, W. J. Carmen, M. T. Stanback, and R. L. Mumme. 1996. Acorn production by oaks in Central Coastal California: Influence of weather at three levels. *Canadian Journal of Forest Research* 26:1677–1683.

Koenig, W. D., D. R. McCullough, C. E. Vaughn, J. M. H. Knops, and W. J. Carmen. 1999. Synchrony and asynchrony of acorn production at two coastal California sites. *Madroño* 46(1):20–24.

Korstian, C. F. 1927. Factors controlling germination and early survival in oaks. Yale University School of Forestry Bulletin 19.

Koukoura, Z., and J. Menke. 1994. Effect of root pinching on growth patterns of blue oak (*Quercus douglasii* H. & A.) seedlings. *Phyton-Horn* 34(1):109–118.

———. 1995. Competition for soil water between perennial bunch-grass (*Elymus glaucus* B.B.) and blue oak seedlings (*Quercus douglasii* H. & A.). *Agroforestry Systems* 32(3):225–235.

Krelle, B., and D. D. McCreary. 1992. Propagating California native oaks in bareroot nurseries. In Proceedings, Intermountain Forest Nursery Association. USDA Forest Service Gen. Tech. Rep. RM-211. 117–119.

Lang, J. F. 1988. Oak regeneration assessment—a problem analysis. Paper prepared for the California Forestry and Fire Protection Program Forest and Rangeland Resources Assessment Program.

Lewis, H. T. 1993. Patterns of Indian burning in California: Ecology and ethnohistory. In T. C. Blackburn and K. Anderson, eds., Before the wilderness: Environmental management by Native Californians. In Ballena Press anthropological papers, no. 40: 55–116. Menlo Park, CA: Ballena Press.

Light, R. H., and T. R. Buckner. 1999. Irrigation and rangeland oaks. In D. D. McCreary, ed., Proceedings of the second conference of the International Oak Society, San Marino, CA. 84–93. Auburn, IL: International Oak Society.

Lippitt, L. 1992. Producing containerized oak seedlings. In Proceedings, Intermountain Forest Nursery Association. USDA Forest Service Gen. Tech. Rep. RM-211. 114–116.

Longhurst, W. M. 1956. Stump sprouting of oaks in response to seasonal cutting. *Journal of Range Management* 9(4):194–196.

Matsuda, K., and J. R. McBride. 1986. Differences in seedling growth morphology as a factor in the distribution of three oaks in Central California. *Madroño* 33(3):207–216.

———. 1989a. Germination characteristics of selected California oak species. The *American Midland Naturalist* 22(1):66–76.

———. 1989b. Seedling growth form of oaks. *Annals of Botany* 64:439–446.

McCarthy, H. 1993. Managing oaks and the acorn crop. In T. C. Blackburn and K. Anderson, eds., Before the wilderness: Environmental management by Native Californians. In Ballena Press anthropological papers, no. 40:213–228. Menlo Park, CA: Ballena Press.

McClaran, M. P. 1986. Age structure of *Quercus douglasii* in relation to livestock grazing and fire. Ph.D. diss., University of California, Berkeley.

McClaran, M. P., and J. W. Bartolome. 1989. Fire-related recruitment in stagnant *Quercus douglasii* populations. *Canadian Journal of Forest Research* 19:580–585.

McCreary, D. D. 1989. Regenerating native oaks in California. *California Agriculture* 43(1):4–6.

———. 1990a. Acorn sowing date affects field performance of blue and valley oaks. *Tree Planters' Notes* 41(2):6–9.

———. 1990b. Field performance of valley oak seedlings under different irrigation regimes. In J. W. van Sambeek and M. M. Larson, eds., Fourth workshop on seedling physiology and growth problems in oak planting (abstracts). USDA Forest Service Gen. Tech. Rep. NC-139. 21.

———. 1991. Seasonal growth patterns of blue and valley oak seedlings established on foothill rangelands. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 36–40.

———. 1995. Augering and fertilization stimulate growth of blue oak seedlings planted from acorns, but not from containers. *Western Journal of Applied Forestry* 10(4):133–137.

