Influence of Floor Management Technique on Grapevine Growth, Disease Pressure, and Juice and Wine Composition: A Review

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Abstract: Vineyard floor management has multiple goals that encompass improving weed management and soil conservation, reducing soil resource availability to control vine vigor, and influencing desirable aspects in wine quality. This review addresses the effects of cultivation, weed control, cover crops, and mulch on vine growth and balance, disease pressure, yield, and juice and wine quality in many growing regions (Australia, New Zealand, South Africa, Europe, and the western United States); offers recommendations for practical use; and highlights research needs. In the last decade, more literature has been published on mulching and cover cropping than on cultivation and herbicide use, suggesting stronger interest in cover cropping and mulching practices for vineyards. Cover crops have the potential to improve soil and vine health, can be adapted to many climates and soils, and may influence vine vigor by adjusting parameters such as the length of their growth period, coverage of the vineyard floor, and aggressiveness. Cover crops increased juice soluble solids, anthocyanins, and other phenolic components and decreased titratable acidity and pH. They were associated with red wines judged superior to those issued from non-cover-cropped vines. Use of organic mulches resulted in improved vine balance, soil water content, and friability, increased yields, and reduced pathogen and pest pressure. Plastic and fabric mulches remain impractical due to high installation cost. Application of newer techniques such as flame weeding or soil steaming is limited due to difficulty in targeting the appropriate stage of weed growth and limited susceptibility of some weed species to these techniques. Research needs include development of multiyear, multidisciplinary studies that use a mechanistic approach to link management practices to soil processes, grapevine responses, grape and wine composition, and sensory characteristics.

Key words: cover crop, mulch, weed control, winegrape, cultivation, vineyard

Principal goals of vineyard floor management include weed management, soil conservation and improvement, soil nutrient and water management, enhanced biodiversity for pest management, refugia for beneficial insects, and diminished resource availability (i.e., nutrients, water) to control vine vigor (Celette et al. 2005, 2009, Jacometti et al. 2007a, 2007b, Baumgartner et al. 2005, 2008, Steenwerth and Belina 2008a, Brugisser et al. 2010, Ripoche et al. 2010). These aspects are important to vine growth, and therefore vineyard floor management has implications for wine quality (Nauleau 1997, Afonso et al. 2003, Wheeler et al. 2005, Nazrala 2008). The best practice for each vineyard site is determined in part by vine age, vineyard design, soil type, and climatic conditions of the vineyard site (Ripoche et al. 2010, Sweet and Schreiner 2010). Environmental regulations and public perceptions regarding the use of various management practices also determine the best practices for a given site (Baker et al. 2005, Thomson and Hoffmann 2007, Smith et al. 2008, Steinmaus et al. 2008). This review addresses the multiple effects of vineyard floor management tools, or tillage, herbicide, cover crops, and mulches on winegrape production (e.g., yield parameters and complex quality metrics).

Few reviews specifically address the broad spectrum of vineyard floor management and the associated consequences of such management on grapevines in different growing regions (Lanini 1988, Lipecki and Berbeć 1997, Ingels et al. 1998, Hartwig and Ammon 2002, Olmstead 2006, Colugnati et al. 2004). Most often, review articles have focused on one specific floor management technique, such as cover cropping (Ingels et al. 1998, Hartwig and Ammon 2002), or a specific region, such as Pacific Northwest vineyards (Olmstead 2006). Other reviews have addressed mulch trials or techniques for soil management for orchards (Lanini 1988, Lipecki and Berbeć 1997) and, more recently, weed management for organic vineyards (Lanini et al. 2011). The most recent review compared floor management techniques and impacts of cover-crop species on yield parameters and juice composition in various Italian regions (Colugnati et al. 2004).

This current review covers research published in the last decade on effects of the dominant floor management practices on grape and fruit quality. We have organized the review into

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four sections representing the four main approaches: cultivation, herbicides, cover crops, and mulches. More literature on the latter two techniques was identified, suggesting stronger interest in cover cropping and mulching practices for vineyards. The benefits and drawbacks of each management practice as well as responses important for production goals will be discussed, including vine growth and balance, disease pressure, yield, and juice and wine quality.

Cultivation

Cultivation, or tillage, is the most traditional practice for controlling weeds. The technique was historically applied using animals until the introduction of tractors in the 1920s. Tillage eliminates surface crusts, leading to less run-off than when herbicides are the sole means of weed control (Merwin et al. 1994). There has been a recent resurgence of cultivation for weed control, particularly on the vine row, as a means to reduce chemical inputs (Gaviglio 2007). The main disadvantages of cultivation include soil compaction and loss of structure, cumulative loss of fertility and soil organic matter, risk of damage to the vine roots, trunks, and arms, and contribution to the directional spread of soil pests and pathogen, such as phylloxera, nematodes, and wood-rotting fungi like *Phaemoniella, Acremonium*, and *Botriosfaeria* (Merwin et al. 1994, Salazar and Melgarejo 2005, Steenwerth and Belina 2008a).

Cultivation is best kept shallow to avoid damage to vine roots (Lanini et al. 2011). In addition, cultivation brings new seeds to the surface and tends to enhance soil nitrogen (N) mineralization, both of which are conducive to weed emergence flushes (Bàrberi 2002). Various authors have reviewed the equipment available to cultivate either the vine row or the interrow of the vineyard (Heinzle 2003, Gaviglio 2007, Lanini et al. 2011) and the effects of cultivation on weed ecology in annual cropping systems (Chauhan et al. 2006).

In studies that compared cultivation with alternative methods, noncultivation techniques tended to be favored (also see the following sections on herbicides and cover crops). An exception was observed in one Bordeaux (France) study on dry-farmed Merlot, Cabernet Sauvignon, and Sauvignon blanc. The cover crop (*Festuca arundinacea*) reduced vigor and yields, vine leaf N (average 0.42% N dry weight in cover crop vs. 0.59% N in the cultivation) and juice N (280 mg/L in cover crop vs. 565 mg/L in the cultivation) (Rodriguez-Lovelle et al. 2000). Higher N in leaves and juice and higher yields and pruning weights in response to cultivation than to other floor management practices were observed in various studies (Rodriguez-Lovelle et al. 2000, Afonso et al. 2003). In contrast, yields were lower under cultivation than under herbicide (both in vine row) at three of four sites in the south of France (Gaviglio 2007). This effect was attributed to reduced nutrient uptake due to damage to surface roots of the grapevine by the cultivation equipment.

Understanding the physiological mechanisms for grapevine responses would facilitate improved timing of management practices such as cultivation with vine demand for N or water, two factors that can influence juice composition and N content. Cultivation affects decomposition and mineralization of existing soil organic N pools and plant residues, providing a pool of inorganic N for vine uptake (Calderón et al. 2001). Quality and quantity of incorporated plant residues also will influence the timing of N release relative to vine demand (Campiglia et al. 2011).

Herbicides

Some advantages of herbicides are their effectiveness when correctly chosen, their low cost, and the ease of use. The main disadvantages include the risk of developing herbicide-resistant weeds, the risk of toxicity—both to the vines and operator—and the potential for herbicide residues leaching to waterways (Merwin et al. 1994, Tourte et al. 2008). Other indirect effects are soil compaction incurred during application and decreased soil fertility from loss of soil organic matter (Smith et al. 2008, Steenwerth and Belina 2010). Herbicide treatment of the vineyard floor is often restricted to the vine row (10 to 15% of the total vineyard floor), and can involve preemergence and/or postemergence herbicides ("knock-downs") (Lang 1990, Dastgheib and Frampton 2000). Herbicides are mostly used at very low dosage, with sprayers equipped with panels that prevent chemical drift. Sprayers with infrared sensors detect weeds and give targeted applications to minimize drift and the amount of herbicide applied (Salazar and Melgarejo 2005, Gaviglio 2007). Both the efficacy and economics of weed control practices in vineyards were evaluated in a five-year study on the Central Coast of California. Postemergence herbicides (glyphosate 2% a.i., plus oxyfluorfen 1% a.i.) required fewer chemical applications than preemergence herbicides (simazine, 2 kg a.i./ha) or cultivation (Tourte et al. 2008). The postemergence herbicide treatments were less costly, yet produced similar yields and fruit quality as the other treatments. When various common floor management treatments under the vine were compared over a two-year period in Lodi, California, a preemergence herbicide (diuron, oxyfluorfen) coupled with a postemergence systemic herbicide (glyphosate) was the most effective and least expensive treatment to manage weed pressure (Elmore et al. 1997). When a fall cultivation pass (Clemens) was paired with a single postemergence herbicide treatment in Napa, California, in spring (glyphosate, 5.6 kg a.i./ha), a level of weed control similar to two herbicide applications was achieved and herbicide usage was cut in half (Baumgartner et al. 2007). However, no cost analysis was included, underscoring gaps in the economic evaluation of best management practices for vineyard weed management.

