Title
Pruning wounds and occlusion: A long-standing conundrum in forestry

Journal
Journal of Forestry, 105(3)

ISSN
0022-1201

Author
O'Hara, Kevin L.

Publication Date
2007-04-01

Peer reviewed

Pruning Wounds and Occlusion: A Long-Standing Conundrum in Forestry

Kevin L. O'Hara

ABSTRACT

The proper method for branch removal is a long-standing question in forestry. If the branch is cut flush with the stem, a larger wound results, but if the branch is cut further from the stem, the resultant clearwood production will be less. Both alternatives have implications for tree health and wood quality. A long, international history of forest pruning research generally indicates that a cut parallel and close to the stem will maximize clearwood production without excessive stem decay. Some exceptions exist for species where potential for stem decay is high. The method recommended in most guidelines for all types of pruning is an outside branch collar approach based primarily on a small number of observational studies. However, maintaining tree health and maximizing clearwood production are not mutually exclusive and a cut close to the stem can meet both objectives. Alternative approaches to branch removal may be useful for other objectives.

Keywords: forest pruning, wound recovery, natural target pruning, stand management, occlusion

Foresters have been pruning forest trees for centuries, having recognized the potential to enhance wood quality and affect tree form (Mayer-Wegelin 1936, Curtis 1937). Objectives of this pruning vary, but usually enhancing the quality of wood sawn from the tree has been a central objective. Despite centuries of experience and thousands of studies on various aspects of pruning (Sisam et al. 1940, O'Hara 1989, Nicolescu 1999), there are conflicting recommendations over a seemingly simple but central concept in pruning: the appropriate technique for cutting the branch. However, despite the historical conundrum, a sample of current guides for both forest and general pruning (Maclaren 1993, Bedker et al. 1995, Emmingham and Fitzgerald 1995, Windell 1996, Iowa State University 1998, Brown 2004, Hanley and Reutebuch 2005, Fazio 2006) and many websites (Table 1) include recommendations for only a single method: a process generally referred to as "natural target pruning."

On a properly pruned tree, the wood formed after recovery from pruning likely will be free of defects and therefore will achieve greater strength properties and yield lumber that earns a higher grade than lumber from a similar location on a comparable unpruned tree. Occlusion is the process of trees forming callus and clearwood over wounds. Usually, the process of branch wound occlusion begins with formation of callus over the branch stub eventually forming a new cambium layer and new clear growth rings. Between the branch stubs and the clear wood is the occlusion zone where the tree forms callus wood and new growth rings occlude the wound. The inner log that contains the unpruned core and the occlusion zone is the defect core, an irregular cylinder that varies in size and shape with the pruning regime (Figure 1). The objective of maximizing clearwood production is achieved when the defect core size is minimized with respect to the log size. Reducing the size of the occlusion zone through the pruning technique is an important means of meeting this objective. Therefore, the size of the defect core is the result of a tradeoff between pruning severity or timing of pruning operations and tree growth. An early or severe pruning will reduce the size of the defect core thereby increasing clearwood production, but it also may reduce tree growth having a negative effect on clearwood production.

Forest trees are pruned also to meet objectives such as fuelwood production, en-

Received October 3, 2006; accepted January 24, 2007.

Kevin L. O'Hara (ohara@nature.berkeley.edu), University of California–Berkeley, Environmental Science, Policy and Management, Berkeley, CA 94720-3114.
Helpful presubmission reviews of this manuscript were provided by Dr. Kristen M. Waring of Northern Arizona University, and Yana Valachovic of University of California Cooperative Extension. The author greatly appreciates the helpful comments of three anonymous Journal of Forestry *reviewers.*

Table 1. Sampling of websites presenting pruning recommendations for forest trees.

www.dnr.wa.gov/htdocs/rp/stewardship/bfs/EASTERN/pruning.html;
www.dnr.wa.gov/htdocs/rp/stewardship/bfs/WESTERN/pruning.html
muextension.missouri.edu/explore/agguides/forestry/g05160.htm;
www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/pruning/pruntoc.htm;
www.forestry.about.com/od/arboriculture/ss/why_prune_5.htm
www.extension.umn.edu/distribution/horticulture/DG0628.html
www.dnr.state.mn.us/fid/october98/10019808.html
www.ume.maine.edu/~woodlot/prune.htm
www.maine.gov/doc/mfs/pubs/htm/fpminfo/pruning.htm

All websites last accessed Aug. 21, 2006.

hancement of aesthetics, reduction of fuel ladders, and to remove or reduce susceptibility to pathogens. Urban trees are pruned also to modify tree form, remove hazardous branches, or improve tree health, but not generally for enhancement of wood quality. Regardless of the situation or the objective for pruning, branches are removed and the techniques used to remove these branches have implications for tree appearance, tree health, and wood quality. This article discusses the current state of our knowledge on branch removal techniques and wound occlusion for pruning forest trees and how the transfer of previous research has affected current practices.

Branch Anatomy

The anatomy of a living tree branch is similar to the stem: xylem and phloem are separated by the vascular cambium. All of these are connected to their counterparts on the stem. Water and nutrients flowing up the functioning xylem or sapwood continue to flow out the branches and carbon produced in photosynthesis flows from the leaves through the branch phloem to the stem phloem. At the base of the branch, where it joins the stem, often there is a branch collar in some species (Figure 2), particularly on larger branches. The branch collar is a swelling of xylem and callus tissues but does not break the link between conducting tissues in the stem and branches. Apparently, its function is as a support structure and as a barrier to fungal infection in the main stem.

A typical dead branch has no living connections to the stem and no live tissues but may have a branch collar. The stem cambium essentially forms a ring around the dead branch that moves outward with formation of each annual ring as long as the dead branch is in place. The disconnection from the cambium and the stem xylem formed after branch death leads to loose knots in wood that is cut from this part of the tree. Because of the differences in anatomy and function of living and dead branches, the wound occlusion after pruning is profoundly different. Pruning a live branch severs the living xylem, phloem, and cambium tissues, whereas removing a dead branch typically will affect no living tissues. The conundrum over pruning primarily involves live branch pruning. However, studies involving dead branch pruning provide some relevant insights into wound occlusion for both types of branches.