———. 1996. The effects of stock type and radicle pruning on blue oak morphology and field performance. *Annales des Sciences Forestieres* 53(2–3):641–648.

———. 1997. Treeshelters: An alternative for oak regeneration. *Fremontia* 25(1):26–30.

———. 1999. Restoration of a grazed riparian area. In R. Rose and D. L. Haase, eds., Symposium proceedings, native plants: Propagating and planting, December 9–10, 1998, Corvallis, OR. 86–91. Corvallis: Oregon State University Nursery Technology Cooperative.

McCreary, D. D., and Z. Koukoura. 1990. The effects of collection date and pre-storage treatment of the germination of blue oak acorns. *New Forests* 3:303–310.

McCreary, D. D., and J. Tecklin. 1993a. Effects of tree shelters and weed control on blue oak growth and survival. In J. R. Thompson, R. C. Schultz, and J. W. van Sambeek, eds., Fifth workshop on seedling physiology and growth problems in oak plantings (abstracts), March 4–5, 1992, Ames, IA. USDA Forest Service Gen. Tech. Rep. NC-158. 4.

———. 1993b. Top Pruning improves field performance of blue oak seedlings. *Tree Planters' Notes* 44(2):73–77.

———. 1993c. Treeshelters accelerate valley oak restoration on grazed rangelands. *Restoration and Management Notes* 11(2):152–153.

———. 1994a. Grasshoppers continue to hamper oak restoration efforts. *Oaks 'n Folks* 9(2). 4.

———. 1994b. Lifting and storing bareroot blue oak seedlings. *New Forests* 8:89–103.

———. 1996. Effects of tree shelters on field performance of oaks in California. In R. M. Tecklaw, ed., Sixth workshop on seedling physiology and growth problems in oak plantings (abstracts), September 18–20, 1995, Rhinelander, WI. USDA Forest Service Gen. Tech. Rep. NC-182. 20.

———. 1997. Effects of seedling protectors and weed control on blue oak growth and survival. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 243–250.

———. 2001. The effects of different-sized treeshelters on blue oak growth. *Western Journal of Applied Forestry,* (forthcoming) October, 2001.

McCreary, D. D., W. D. Tietje, R. H. Schmidt, R. Gross, W. H. Weitkamp, B. L. Willoughby, and F. L. Bell. 1991. Stump sprouting of blue oaks. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 64–69.

McDonald, P. M. 1978. Silviculture-ecology of three native California hardwoods on high sites in north-central California. Ph.D. diss. Oregon State University, Corvallis.

———. 1990. *Quercus douglasii* Hook. & Arn. Blue Oak. In M. Burns and B. H. Honkola, tech. coords., Silvics of North America. Vol. 2, Hardwoods. USDA Forest Service Agriculture Handbook no. 450. 631–639. Washington, D.C.: Government Printing Office.

McKibben, L., and W. C. Graves. 1987. Managing blue oak for wildlife based on acorn production. In T. R. Plumb and N. H. Pillsbury, tech. coords., Proceedings of the symposium on multiple-use management of California's hardwood resources, November 12–14, 1986, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-100. 227–229.

Mensing, S. A. 1988. Blue oak (*Quercus douglasii*) regeneration in the Tehachapi Mountains, Kern County, California. M.A. thesis. University of California, Berkeley.

———. 1991. The effect of land use changes on blue oak regeneration and recruitment. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 230–232.

———. 1992. The impact of European settlement on blue oak (*Quercus douglasii*) regeneration and recruitment in the Tehachapi Mountains, California. *Madroño* 39(1):36–46.

———. 1998. 560 years of vegetation change in the region of Santa Barbara, California. *Madroño* 45(1):1–11.

Meyer, V. C. 1991. Soil moisture availability as a factor affecting valley oak (*Quercus lobata*) seedling establishment and survival in a riparian habitat, Cosumnes River Preserve, Sacramento County, California. M.S. thesis. California State University, Sacramento.

Momen B., J. W. Menke, J. M. Welker, K. J. Rice, and F. S. Chapin. 1994. Blue-oak regeneration and seedling water relations in four sites within a California oak savanna. *International Journal of Plant Sciences* 155(6):744–749.