A buildup of weeds resistant to herbicides can be a consequence of herbicide use. For example, some weeds found in vineyards have recently shown resistance to glyphosate in California, such as horseweed (*Conyza canadiensis*) (Shrestha et al. 2010) and Italian ryegrass (*Lolium multiflorum*) (Jasienuk et al. 2008). Resistance of *Senecio vulgaris* and ryegrass (*Lolium rigidum*), both found in vineyards, also has been reported (Institut National de la Recherche Agronomique 2008). Today, 348 resistant biotypes and 194 weed species are resistant to herbicides, forcing growers and other land managers

to use alternative methods to eliminate these weeds (http://www.weedscience.org/In.asp). Few studies were found that addressed management of herbicide resistant weeds in vineyards and their potential impacts on vine growth (but see Alcorta et al. 2011a, 2011b).

Another result of sustained herbicide use is a shift in weed communities (Elmore et al. 1997, Afonso et al. 2003, Gago et al. 2007, Baumgartner et al. 2007, Sanguankeo et al. 2009). When annual weeds are controlled through herbicides, perennial weeds can become more common and difficult to control (Elmore et al. 1997). Species that tended to be favored by an herbicide treatment varied widely across trials, in some cases due to the specific mode of action of the herbicide applied (e.g., Elmore et al. 1997, Sanguankeo and Leon 2011). Also, timing of herbicide application can shift the weed community, especially if applied when weeds are less susceptible to chemical control (Baumgartner et al. 2007).

Organic herbicides are being developed in response to public interest in reducing pesticide inputs in the vineyard and in managing weed vegetation by alternative methods (Elmore et al. 1997, Tourte et al. 2008). A number of herbicides accepted for organic production, including clove oil, acetic and citric acid products, and corn gluten meal, have been tested (Lanini et al. 2011). Recommendations to improve weed control include high application rates, adding an organically accepted surfactant, treating weeds at warm temperatures, and treating when weeds are at young stages. However, most organic herbicides are expensive and ineffective on grasses and weeds with waxy or hairy leaves.

Herbicides have also been combined with mulches to control seed germination and seedlings in vineyards. A mulch consisting of fresh residues of wheat (*Triticum aestivum*), oats (*Avena sativa*), and barley (*Hordeum vulgare*) grown in the interrows, which was chopped and transported to the vine rows (Trimax frail mower with Mulchmasta conveyor), was effective in controlling weeds in Lodi, California (Elmore et al. 1997). This technique was particularly effective the second year, when the cover-crop biomass was higher and when glyphosate was used to clean the vine row just before placing the mulch, thus ensuring uniformity of mulch application. Desiccation of a cover crop in the vine row by an herbicide provides another mulching option. A rye (*Secale cereale* L.) cover crop grown in the vine row was chemically desiccated using glyphosate. The desiccated cover-crop mulch provided better weed suppression than when the same cover crop was either mowed or incorporated into the soil in Indiana (Bordelon and Weller 1997).

Grapevines have significant N stores (Schreiner et al. 2006), and thus effects of vineyard floor management practices on grape nutrition may occur over the long term, especially when N fertilizer is part of the management scheme (Smith et al. 2008). Weed management practices can directly influence soil N availability and short-term N transformations (Steenwerth and Belina 2010). After five successive years of weed control treatments in a Chardonnay vineyard in the Central Coast of California, annual nitrate leaching and short-term nitrous oxide emissions after fertigation were greater from an herbicide regime than from a cultivation treatment that supported relatively greater weed cover (Smith et al. 2008, Steenwerth and Belina 2010), suggesting there were changes in soil characteristics related to soil N availability. Nonetheless, the winegrapes had similar leaf and petiole nutrition over this five-year trial, but N content of the winegrapes was not assessed (Smith et al. 2008).

In addition to weed control, herbicides can provide an effective tool to control periods of competition between the cover crop and vine. In a coastal vineyard in South Africa, a postemergence herbicide was applied to precisely eliminate competition from a cover crop either before or after budbreak (Fourie et al. 2006). Using an herbicide to kill cover crops before vine budbreak increased shoot biomass and crop yields. This practice was particularly beneficial in new vineyards, where it helped accelerate the young vine development. In contrast, in a study conducted in Corce, France, yields were reduced when native vegetation was killed before (March) or after (June) vine budbreak (Bourde et al. 1999). Here, the decomposing cover-crop biomass that was desiccated prior to budbreak could cause microbial N immobilization and limit soil inorganic N required by vines during budbreak, whereas cover crops not desiccated until after budbreak could sequester N via uptake and compete with vines for water (Steenwerth and Belina 2008b, Celette et al. 2009). The cover crop desiccated after budbreak produced wines higher in alcohol, anthocyanins, and total polyphenols, lower in acidity, and overall were judged superior by an expert taste panel compared to wines produced with a cover crop desiccated before budbreak. This suggests that only when the presence of the cover crop was extended during most of the vine growing season did the cover crop exert sufficient competition for nutrients and/or water to modify the wine chemistry.

In summary, herbicides were more effective than cultivation in controlling vineyard weeds and generally were more cost-effective, justifying their role in vineyard floor management. Additionally, herbicides can enhance other floor management techniques. Examples include bolstering the weed control by cultivation, mulching, and providing a precise on/off switch to deactivate the weed or cover-crop competition with the vines. However, development of models for understanding long-term effects of management practices on weed composition and control, soil health, and vine growth are needed. Such models exist for many annual cropping systems (e.g., see review by Holst et al. 2007), but must still be developed for vineyard systems.

Cover Crops

A cover crop can be purposely seeded or consist of resident species that cover the vineyard floor. In the last decade, use of cover crops has become a common vineyard floor management practice due to their many benefits: soil protection from erosion and crusting, vine growth regulation, improved soil fertility, structure, and water-holding capacity, increased soil biological diversity, weed suppression, habitat for beneficial predators, and early firm footing for cultural operations (Hartwig and Ammon 2002, Morlat and Jacquet 2003,

McGourty 2004, Colugnati et al. 2004, Monteiro et al. 2008, Smith et al. 2008, Fourie 2010). Potential disadvantages include competition with vines for water and nutrients, cost of establishment, need for regular maintenance, increased risk of spring frost, and vine damage from increased rodent populations (Tan and Crabtree 1990, Carsoulle 1995, McGourty 2004, Colugnati et al. 2004, Ingels et al. 2005, Celette et al. 2008, 2009). Overall, cover crops are clearly considered a quality element in a vineyard, with benefits to the vine outweighing the disadvantages (Salazar and Melgarejo 2005). It has been suggested that as vines and cover crops coexist in vineyards, management of irrigation, fertilization, and other practices must meet the needs of both (Colugnati et al. 2004).

General aspects of cover crops. Cover crops can be annual, biennial, or perennial herbaceous plants grown in a pure or mixed stand during all or part of the year (Sullivan 2003). The most commonly used cover crops belong to the Poaceae (cereals or grasses) and the Fabaceae (legumes) families. A third, less common, type of cover crops consists of broadleaved herbaceous plants, also known as forbs, which include a wide variety of plant families, such as Brassicaceae and Asteraceae (McGourty and Reganold 2005). Available cover-crop selections are diverse: over 50 plant species are commonly used as cover crops for vineyards in California (Ingels et al. 1998). Various studies have compared species for use as cover crops in nontilled organic vineyards in the north coast of California (Bugg et al. 1996, McGourty et al. 2006, 2008). Common vetch (*Vicia sativa* L.), annual ryegrass (*Lolium multiflorum* Lamarck), oats (*Avena fatua* L.), and berseem clover (*Trifolium alexandrinum*) showed the greatest percentage of soil coverage, whereas the following were rated highly for regeneration: soft chess (*Bromus hordeacens* L.), California brome (*Bromus carinatus* Hooker & Arnott), annual ryegrass (*L. multiflorum*), blue wildrye (*Elymus glaucus* Buckely), oats (*A. fatua*), rye (*S. cereale*), crimson clover (*T. incarnatum*), subterranean clover (*T. subterraneum*), and strawberry clover (*T. fragiferum* L.) (Bugg et al. 1996). Top performers among the clovers included crimson clover (*T. incarnatum* L.) (well-adapted to cool, wet conditions), subterraneum clover (*T. subterraneum* L. Antas) (well-adapted, large seed producer, fast soil coverage), and Balensa clover (*T. micheliaunun*) (prolific flowering) (McGourty et al. 2006, 2008). Cover-crop recommendations from various authors are summarized in Table 1.