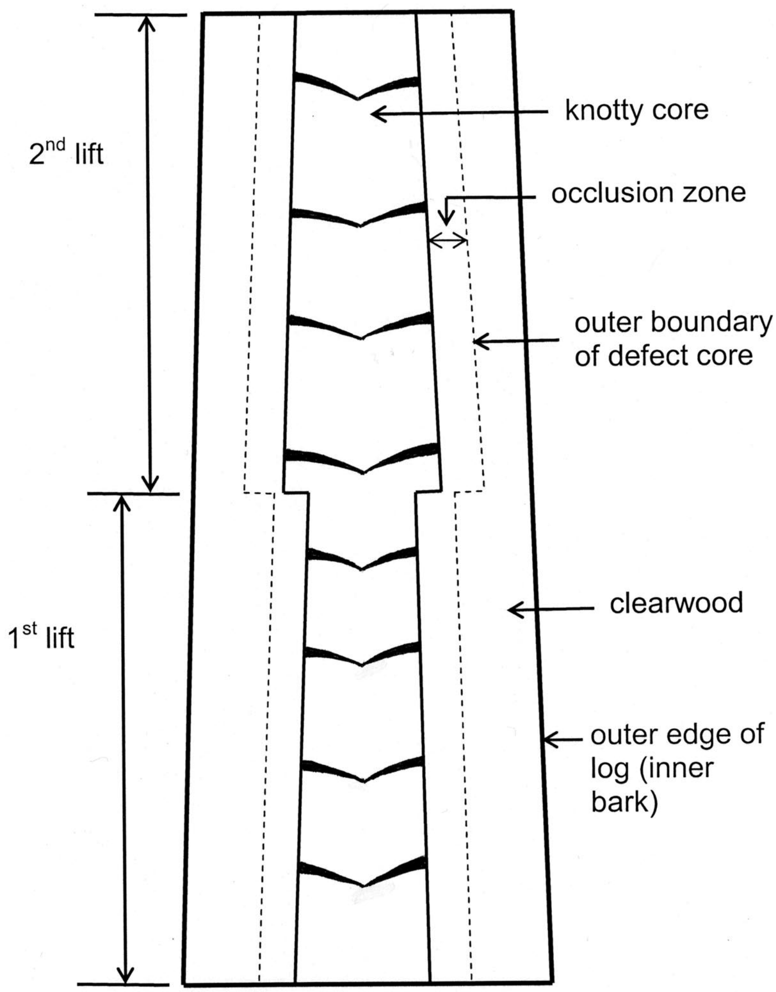

Figure 1. Schematic of pruned bole showing the occlusion zone and the clearwood formed outside the knotty or defect core. This example shows a bole pruned in two lifts. The defect core includes both the knotty core and the occlusion zone. Schematic is not to scale.

The Conundrum

The conundrum over pruning techniques involves the branch collar or any additional living tissues at the base of the branch. Branch diameter decreases quite dramatically in a short distance from the stem (Herring et al. 1958). If the branch is cut flush with the stem (i.e., a flush or close cut), the resulting wound is larger than if the branch is cut outside the branch collar. If the branch is cut farther from the stem (i.e., an outside branch collar cut), the resulting wound at the end of the branch stub is smaller but the defect core will be larger because branch stubs are longer. The conundrum is whether a larger wound and smaller defect core are preferable to a larger defect core and a smaller wound.

Solutions to this conundrum are related to the objectives of pruning. For forest pruning, minimizing the size of the defect core

Figure 2. Branch collars of coast (A) Douglas-fir, (B) radiata pine, (C) *E. globulus* (Labill.), and (D) northern red oak (*Q. rubra* L.). Branch collars are highly variable between species and generally are smaller in young trees with small branches.

and maximizing clearwood production is a common objective. The flush or close cut therefore would minimize the defect core if there was not a corresponding increase in the occlusion zone, fungal infection, or the time required for occlusion. A different set of solutions would be appropriate for objectives other than maximizing clearwood production such as aesthetics, hazard branch removal, or fuelwood production.

Natural Target Pruning

Building on his work with compartmentalization of decay in trees (Shigo and Marx 1977, Shigo 1984a, 1985a), Shigo developed a "natural target pruning" approach (Shigo 1984b) that removes branches by cutting outside the branch collar (Figure 3). Natural target pruning severs the branch to preserve the branch collar but emphasizes that no additional stub length should be left. Shigo (1985b) described the branch collar as providing a protection zone that forms as branches begin to die. According to this work, removal of the branch collar leaves the wound susceptible to internal spread of discoloration and decay (Green et al. 1981, Shigo 1985b).

Shigo (1984b) recommended a pruning approach that identified the intersection of the branch and the branch collar on the upper and lower sides of the branch. These "targets" form the points of initiation and termination of the cut. By preserving the branch collar and not leaving any additional branch stub, this method was designed to meet the singular objective of maintaining tree health. Therefore, a tree's potential to occlude quickly and prevent infection is fundamental to this pruning method.