Morgan, D. L. 1979. Vegetative propagation of Texas live oaks. *Combined Proceedings, International Plant Propagators Society,* 29:113–115.

Muick, P. C. 1991. Effects of shade on blue oak and coast live oak regeneration in California annual grasslands. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 21–24.

Muick, P. C., and J. Bartolome. 1986. Oak regeneration on California's hardwood rangelands. *Transactions, Western Section of the Wildlife Society* 22:121–125.

———. 1987. Factors associated with oak regeneration in California. In T. R. Plumb and N. H. Pillsbury, tech. coords., Proceedings of the symposium on multiple-use management of California's hardwood resources, November 12–14, 1986, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-100. 86–91.

Olson, D. F. Jr. 1974. *Quercus* L. Oak. In C. S. Schopmeyer, tech. coord., Seeds of woody plants in the United States. USDA Forest Service Agriculture Handbook no. 450. 692–703. Washington, D.C.: Government Printing Office.

Pavlik, B. M., P. C. Muick, S. Johnson, and M. Popper. 1991. Oaks of California. Los Olivos, CA: Cachuma Press.

Phillips, R. L., N. K. McDougald, R. B. Standiford, D. D. McCreary, and W. E. Frost. 1997. Blue oak regeneration in southern Sierra Nevada Foothills. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 177–181.

Plumb T. R., and B. Hannah. 1991. Artificial regeneration of blue and coast live oaks in the Central Coast. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 74–80.

Plumb T. R., and P. M. McDonald. 1981. Oak management in California. USDA Forest Service Gen. Tech. Rep. PSW-54.

Ponder, F. Jr. 1996. Tree shelter effects on stem and root biomass of planted hardwoods. In J. C. Brissette, ed., Proceedings of the tree shelter conference, June 20–22, 1995, Harrisburg, PA. USDA Forest Service Gen. Tech. Rep. NE-221. 19–23.

Potter, M. J. 1988. Treeshelters improve survival and increase early growth rates. *Journal of Forestry* 86:39–41.

———. 1991. Treeshelters. Forestry Commission Handbook 7. London: HMSO Publications Centre.

Raabe, R. D. 1980. Diseases of oaks in the landscape. In T. R. Plumb, tech. coord., Proceedings of the symposium on the ecology, management and utilization of California oaks, June 26–28, 1979, Claremont, CA. USDA Forest Service Gen. Tech. Rep. PSW-44. 195–201.

Regan, R. P., T. L. Landis, and J. L. Green. 1993. The potential for chemical root pruning in container nurseries. *Combined Proceedings, International Plant Propagators Society* 43:209–212.

Rendle, E. L. 1985. The influence of tube shelters on microclimate and growth of oak. In Proceedings, sixth national hardwoods programme. 8–16. Oxford, England: University of Oxford Forestry Institute.

Rice, K. J., J. H. Richards, and S. L. Matzner. 1997. Patterns and processes of adaptation in blue oak seedlings. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 109–115.

Riggs, L. A., C. I. Millar, and D. L. Delany. 1991. Genetic variation sampled in three California oaks. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 244–234.

Ruehle, J. L. 1984. Ectomycorrhizal fungus inoculation improves quality of oak seedlings used for artificial regeneration. In P. S. Johnson and J. D. Hodges, eds. Second workshop on seedling physiology and growth problems in oak planting (abstracts), February 8–9, 1983, Mississippi State, MS. USDA Forest Service Gen. Tech. Report NC-99.

Ruehle, J. L., and P. C. Kormanik. 1986. Lateral root morphology: A potential indicator of seedling quality in northern red oak. USDA Forest Service Res. Note SE-344.

Rundel, P. W. 1980. Adaptations of Mediterranean climate to environmental stress. In T. R. Plumb, tech. coord., Proceedings of the symposium on the ecology, management and utilization of California oaks, June 26–28, 1979, Claremont, CA. USDA Forest Service Gen. Tech. Rep. PSW-44. 43–54.

Schettler, S., and M. Smith. 1980. Nursery production of California oaks. In T. R. Plumb, tech. coord., Proceedings of the symposium on the ecology, management and utilization of California oaks, June 26–28, 1979, Claremont, CA. USDA Forest Service Gen. Tech. Rep. PSW-44. 143–148.

