EB2018E

Canopy Management for Pacific Northwest Vineyards

Mercy Olmstead

Kathleen Williams

Markus Keller

WASHINGTON STATE UNIVERSITY EXTENSION

Canopy Management for Pacific Northwest Vineyards

By:
Mercy Olmstead
Kathleen Williams
Markus Keller

Growing grapes in the Pacific Northwest (PNW) can be challenging and rewarding due to highly variable vegetative growth within the region. For example, growers with vineyards located in maritime climates (e.g., Puget Sound American Viticultural Appellation [AVA]) are largely concerned with controlling vegetative growth and increasing fruit exposure to sunlight, while those in the inland PNW (e.g., Yakima or Columbia Valleys) often need to adjust their vegetative management to protect their canopy and fruit from sun exposure. Growers need to carefully assess their vineyard site, including soil characteristics, annual precipitation, and precipitation timing, to determine the best fit with specific grape varieties in terms of potential vine vigor, productivity, and fruit quality. Proper canopy management can lead to good profits for the grower and high quality fruit for the winemaker.

Throughout the world, management of grapevine canopies has changed over the years. Many European countries now use a tightly spaced, minimal height vineyard with no trellis support, while some New World countries opt for a wider spacing and trellis system. Benefits can be realized for both types of systems and those in between, depending upon grape variety characteristics and climate.

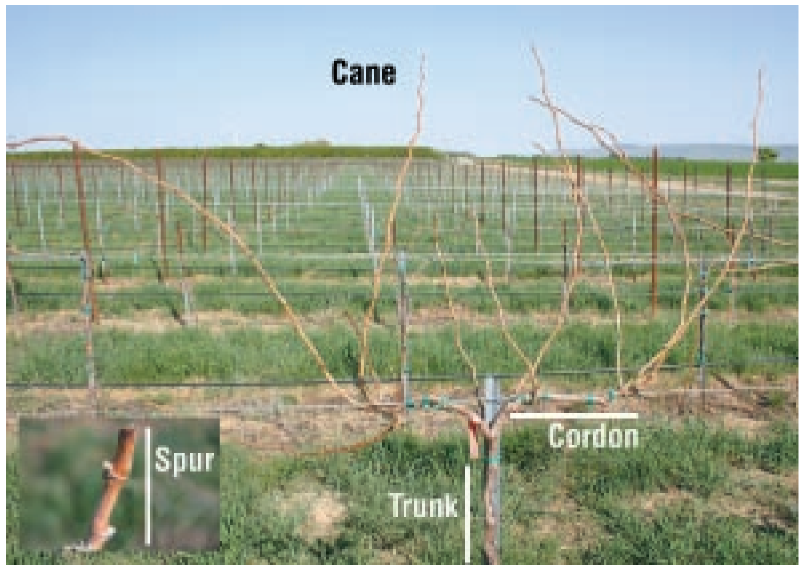

Figure 1. *A typical cordon-trained grapevine and its associated components before spur pruning.*

Definitions of Canopy and Canopy Components

Canopy, as defined in this publication, includes all vegetative and reproductive plant parts that are above-ground: the trunk, cordons, canes, spurs, shoots, fruit, and leaves (Figs. 1 and 2). The management of canopies involves manipulating these components in order to achieve a balance between vegetative and reproductive growth for optimum fruit yield and quality.

Shoots are comprised of vegetative and reproductive growth in the form of leaves, tendrils, and fruit from the basal end to the growing tip, produced in the current growing season. The rachis is the main structure of the cluster on which berries develop (Fig. 2). The growing tip is where leaves emerge; monitoring shoot tip growth can distinguish between optimum growing conditions and vine stress. Shoots originate from buds that occur on canes, spurs,

