Compost Benefits and Quality for Viticultural Soils

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Abstract: One of the most beneficial uses of compost is re-aggregation of soil structure damaged by excessive tillage and trafficking. Vineyard preparation, often done when surface soil is too dry, effectively destroys favorable soil structure. Heavy tractors, multiple ripping, disking, tilling, rolling, and smoothing reduces aggregates in the upper 300 mm of soil to powder and dust. Surface soil organic matter drops rapidly and the vineyard starts with the worst possible soil structure, leading to surface crusting and hardsetting, reduced infiltration of water, and restricted root development of young vines and cover crop. Research and experience shows that adding compost before planting assists in restoration of favorable soil structure. However, the method of application and the quantity and quality of compost play a decisive role in the success of amelioration. Knowledge of the factors that determine the way soil structure is re-formed and the threats that various contaminants pose to both structure regeneration and vine growth help to avoid failure. These factors are discussed in this paper, which aims to develop a protocol for optimum compost use and to establish quality standards that aid in selecting the best possible compost for structure regeneration and improved vine growth. Quality assurance parameters of importance include compost maturity (C:N ratio), salt, nitrogen, chloride and boron content, ratio of ammonium to nitrate, heavy metal concentrations, and presence of waste material contaminants.

Key words: XXX

Vineyard development and management usually involves intensive tillage and high traffic loads that progressively destroy favorable soil structure by fracturing and crushing soil aggregates at the soil surface and down to the lowest depth of tillage. Much of the natural porosity in the soil can be lost in this process and the pore-size distribution forced toward a greater proportion of fine pores. The fractured aggregates expose new surfaces to the soil atmosphere, creating conditions where oxidation of soil organic matter is accelerated to form carbon dioxide and water, which are lost from the disturbed soil. Soil biological activity is reduced and normal cycles of organic matter turnover are retarded.

Soil physical properties mediate many biological processes responsible for creating humus from organic matter. Breakdown of structure means deterioration of vineyard physical function that generally impacts negatively on vine performance. A suite of secondary physical properties decline in response to the pore structural changes: greater soil strength and anoxia, lower infiltration rate, lower hydraulic conductance, and poorer drainage rate. These physical changes affect the biological activity of the soil, reducing root growth and microbial activity. Regeneration of organic matter in soil is affected, introducing a downward spiral in soil physical quality.

Targeted and restrained tillage with addition of compost to the soil can restore favorable structure and boost the organic matter level, counteracting the downward spiral of decreasing soil organic matter. Compost is effective in stabilizing existing soil structure and, indirectly, in creating new structure. The response to compost addition depends on the effectiveness of tillage in creating new pores, the effect of the compost in stabilizing the newly created porosity, and the management changes that are adopted to avoid systematic destruction of the newly created soil structure.

Compost can also be used as a source of plant nutrients. However, premium winegrape production requires precise fertilizer application, carefully timed and located. That means the use of compost as a fertilizer is impractical because of the variability of nutrient concentrations in compost and the difficulty in applying sufficient nutrient in balanced proportions. Consequently, the value of compost for structure remediation properties may outweigh its use as a fertilizer source. Because compost may be applied in large amounts, the difficulty found in controlling nutrient addition via compost application also means that undesirable constituents in compost may inadvertently be added to soil, introducing unforeseen problems. Compost quality is an issue that needs careful consideration before it is applied (Robinson 2001).

The purpose of this paper is to describe the soil physical problems that beset many vineyards and review evidence of how compost and tillage can be used to correct these problems. Because the constituents of compost play a decisive role in the success of compost addition, the issue of compost quality is addressed and standards for judging compost quality for vineyard soil remediation are proposed.

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Processes of Soil Physical Deterioration

The processes of soil structure breakdown that occur because of tillage, traffic, reduced organic matter, and poor biological activity are coalescence, slaking, dispersion, compaction, and tillage damage by pulverization and smearing of aggregates. These processes are reviewed here in some detail as an aid to recognizing them in the vineyard.