Cover crops can be classified by their dominant functions and characteristics. Grasses have fibrous roots that effectively

Table 1 Cover-crop species recommended for vineyards from various sources.

Location / Crop name (reference)	Comment
California, North Coast (McGourty 2004)	
Legumes	
Trifolium subterraneum (sub. cover)	Fits most situations; use Nugaria, Seaton Park, York when rain limited; use Antas, Koala, Mt. Barber with more rain
Trifolium resupinatum (Persian clover)	Tolerates water-logging once germinated; use Nitro for self-reseeding; use Lightning to reseed annually
Trifolium michelianun (Balansa clover)	For cool, moist winters, tolerates water-logging; use Frontier for dry, shallow soils; use Bolta for cooler, wetter sites
Trifolium incarnatum (crimson clover)	Lots of biomass that can be difficult to incorporate
Trifolium hirtum (rose clover)	
Medicago polymorpha (bur medic)	For areas with lots of rain; Santiago is bur-less
Pisum sativum (Magnus winterpea)	For cool, moist climate
Grasses	
Festuca arundinacea (tall fescue)	For perennial covers in vigorous vineyards
Dactylis glomerata (orchardgrass)	For perennial covers in vigorous vineyards
Lolium perenne (perennial ryegrass)	For perennial covers in vigorous vineyards
Festuca rubra (red fescue)	For perennial covers in moderate vigor vineyards
Festuca ovina (sheep or hard fescue)	For perennial covers in moderate vigor vineyards
Festuca longifolia (hard fescue)	For perennial covers in moderate vigor vineyards
Vulpia myuros v. *hirsuta* (Zorro fescue)	For perennial covers in moderate vigor vineyards
Bromus hordeaceous (Blando brome)	For areas with limited rain
Italy (Colugnati et al. 2004)	
Legumes	
Trifolium pratenses (field clover)	For cool, humid conditions
Trifolium repens (white clover)	Tolerates high temperatures
Trifolium fragiferum (strawberry clover)	Good resistance to both cold and dryness
Grasses	
Festuca rubra	Good resistance to both cold and dryness
Festuca ovina	Good resistance to both cold and dryness
Festuca arundinacea	More aggressive, keep just for interrows
Lolium perenne	For cool climates
Poa pratensis (meadow grass or bluegrass)	For moist conditions
Dactylis glomerata	Good resistance to both cold and dryness; rather aggressive, tends to dominate mixes
Dactylis hispanica (Spanish grass)	Good resistance to both cold and dryness; rather aggressive, tends to dominate mixes
Bromus inermis	Resistant to cold, but does not like wet soils
Bromus	Resistant to cold, but does not like wet soils

penetrate and aggregate the soil (Colugnati et al. 2004). Their high C:N ratio is associated with slower decomposition rates than those of legumes (McGourty and Reganold 2005, Olmstead 2006). Grasses are able to provide a large amount of biomass that can help increase vineyard organic matter over time, hold soil in place, and reduce soil compaction (Colugnati et al. 2004, McGourty and Reganold 2005, Olmstead 2006). On the other hand, legumes have lower C:N ratios, allowing them to decompose rapidly after incorporation and better meet microbial N needs (Faria et al. 2004, McGourty

Table 1 (continued) Cover-crop species recommended for vineyards from various sources.

Location / Crop name (reference)	Comment
Washington State (Olmstead 2006)	
Legumes	
Trifolium incarnatum (crimson clover)	Good reseeder
Trifolium subterraneum (subter. clover)	
Trifolium hirtum (rose clover)	
Trifolium repens (white clover)	For nontilled vineyards (perennial); performs better on heavy soils
Pisum sativum (field pea)	Often mixed with grasses
Medicago polymorpha (bur medic)	
Medicago truncatula (barrel medic)	
Medicago kupulina (black medic)	
Vicia sativa (common vetch)	Shorter and less likely to interfere with vines; can be used in mixes with grasses to provide a support for the vetches to climb
Vicia villosa (hairy vetch)	More cold tolerant than common vetch
Brassica juncea (oriental mustard)	Not a legume, but a forb; good for dry environments; can act as fumigants and weed suppressants
Sinapsis spp. (white mustard)	Not a legume, but a forb; good for dry environments; can act as fumigants and weed suppressants
Grasses	
Lolium multiflorum (annual ryegrass)	Typically tilled in late spring
Hordeum vulgare (barley)	Often interplanted with vetches; barley and wheat more drought tolerant than oats or triticosecale
Triticum aestivum (wheat)	
Avena sativa (oats)	
Triticale (triticosecale hexaploide)	
Secale cereale (rye)	Good to raise organic matter; very cold tolerant; extensive root system than can compete; with vines for water and nitrogen
Festuca arundinacea (tall fescue)	
Festuca ovina (sheep fescue)	
Festuca rubra (red fescue)	
Hordeum brachiantherum (meadow barley)	Best for wet areas; can tolerate serpentine (Mg rich) soils
Orzyopsis hymenoides (Indian ryegrass)	Good for erosion control
Lolium perenne (perennial ryegrass)	Good for erosion control
Aropyron spp. (wheatgrass)	
Germany (Breil 1999)	
Legumes	
Trifolium medic (white clover)	
Grasses	
Lolium perenne (ryegrass)	For deep, rich soils
Poa pratensis (bluegrass)	For deep, rich soils
Poa trivialis (rough fescue)	For deep, rich soils
Agrostis capillaries (brown brent or brown watergrass)	For shallow soils with low rain
Festuca ovina (sheep fescue)	For hill vineyards and shallow soils
Festuca rubra (red fescue)	For hill vineyards and shallow soils
Festuca pratensis (meadow fescue)	For hill vineyards and shallow soils
South Africa (Fourie et al. 2006)	
Legumes	
Medicago truncata v. *Paraggio* (medic)	For young vineyards
Grasses	
Secale spp. (rye)	For mature vineyards, alternate 4 years of legumes
Avena spp. (oats)	
Switzerland (Spring and Mayor 1996)	
Legumes	
Trifolium spp. (clovers)	Avoid *Trifolium repens* unless plenty of water
Vicia spp. (vetches)	
Grasses	
Festuca rubra (red fescue)	
Poa spp. (bluegrass)	Avoid *Lolium multiflorum* because too aggressive and glyphosate-resistant

and Reganold 2005, Fourie et al. 2006). Optimum C:N ratios for rapid cover-crop decomposition range from 15:1 to 25:1 (e.g., C:N ratios for various cover crops/mulches: red clover 15:1, hairy vetch 10:1 to 15:1, mature rye 20:1, and corn stalks 60:1; Sullivan 2003). The amount of atmospheric N fixed by legumes varies greatly depending on type, inoculation effectiveness, and soil moisture and temperature (Madge 2005). Estimations of N fixation by vetches (*Vicia* sp.) ranged from 50 to over 220 kg/ha, and for strawberry clover (*Trifolium fragiferum* L.) from 100 to over 330 kg/ha (Ingels et al. 1998).