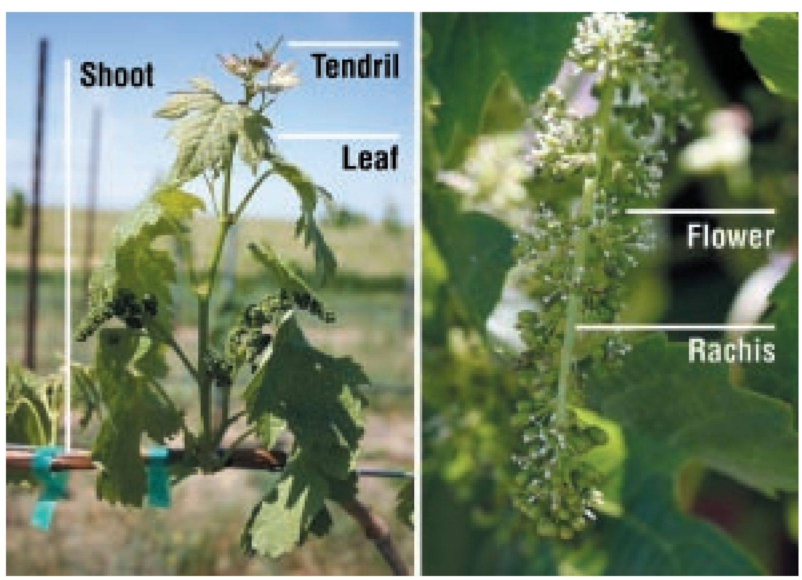

Figure 2. *Grapevine shoot components.*

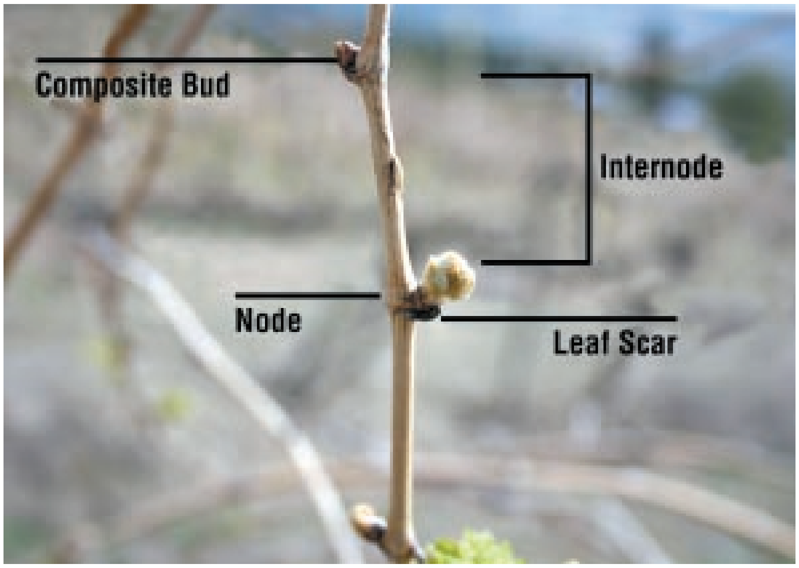

Figure 3. *Shoot anatomy showing nodes, internodes, composite bud, and leaf scar.*

cordons, the trunk, and even from below ground level (when they emerge as suckers).

Canes are mature, lignified wood from the current or previous season's growth. Canes and shoots are comprised of **nodes**, with spaces between nodes defined as **internodes** (Fig. 3). At each node is a composite bud containing three sets of buds (primary, secondary, and tertiary). The primary bud is the most fruitful, while the tertiary bud is the least fruitful. Buds can be dissected before pruning to aid in determining the potential crop load (Morrison, 1991) and help with decisions about pruning severity (Fig. 4).

Pruning weight is determined by the amount of wood that is pruned off one vine in a single season. This can be used in formulas to determine how many buds should be removed and/or left on the vine as part of balanced pruning techniques (Reynolds, 1988). The amount of pruning wood is determined by how the canopy is managed throughout the previous season. Thus, if a vineyard is on a particularly vigorous site, a large amount of pruning wood can be accumulated. However, on a low vigor site the canopy may be fairly small, leading to shorter and thinner canes and lower pruning weight.

Crop load is used to describe the ratio of yield to the pruning weight or leaf area. **Vine capacity** defines the maximum amount of shoots that the vine can support and fruit that will ripen. These two concepts often are quite different, as crop load determines optimal vine balance, while vine capacity determines the maximum amount of growth that can ripen mature fruit.

Vine vigor describes shoot growth rate and depends on a combination of factors, including soil type, texture, and depth, water and nutrient availability, and variety choice. Inherently, some grape varieties are more vigorous (e.g., Syrah and Sangiovese) than others, which in turn can produce canopies with an excess amount of leaf area that require more intense management.

Most canopy management is directed at manipulating **canopy microclimate**, which is the climate surrounding and within a canopy (Tarara, 2005). Microclimate comprises a number of factors including solar radiation, temperature, wind speed, humidity, and evaporation rates. Because leaves tend to alter these factors, canopy microclimate depends upon the number of leaves and their spatial arrangement (Smart, 1985).