Pruning Wound Occlusion

The process of occlusion of a pruning wound is central to this conundrum because occlusion must occur before clearwood is formed and rapid occlusion is a key defense against infection by stem decay fungi (Mayer-Wegelin 1936, Boyce 1961, 373; Shigo 1986 Chap. 38; Biggs 1992). Previous research on pruning wound occlusion indicates that this is not a new conundrum: Mayer-Wegelin (1936), in probably the most comprehensive review of pruning at that time, cites scores of studies on wound occlusion from Europe dating back to the 18th and 19th centuries. The most significant of these early studies included the detailed branch anatomy studies of Kienitz (1878), who examined orientation of branch and stem fibers. He concluded more rapid occlusion would result from a cut through the

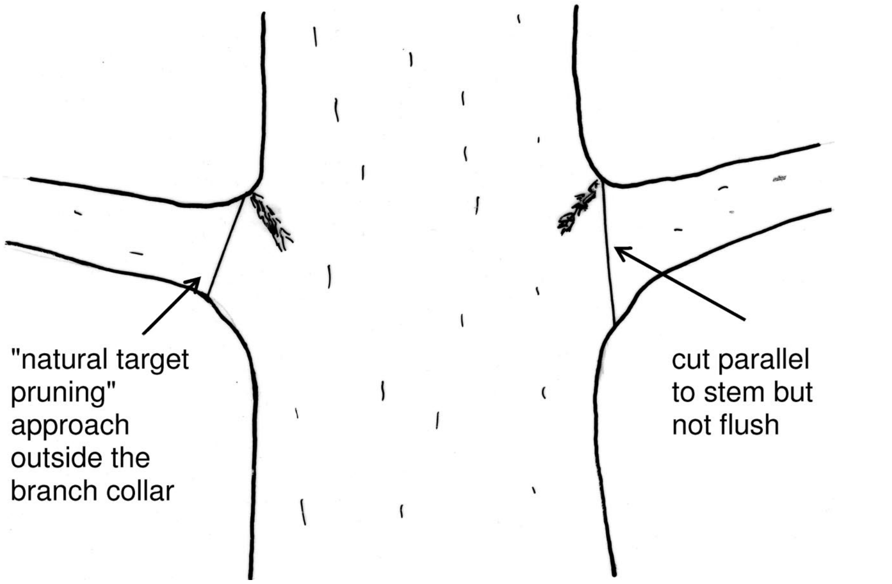

Figure 3. Cutting approaches for a natural target pruning approach (left) and a close cut parallel to the stem but not quite flush (right). The "close cut" leaves a larger wound but previous research indicates it would occlude more quickly than the natural target pruning cut and would reduce the size of the defect core.

branch collar because the angle of severed branch fibers favored more rapid occlusion than branch cuts outside the branch collar. Mayer-Wegelin's (1936) assessment of prior research led him to recommend not only a close cut, but also cutting into the bark and outside the annual ring to minimize the length of the branch stub. An extreme example of a close-to-the-stem cutting approach was recommended by Des Cars (1900, 35) in his classic book on pruning: branches should be "evenly cut and shaped as nearly as possible to the trunk of the tree."

Similar questions were asked and similar studies were undertaken in the 20th Century. Adams and Schneller (1939) completed a detailed comparison of pruning through the branch collar and outside the branch collar in eastern white pine (*Pinus strobus* L.). They looked at resin flow and callus formation on dead and live branch wounds 1 year after pruning. Resin flow is an initial defense to infection and during the growing season may occur within minutes of cutting. The chemical composition of resin changes after wounding to be more resistant to infection (Gref and Ericsson 1985, Cook and Hain 1987). Cutting branches through the branch collar increased both resin flow and callus formation. Additionally, resins are concentrated in the branch base: Köster (1934) reported resin concentrations in the branch bases in Norway spruce (*Picea abies* [L.] Karst.) 10 times greater than those in the branch or bole. Adams and Schneller (1939) found over 97% of branches sawn through the branch base showed callus formation after 1 year compared with 18.9% of branches cut outside the branch collar. Paul (1938) concluded pruning cuts should be "well into the collar at the base of the branch" in eastern white pine and red pine (*Pinus resinosa* Ait.), as did Barrett and Downs (1943) with eastern white pine in the southern Appalachians.

Helmers (1946) compared close cutting with cutting outside the branch collar in both live and dead branches of ponderosa pine (*Pinus ponderosa* P.&C. Lawson) and western white pine (*Pinus monticola* Dougl. ex D. Don). He found greater occlusion with the close cutting than with the outside branch collar cutting on both live and dead branches, greater occlusion on smaller branches than on larger branches, and greater occlusion in open stands, despite these stands having larger branches, than in denser stands. Olsen and Paul (1948) also reported more rapid initiation of occlusion in ponderosa pine when cuts were closer to the stem. Huey (1950) found the greatest increase in lumber quality came from confining knots to the "smallest possible core" in ponderosa and western white pines.

Childs and Wright (1956) found close cuts occluded more quickly in coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco) despite their larger size and—like Mayer-Wegelin (1936)—also suggested occlusion might be hastened by injuring the cambium. In studies in the United Kingdom, Donald (1936) and Anderson (1937) advocated a close cut approach in Norway spruce, Sitka spruce (*Picea sitchensis* [Bong.] Carr.), Scots pine (*Pinus sylvestris* L.), and coast Douglas-fir. Similarly, Henman (1963) recommended "close pruning" with Norway spruce and Sitka spruce.

There are fewer studies of wound occlusion in broad-leaved species; historically, they probably have been pruned less often for clearwood production. Meyer-Wegelin's (1936) recommendations to use close cuts based on research to that date in Europe included broad-leaved species. With European beech (*Fagus sylvatica* L.), Zimmerle (1943) found greater occlusion with close cuts. Occlusion was more rapid with cuts that damaged the branch collar in red alder despite these cuts leaving larger wounds (Brodie and Harrington 2006, DeBell et al. 2006). In eastern North America, Roth (1948) examined occlusion and defects in four oak species (*Quercus* spp.) and recommended close cuts for live branch removal and cutting into the living tissues at the base of dead branches. Similarly, faster occlusion was found with close cuts in several broad-leaved species in New England (Moss 1937). Skilling (1958) also found leaving even a small stub would increase time to occlusion in sugar maple (*Acer saccharum* Marsh.) and American elm (*Ulmus americana* L.). For black cherry (*Prunus serotina* Ehrh.), Grisez (1978) recommended cutting close to the stem after observing no serious problems after pruning. With black walnut (*Juglans nigra* L.), Shigo et al. (1978, 1979) recommended close cuts only for small branches. However, for (larger) branches on older trees they recommended not cutting branch collars because dead and dying branches have already compartmentalized (see Shigo and Marx [1977]), creating a potential for formation of ring shakes and discolored wood. No significant decay was noted and close pruning was recommended in young trees with fast growth rates (Shigo et al. 1978, 1979).