Cover crops can be classified not only by their botanical or functional characteristics, but also according to their management as tilled or permanent (nontilled). Most permanent cover crops are best suited for soils with high water-holding capacity and fertility or sites with abundant (>500 mm/yr) water availability due to potential competition with vines, especially under dry-farming practices (Colugnati et al. 2004). A permanent cover crop can be introduced in a vineyard by continually mowing weeds naturally growing in abundance, a practice that tends to reduce the majority of broadleaf weeds, allowing the grasses to dominate (Lipecki and Berbeć 1997). Alternatively, the permanent cover crop can be a seeded perennial or a naturally reseeding annual. Annual cover crops, often used in tilled systems, present a challenge due to imperfect reseeding, but they can persist for years once a sufficient cover and seedbank are achieved (McGourty 2008). During establishment, mowing legumes at the flowering stage, and grasses earlier than that, tends to enhance rapid soil coverage (Colugnati et al. 2004). Permanent cover crops consisting of grasses tend to benefit from N fertilization, particularly with tall species that compete with the vines (Carsoulle 1995, Spring and Mayor 1996, Agulhon 1998, Colugnati et al. 2004). Compost may normally provide sufficient N, phosphorus, and potassium (K) to meet cover-crop needs (McGourty 2004). Because of the greater duration of imposed effects on the vines, permanent cover crops have the greatest potential for impacting vine growth and grape quality (see subsequent sections).

The decomposition rate of a cover crop can be used to time its mowing and/or incorporation to ensure that N release coincides with the appropriate vine growth stage (Olmstead 2006), but few studies on cover crops have documented their decomposition rates and linked them to vine uptake. However, in one case, stable isotopes (e.g., ^{15}N) were used to identify interactions between the vines and a dormant season cover crop grown in the interrow (Patrick et al. 2004). The labeled cover crop was tilled to a depth of 0 to 15 cm, and the ^{15}N label was found in grapevine leaf tissue within six weeks. Developing N budgets in the vineyard is challenging due to difficulties in achieving total ^{15}N recovery (Patrick et al. 2004). A recent integrative study of vineyard N and water dynamics conducted over three years in an unfertilized, dry-farmed vineyard in Montpellier, France, underscores the importance of studying both the spatial and temporal aspects of N uptake and water use by both the cover crop and grapevines (Celette et al. 2009). The temporal changes in N content in both the tissue of grapevines and cover crops in relation to soil N pools indicated that the permanent grass cover crop, a perennial grass, competed for N more strongly than the nonpermanent cover crop or barley and elicited N reductions in grapevine storage organs. This suggests that cover crops influence both the current and subsequent season's grapevine nutrition. The strength of the reduction in grapevine growth varied among years, but was greater in years when water availability was more limiting.

Growers have major concerns regarding water consumption by cover crops. In Rheingau, Germany, cover-crop and weed species had higher leaf transpiration rates than did 25-year-old Riesling vines (Lopes et al. 2004). Based on estimated leaf area per unit of soil surface, a pure stand of red fescue (*Festuca rubra*) contributed less than 1 mm H_2O d^{-1} to the vineyard evapotranspiration, whereas a stand of common mallow (*Malva neglecta*) could contribute greater than 5 mm H_2O d^{-1}. In comparison, vine transpiration rates were 0.9 mm H_2O d^{-1}. Water consumption for all herbaceous species peaked between 12 and 15 hr, in contrast to grapevines whose water consumption peaked earlier in the day (8 to 10 hr).

In an attempt to achieve several benefits simultaneously, vineyard cover crops are often a mix of grasses, legumes, and forbs. Cover-crop mixes have been studied for their adaptability to soil types and topographies (Breil 1999) (Table 1). For example, for deep soils with presumably adequate available soil moisture, the recommended mix included more aggressive grass species, whereas for shallow soils receiving limited rainfall and for hillside vineyards, the recommended mix contained a variety of fescues (*Festuca* spp.). Soil N mineralization and nitrification rates associated with decomposition of single species grown alone are not necessarily additive when grown in a mixture (e.g., annual grasses and perennial grasses) (Eviner and Hawkes 2008), revealing a need for more research on implications of such phenomena on vine growth and N storage.

Impact on pests and natural enemies. The management of ground covers, such as seeded cover crops or natural vegetation, is an important component of integrated pest management in California (Costello and Daane 1998). By increasing species diversity, cover crops may stabilize the ecosystem and enhance the natural control of pests by bringing pest-predator relationships into balance (Sullivan 2003). Some vineyard pests, like cutworms, prefer to feed on broadleaf covers more than on grasses, and the presence of a broadleaf cover can reduce the number of bud strikes during the early spring season (Olmstead 2006). In such cases, it is recommended to delay tillage of the cover crop until the cutworm threat damage has passed. In fact, conservation tillage and strip tillage are considered better options than conventional tillage because they leave more cover-crop residue on the soil surface to harbor beneficial insects (Sullivan 2003).

In California, the primary insect pests in the vineyard ecosystem are leafhoppers (*Erythroneura* spp.), moths (*Desmia funeralis, Harrisina brillians, Platynota stultana*), spider mites (*Tetranichus pacificus, Eotetranichus willametti*), and mealybugs (*Pseudococcus* spp.) (Costello and Daane 1998). Each of these pests has natural enemies that can be either specialist or generalist predators. These latter include whirligig

mite (*Anystis agilis*), convergent ladybeetle (*Hyppodamia convergens*), damselbug (*Nabis americoferus*), green lacewings (*Chrysoperla* spp., *Crysopa* spp.), and various spider species (Costello and Daane 1998). Even though cover crops increased spider species diversity in a vineyard in Fresno, California, when compared to a bare soil control, spider abundance was not changed sufficiently to increase generalist predator populations (Costello and Daane 1998). Unlike the outcome with spiders, native cover crops (e.g., wallaby, *Austrodanthonia richardsonii*; windmill, *Chloris truncate*; saltbrush, *Atriplex semibaccata* and *A. suberecta*) supported a greater number of natural enemies (e.g., *Trichogramma* and *Danthonia*) than did oats (*Avena sativa*) in South Australia (Thomson et al. 2009). These were grown as a means to provide natural enemies against common pests, such as lightbrown apple moth (LBAM) (*Lobesia* spp.), scale (Coccidiae), and mealybugs (*Pseudococcus* spp.). In particular, more LBAM egg masses were parasitized in the native cover crops than in the oats. Addition of wild flowers and various dicotyledons to a cover-crop mix can also increase populations of beneficial insects (Spring and Mayor 1996, McGourty 2008). However, a permanent cover of subterranean clover (*T. subterraneum*) in central Italy initially lowered beneficial invertebrate populations, but increased them after the second year through the input of vegetable residue, which caused an increase in organic matter (Favretto et al. 1992).

Vegetation can also influence soil-borne pathogens and pests. The permanent natural vegetation present in two Australian vineyard sites in Wagga Wagga (warm climate) and Tumbarumba (cool climate) increased the populations of parasitic beneficial nematodes several fold, and decreased the populations of plant parasitic nematodes after three years (Rahman et al. 2009). Cover crops also reduced soil water content and decreased *Botrytis* incidence by opening up the vine canopy (decreasing the leaf layer number and percentages of internal clusters and leaves and increasing the percentage of gaps) (Morlat and Jacquet 2003, David et al. 2001, Tesic et al. 2007). Choice of cover crops can affect rodent populations. A higher population of gophers was more attracted to a clover mix than a green manure mix in the California Central Valley (Ingels et al. 2005).

Some research has revealed a weed-suppressive effect of Brassicaceae cover crops, such as kale (*Brassica* spp.), arugula (*Eruca* spp.), and mustard (*Sinapis* spp.), due to the release of toxic isothiocyanates after destruction of their plant tissues (Angelini et al. 1998). Mustard cover crops are sometimes grown and incorporated before vineyard establishment (i.e., biofumigation) when a chemical fumigant is not desired (Matthiessen and Kirkegaard 2006, Olmstead 2006). The amount of weed suppression depends on the biofumigant species and cultivar. For example, white mustard (*Sinapis alba* L.) is more suppressive than Indian mustard (*Brassica juncea* L.) (Brown et al. 2004, cited by Melander et al. 2005). Within the grasses, rye (*Secale cereale*) has been shown to release allelopathic compounds (Bàrberi 2002) and sorghum (*Sorghum* spp.) contains sorgoleone, a compound that reduces weed emergence (Duke et al. 2000). Also, tall fescue (*Festuca arundinacea*), a grass commonly used as a cover crop, has shown allelopathic effects when in association with some woody plants (Smith et al. 2001). In contrast, the weed-suppressive ability of legumes is usually low (Bàrberi 2002). One study suggested that the weed-suppressive effect of decomposing cover crops could be attributed more to the physical effect of the mulch generated than to an allelochemical effect (Teasdale and Mohler 2000). However, because allelopathic effects are difficult to disentangle from resource competition, and allelochemical production is highly dependent on environmental conditions, allelopathy is more likely to become a complementary tactic within a wider weed management strategy, rather than the dominant weed management tool per se (Bàrberi 2002). Biofumigants are often grown in the vineyard interrow for nematode control, but the heterogeneity of the vineyard floor has implications for nematode distribution and control. When nematode composition was compared in the vine row where weed control treatments were applied (i.e., cultivation or herbicide for five successive years, see Smith et al. 2008), the nematode community in the vine row was dominated by plant parasitic taxa, primarily of the genus *Criconemoides* (Parker 2010). The interrow was generally dominated by bacterivores and fungivores. The bacterivores with greater abundance in the interrow than vine row included the genera *Mesorhabditis*, *Acrobeles*, and *Acrobeloides* and the fungivores included *Aphelenchus* and *Aphelencoides*. These compositional shifts occurred over a very short distance (~30 to 50 cm).