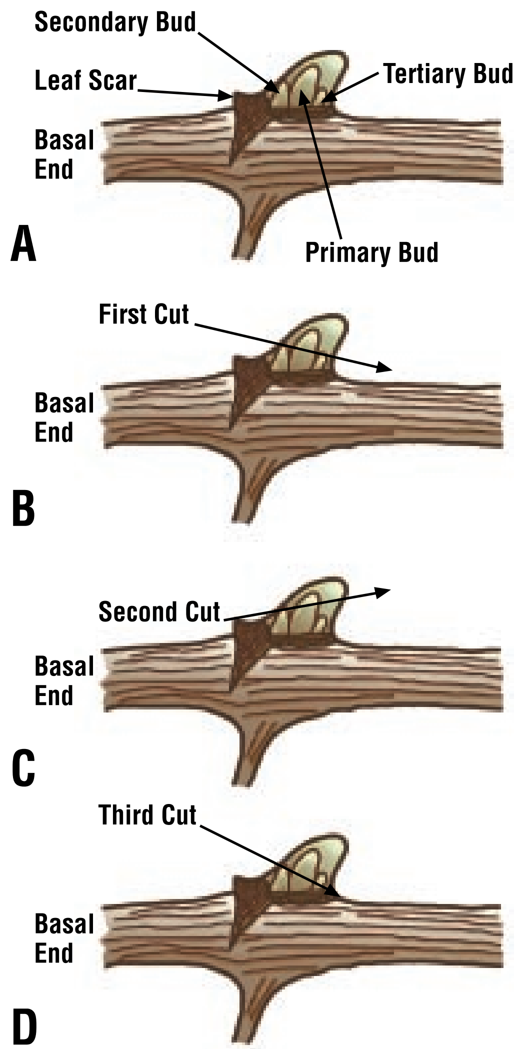

Figure 4. *Bud assessment for crop load and cold damage. Primary, secondary, and tertiary buds (A) can be assessed by making three consecutive cuts on the fruit bud (B–D). Drawings courtesy of Lynn Mills.*

Goals of Canopy Management

- Establish and maintain vine shape to facilitate uniformity in growth and fruit production
- Maintain vine shape to utilize mechanical means for carrying out vineyard tasks
- Produce optimum quality fruit through:
  - ~ Manipulation of vegetative growth
  - ~ Control of crop load
- Promote annual production of fruitful buds where desired (depending upon trellising system)
- Mitigate cold damage through allocation of carbohydrate resources to the permanent structures of the vine (trunk, cordons, roots)

Light and Temperature Effects of Canopy Manipulation

In order to understand how light and temperature affect vine growth, a brief review of some basic plant physiology is necessary. Plants fix carbon (i.e., produce sugars) from the atmosphere through photosynthesis. This process, which occurs in all green plant organs, takes carbon dioxide from the atmosphere in addition to water and, using light energy, builds a carbohydrate molecule while giving off oxygen, as represented by the following formula:

$$6CO_2 + 6H_2O \xrightarrow{\text{Light Energy}} C_6H_{12}O_6 + 6O_2$$

Through photosynthesis, carbohydrate in plants is fixed during the day, and energy is generated via respiration, which occurs day and night. During respiration, some of this carbohydrate is used to make energy that drives other plant processes (e.g., growth, nutrient uptake, fruit ripening).

Plants need a certain quantity of light (measured in µmol photons/m^2s) in order to achieve their maximum sugar production. In grapes, from 30 to 40% of full sunlight (≥ 800 µmol/m^2s) satisfies the maximum photosynthesis requirement (Keller et al., 1998; Smart, 1988). For comparison, a bright sunny day in most of the PNW has about 2,000 µmol/m^2s, although this may vary according to the year, specific latitude, and time during the growing season. Light quality is also an important factor in plant growth, as plants need certain wavelengths (measured in nanometers [nm]) of light for optimal growth. Leaves strongly absorb light at peaks in the blue (430 nm) and red (660 nm) range of the visible spectrum (Fig. 5). The range of the spectrum that plants use for photosynthesis is called photosynthetically active radiation (PAR), which is approximately the visible light range from 400 to 700 nm.

Grape leaves are very efficient at absorbing solar radiation, with over 85% of PAR absorbed by the outer layer of the canopy (Fig. 6; Smart et al., 1985). The remaining 10–15% is either transmitted through the leaf or reflected up to the atmosphere. Canopy structure determines the amount of light intercepted by exterior leaves. Beyond the first layer of leaves, only 10% of the PAR reaches the interior; further into the canopy, this is reduced to less than 1% (Smart and Robinson, 1991).

Light quality is also significantly altered in the deep interior of canopies. Sunlight interception by leaves can be via direct or diffuse radiation. Direct radiation interception by exterior leaves drives canopy photosynthesis more efficiently than interception of diffuse (or scattered) radiation (Smart, 1984; Smart et al., 1988). Leaf orientation within a canopy (i.e., perpendicular to angle of solar radiation) must be optimal to efficiently intercept solar radiation.