Coalescence. All disturbed soil, especially after tillage, is subject to settlement over time in a process called "coalescence." It involves slow migration of individual soil particles (clay or silt) from the surface of aggregates toward contact points between aggregates, where they are deposited and slowly "weld" the aggregates together to form larger and larger structures that eventually coalesce into "massive" structure. Coalescence is slow, occurring over a period of days to months. Soils that have been tilled in a very dry state where aggregates are crushed to very fine microaggregates (<0.25 mm, or 0.01 inch diameter: i.e., "powder") are particularly susceptible to coalescence simply because they have many contact points.

Massive structure is characterized by few large pores and many very small pores, making it less pervious to air and water movement and harder for roots to penetrate. The driving force for particle migration is the repeated wetting and drying of soil that is part of the natural hydrologic cycle (Bresson and Moran 2004**)**. Organic matter, particularly fragments large enough to interfere with particle migration, retards coalescence. High biological activity slows the rate of coalescence by creating organic bonds that stabilize aggregates, create porosity, and promote root function.

Slaking. Slaking in soils is the process of structural collapse when dry soil aggregates with less than 2% organic carbon (C) are rapidly wetted by rain water or irrigation. Slaking includes three main stages: aggregate disruption, material relocation, and compaction (Bresson and Moran 2004). The process of slaking is rapid, occurring over minutes or hours, and is initiated by an imbalance between the adhesive strength of individual aggregates and the forces generated by the surface tension of water acting on soil particles and the compression of gas within the aggregate by in-rushing water. This imbalance reaches a maximum when aggregates are very dry (especially surface aggregates) and wetting is very rapid (e.g., intense thunderstorms, rapid irrigation as directly under drip emitters). The destructive forces of wetting are more or less constant in a vineyard but the cohesive strength of soil aggregates is dependent on the amount of organic matter in the aggregate and the form in which the organic C is distributed. Soils with low organic C (<2% by mass) and with low biological activity are subject to rapid slaking. Where organic C levels are higher, and organic polymers more numerous, soils tend to resist slaking and maintain an open porous structure. Slaked soil is compact, lacks large and very large pores, and dries to a hard consistency; it is impenetrable to roots and impervious to water and air exchange.

Dispersion. Dispersion is not directly initiated by lack of organic C in soil but is a secondary process usually initiated by slaking. Microaggregates, the products of slaking, disintegrate into individual particles of sand, silt, and clay because of high forces of repulsion between clay particles. These forces usually arise from high concentration of exchangeable sodium (Na) in relation to calcium (Ca) on the clay exchange sites. Dispersion of clays occurs when the attractive forces between the clay particles are not strong enough to hold them together under wetting conditions and the electrolyte concentration of the solution decreases below the flocculation value (Van Olphen 1977). Clay minerals vary in dispersability: Illite and montmorillonite are more dispersive than kaolinite (Singer 1994). Knowledge of soil type before adding compost with potentially high salinity is important for preventing excessive dispersion.

The effects of dispersion are catastrophic for physical soil structural quality because no structural arrangement of soil particles exists after dispersion. The properties of dispersive soils are characterized by low porosity, development of very high soil strength on drying, poor drainage, poor available water resources, and severe anoxic conditions around roots. The sodic conditions that promote dispersion are rare in North Coast vineyards but can occur in more arid regions. However, while the remedy for dispersive soils is not organic matter, a high concentration of organic C in soils is an important mitigating factor for the worst effects of high Na.

Compaction. Compaction is caused by heavy machine traffic and tillage. Compaction degrades favorable soil structure by reducing the volume of soil through destruction of pore space, mostly large pores. Compaction is a major cause of the physical degradation of viticultural soils (Flowers and Lal 1998, Hakansson and Lipiec 2000, Wiermann et al. 2000). Few soils can resist the pressure imposed by modern trafficking with inflated rubber tires. Compactability varies with water content, soil texture, mineralogy, and structure. Coarse-grained soils (gravelly sands) are less compactable than fine-grained soils (fine sandy, silty, and clayey) and soils with high organic C contents (>3 to 4% by mass) are less compactable than soils deficient in organic C (Horn and Lebert 1994).