Impact on vine growth and yield. Cover crops can affect soil properties, including spatial and temporal modification of the water in the soil profile (Celette et al. 2008), soil nitrate and ammonium pools, and N mineralization rates (Steenwerth and Belina 2008b). They can also improve structure and depth of "soft" (low bulk density) soil (Wheaton et al. 2008) and increase soil organic matter (Merwin et al. 1994, McGourty and Reganold 2005) and microorganism populations (Petgen et al. 1998, Baumgartner et al. 2005, Ingels et al. 2005, Steenwerth and Belina 2008a). Such soil alterations are likely to affect both the underground and aboveground development of the vine. For example, fine roots (<1 mm diam) within soil depth increments to 0.65 m were more numerous in response to a cover-crop treatment (*Festuca arundinacea* cv. Manade) than to an herbicide treatment applied closer to the vine row (0.15 m) (Morlat and Jacquet 2003). This distribution was reversed when farther away from the vines (1.6 m, center of the interrow), where roots were much more numerous in the herbicide treatment, indicating a negative effect of cover-crop roots on vine roots, particularly fine roots. Woody roots (>2 mm) generally were not affected by other treatments. Grapevine roots also tend to occupy lower soil depths when grown with permanent cover crops under dry-farm conditions (van Huyssteen 1988), but potential mechanisms of competition and interactions have not been clearly elucidated.

Early studies conducted in the 1980s in Bordeaux, France, to evaluate the consequences of permanent cover crops showed reductions in vine vigor, yield, leaf N, and *Botrytis* infection (Carsoulle 1995). In most studies reviewed here,

cover crops had a devigorating effect on the vines. In a 17-year trial conducted in the Loire Valley, France, (550 mm annual rainfall), increasing levels of soil coverage by tall fescue (*F. arundinacea*) inhibited vine growth (i.e., lower pruning weights, fewer lateral shoots, lower yield), increased canopy exposure and temperature, and decreased *Botrytis* infection (Morlat and Jacquet 2003). In New South Wales, Australia, canopy openness increased (i.e., fewer interior leaves) and shoot length decreased with increasing percentage of soil coverage by permanent cover crops (Tesic et al. 2007). Berry weight, cluster number, and yield were reduced after the third year with a cover crop. These effects were more pronounced in a dry, warm site (304 mm annual rainfall) than in a cool, humid site (492 mm annual rainfall), suggesting that irrigation and fertilization practices were the best ways to compensate for establishment of a permanent cover crop in a warm climate. In a Swiss study, berry, cluster, and pruning weights were also reduced by cover crops, particularly tall fescue (*F. arundinacea*), which increased canopy aeration and caused vine growth to stop earlier than did low fescue (*F. rubra*), a fescue/ryegrass mix (*F. rubra* 70%, *Lolium perenne* 30%) or a control treatment of herbicide (David et al. 2001). In general, competition between cover crops and vines increased and then leveled off after four years. However, even with the deep soil and abundant water at the Swiss site, the competition exerted by the tall fescue was excessive, as determined by the associated pale green color of the canopy. Similarly, a cover crop grown with Gamay at the Agricultural Research Station of Changins, Switzerland, caused a reduction in pruning weights in all four years of the study, but total yield was not affected (Maigre and Aerny 2001a). These trends were maintained even when the whole vineyard floor was fertilized (100 kg/ha N). In the California Central Valley, a native grass mix (barley, brome, and wild rye), followed by a cereal mix (barley and oats 50-50), caused the greatest reduction (30%) in pruning weights and the lowest leaf N at bloom when cover crops were compared (Ingels et al. 2005). Similar devigorating effects (30% yield reduction) occurred when the cover crop was killed with an herbicide at the beginning of summer and left as a dry mulch (Bourde et al. 1999). In all these cases, permanent cover crops growing in the interrows, when they were eliminated during the summer months to avoid severe competition with the vines, tended to have a weakening effect on both vegetative and reproductive growth, despite the presence of deep soils and/or fertilization. However, a recent study demonstrated that response times in grapevine vigor to changes in floor management varied annually (Ripoche et al. 2011a). In the first year after incorporation of a permanent cover crop (intercrop destroyed), the yield was still greater in a bare soil treatment or where cover crop was established in previously bare alleys (intercrop introduced). In the second year after incorporation, this ranking altered: the yield was greatest in the bare soil and intercrop destroyed followed by the permanent cover-crop and intercrop introduced treatments. The combination of factors (i.e., soil nutrient status, water regime, species aggressiveness, area covered, length of presence, age of the vines) that would allow a cover crop to exist with the vines without causing a devigorating effect is complex and still poorly defined.

In vineyards that can tolerate or would benefit from devigoration and yield reduction, a permanent cover crop can also improve soil physical properties and juice quality (Morlat and Jacquet 2003). In a number of studies, cover crops successfully corrected high-vigor situations. In Hawke's Bay, New Zealand, two years of cover cropping improved the viticulture and enological characteristics of a vigorous Cabernet Sauvignon (Wheeler et al. 2005). Both permanent chicory (*Chicorium intybus*) and chicory killed with an herbicide at veraison were effective in reducing soil moisture and shoot growth. Overall, the cover-crop treatments were more effective at devigorating vines (i.e., decreased shoot length, lower pruning weights, lower petiole N) than were cultivation or herbicide treatments. A Portuguese study found a similar devigorating effect (i.e., reduced pruning weights) of a native cover crop consisting mostly of legumes and grasses on a vigorous Alvarinho site after comparing a wide variety of floor management techniques (Afonso et al. 2003). Unlike the cover crop, the herbicide and the cultivation treatments tended to increase the already excessive vigor. The cover crop reduced pruning weights by 21% and yield by 32% (i.e., lower cluster weights) compared to the cultivation or the herbicide treatments, which produced similar results. These effects were insufficient to influence fruit composition, suggesting that the vine may have self-adjusted in response to the cover-crop competition by reducing both its growth and production so that the source/sink relationship was maintained.

Not all cover-crop studies found vine devigoration as a response. In a 10-year trial in a coastal region in South Africa, a medic (*Medicago scuttelata*) cover crop that was desiccated by herbicide before budbreak was correlated with the greatest petiole N at bloom and juice N (at harvest) and was the recommended management practice in young vineyards (Fourie et al. 2006). However, the supply of additional N by this and other legume cover crops may lead to excessive vigor in the long term, as was the case after the fifth year of the study, suggesting that rotating an N-scouring grass species with legumes would diminish high vigor due to excess soil N. To do so, a cover crop would sequester inorganic N in its tissue as well as support greater microbial biomass where N could be immobilized (Jackson 2000, Steenwerth and Belina 2008a, 2008b). In a three-year study in Napa, California, comparing no-till annuals (rose clover, soft brome, zorro fescue), no-till perennials (blue wildrye, California brome, meadow barley, red fescue, yarrow), tilled annual grain (triticale), and a no-cover-crop tilled control, there were no effects on pruning weights, plant nutrition, and yield (Baumgartner et al. 2008). When five different cover-crop mixtures (various mixes included perennial and annual grasses, grains, and legumes) in western Oregon vineyards were mowed periodically over two years and compared to a clean cultivated control and a resident vegetation treatment, there was no consistent effect on shoot growth, pruning weights, leaf water potential, fine root density, and cluster weights, as well juice soluble solids, pH, or titratable acidity (Sweet and Schreiner 2010).