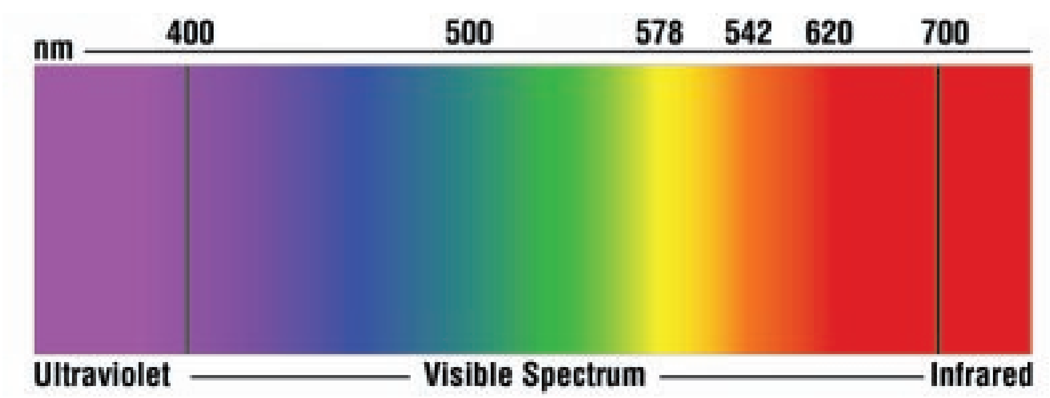

Figure 5. *The visible light spectrum. Plants use wavelengths in the blue (430 nm) and red (660 nm) regions to conduct photosynthesis.*

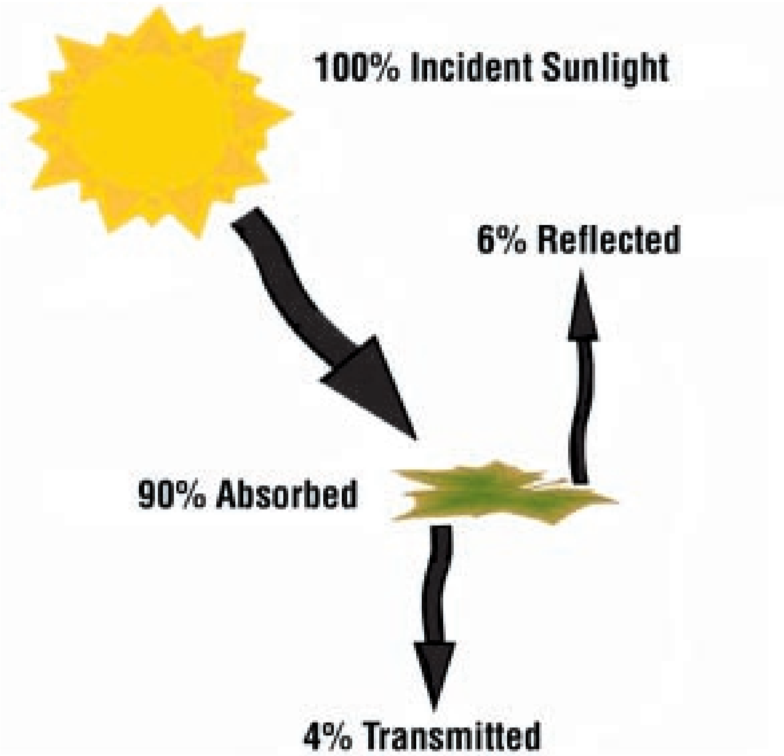

Figure 6. *Balance of solar radiation absorbed, transmitted, and reflected from a grape leaf.*

Effects of Low Light Quantity on Grapevines

(Dry, 2000; Keller et al., 1998; Keller and Hrazdina, 1998; Morgan et al., 1985; Petrie et al., 2003)

- Decreased terminal shoot growth, but increased lateral shoot growth
- Decreased fruit set
- Delayed fruit maturity
- Reduced fruit color
- Reduced acid degradation
- Reduced fruit cluster initiation for subsequent seasons
- Increased disease incidence (e.g., powdery mildew)
- Increased pest populations (e.g., leafhoppers)
- Increased internode length

Effects of Low and Very High Temperatures on Grapevine Canopies

Temperature can also have a significant effect on shoot growth and fruit quality. Typically, as temperatures increase, the rate of shoot growth increases. However, high temperatures (> 90°F or 35°C) can decrease shoot growth by shutting down photosynthesis (Ferrini et al., 1995), leading to reduced sugar accumulation and reserves and rapid acid degradation. Grape clusters in direct sunlight can experience temperatures 55–60°F (13–15°C) higher than ambient (Spayd et al., 2002), which will slow or even stall fruit ripening and impede color development.

Low temperatures (< 50°F or 10°C) can also decrease grapevine growth by slowing photosynthesis, but will also reduce acid degradation. This can have a cascading effect on fruit set, development, ripening, and storage of reserves in the grapevine for subsequent growing seasons.

Knowledge of temperature differences between sites can be useful for matching site to variety and also determining ripening times. It is more important to grow appropriate varieties for specific sites than to grow mediocre quality grapes on inappropriate sites. Separate vineyards can be planted to stagger ripening times to ensure that deliveries to wineries will be handled in a timely fashion. This underlines the importance of site selection and communication between the grower and winemaker.