Schubert, G. H, R. S. Adams, and L. E. Richey. 1975. Reforestation practices for conifers in California. Sacramento: State of California Division of Forestry.

Schultz, R. C., and J. R. Thompson. 1997. Effect of density control and undercutting on root morphology of 1+0 bareroot hardwood seedlings: Five-year field performance of root-graded stock in the central USA. *New Forests* 13:225–236.

Scott, T. A., and N. L. Pratini. 1997. The effects of native soils on Engelmann oak seedling growth. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 657–660.

Shuler, T. M., and G. W. Miller. 1996. Guidelines for using tree shelters to regenerate northern red oak. In J. C. Brissette, ed., Proceedings of the tree shelter conference, June 20–22, 1995, Harrisburg, PA. USDA Forest Service Gen. Tech. Rep. NE-221. 37–45.

South, D. B. 1996. Top-pruning bareroot hardwoods: A review of the literature. *Tree Planters' Notes* 47(1):34–40.

Standiford, R. B. 1997. Growth of blue oak on California's hardwood rangelands. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 169–176.

Standiford, R. B., D. D. McCreary, S. Barry, L. Forero, and R. Knight. 1996. Impact of firewood harvesting on hardwood rangelands varies with region. *California Agriculture* 50(2):7–12.

Sternberg, G. 1996. Oaks to know and to grow: The promise and problems of the genus. *Combined Proceedings, International Plant Propagators Society* 46:464–468.

Strobl, S., and R. C. Wagner. 1996. Early results with translucent tree shelters in southern Ontario. In J. C. Brissette, ed., Proceedings of the tree shelter conference, June 20–22, 1995, Harrisburg, PA. USDA Forest Service Gen. Tech. Rep. NE-221. 13–18.

Sudworth, G. B. 1908. Forest trees of the Pacific slope. USDA Forest Service. Washington, D.C.: Government Printing Office.

Swiecki, T. J., and E. A. Bernhardt. 1998. Understanding blue oak regeneration. *Fremontia* 26(1):19–26.

———. 1999. Effects of fire on naturally occurring blue oak seedlings and planted valley oak seedlings. In D. D. McCreary and J. G. Isebrands, eds., Seventh workshop on seedling physiology and growth problems in oak plantings (abstracts), September 20–21, 1999, South Lake Tahoe, CA. USDA Forest Service Gen. Tech. Rep. NC-206. 3.

Swiecki, T. J., E. A. Bernhardt, and R. A. Arnold. 1991. Insect and disease impacts on blue oak acorns and seedlings. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 149–155.

———. 1997. The California oak disease and arthropod (CODA) database. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 543–552.

Swiecki, T. J., E. A. Bernhardt, and C. Drake. 1997a. Factors affecting blue oak sapling recruitment and regeneration. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 157–168.

———. 1997b. Stand-level status of blue oak sapling recruitment and regeneration. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 147–156.

Tappeiner, J., and P. M. McDonald. 1980. Preliminary recommendations for managing California black oak in the Sierra Nevada. In T. R. Plumb, tech. coord., Proceedings of the symposium on the ecology, management and utilization of California oaks, June 26–28, 1979, Claremont, CA. USDA Forest Service Gen. Tech. Rep. PSW-44. 107–111.

Tecklin, J. 1993. Treeshelters are for the birds. *Oaks 'n Folks* 8(1):6.

Tecklin, J., and D. D. McCreary. 1991. Acorn size as a factor in early seedling growth of blue oaks. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 48–53.

———. 1993. Dense vegetation may encourage vole damage in young oak plantings. *Restoration and Management Notes* 11(2):153.

Tecklin, J., J. M. Connor, and D. D. McCreary. 1997. Rehabilitation of a blue oak restoration project. In N. H. Pillsbury, J. Verner, and W. D. Tietje, tech. coords., Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160. 267–273.

Teclaw, R. M., and J. G. Isebrands. 1986. Collection procedures affect germination of northern red oak (*Quercus rubra* L.) acorns. *Tree Planters' Notes* 37(3):8–12.