An alternative approach to this conundrum are studies that dissect pruning wounds and develop models to predict either time to occlusion or the size of occlusion zone from branch stub length and diameter. Studies using this approach in slash pine (*Pinus elliottii* Engelm.), red pine, sugi (*Cryptomeria japonica* D. Don.), radiata pine (*Pinus radiata* D. Don), Norway spruce, ponderosa pine, and coast Douglas-fir have found stub length was far more important in delaying occlusion than stub width (Hogan 1957, Lohrey 1963, Takeuchi 1981, Gosnell 1987, Vadla 1989, O'Hara and Buckland 1996, Petruncio et al. 1997). Bauger and Orlund (1962) used a similar but graphical analysis to reach similar conclusions for Norway spruce, Sitka spruce, grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.), and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). DeBell et al. (2006) report similar conclusions for red alder (*Alnus rubra* Bong.) based on correlation analysis. The sensitivity of occlusion to stub length relative to stub diameter in these studies indicates the advantages of close cuts when the pruning objective is to minimize the size of the occlusion zone.

Another common finding in pruning studies with both conifers and broad leaves is more rapid occlusion in trees with faster radial growth rates (Mayer-Wegelin 1936, Roth 1948, Lohrey 1963, O'Hara and Buckland 1996, Petruncio et al. 1997). More rapid radial growth rates indicate greater xylem production and result in more rapid occlusion. Similarly, Rapraeger (1939) found both greater branch size and more rapid occlusion higher in the bole of western white pine. In Scots pine, Pietilä (1989) found both faster growth rates and a smaller occlusion zone with increasing height. Because occlusion is the result of callus/xylem formation over the branch stub, more rapid radial growth rates—as often are found in the upper stem of pruned trees (Mayer-Wegelin 1936, Staebler 1963, Keller 1968)—result in more rapid occlusion.

Many studies have noted the more rapid occlusion of live branches than dead branches. For example, Paterson (1938) and Vadla (1989) in Norway spruce, Adams and Schneller (1939) in eastern white pine, Romell (1940) in Norway spruce and Scots pine, Henman (1963) in Norway spruce and Sitka spruce, Smith et al. (1988) in ponderosa pine, and Miler et al. (1990) in Scots pine reported slower occlusion in dead branches. This slower occlusion probably is related to lower radial growth rates on the stem in the area of dead branch attachment. Results from cutting method studies with dead branches resemble those for live branches. Curtis (1936) reported that when the branch base of eastern white pine was cut, exposing a larger wound, 63% of cuts showed callus development compared with 7.8% for outside the branch collar. Similar results, by Adams and Schneller (1939), were obtained 1 year after pruning eastern white pine. Several studies have recommended that the branch base be injured during cutting to stimulate occlusion (Meyer-Wegelin 1936) because there is the potential for the tree to fail to occlude a dead branch wound. Collectively, these studies suggest that wounding the cambium is not necessarily bad for the tree and it may stimulate more rapid occlusion.

Although the objective of maximizing clearwood production generally is unique to forest pruning, similar results with wound occlusion have been reported in the arboriculture literature. Neely (1988a, 1988b) found faster occlusion with a "conventional cut" that removed part of the branch collar than with a cut outside the branch collar in several broad-leaved species including pin oak (*Quercus palustris* Muenchh.), American sycamore (*Plantanus occidentalis* L.), and Norway maple (*Acer platanoides* L.). Despite wounds that were as much as 51% larger using the conventional cut, by the end of the 2nd year after pruning, 44% of conventional cuts were occluded compared with 36% for the outside the branch collar cut.

Pruning Wounds as Infection Sites

Infection of fungal decay organisms always has been a concern with pruning and is a primary factor in assessing branch cutting techniques. Meyer-Wegelin (1936) reported problems with decay in the 1800s that were attributed to poor pruning practices: leaving long stubs and ax pruning. Once these were corrected, decay was not a problem. Subsequent work with Norway spruce has produced mixed results. Paterson (1938), Romell (1940), and Henman (1963) reported no issues with fungal infection, whereas Bauer (1945) and Risley and Silverborg (1958) reported severe problems. In Norway, Vadla (1989) found 12% of pruned Norway spruce trees with some decay or staining, but only approximately 1% of branch wounds were infected in all trees and this decay was attributed to poor pruning practices. In coast Douglas-fir, infections of heartrot fungi occurred after pruning, but Childs and Wright (1956) found these infections were small and died soon after occlusion. Others have reached similar conclusions with coast Douglas-fir (Anderson 1951, Stein 1955, Lukert 1959, Henman 1963), radiata pine (Roche and Hocking 1937), Scots pine (Romell 1940, Henman 1963, Vuokila 1976), Sitka spruce (Henman 1963), loblolly pine (Mann 1952), and ponderosa pine (Roche and Hocking 1937, Andrews 1954). In eastern white pine, Cline and Fletcher (1928) observed no decay problems in small limbs but Spaulding et al. (1935) found problems after pruning larger limbs. Similarly, Paul (1938) found no decay problems in eastern white pine and red pine after pruning. Chou and MacKenzie (1988) used artificial inoculations and found greater probability of infection with increasing wound size in radiata pine in New Zealand.

For broad-leaved trees, there have not been many reports of stem decay after pruning in the northern hemisphere. Nylinder (1955) described the risk of rot after pruning pedunculate oak (*Quercus robur* L.) in Sweden as "slight." Skilling (1958) found no evidence of decay in sugar maple and American elm and found less decay in pruned trees than unpruned trees. Similarly, there have been no significant studies indicating fungal decay problems after pruning in silver birch (*Betula pendula* Roth.; Vuokila [1976]) or red alder (DeBell et al. 2006). In Taiwan, wood decay was infrequent in smaller branches of zelkova (*Zelcova serrata* Hay.; Chiu et al. [2002]). In European beech, Volkert (1953) found decay and discoloration but reported that fungal activity essentially ceases by approximately 9 years after pruning.