Canopy Assessment Methods

Shading Indices

In upright canopy systems, the surface area of the vine is estimated by the height and width of the full-grown canopy. The greater the surface area, the more solar radiation is intercepted for photosynthesis. Volume also should be considered when assessing canopies, which is determined by the height and width of the vines trained to a specific trellising system. The larger the volume, the greater the number of leaves, which can result in too much shade. One easy way to determine fruit exposure to sunlight is to calculate the surface-area-to-volume ratio. This can be easily done with a meter stick or measuring tapes to derive the exterior canopy dimensions.

Sunfleck Analysis

This method assesses the amount of canopy gaps, and can be done throughout the season. Estimate the proportion of gaps in the canopy, especially around the fruiting zone. There should be adequate light reaching the fruiting zone from the top or exterior portion of canopy to the cordon or cane. An easy way to measure this is to set a sheet or tarp underneath the canopy under the fruiting zone and assess canopy gaps within a defined area, which can be drawn on the sheet (e.g., 1 ft^2 or 1 m^2). When completed, the percentage of sun reaching the ground for vertical canopies should be 2–10% (Smart, 1973).

Point Quadrat

This method can be used in conjunction with calculating shading indices and sunfleck analysis to assess canopy density. The point quadrat method requires a thin metal rod randomly inserted into the canopy. Multiple areas within the canopy should be assessed, at least 50 to 100 times in order to get good, representative data (Smart and Robinson, 1991). Be sure to avoid bias by choosing a uniform random method of inserting the rod throughout the vineyard row or block (e.g., every X number of steps). Record each leaf, cluster, and canopy gap (i.e., when the rod does not touch anything) that the rod passes through from one side of the canopy to the other.

Once you have recorded your information from the point quadrat canopy assessment, you can calculate percent gaps, leaf layer number (LLN), percent interior leaves, and percent interior clusters (Smart and Robinson, 1991) as follows:

- % gaps = total gap #/# of insertions x 100
- LLN = total # of leaf contacts/# of insertions
- % interior leaves = # interior leaves/total leaf # recorded x 100
- % interior clusters = # interior clusters/total cluster # recorded x 100

Ideal numbers for this method should be 20–40% canopy gaps, 1.0–1.5 LLN, < 10% interior leaves, and < 40% interior clusters. For white varieties, percent interior clusters can be higher than for red varieties (e.g., 35% vs. 25%). In addition, for vineyards that experience mild temperatures (i.e., maritime climate), the percent interior clusters should be less than for those in the inland PNW to avoid an increase in disease and pest problems.

Techniques for Canopy Manipulations

Training Systems

Training systems such as trellises that facilitate upright positioning of shoots (i.e., Vertical Shoot Positioning [VSP]) generally also allow adequate light penetration and air movement through the canopies of most grape varieties grown in the PNW. However, these systems can allow too much fruit exposure in high-solar radiation inland areas, causing sunburn. In these areas, a system that allows for shading (e.g., simple sprawl) can optimize light in the fruit zone. Divided canopy systems with hanging shoots like Geneva Double Curtain (GDC) or Scott-Henry are more apt to produce greater leaf area with a well-exposed fruit zone due to the positioning of shoots upwards and downwards. Scott-Henry systems are especially good for those varieties and sites that can be particularly vigorous. However, when a divided canopy is used, yields increase due to the higher number of buds on the vine. In these cases, crop load must be carefully balanced with vegetative growth for optimum fruit quality. In one study of single canopy trellis training systems, the leaf-area-per-crop weight ratio ranged from 4 to 6 ft^2 leaf area per pound of fruit (0.8–1.2 m^2/kg; Kliewer and Dokoozlian, 2005). In the same study, a divided canopy system (e.g., GDC or Lyre) had an optimum leaf area/fruit weight ratio of from 2.5 to 4.0 ft^2 leaf area per pound of fruit (0.5–0.8 m^2/kg).

When laying out your vineyard, be sure to optimize light absorption by equalizing the height of the trellising system and width between rows. Optimizing trellis height with row width should result in a 1:1 ratio between rows and trellis height (Smart et al., 1982) to avoid light bleeding through and inefficiencies in the vineyard regarding the capture of sunlight. However, if vineyard rows are too closely spaced, it is possible to get cross-row shading, which can lead to shaded leaves close to the fruiting zone.

Pruning

Grapevines have a fixed capacity, meaning a given vine can ripen a certain amount of fruit and support a certain amount of shoots. One of the main goals of pruning is to ensure that there is enough potential vegetative growth to ripen the crop and a sufficient number of fruitful buds to provide an adequate crop load. Large canopies can negatively affect fruit quality by increasing disease incidence and decreasing penetration of fungicides and pesticides. In addition, getting light into the canopy helps form fruitful buds for the following year and hardens the canes for the winter. Canes that are not properly hardened off (i.e., green in color) are more prone to winter damage and crop loss in the subsequent year. Other pruning objectives include obtaining easy access to farm equipment and around vineyard traffic, and maintaining vine structure according to your trellis system.