Thompson, J. R., and R. C. Schultz. 1995. Root system morphology of *Quercus rubra* L. planting stock and 3-year field performance in Iowa. *New Forests* 9(3):225–236.

Tietje, W. D., S. N. Nieves, J. A. Honig, and W. H. Weitkamp. 1991. Effect of acorn planting depth on depredation, emergence, and survival of valley and blue oak. In R. B. Standiford, tech. coord., Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Forest Service Gen. Tech. Rep. PSW-126. 14–20.

Trencia, J. 1996. Influence of seed position on first-year survival and growth of directly seeded northern red oak. *Tree Planters' Notes* 14(2):68–75.

Tuley, G. 1983. Shelters improve the growth of young trees in the forest. *Quarterly Journal of Forestry* 77:77–87.

———. 1985. The growth of young oak trees in shelters. *Forestry* 58:181–195.

Vickers, G. 1999. Maintenance of tree shelters. British Forestry Commission Technical Development Branch Technical Note.

Vieitez, A. M., M. C. San-Jose, and E. Vieitez. 1985. In vitro plantlet regeneration from juvenile and mature *Quercus robur* L. *Journal of Horticulture Science* 60(1):99–106.

Welker, J. M., and J. W. Menke. 1987. *Quercus douglasii* seedling water relations in mesic and grazing-induced xeric environments. In Proceedings, international conference on measurements of soil and plant water status, vol. 2, Plants, July 6–10, 1987, Logan, UT. 229–234. Utah State University.

———. 1990. The influence of simulated browsing on tissue water relations, growth and survival of *Quercus douglasii* (Hook and Arn.) seedling under slow and rapid rates of soil drought. *Functional Ecology* 4(6):807–817.

White, K. L. 1966. Structure and composition of foothill woodland in central-coastal California. *Ecology* 47(2):229–237.

Wieslander, A. E. 1935. A vegetation type map of California. *Madroño* 3:140–144.

Williamson, D. R. 1992. Establishing farm woodlands. Forestry Commission Handbook 8. London: HMSO Publications Centre.

Windell, K. 1992. Tree shelters for seedling protection. USDA Forest Service Technology and Development Program. 2400-Timber. 9224-2834-MTDC.

———. 1993. Seedling protection in England - trip report. USDA Forest Service Technology and Development Program. 2400-Timber. 9324-2845-MTDC.

Windell, K., and J. D. Haywood. 1996. Intermediate results of treeshelter durability study. In J. C. Brissette, ed., Proceedings of the tree shelter conference, June 20–22, 1995, Harrisburg, PA. USDA Forest Service Gen. Tech. Rep. NE-221.

Zaczek, J. J., C. W. Heuser, and K. C. Steiner. 1997. Effect of shade and IBA levels during the rooting of eight taxa. *Journal of Environmental Horticulture* 15(1):56–60.

Bibliography

Brissette, J. C., ed. 1996. Proceedings of the tree shelter conference, June 20–22, 1995, Harrisburg, PA. USDA Forest Service Gen. Tech. Rep. NE-221.

Brown, L. R., and C. O. Eads. 1965. A technical study of insects affecting the oak tree in Southern California. California Agricultural Experiment Station Bulletin 810. Berkeley, CA: University of California Division of Agricultural Sciences.

Bush, L., and R. Thompson. 1989. Acorn to oak: A guide to planting and establishing native oaks. Windsor, CA: Circuit Rider Productions.

California Oak Disease and Arthropod (CODA) Database. http://www.phytosphere.com

Churches, K. R., and J. Mitchell. 1990. Oak tree project. San Andreas: University California Cooperative Extension. TEL: 209-754-6477.

Dreyer, E., and G. Aussenac. 1996. Ecology and physiology of oaks in a changing environment: Selected papers from an international symposium in Nancy, France, September, 1994. *Annales des Sciences Forestieres* 53(2–3).

Faber, P., ed. 1990. Year of the oak. *Fremontia* 18(3).

Griffin, J. R. 1977. Oak woodland. In M. G. Barbour and J. Major, eds., Terrestrial vegetation of California. 383–415. New York: John Wiley and Sons.