Exceptions to the minimal fungal decay problems associated with pruning are in *Eucalyptus* and *Acacia* species. Glass and McKenzie (1989) reported decay problems in *Eucalyptus regnans* (F. Mueller) after pruning in New Zealand and similar problems have been observed in other eucalypts (see Montagu et al. [2003] and Barry et al. [2005]). These problems were more common in large branches (Glass and McKenzie 1989).

Pruning also led to a greater incidence of decay in *Acacia mangium* (Willd.) in Asia (Lee et al. 1988, Barry et al. 2005). No studies, including these studies, with eucalypts and acacias, report decay spreading into wood formed after pruning.

Although there are reasons to be cautious regarding potential infection of trees by fungal decay organisms when developing a pruning regime, the evidence that close cutting contributes to these problems is minimal. With the notable exception of the problems in eucalypts and acacias, pruning does not appear to be a major factor in affecting stem decay or related defects in the great majority of pruning studies. Where stem decay infection is a potential problem, pruning in younger stands where branch size is minimized is recommended or avoiding

Figure 4. Ponderosa pine whorl after pruning showing cuts generally parallel to the stem but not flush. In this case, flush cuts would nearly girdle the tree.

pruning species in locales where problems are significant. It is also interesting that several studies noted the potential of pruning to *reduce* infections in both conifers and broad leaves (Andrews 1954, Skilling 1958, Grisez 1978, Barry et al. 2005).

Forest Pruning Recommendations

An old idiom says "there's more than one way to skin a cat." There also are many ways to prune tree branches and—contrary to many sources—more than one may be correct. Correctness is primarily a function of management objectives and species. For plantation forestry regimes, the two objectives of maintenance of tree health and maximization of clearwood production are not mutually exclusive. It follows that for production of clearwood on conifers, particularly in plantations, a cut parallel and reasonably close to the stem is a logical means to minimize the size of the defect core and maximize clearwood production. For broadleaved trees, a similar recommendation should be successful except in the situation where branches are excessively large, resulting in many years for occlusion to occur. The expectation in most situations is that this will not lead to significant fungal infection. There will be exceptions, e.g., eucalypts and acacias that have a high probability of fungal infection after pruning. Close cuts of conifer branches that occur in whorls with branch collars or nodal swelling may girdle the tree (Figure 4). Close cuts also may exacerbate other problems such as Douglas-fir pitch moth (*Stynanthedon navaroensis* [Hy. Edwards]) attacks in coast Douglas-fir (Briggs 2000). Additionally, available knowledge is almost exclusive to temperate forests and may not apply to tropical species.

Pruning should be integrated into stand management regimes that include careful density management to control branch sizes. Stand density affects branch length and diameter and radial growth rates; therefore, there will be a tradeoff between minimizing branch size and maximizing growth rates. Pruning early in a rotation often is recommended because it minimizes the size of the defect core; additionally, early rotation pruning is likely to involve smaller branches that are still alive and associated with more rapid occlusion, thinner bark, and less decay. In situations where stem decay is a potential deterrent to pruning, light pruning regimes or multiple pruning lifts can result in "earlier" pruning that removes smaller, live branches; these treatments led to fewer infections in radiata pine artificially inoculated with *Diplodia pinea* (Chou and MacKenzie 1988). Season of pruning also may affect infection potential; however, there is no consensus across species on optimal season to prune (Uotila 1990).

Science and the Conundrum

It is logical to question why science has not solved this conundrum when it has been recognized for so long. Science often works this way. It is not linear and it is not always correct, but it is usually directional. The scientific method involves developing hypotheses; making predictions from hypotheses; testing these predictions with observable, empirical, and measurable evidence; and refining these hypotheses into new theories. In this case, the issues are clouded from a myriad of variables that affect pruning wound responses. These include species, regional differences in pathogen virulence, season of pruning, age of trees, and genetic variation within species and affects on occlusion.

There have been three general approaches to this problem: (1) the extension of observational studies of wood anatomy to recommendations on pruning, (2) comparative treatment studies of different pruning methods with dissections and either direct comparisons of pruning methods or inferences to pruning methods from observations of occlusion, and (3) models of occlusion based on radial growth rates and the length and diameter of the branch stub. The first approach is a useful means of developing hypotheses that might later be tested with comparisons of alternate approaches. In this case, the extensive international research that preceded the development of the "natural target pruning" method and demonstrated the merits of close cutting approaches should have—at a minimum—warranted thorough testing of alternative hypotheses. The latter two approaches are the quantitative means generally accepted by science for hypothesis testing.

The emphasis on the "natural target pruning" approach in current guidelines also establishes the persuasive power of books in our society. The common sources in pruning guidelines (e.g., Bedker et al. [1995], Table 1) and textbooks (Kozlowski et al. 1991, 500; Nyland 2002, 470–471) for the outside branch collar approach are a series of books written and published by Shigo (1986, 1989, 1991). Not only were all three of these books self-published, they apparently underwent no peer review. Although these books were built, in part, on the author's substantial body of previous research—some of which was published in the peer-reviewed literature—the thrust of this work is primarily observational descriptions of tree responses to injury; there is a general lack of quantitative data and no statistical comparisons of pruning methods.

Science also should build on previous knowledge, but in the case of pruning research, there has been a disconnect between the extensive research in the past and the observational studies that led to "natural target pruning." An additional problem has been the assumption that pruning techniques should be consistent regardless of the pruning objective and species. Although a close cut may be appropriate for maximizing clearwood production, it may produce an unattractive wound on an ornamental tree, it may increase costs for pruning to remove diseased branches, or it may form an infection site in some species. A search for a universal model for tree wound response for all species, objectives, and situations is flawed and probably hinders our scientific progress in this area.