Specific pruning recommendations depend on your training system (e.g., spur pruning for cordon-trained systems), variety (e.g., cane pruning can overcome the natural tendancy of some varieties to not produce fruitful buds), and vine vigor. In most training systems, a significant portion of the previous year's growth is removed (e.g., 80–90% in spur-

Figure 7. *Evenly spaced spurs in a vertically-trained, bilateral cordon system.*

Figure 8. *Non-count buds are those less than one finger's width from the cordon as seen here in a spur-pruned, cordon-trained system.*

pruned systems). In cordon-trained systems, 2–3 bud spurs should be evenly spaced along the cordon (Fig. 7). In cane-pruned systems, be sure to choose canes that have adequate spacing between nodes for fruiting wood. Distinguish between count and non-count buds; only buds that are one finger width above the cordon should be included in the final bud count for that spur (Fig. 8). Buds close to the cordon are basal buds and usually remain dormant. Potential crop load can be determined by sectioning buds, which is best done before pruning to give an idea of buds that may be damaged by winter temperatures.

Balanced pruning may be used as a tool to adjust crop load in areas of variable vigor. This technique incorporates prunings from several representative vines and estimates the vines' capacity based on the weight of these prunings. Thus, if a vine had weak growth the previous season, fewer buds would be left to encourage the vigor of the remaining shoots. A vigorous vine would benefit from a lighter pruning (more buds), thus balancing leaf area and crop load while decreasing the vigor of the remaining shoots. The bud number to be retained is usually a minimum per vine plus a certain number for each pound of canes removed. For winegrapes, numbers for balanced pruning depend upon the variety (Smart and Robinson, 1991). As a rule of thumb, leave about 15 buds per pound (30/kg) of pruning weight.

One more issue to consider is the crop-to-pruning weight ratio, which can be calculated by dividing the pounds (kgs) of fruit per vine by the pounds (kgs) of pruned canes per vine. This will give an idea of the balance of the vine. If this number is too low (< 5), the vine may be able to support more crop load than what was harvested from it last year, and bud numbers/vine can be increased per vine. If it is too high (> 10), the crop may need some thinning, or the bud number may need to be reduced per vine.

Shoot Thinning

Often after bud break, a number of shoots will emerge from latent buds in the cordon of spur-trained systems, or bud position may not be optimum in cane-pruned systems. Shoot thinning can be used to help improve light penetration and air movement through a canopy, adjust crop load (by thinning fruitful shoots to reduce the crop), and increase the leaf-area-to-crop ratio (by thinning non-fruitful shoots). Spacing between shoots should be about 3 inches (~7 cm), with optimal removal after they push out at least 4–6 inches (10–15 cm).

Shoot Positioning

Shoot positioning can be used to direct shoot growth upwards or downwards. Shoots are usually tucked under a number of catch wires, depending upon your trellis design. The main goal of shoot positioning is to expose the fruit for color development (in red varieties) and increase air movement around the cluster to reduce disease incidence. The earlier berries and clusters are exposed, the less chance there is of inducing sunburn because the skins develop secondary metabolites (phenolics such as quercetin) similar to melatonin production in human skin (a.k.a. your suntan) that protect the berry from harsh solar UV radiation. Sunburn can be a problem if you do shoot positioning too late into the season, especially with white varieties. Optimum timing for shoot positioning is mid-June through early August.

Cluster Thinning

There are many opportunities in the life of a vineyard to adjust crop load (Table 1). Site selection, vine spacing, training system, and pruning technique are just a few influential factors. Vines that are over-cropped due to a small canopy size can benefit from cluster thinning to bring the vine back into balance. At least 30–40% of the crop must be removed to yield any differences in fruit composition upon harvest.

Proper timing can influence whether the benefits of cluster thinning are realized or not. The earlier this type of thinning is practiced, the larger the berries will be due to reduced competition for resources from the remaining berries. Flower thinning will allow for more open clusters, while cutting flower clusters in half can lead to elongation of the rachis and hence, less compact clusters. However, caution should be exercised so that fruit set is not negatively affected. Early cluster thinning after fruit set can reduce bunch compactness and Botrytis susceptibility, but may encourage lateral shoot growth (Keller, 2001). If clusters are removed at veraison (i.e., when the berries change color), maturity can be advanced in the remaining clusters, especially if lagging clusters are removed. Late cluster removal will reduce yield.

Cluster thinning should not be a long-term practice in the vineyard because it is an expensive practice to do on an annual basis, and if vines are continuously overcropped, pruning and shoot thinning strategies should be revisited.

Methods to Improve Fruit Exposure to Light

Hedging

Canopies that are overly vegetative and large can increase disease incidence and reduce air flow, light quantity, and fruit quality. Hedging (Fig. 9) can be used to remove the top portions of a canopy (10–20%) to reduce shoot growth and young leaves that act as a sink for carbohydrates. However, timing is very important, as vines can compensate for the reduction in leaf area by increasing lateral shoot growth (Candolfi-Vasconcelos and Koblet, 1990; Candolfi-Vasconcelos et al., 1994).