Impact on juice and wine composition. In general, cover-crop effects on juice quality can arise through competition for water and nutrients, which reduces vigor and enhances fruit exposure (David et al. 2001, Maigre and Aerny 2001a), increases water stress leading to reduced berry size and yield (Afonso et al. 2003, Wheeler et al. 2005, Tesic et al. 2007), and lowers ambient/canopy temperature and *Botrytis* incidence caused by cover-crop transpiration (Morlat and Jacquet 2003, Nazrala 2008). General effects of the adoption of permanent cover crops in the Bordeaux area on juice composition were increased soluble solids and phenolic compounds and decreased titratable acidity, pH, and N (Carsoulle 1995). In addition to the overall increase in juice quality, cost benefits associated with eliminating vineyard operations such as fruit thinning and leaf pulling were accrued with cover cropping. In later studies, most grapes grown under permanent cover crops showed an increase in soluble solids levels, often linked to the reduced yield in France (Agulhon 1998, David et al. 2001, Morlat and Jacquet 2003) and New Zealand (Wheeler et al 2005). In other instances, the permanent cover had no effect on soluble solids levels in Switzerland (Maigre and Aerny 2001b), Portugal (Afonso et al. 2003), and Uruguay (Nazrala 2008) or it led to a reduction in soluble solids, as was the case with a clover cover in France (Nauleau 1997). Several studies found titratable acidity and pH were reduced by cover cropping relative to bare soil due to an increase in the ratio of tartaric to malic acids (Nauleau 1997, Morlat and Jacquet 2003, Wheeler et al. 2005). However, in one study, titratable acidity increased and pH decreased when vines were grown with a cover crop as compared to a bare soil control (Nazrala 2008). This response was attributed to reduction in reflected radiation (170 vs. 370 μmol m^{-2} s^{-1}) and lower vine canopy temperature (26.7 vs. 30.8°C) with cover crops. In addition, soil temperature effects on K absorption may influence juice acidity and pH and should be further studied (Nazrala 2008). There was agreement in the literature that permanent cover crops reduced leaf petiole N at bloom, lowered juice N levels at harvest, and extended duration of fermentations (Agulhon 1996, Le Goff et al. 2000, David et al. 2001, Maigre and Aerny 2001b). The latter was often corrected with N additions during fermentation.

Another observed effect of permanent cover crops is the general increase in anthocyanins and tannin levels, both in juice and wine (Agulhon 1998, Bourde et al. 1999, Morlat and Jacquet 2003, Wheeler et al. 2005, Nazrala 2008). In Cabernet Sauvignon, the effect of a cover crop (native mixed vegetation) depended on the type of phenolic compound, as well cultural method used to manage the cover crop—living (green cover) or dead (yellow cover) (Nazrala 2008). The green cover had the lowest amount of reflected light and the bare soil the highest (170 and 370 μmol m^{-2} s^{-1}, respectively). The red/far-red ratio of the reflected light was also lower in the green cover than in the cultivated, bare soil (0.71 and 1.03, respectively). These differences translated into lower photosynthetic active radiation (PAR) at the cluster level in the green cover than bare soil (9 vs. 19 μmol m^{-2} s^{-1}). However, mean temperatures in the interior grapevine canopy were lowest in the green cover (26.72°C), followed by the yellow cover (29.11°C), and bare soil (30.83°C). As a result, the green cover crop increased anthocyanins, but decreased proanthocyanidin levels, when compared to the cultivated, bare soil. In contrast, flavonols and oligomeric flavanols were significantly lower in response to the green cover crop than cultivation. The dead cover crop resulted in intermediate levels of berry phenolics (Nazrala 2008). Similarly, grape clusters exposed to direct sunlight had greater total polyphenols, anthocyanins, and flavonols than those growing in moderate sunlight exposure or shade, as did the respective wines made from each treatment (Price et al. 1995). Flavanols and flavanol polymers respond more to water stress than to changes in light or temperature regimes (Ojeda et al. 2002). Recent work on isolated effects of temperature and sunlight exposure, which could result from changes in canopy architecture, may provide insight on such changes in grape nutrition and juice composition observed from cover cropping (e.g., Spayd et al. 2002, Tarara et al. 2008). For example, total skin monomeric anthocyanins (TSMA) increased due to sunlight over two years, regardless of fruit temperature, while heating of shaded clusters decreased TSMA at least in one of two years. The variation in juice composition observed in response to management practices is not surprising considering the wide range of climatic, edaphic, and cover-crop conditions.

Impact on wine sensory evaluation. Very few studies on cover crops include a sensory evaluation of the resulting wines. Those that do often used a hedonic approach. Only those studies which reported the use of a nonhedonic, descriptive approach are covered here. In white wines, the tasting results from seven years of trials on White Colombard showed that the wines issued from three types of cover-cropped plots (*Festuca arundinacea*, *F. rubra,* or a mix *F. rubra/Lolium perenne*) had a better mouth balance and a lower acidity than those from bare soil plots, but the aromatic intensity was always high in the latter (David et al. 2001). The loss of aromas in response to the cover-crop treatment was attributed to the longer fermentations brought about by the reduced juice N levels.

In red wines, effects of cover crops on sensory characteristics appeared to be influenced by the mere presence of the cover crop as well as the timing of its removal. For instance, a cover crop reduced the overall wine quality of Gamay in a four-year study (Maigre and Aerny 2001b). In a well-organized tasting conducted all four years of the study, wines issued from the cover-crop treatment were considered to have less typicity, a closer nose, and more aggressive tannins. When the tasting was repeated after three years of aging, the control wines tended to age more rapidly, but overall, their tannin quality was still considered superior to those from the cover-crop vines. Sensory descriptive analysis was conducted for wines of Nielluccio noir vines issued from vineyard plots with a cover crop (natural vegetation) allowed to compete with the vines until after budbreak or before budbreak (Bourde et al. 1999). Elimination of the cover crop after budbreak resulted in wines with an increased intensity of fruit, spicy, and balsamic notes, no vegetative notes, and better mouthfeel characteristics (i.e., acidity, alcohol, tannin quality, tannin quantity, density,

body, balance, aromatic persistence). Retention of the cover crop after budbreak increased the wine color intensity, while absence of a cover crop resulted in lowest color intensity. Similarly, cover cropping when compared to cultivation (bare soil) increased the color intensity of a Cabernet Sauvignon wine (Nazrala 2008). In contrast, cover cropping compared to bare soil resulted in wines with less color unless the maceration was extended for two additional days (Agulhon 1998). In most studies, color intensity was greater in wines originating from cover-cropped vineyard plots than in those from vines on bare ground (Nauleau 1997, Bourde et al. 1999, Maigre and Aerny 2001b, Nazrala 2008). The impact of floor management practices on wine quality in studies conducted in several French regions (i.e., Champagne, Val de Loire, Bourgogne, Bordeaux, Beaujolais, and Languedoc-Rousillon), including both white (Chardonnay, Sauvignon blanc, Muscadelle) and red (Cabernet franc, Gamay, Grenache, Nielluccio noir) (Nauleau 1995, 1997, Agulhon 1998, Bourde et al. 1999) varieties, have been summarized by others. These trials compared wines from bare (control) plots against those produced from plots with either a permanent cover crop or a cover crop tilled in the summer to reduce competition (*enherbement naturel maitrisé*, or managed natural cover). Common to most trials, wine quality decreased as fermentation length increased due to lower juice N, which resulted from permanent cover cropping that reduced the quality of the vines. However, in the cases where the fermentation was either supplemented with N or the red macerations were prolonged for two additional days to compensate for the cover crop, the results were reversed, and the wines from the cover crop plots were rated the highest by descriptive analysis (Agulhon 1998). As for the wines from plots with a managed natural cover, the difference in juice N levels was small, and there was no clear preference over wines from bare ground plots.

In summary, permanent cover crops had generally a positive effect on wine quality. The few exceptions were associated with excess competition from the cover crop followed by sluggish fermentations or a loss of typicity. More research is needed to understand the interaction of microclimate and site characteristics (e.g., vineyard age and winegrape variety, soil fertility, depth to groundwater) with cover-crop selection and management so as to avoid excessive competition leading to severe devigoration, lower juice N content, and reduced wine sensory quality. Review of these studies has revealed the need to develop models to understand not only linkages between N and water dynamics within the vineyard but also cover-crop effects on grapevine physiology and metabolism, canopy growth, which affects canopy temperature and radiation, and successive components that influence wine composition (but see VERDI model; Ripoche et al. 2011b).