Griffin, J. R., P. M. McDonald, and P. C. Muick. 1987. California oaks: A bibliography. USDA Forest Service Gen. Tech. Rep. PSW-96.

Hu, S. C., H. E. Kennedy, Jr., N. E. Linnartz, and P. Y. Burns. 1989. Eight major species of southern oaks: A bibliography, 1876-1987. Louisiana Agricultural Experiment Station Bulletin no. 805.

Johnson, P. S., and H. E. Garrett, eds. 1980. First workshop on seedling physiology and growth problems in oak planting (abstracts), November 6–7, 1979, Columbia, MO. USDA Forest Service Gen. Tech. Rep. NC-82.

Johnson, P. S., and J. D. Hodges, eds., 1984. Second workshop on seedling physiology and growth problems in oak planting (abstracts), February 8–9, 1983, Mississippi State, MS. USDA Forest Service Gen. Tech. Rep. NC-99.

Keator, G. 1998. The life of an oak. Berkeley, CA: Heyday Books; Oakland, CA: California Oak Foundation.

Loftis, D. L., and C. E. McGee, eds. 1993. Symposium proceedings, Oak regeneration: Serious problems, practical recommendations, September 8–10, 1992, Knoxville, TN. USDA Forest Service Gen. Tech. Rep. SE-84.

McCreary, D. D., and J. Isebrands, eds. 1999. Seventh workshop on seedling physiology and growth problems in oak plantings (abstracts), September 20–21, 1999, South Lake Tahoe, CA. USDA Forest Service Gen. Tech. Rep. NC-206.

Pavlik, B. M., P. C. Muick, S. Johnson, and M. Popper. 1991. Oaks of California. Los Alamos, CA: Cachuma Press.

Pillsbury, N. H., J. Verner, and W. D. Tietje, tech. coords. 1997. Proceedings of a symposium on oak woodlands: Ecology, management and urban interface issues, March 19–22, 1996, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-160.

Plumb T. R, tech. coord. 1980. Proceedings of the symposium on the ecology, management and utilization of California oaks, June 26–28, 1979, Claremont, CA. USDA Forest Service Gen. Tech. Rep. PSW-44.

Plumb, T. R., and N. H Pillsbury, tech. coords. 1987. Proceedings of the symposium on multiple-use management of California's hardwood resources, November 12–14, 1986, San Luis Obispo, CA. USDA Forest Service Gen. Tech. Rep. PSW-100.

Potter, M. J. 1991. Treeshelters. Forestry Commission Handbook 7. London: HMSO Publications Centre.

Rauscher, M. H., D. L. Loftis, C. E. McGee, and C. V. Worth. 1997. Oak regeneration: A knowledge synthesis. United States Forest Service Southern Research Station. http://www.srs.fs.fed.us/pubs/misc/oak_regeneration.htm

Standiford, R. B., tech. coord. 1991. Proceedings, symposium on oak woodlands and hardwood rangeland management, October 31–November 2, 1990, Davis, CA. USDA Gen. Tech. Rep. PSW-126.

Tecklaw, R. M., ed. 1996. Sixth workshop on seedling physiology and growth problems in oak plantings (abstracts), September 18–20, 1995, Rhinelander, WI. USDA Forest Service Gen. Tech. Rep. NC-182.

Thompson, J. R., R. C. Schultz, and J. W. van Sambeek, eds. 1993. Fifth workshop on seedling physiology and growth problems in oak plantings (abstracts), March 4–5, 1992, Ames, IA. USDA Forest Service Gen. Tech. Rep. NC-158.

University of California Integrated Hardwood Range Management Program. http://danr.ucop.edu/ihrmp/

van Sambeek, J. W., and M. M. Larson, eds. 1990. Fourth workshop on seedling physiology and growth problems in oak plantings (abstracts), March 1–2, 1989, Columbus, OH. USDA Forest Service Gen. Tech. Rep. NC-139.

van Sambeek, J. W., G. Rink, and P. S. Johnson, eds. 1988. Third workshop on seedling physiology and growth problems in oak plantings (abstracts), February 12–13, 1986, Carbondale, IL. USDA Forest Service Gen. Tech. Rep. NC-121.