Figure 9. *Hedging in a vineyard can be used to prepare vines for bird netting or slow vertical growth. Photo courtesy of Jeff Jernegan.*

Table 1. *Influences of vineyard establishment and management on grapevine yield components.*

Component	Determined During	Management Options
Vines/acre	Planting	Density/trellis design
Nodes/vine	Winter pruning	Pruning level
Shoots/node	Budbreak	Pruning level
Clusters/shoot	Cluster initiation	Nutrition, canopy management
Flowers/cluster	Budbreak	*Further research needed*
Berries/cluster	Fruit set	Irrigation, nutrition, temperature
Berry weight	All season	Irrigation, nutrition

Adapted from Pearce and Coombe, 2004

Hedging during bloom can increase fruit set under unfavorable conditions. If hedging is done midway through fruit development (i.e., lag phase), the vine will produce new leaves for sugar production later in the season (Cartechini et al., 2000). Late or repeated hedging will direct the vine's energy to a new flush of lateral shoot growth rather than to the developing fruit, which can delay ripening. As with cluster thinning, if repeated hedging is necessary, it is time to revisit your pruning and crop load strategies.

Leaf Removal

In vineyards where there is excess vigor or lateral growth, leaf removal can increase fruit exposure to light and better balance vine and fruit growth. With this technique, leaves are removed in the bottom portion of the canopy (~12 in or 30 cm) by either hand or mechanical means (Fig. 10). Excess removal of leaves around the fruiting zone, however, may delay ripening and reduce sugar accumulation due to a period of adjustment in the vine to source sugars from other leaves further above on the shoot. Thus, timing leaf removal is very important; under warm conditions (e.g., mid- vs. late-season in the interior PNW), it does not affect yield components or fruit composition (Kliewer and Bledsoe, 1987).

Early leaf removal from fruit set to bunch closure seems to be the best time to get maximum benefit of increased exposure. Late leaf removal (i.e., around veraison) can increase the risk of sunburn in grape berries because they do not develop protective compounds to absorb harmful UV light. Damage from UV light can lead to reduced anthocyanin production and delayed ripening (Spayd et al., 2002). In addition, leaf removal should be concentrated on the east side of the vine in rows oriented north-south to avoid cluster over-exposure on the west side of the vine during the hot afternoon hours.

Figure 10. *Leaf removal can be employed to get better light exposure and air movement into the fruit zone. Extreme leaf removal, as seen here, can leave clusters open to sunburn and delays in fruit ripening.*

The Ideal Canopy

The ideal canopy can be defined by a number of characteristics (Smart and Robinson, 1991):

- 1:1 canopy height-to-width ratio to avoid cross-row shading and optimize sunlight interception
- Row orientation appropriate for a particular site
- Vertical training systems to maximize sunlight interception
- 8,500 yd^2/ac (~21,000 m^2/ha) of canopy surface area
- Leaf area/surface area = < 1.5
- Leaf layers ≤ 3.0
- 1–2 in^2 (7–14 cm^2) leaf area per gram of fruit
- 36–60 in (1.0–1.5 m) shoot length
- Internode length = 2–3 in (6–8 cm)
- Yield to pruning weight ratio = 5–10
- 20–40% canopy gaps

Although these recommendations are a good guide, be sure to take into consideration your vineyard site, grape variety, trellis system, and vigor before comparing your canopy to the ideal. Use your experience with particular varieties on particular sites to adjust or fine-tune these numbers as needed. The goal in every case should be to have the proper balance of vegetative and reproductive growth to optimize fruit quality and yield.

Concluding Remarks

Successful canopy management must start with proper site selection, soil evaluation, and variety choice. Following vineyard establishment, a number of factors can be manipulated to enhance fruit quality and yield. Good fruit exposure to light balanced with optimal shoot growth through good water and nutrition management is essential in this context. With appropriately applied tools for canopy assessment and manipulation, the ideal canopy and a well-balanced grapevine is within reach.

References and Useful Literature

Candolfi-Vasconcelos, M.C. and W. Koblet. 1990. Yield, fruit quality, bud fertility and starch reserves of the wood as a function of leaf removal in *Vitis vinifera*—evidence of compensation and stress recovering. *Vitis* 29: 199–221.

Candolfi-Vasconcelos, M.C., W. Koblet, G.S. Howell, and W. Zweifel. 1994. Influence of Defoliation, rootstock, training system, and leaf position on gas exchange of Pinot noir grapevines. *American Journal of Enology and Viticulture* 45: 173–180.

Cartechini, A., A. Palliotti, and C. Lungarotti. 2000. Influence of timing of summer hedging on yield and grape quality in some red and white grapevine cultivars. *Acta Horticulturae* 512: 101–110.