Mulches

Mulch is any bulk material placed on the soil surface to control weeds and/or preserve moisture. The advantages of mulches include weed control (Frederikson et al. 2011) comparable to cultivation (Steinmaus et al. 2008), minimization of water loss and improved soil infiltration (Pinamonti 1998, Varga and Májer 2004), improved soil structure and decreased soil compaction (Oliveira and Merwin 2001, Agnew et al. 2002, Némethy 2004), increased availability of nutrients and of organic matter (for organic mulches only) (Jacometti et al. 2007a, Thomson and Hoffmann 2007), soil insulation from temperature extremes (except plastic mulches) (Pinamonti 1998), increased soil biological activity (Sauvage 1995, Thomson and Hoffmann 2007), and increased vine health (Mundy and Agnew 2002). Some disadvantages of mulches include increased vertebrate problems (Lanini et al. 1988), energy consumption during manufacturing, initial cost of specialized equipment for spreading organic material, and installation of plastic film and disposal (Sauvage 1995). Organic mulches need to be at least 10 cm thick to block light and be effective (Lanini et al. 2011). The thickness of organic mulch typically declines by 60% in the first year, depending on the material. In general, the coarser the mulch material, the longer it will last (i.e., relatively slower decomposition), but most mulches need to be reapplied every two to three years (Lanini et al. 2011).

Impact on pests and natural enemies. An increased incidence of fungal diseases due to increased soil water content might be expected in mulched vineyards (Varga and Májer 2004). However, *Botrytis* bunch rot did not increase when various mulch materials (vineyard prunings, pomace, green waste, pine bark, animal manure, and mussel shells) were tested in several commercial vineyards in Malborough, New Zealand (Mundy and Agnew 2002). Surprisingly, at some sites, *Botrytis* incidence was lower in mulched than bare plots. In another New Zealand study that compared mulches of pomace (marc) fermented either aerobically or anerobically, grass clippings, and paper in a Riesling vineyard (Jacometti et al. 2007a), the two pomace and paper mulches increased yields, berry skin strength, and berry resistance to *Botrytis* infection (Jacometti et al. 2007b). The increased skin strength was attributed to the soil calcium and/or the higher cation exchange capacity (CEC) in mulched soils, which likely triggered a higher nutrient absorption in the mulched vineyards. The effects of mulches for New Zealand vineyards have been compiled in a downloadable report (Agnew et al. 2002).

Addition of straw and compost mulches to a Yarra Valley, Australia, vineyard increased a wide array of beneficial species in the soil and the canopy, including predatory and/or parasitic Diptera and Hemiptera as well as earthworm populations (Thomson and Hoffmann 2007). Given the direct impact of beneficial invertebrate populations on pest abundance and soil health, such findings support using the abundance of beneficial species as a sustainability indicator for the viticulture industry (Thomson et al. 2007). In two phylloxera-infected sites near Geisenheim, Germany, reduced phylloxera abundance and vine symptoms were observed after a three-year application of a spruce sawdust mulch and were attributed to the increased soil moisture content under the mulch (Huber et al. 2003). The sawdust-mulched vines had larger canopies and produced greater yields than nonmulched vines. Vineyards mulched with compost had increased populations of

organisms antagonistic to *Fusarium* (Brzeski et al. 1993), but perennial weeds, such as bindweed (*Convolvulus arvensis*), were not controlled.

Impact on vine growth and yield. Use of mulches in orchards has been found to increase tree growth and yields (see review by Lanini et al. 1988). In New Zealand, mulches increased shoot length and leaf N and K at four sites, and although soils were cooler under the mulches, budbreak was not delayed (Agnew et al. 2002). The mulches also encouraged the development of surface roots, but problems normally associated with shallow roots (e.g., potential interference with cultivation or chemical pick up) were not detected. Effects on yield were small and inconsistent, but yield increases were detected in response to mulch that included at least 6% of manure by volume. Waste mulches stimulated vine growth and increased pruning weights and plastic mulch increased yields (Pinamonti 1998). In South Africa, soil warming was delayed in a mulched straw treatment and overall had lower soil temperatures than various cover-crop and bare soil treatments (Fourie and Freitag 2010). The mulched straw treatment had reduced bud numbers (Chardonnay/99 Richter) in midspring, indicating that the onset of budbreak was delayed by the mulch, presumably by the lower soil temperatures.

Although the benefits of a compost mulch may take a few years to manifest, improvements in vine vigor and increased yields (up to 2.2 more tons/ha) were observed after the third year of application (Porter 1999). The slow release of N from compost compared to other fertilizers is a feature generally considered beneficial for the vines. Application rates at the commercial vineyards ranged from 2 to 20 tons/ha, and minimum thickness was 8 cm (or 15 cm to avoid reapplying the following year).

Impact on juice composition. Mulch composed of fresh plant residues increased grape juice TA and, in dry years, increased juice soluble solids (Varga and Májer 2004). City waste mulches also increased tartaric acid and potassium levels (Pinamonti 1998). In vineyards, unsorted solid waste mulch (composted) high in heavy metals increased leaf Ni and Cd and must Cd and Cr. In contrast, the wastewater purification sludge compost did not affect leaf or must characteristics and in soil caused only an increase in soil Zn. Wastewater sludge in combination with bark, which reduced the need for chemical weed control without reducing vigor, yields, or must quality, was a suitable alternative to fertilizers for the sustainable production of grapes. In New Zealand, researchers found benefits to vine and must characteristics of mulches composed of vineyard prunings, pomace, bark, animal manure, and/or mussel shells (Mundy and Agnew 2002). Mulching increased grape juice potassium by 16% at four sites and yeast available nitrogen (YAN) by 38% at one site. The response of K lends some credence to winemaker concerns that, by making nutrients such as K more available, mulches might increase juice and wine pH. In contrast, effects on vine growth and nutrition or juice composition are not always observed when using natural mulches such as bark (fresh or composted) and hay (Sauvage 1995, Chan and Fahey 2011). Further, fermentation duration and wine sensory characteristics may not be affected (Agulhon 1998, Sauvage 1995, Fourie 2011). These variations in response to mulches across trials are expected, considering the wide variation in mulch composition. The high content of grape skins (rich in K) and green waste/manure (rich in N) in some of the mulches may explain the observed K and YAN levels. A list of mulch materials evaluated by various authors is presented in Table 2.

Inorganic mulches. Mulches consisting of translucent, colored plastic film, reflective materials, and breathable geotextiles have been tested in a variety of studies. The benefits of inorganic mulches are weed control, increased vine vigor and pruning weights, and increased yield (Hostetler et al. 2007a, 2007b, Sandler et al. 2009). The disadvantages include the high cost of installation, short life span (often one year), and the creation of nonrecyclable waste (Hostetler

Table 2 Materials used as mulches in vineyards.

Material (reference)	Comment
Green waste (Varga and Májer 2004)	Higher cluster weight than with native vegetation cover; increased TA; increased *Botrytis* pressure (strong fungicide program recommended); should be collected before pasture seeds ripen
Cover-crop mowings (Steinmaus et al. 2008)	Similar in-row weed suppression as herbicide or cultivation
Compost (Porter 1999)	2 to 20 tonnes/ha; benefit of slow nitrogen release; unable to control perennial weeds
Hay (Sauvage 1995)	Needs frequent reappliccation
Bark (fresh or composted) (Sauvage 1995)	Increased worm populations
Sawdust (Huber et al. 2003)	Increased vigor; reduced *Phylloxera* populations and symptoms
Pomace, shredded paper (Jacometti 2007)	Increased berry skin strength and increased *Botrytis* resistance
Wastewater sludge (+ bark) (Pinamonti 1998)	Increased soil Zn; suitable fertilizer alternative for sustainable grape production
Vineyard prunings, animal manure, mussel shells (Mundy and Agnew 2002)	Increased *Botrytis* resistance
Gravel (Nachtergaele et al. 1998)	Increased radiation in fruit zone; increased soil temperature; increased evapotranspiration

et al. 2007a, 2007b). Benefits of reflective mulches include altered quality and increased intensity of light reflected to the fruit—causing an advancement of veraison and increased soluble solids, total phenols, flavanols, and anthocyanins—and reduced aphid and leafhopper populations (Coventry et al. 2005, Igounet et al. 1995). In Rhode Island, an aluminized reflective mulch and a white reflective woven material both improved photosynthetic active radiation (PAR) reflected into the canopy but had no impact on Merlot yield or fruit composition (Sandler et al. 2009). A mulch of crushed white mollusk shells (quahog, *Mercenaria* spp.) resulted in increased canopy densities, yields (both higher cluster weight and cluster number), and juice soluble solids. The shell mulch also increased soil Ca levels, which resulted in higher juice pH and Ca:Mg ratios.