Finally, this conundrum leaves room for more long-term studies of pruning wound occlusion after different branch removal methods. Studies that compare pruning techniques in trials that follow individual wounds and then dissect them will yield the strongest conclusions. Observational studies of dissected branch wounds without information on their origin and subsequent development of conclusions without appropriate controls or alternative treatments is not likely to solve this problem. Planned trials of different branch removal methods also will be most amenable to statistical comparisons that permit testing of hypotheses.

Conclusions

There is a considerable international body of literature on forest pruning and much of it pertains to methods of branch removal and subsequent wound occlusion. This branch removal literature includes designed studies to compare occlusion response with different pruning methods, quantitative assessments of dissections of previous pruning wounds, and observational and pictorial evidence of pruning wound response. The clear majority of this work indicates that a cut close to the stem is effective for pruning forest trees to enhance wood quality without detrimental infections of fungi or bacteria. This body of work indicates that pruning early when branches are small will minimize problems with infections. Other work recommends an outside-the-branch collar method of branch removal and is based on observations of wound response. One consensus that is apparent in this literature is that forest pruning is most likely to be successful in young, fast-growing trees with small branches that occlude quickly and are less likely to be infected by stem decay fungi. This is consistent with objectives in forest pruning of minimizing the defect core and reducing costs of pruning branches.

There is also a theme in recent forest pruning guidelines to recommend only a single method of branch removal regardless of the pruning objective. Branches are removed for a variety of objectives in forests and different methods probably would be more suited for some objectives than others. Likewise, pruning in nonforest situations may require a diversity of approaches depending on objectives. Foresters and arborists must integrate their knowledge of branch wound response with the suitability of different branch removal methods rather than assuming that a single method is best in all situations.

Literature Cited

Adams, W.R., and M.R. Schneller. 1939. *Some physiological responses to close pruning of northern white pine*. Bull. 444, Vermont Agricultural Experiment Station, Burlington, VT. 26 p.

Anderson, E.A. 1951. *Healing time for pruned Douglas-fir.* USDA For. Serv. For. Prod. Lab. Rep. R1907. 17 p.

Anderson, R.T. 1937. Pruning of green branches of conifers. *Quart. J. For.* 31:29–31.

Andrews, S.R. 1954. Effect of pruning on western red rot in young ponderosa pine in the southwest. *J. For.* 52:33–39.

Barrett, L.I., and A.A. Downs. 1943. Growth responses of white pine the southern Appalachians to green pruning. *J. For.* 41(7):507–510.

Barry, K.M., M.F. Hall., and C.L. Mohammed. 2005. The effect of time and site on incidence and spread of pruning-related decay in plantation-grown *Eucalyptus nitens. Can. J. For. Res.* 35:495–502.

Bauer, B. 1945. Consequences of pruning Norway spruce. *Skogsägaren* 21(3):52–53.

Bauger, E., and A. Orlund. 1962. Undersøkelser etter kvisting i treslagene sitkagran, *Abies grandis*, hemlock, grun og *Thuja. Meddelelser Vestlandets Forstlige Forsoksstasjon* 11(4)36:169–197.

Bedker, P.J., J.G. O'Brien, and M.M. Mielke. 1995. *How to prune trees.* USDA For. Serv. State and Private Forestry NA-FR-01-95. 12 p.

Biggs, A.R. 1992. Anatomical and physiological responses of bark tissues to mechanical injury. P. 13–40 in *Defense mechanisms of woody plants against fungi*, Blanchette, R.A., and Biggs, A.R. (eds.). Springer-Verlag, Berlin. 458 p.

Boyce, J.S. 1961. *Forest pathology*. McGraw-Hill Book Co., New York. 572 p.

Briggs, D. 2000. *Can the Douglas-fir pitch moth, Synanthedon novaroensis, (Hy. Edwards) ruin pruning investments?* SMC Fact Sheet, Vol. 5, Stand Management Cooperative, Univ. of Washington, Seattle, WA. 2 p.

Brodie, L.C., and C.A. Harrington. 2006. Response of young red alder to pruning. P. 95–102 in *Red alder—a state of knowledge*, Deal, R.L., and Harrington, C.A. (eds.). USDA For. Serv. Gen. Tech. Rep. PNW-GTR-669. 150 p.

Brown, G.E. 2004. *The pruning of trees, shrubs and conifers*, 2nd Ed. Timber Press, Portland, OR. 338 p.

Childs, T.W., and E. Wright. 1956. *Pruning and occurrence of heart rot in young Douglas-fir.* USDA For. Serv., Res. Note 132, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 5 p.

Chiu, C.-M., C.C.N. Lo, and M.Y. Suen. 2002. Pruning method and knot wound analysis of Taiwan zelkova (*Zelkova serrata* Hay.) plantations. *Taiwan J. For. Sci.* 17:503–513.

Chou, C.K.S., and M. MacKenzie. 1988. Effect of pruning intensity and season on *Diplodia pinea* infection of *Pinus radiata* stem through pruning wounds. *Eur. J. For. Pathol.* 18:437–444.

Cline, A.C., and E.D. Fletcher. 1928. *Pruning for profit as applied to eastern white pine.* The Harvard Forest and Massachusetts Forest Association, Boston, MA. 24 p.

Cook, S.P., and F.P. Hain. 1987. Four parameters of the wound response of loblolly and shortleaf pines to inoculation with the blue-staining fungus associated with the southern pine beetled. *Can. J. Bot.* 65:2403–2409.

Curtis, J.D. 1936. A method of pruning dead branches. *For. Chron.* 12:291–299.

Curtis, J.D. 1937. Historical review of artificial forest pruning. *For. Chron.* 13:380–395.

DeBell, D.S., C.A. Harrington, B.L. Gertner, and R. Singleton. 2006. Time and distance to clear wood in pruned red alder saplings. P. 103–113 in *Red alder—a state of knowledge*, Deal, R.L., and C.A. Harrington (eds.). USDA For. Serv. Gen. Tech. Rep. PNW-GTR-669. 150 p.