Dry, P.R. 2000. Canopy management for fruitfulness. *Australian Journal of Enology and Viticulture* 6: 109–115.

Ferrini, F., G.B. Mattii, and F.P. Nicese. 1995. Effect of temperature on key physiological responses of grapevine leaf. *American Journal of Enology and Viticulture* 46: 375–379.

Keller, M. 2001. Principles to have in mind when deciding on a thinning strategy. *Australian Viticulture* 5: 27–29.

Keller, M., K.J. Arnink, and G. Hrazdina. 1998. Interaction of nitrogen availability during bloom and light intensity during veraison. I. Effects on grapevine growth, fruit development, and ripening. *American Journal of Enology and Viticulture* 49: 333–340.

Keller, M. and G. Hrazdina. 1998. Interaction of nitrogen availability during bloom and light intensity during veraison. II. Effects on anthocyanin and phenolic development during grape ripening. *American Journal of Enology and Viticulture* 49: 341–349.

Kliewer, W.M. and A.M. Bledsoe. 1987. Influence of hedging and leaf removal on canopy microclimate, grape composition, and wine quality under California conditions. *Acta Horticulturae* 206: 157–168.

Kliewer, W.M. and N.K. Dokoozlian. 2005. Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. *American Journal of Enology and Viticulture* 56: 170–181.

Morgan, D.C., C.J. Stanley, and I.J. Warrington. 1985. The effects of simulated daylight and shade-light on vegetative and reproductive growth in kiwifruit and grapevine. *Journal of Horticultural Science and Biotechnology* 60: 473–484.

Morrison, J.C. 1991. Bud development in *Vitis vinifera* L. *Botanical Gazette* 152: 304–315.

Pearce, I. and B. Coombe. 2004. Grapevine phenology. In: *Viticulture. I. Resources.* P.R. Dry and B.G. Coombe, eds. Winetitles, Adelaide, AU, p. 152.

Petrie, P.R., M.C.T. Trought, G.S. Howell, and G.D. Buchan. 2003. The effect of leaf removal and canopy height on whole-vine gas exchange and fruit development of *Vitis vinifera* L. Sauvignon Blanc. *Functional Plant Biology* 30: 711–717.

Reynolds, A.G. 1988. Response of Riesling vines to training system and pruning strategy. *Vitis* 27: 229–242.

Smart, R.E. 1973. Sunlight interception by vineyards. *American Journal of Enology and Viticulture* 24: 141–147.

Smart, R.E. 1984. Some aspects of climate, canopy microclimate, vine physiology, and wine quality. Proceedings of the First International Cool Climate Viticulture and Enology Symposium. Oregon State University, Corvallis, pp. 1–19.

Smart, R.E. 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. A review. *American Journal of Enology and Viticulture* 36: 230–239.

Smart, R.E. 1988. Shoot Spacing and canopy light microclimate. *American Journal of Enology and Viticulture* 39: 325–333.

Smart, R.E., J.B. Robinson, G.R. Due, and C.J. Brian. 1985. Canopy microclimate for the cultivar Shiraz. I. Definition of canopy microclimate. *Vitis* 24: 17–31.

Smart, R.E. and M. Robinson. 1991. *Sunlight Into Wine: A Handbook for Winegrape Canopy Management*. Winetitles, Adelaide, AU.

Smart, R.E., N.J. Shaulis, and E.R. Lemon. 1982. The effect of Concord vineyard microclimate on yield. I. The effects of pruning, training, and shoot positioning on radiation microclimate. *American Journal of Enology and Viticulture* 33: 99–108.

Smart, R.E., S.M. Smith, and R.V. Winchester. 1988. Light quality and quantity effects on fruit ripening for Cabernet Sauvignon. *American Journal of Enology and Viticulture* 39: 250–258.

Spayd, S.E., J.M. Tarara, D.L. Mee, and J.C. Ferguson. 2002. Separation of sunlight and temperature effects on the composition of Vitis vinifera cv. Merlot berries. *American Journal of Enology and Viticulture* 53: 171–182.

Tarara, J.M. 2005. A climatology refresher for vineyard managers and winemakers. *WSU Wine and Grape Research and Extension Newsletter* 15: 2–5.

College of Agricultural, Human, and Natural Resource Sciences

You may order copies of this and other publications from the WSU Bulletin office, 1-800-723-1763, or online at http://pubs.wsu.edu.

Issued by Washington State University Extension and the U.S. Department of Agriculture in furtherance of the Acts of May 8 and June 30, 1914. WSU Extension programs and policies are consistent with federal and state laws and regulations on nondiscrimination regarding race, sex, religion, age, color, creed, national or ethnic origin; physical, mental or sensory disability; marital status or sexual orientation; and status as a Vietnam-era or disabled veteran. Evidence of noncompliance may be reported through your local WSU Extension office. Trade names have been used to simplify information; no endorsement is intended. Published December 2006. Subject code 233. EB2018E