The color of a plastic mulch—or of the soil itself, depending on its various mineral and organic constituents and degrees of wetness—may be critical to the amount and type of radiation reflected (Meinhold et al. 2010), and therefore, to grape quality (Nazrala 2008). The microclimate modifications detected under different plastic mulches were thoroughly reviewed (Tarara 2000). For example, in tomatoes (*Lycopersicum esculentum*), yields were higher with red or black mulches than with white and reflective mulches (Decoteau 1989, cited by Tarara 2000). Turnips (*Brassica rapa* L.) produced longer leaves and higher shoot-to-root ratios on blue or green mulch than on white mulch (Antonius 1996, cited by Tarara 2000). In grapevines, fruit composition can be affected not only by the total amount of PAR intercepted by clusters, but also by the ratio of red and far-red radiation (R:FR), which regulates the levels of the phytochrome involved in many aspects of vine metabolism and growth (Smart et al. 1988). Red and black mulches reflect similar amounts of PAR, but light reflected by red plastic is higher in R:FR, whereas reflected light from white and green mulches (most frequent color of natural cover crops) has low R:FR due to strong absorption of red light by the mulches. In the Okanagan Valley, British Columbia, Canada, a wavelength-selective polyethylene mulch had no detectable effects on Merlot vine development, yield, or fruit composition (Bowen et al. 2004). White and green plastic films had little impact on weeds, whereas brown, black, blue, and white on black (double color) films prevented weeds from emerging (Bond and Grundy 2001). Plastic mulches may be less influential to vines than other row crops because the fruit is suspended high above the mulch, where other sources of reflected light may play a more relevant role.

In most cases, high costs make plastic and geotextile mulches impractical. Despite the higher yields obtained under mulches, a cost study comparing a geotextile against a traditional cover crop with herbicide in the vine rows showed higher net gains with the traditional system (Hostetler et al. 2007b). Plastic mulches were useful in extreme climatic situations. Some examples include a cool, short season site in Ontario, Canada, where advancing ripening was essential (Coventry et al. 2005), and a very hot, high evaporative vineyard in Egypt, where conserving water was crucial (Hegazi 2000).

Finally, gravel mulching is a traditional technique still practiced in some countries. A study in Chamoson, Switzerland, found that a gravel mulch consisting of nonporous limestone fragments (2 to 8 cm diam, spread 15 cm thick) enhanced reflected radiation to the vines and increased soil temperatures at various depths (0, 3, and 10 cm), thus preventing root exposure to cold temperatures (Nachtergaele et al. 1998). The gravel mulch caused an unexpected increase in evaporation from soil during the summer months when, at that location, the annual precipitation was 597 mm.

In summary, inorganic mulches seem impractical for large vineyards in most climates. The benefits of organic mulches seem to outnumber potential negative aspects (e.g., higher juice K, rodent damage). Still, more research is needed to determine the most adequate (nontoxic, easy-to-apply, cost-effective) mulching materials and their associated impact on grape composition.

Other Techniques

Flame weeding, first used by organic growers in Germany and Switzerland in the 1970s, has renewed interest as a means of weed control in organic production (Cisneros and Zandstra 2008). The main advantages of flame weeding are a lack of chemical residues, including persistent herbicides, wide-spectrum weed control, effectiveness when soil is too moist for cultivation, absence of weed resistance, and compatibility with no-tillage techniques and organic production (Bond and Grundy 2001, Vitelli and Madigan 2004). The main disadvantages include resistance of some weeds to flames, short-term effectiveness to herbicides, consumption of costly fossil fuels and production of greenhouse gases, safety concerns, and fire risks (Heinzle 2003, Hansson and Ascard 2002). In flame weeding, plant cells expand, causing cell wall rupture and plant death (Vitelli and Madigan 2004). Efficacy of flame weeding also is attributed to subsequent plant desiccation (Ascard 1995). There are two main types of thermal weeders: true "flame" weeders, reaching temperatures of 1,900°C, and infrared weeders, with essentially no visible flame and heating to 900°C (Laguë 2001, cited by Melander et al. 2005). Flamers with covered burners are generally more energy efficient and safer than open burners. Shield design is critical to keep the combusting gases close to the ground for as long as possible (Bond and Grundy 2001). Most flame weeders use propane, but renewable fuels such as hydrogen have been evaluated (Ardensen 1997, cited by Bond and Grundy 2001).

The effectiveness of thermal weed control is determined by several factors, the most important being weed species, growth stage, amount of heat transferred, and exposure time. Annual weeds are more susceptible to heat than biennials and perennials (Mojžiš 2002, cited by Cisneros and Zandstra 2008). Broadleaf plants are also more susceptible than grasses, which have a sheath that protects the growing point. When the susceptibility of various species common to North Queensland, Australia, to flaming and various exposure lengths was evaluated, the most susceptible species had the following characteristics in common: low capacity for root suckering, thin bark, high bark moisture content, and low

bark density (Vitelli and Madigan 2004). The growth stage at which the treatment is executed is crucial because growth stage determines the location of the plant's growing points, the degree of protection of shoot apices, and the level of lignification. Overall, no important differences in percentage of mortality were recorded for heating periods of 60 seconds or longer. In general, young seedlings with an exposed shoot apex are more susceptible than older seedlings where the shoot apex is protected by surrounding leaves. However, when flaming weeds at a 0- to 2-leaf stage or at a 2- to 4-leaf stage, the most sensitive stage was species-dependent (Cisneros and Zandstra 2008). When three flaming speeds (2, 4, and 6 km/hr) were tested, there was significant regrowth even at the lowest speed, particularly in species with underground growing points. Two successive flamings seemed more effective than a single treatment (Bond and Grundy 2001). Flame weeding does not appear to reduce subsequent weed emergence and may even increase the germination of some species (Ascard 1995). In orchards, flame weeding reduced weed pressure in a young orchard, where treatments were initiated on a clean soil, but it was insufficient to control well-established perennial weeds in a mature orchard (Bond and Grundy 2001). Most research on flaming addressed weed control for vegetable row crops where it has the widest application.

Other heat-related weeding techniques include hot-water applications (Hansson and Ascard 2002), soil steaming (Melander et al. 2005), and weed microwaving (Sartorato et al. 2006), but high energy consumption by these techniques limits their practical application. Weed control through the use of freezing temperatures was also evaluated by using either liquid N or dry ice as freezing agents. Liquid N had greater efficacy than dry ice, but both were less effective than flaming (Bond and Grundy 2001). Performing soil cultivation in the dark to prevent exposure of weed seeds to daylight, thereby breaking dormancy, has produced some degree of success in row crops (Fogelberg 1999). Finally, high-tech solutions for weed control have been developed, including electroporation (i.e., application of electric pulses to the soil), carbon dioxide lasers, and weed optical detection, but the high capital investment in the equipment makes their widespread use unlikely even in high-value crops such as grapes (Bàrberi 2002).

Summary

The studies in this review emphasize the need for continued expansion of multiyear, multidisciplinary studies that use a mechanistic approach to link management practices to grapevine responses, grape and wine composition, and sensory characteristics. Understandably, no study clearly integrated the spectrum of vineyard floor management practices, associated soil nutrient management and dynamics, canopy and water management, yield and juice composition, and variations in fermentation practices and chemical characteristics of the wine, including sensory characteristics and consumer preference, although most studies addressed one or two of these aspects. Temporal (e.g., different growth seasons for cover crops and vines, timing of cover-crop desiccation) and spatial heterogeneity (e.g., different vine spacing and row widths, inrow vs. interrow regions, trellising options, cover-crop planting widths) within vineyards also must be addressed to enhance our understanding of observed phenomena in grapevines. Additional complexities are added by varietal responses, regional climates, microclimates, and the wide variety of suitable soils for production. As winegrapes are also a perennial crop that can be sustained for decades, elucidating the mechanisms involved in quality wine production must undoubtedly involve a long-term investment by multidisciplinary research teams and funding agencies.

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