Des Cars, A. 1900. *A treatise on pruning forest and ornamental trees.* Massachusetts Society for the Promotion of Agriculture, Boston. 65 p.

Donald, G.H. 1936. Pruning studies at Princes Risborough. *Quart. J. For.* 30:111–120.

Emmingham, W., and S. Fitzgerald. 1995. *Pruning to enhance tree and stand value*. Extension Serv. Pub. EC 1457, Oregon State Univ., Corvallis, OR. 12 p.

Fazio, J.R. 2006. *How to prune young shade trees.* Tree City USA Bull., The National Arbor Day Foundation, Nebraska City, NE. 8 p.

Glass, B.P., and H. McKenzie. 1989. Decay distribution in relation to pruning and growth stress in plantation-grown *Eucalyptus regnans* in New Zealand. *New Zeal. J. For. Sci.* 19:210–222.

Gosnell, T. 1987. *Equations for predicting defect core size for pruned radiata pine butt logs.* New Zealand Forest Research Institute FRI Bull. 131. 20 p.

Green, D.J., W.C. Shortle., and A.L. Shigo. 1981. Compartmentalization of discolored and decayed wood in red maple branch stubs. *For. Sci.* 27:519–522.

Gref, R., and A. Ericsson. 1985. Wound-induced changes of resin acid concentrations in

living bark of Scots pine seedlings. *Can. J. For. Res.* 15:92–96.
GRISEZ, T.J. 1978. *Pruning black cherry in understocked stands.* USDA For. Serv. Res. Pap. NE-395. 9 p.
HANLEY, D.P., AND S. REUTEBUCH. 2005. *Conifer pruning basics for family forest landowners.* Washington State Univ. Extension, Pullman, WA. EB1984. 8 p.
HELMERS, A.E. 1946. *Pruning wound healing on western white and ponderosa pines.* USDA For. Serv., Res. Note 45, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, MT. 6 p.
HENMAN, D.W. 1963. *Pruning conifers for production of quality timber.* Great Britain Forestry Commission Bull. 35. 49 p.
HERRING, H.G., V.J. RUDOLPH., AND W.A. LEMMIEN. 1958. Wound area as influenced by closeness of pruning. *J. For.* 56:219–220.
HOGAN, L.D. 1957. *The relationship between years to heal and certain measurable variables in pruned slash pine (Pinus elliottii).* MS thesis, Univ. of Georgia, Athens, GA. 35 p.
HUEY, B.M. 1950. *The profit in pruning western white and ponderosa pine.* USDA For. Serv., Res. Note 85, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, MT. 6 p.
IOWA STATE UNIVERSITY 1998. *Pruning forest trees.* Iowa State Univ. Extension, Pm-1133, Ames, IA. 4 p.
KELLER, R. 1968. L'élagage artificiel de branches vivantes sur resineux. *Rev.For. Fr.* 20(7/8): 458–473.
KIENITZ, M. 1878. Über die Aufastung der Waldbäume. *Allg. Forst-. und Jagdzeitung.* 58 p.
KÖSTER, E. 1934. Die astreinigung der fichte. *Maitteil. Forstwirtsch. Fortstwiss.* 5(3):393–416.
KOZLOWSKI, T.T., P.J. KRAMER, AND S.G. PALLARDY. 1991. *The physiological ecology of woody plants.* Academic Press, San Diego, CA. 657 p.
LEE, S.S., S.Y. TENG., M.T. LIM, AND R.A. KADER. 1988. Discolouration and heartrot of *Acacia mangium* Willd.—some preliminary results. *J. Trop. For. Sci.* 1:170–177.
LOHREY, R.E. 1963. *Healing time for pruning wounds in a red pine plantation.* USDA For. Serv., Res. Note LS-24, Lake States Forest Experiment Station, St. Paul, MN. 2 p.
LUKERT, J.L. 1959. *The effects of pruning on the growth and development of a Douglas-fir plantation.* MS thesis, Oregon St. College, Corvallis, OR. 42 p.
MACLAREN, J.P. 1993. *Radiata pine growers' manual.* FRI Bull. 184, New Zealand Forest Research Institute. 140 p.
MANN, W.F. JR. 1952. *Loblolly pruning scars heal rapidly.* USDA For. Serv., Southern Forest Experiment Station Southern Forestry Notes 77: 3–4. New Orleans, LA.
MAYER-WEGELIN, H. 1936. Ästung. M.& H. Schaper, Hanover, Germany (extracts in US For. Serv. Div. of Silvics, translation no. 264, 1936).
MILER, Z., T. CYBULKO, W. PAZDROWSKI, AND S. DROGOSZ. 1990. Zmiennosc zarastania ran u podkrzesywanej sosny pospolitej (*Pinus silvestris* L.). *Praec.* Z. *Zakresu Nauk Lesnych.* 66: 71–78.
MONTAGU, K.D., KEARNY, D.E., AND R.G.B. SMITH. 2003. The biology and silviculture of pruning planted eucalypts for clear wood production—a review. *For. Ecol. Manage.* 179:1–13.
MOSS, A.E. 1937. Pruning second growth hardwoods in Connecticut. *J. For.* 35:823–828.
NEELEY, D. 1988a. Tree wound closure. *J. Arboricult.* 14:148–152.
NEELEY, D. 1988b. Closure of branch pruning wounds with conventional and 'Shigo' cuts. *J. Arboricult.* 14:261–264.
NICOLESCU, N.-V. 1999. *Artificial pruning—a review.* Univ. of Transylvania of Braşov, Romania. 65 p.
NYLAND, R.D. 2002. *Silviculture: Concepts and applications,* 2nd Ed. McGraw-Hill, New York. 682 p.
NYLINDER, P. 1955. Kvistingsundersökningar. I. Grönkvistning av ek. *Meddelanded fræan Statens Skogsförsöksanstalt.* 45(12):1–44.
O'HARA, K.L. 1989. *Forest pruning bibliography.* Univ. of Washington, Institute of Forest Resources Contribution No. 67. 74 p.
O'HARA, K.L., AND P.A. BUCKLAND. 1996. Prediction of pruning wound occlusion and defect core size in ponderosa pine. *West. J. Appl. For.* 11:40–43.
OLSEN, D.S., AND B.H. PAUL. 1948. Some results of artificial pruning of ponderosa pine. *West Coast Lumberman* 75(5):94–96, 104.
PATERSON, A. 1938. The occlusion of pruning wounds in Norway spruce (*Picea excelsa*). *Ann. Bot. (UK)* 2(7):681–698.
PAUL, B.H. 1938. *Knots in second-growth pine and the desirability of pruning.* USDA Misc. Pub. 307. 35 p.
PETRUNCIO, M., D. BRIGGS, AND R.J. BARBOUR. 1997. Predicting pruned branch stub occlusion in young, coastal Douglas-fir. *Can. J. For. Res.* 27:1074–1082.
PIETILA, J. 1989. Factors affecting the healing-over of pruned Scots pine knots. *Silva Fenn.* 23:125–158.
RAPRAEGER, E.F. 1939. Development of branches and knots in western white pine. *J. For.* 37: 239–245.
RISLEY, J.H., AND S.B. SILVERBORG. Stereum sanguinolentum on living Norway spruce following pruning. *Phytopathology* 48:337–338, 1958.
ROCHE, H., AND G.H. HOCKING. 1937. Artificial pruning of exotic conifers. *New Zeal. J. For.* 4(2):86–91.
ROMELL, L.-G. 1940. Kvistningsstudier æa tall och gran (Studies on pruning in Scots pine and Norway spruce). *Meddelanden fræan Statens Skogförsöksanstalt.* 32:143–194.
ROTH, E.R. 1948. Healing and defects following oak pruning. *J. For.* 46:500–504.
SHIGO, A.L. 1984a. Compartmentalization: A conceptual framework for understanding how trees grow and defend themselves. *Ann. Rev. Phytopathol.* 22:189–214.
SHIGO, A.L. 1984b. Tree decay and pruning. *Arboricult.l J.* 8:1–12.
SHIGO, A. L 1985a. Compartmentalization of decay in trees. *Sci. Am.* 252(4):96–104.
SHIGO, A.L. 1985b. How tree branches are attached to trunks. *Can. J. Bot.* 63:1391–1401.
SHIGO, A.L. 1986. *A new tree biology: Facts, photos, and philosophies on trees and their problems and proper care.* Shigo and Trees, Associates, Durham, NH. 595 p.
SHIGO, A.L. 1989. *Tree pruning: A worldwide photo guide.* Shigo and Trees, Associates, Durham, NH. 186 p.
SHIGO, A.L. 1991. *Modern arboriculture.* Shigo and Trees, Associates, Durham, NH. 424 p.
SHIGO, A.L., AND H.G. MARX. 1977. Compartmentalization of decay in trees. [CODIT] USDA For. Serv. Info. Bull. 405.
SHIGO, A.L., N.F. ROGERS, E.A. MCGINNES JR., AND D.T. FUNK. 1978. *Black walnut on Kansas strip mine spoils: Some observations 25 years after pruning.* USDA For. Serv. Res. Pap. NE-393.
SHIGO, A.L., E.A. MCGINNES JR., D.T. FUNK, AND N. ROGERS. 1979. *Internal defects associated with pruned and nonpruned branch stubs in black walnut.* USDA For. Serv. Res. Pap. NE-440.
SISAM, J.W.B., I. KISSING, AND P.G. BECK. 1940. Recent work on the pruning of forest trees with particular references to *Pinus* spp. *For. Abstr.* 2(2):97–107.
SKILLING, D.D. 1958. Wound healing and defects following northern hardwood pruning. *J. For.* 56:19–22.
SMITH, R.C., W.B. KURTZ., AND T.E. JOHNSON. 1988. Cost efficiency of pruning Black Hills ponderosa pine. *West. J. Appl. For.* 3:10–14.
SPAULDING, P., H.J. MACALONEY, AND A.C. CLINE. 1935. *Stereum sanguinolentum, a dangerous fungus in pruning wounds on northern white pine.* USDA For. Serv., Northeastern Forest Experiment Station, Radnor, PA. Tech. Note. No. 19. 2 p.
STAEBLER, G.R. 1963. Growth along the stems of full crowned Douglas-fir trees after pruning to specified heights. *J. For.* 61:124–127.
STEIN, W.I. 1955. Pruning to different heights in young Douglas-fir. *J. For.* 53:352–355.
TAKEUCHI, I. 1981. Studies on the occlusion of branch stubs after artificial pruning of mature stands (I). In a 72-year-old sugi stand. *J. Jap. For. Soc.* 63:39–45.
UOTILA, A. 1990. Infection of pruning wounds in Scots pine by *Phacidium coniferarum* and selection of pruning season. *Acta For. Fenn.* 215: 36.
VADLA, K. 1989. Stammekvisting av gran (*Picea abies* (L.) Karst.). *Meddelelser fra Norsk Institutt for Skogforskning* 43(3):1–42.
VOLKERT, E. 1953. Untersuchungen uber das verhalten von astabfall bei rotbuche. *Forstwiss. Centralblatt* 72(3/4):110–124.
VUOKILA, Y. 1976. *Karsimisen vaikutus mannyn ja koivun terveystilaan (Effect of green pruning on the health of pine and birch).* Folia Forestalia, Institutum Forestale Fenniae No. 281. 13 p.
WINDELL, K. 1996. *Pruning in timbered stands.* USDA For. Serv. Tech. Rep. 9624-2815-MTDC, Missoula Technology and Development Center, Missoula, MT. 112 p.
ZIMMERLE, H. 1943. Uber astungsversuche bei der rotbuche. *Allg. Forst. Jagdstg.* 119:88–104.