Pressure below the wheel imprints of modern farming machines with rubber tires varies from 50 to well over 200 to 300 kPa (10 to over 40 psi) (Yong et al. 1984, Vermeulen and Perdok 1994). In contrast, pressure beneath track-laying machines is lower, varying from less than 20 to 60 MPa or less than 4 to 12 psi (Tijink 1994). Clearly, compaction by track-laying tractors is considerably less than rubber-tire tractors.

Compaction triggers a chain of physical reactions in soil affecting soil structure and pore-size distribution (Richard et al. 1999). Large pores of 0.075 to 5 mm diameter are the first pores to disappear during compaction (Kooistra and Tovey 1994), which reduces flux of water, air, heat, and roots in the soil environment (Hakansson and Lipiec 2000, Aragon et al. 2000, Ferreras et al. 2000). Compaction increases the proportion of very small and small pores at the expense of very large and large pores at the soil surface but also to some depth (up to 600 mm, 24 inches or more) in the soil profile. However, if soil organic matter is high (>2% by mass of organic C), not only is aggregate resistance to compaction greater but also the soil body as a whole exhibits an elastic resilience to compaction such that compacted soil rebounds to reverse at least part if not all the compaction.

Aggregate pulverization. Vineyard preparation of soil for planting usually involves tillage. If soil is tilled when dry, tillage reduces larger aggregates to microaggregates (powder). Soil with this fine aggregate structure is prone to coalesce, slake, disperse, and compact. These processes are seen when the soil is wetted by rain or irrigation or trafficked and cause development of hard, massive structure on drying. Poor tillage techniques lead to the modification of soil-pore-size distribution, which alters vital processes occurring in the soil. For example, reduced pore size blocks mass flow and diffusion (Tarawally et al. 2004). Reduced pore size also impedes soil biological activities by reducing aeration porosity and soil water-holding capacity and reduces penetration by plant roots. These factors often account for variable vine growth in tilled vineyards.

The mechanical behavior of soil changes as moisture content changes. Tillage of soil that is too wet destroys aggregates because soil strength is at a minimum and aggregates are destroyed by smearing. Tillage too dry also destroys many aggregates by pulverization to fine powder. However, at the so-called Lower Plastic Limit water content, where soil mechanical behavior is changing from brittle to plastic (Cass et al. 2003), tillage of soil creates optimum aggregates sizes (5 to 25 mm diameter). These variable-sized aggregates ensure that variable-sized pores are created (Adem et al. 1984). The larger pores ensure that the soil is well aerated and able to conduct water and air into and through the root zone without impediment. Soils with large aggregates are resistant to slaking, dispersion, and compaction, especially if biological activity produces organic products that stabilize these structures (Tisdall and Oades 1982). Adding organic material to the soil followed by tillage at the Lower Plastic Limit generally has a positive effect on physical, biological, and chemical properties (**Giusquiani et al. 1992**).

Improved Soil Structure from Compost Application

Soil physical constraints are often the limiting factor for vine growth. Addition of organic matter to soil has been one of the most common rehabilitation practices to improve soil physical properties (Biala 2000, Wilkinson 2001). Compost provides the raw material to stimulate microbial activity, which produces secondary compounds that act as binding substances to stabilize soil fragments created by tillage. In addition, compost stimulates biological activity and increased macrofaunal activity and root growth creates additional porosity. Applying compost to the soil surface as mulch may have some benefits for moisture conservation and weed control that can improve soil structure (Pinamonti et al. 1997). However, full benefits of compost probably cannot be realized unless the compost is mixed with soil.

Pore-size distribution. Incorporating compost by careful tillage has been shown to produce long-lasting improvements to total porosity and more heterogeneous pore-size distribution (Korboulewsky et al. 2002) with positive effects on biological habitat, hydrology, aeration, and trophic conditions (**Giusquiani et al. 1992**). Effective tillage creates large pores (tillage voids) (Kooistra and Tovey 1994). Addition of compost provides substrate for a variety of soil fauna such as earthworms. Enhanced biological activity favors greater root growth and tap roots and grass nodal roots, which, with the larger soil fauna, create large pores.

Large pores (macropores, 0.075 to 0.5 mm) store air and allow oxygen (O_2) and carbon dioxide exchange to replenish O_2 consumed by plant roots during respiration (Hamblin 1985). Large pores also reduce soil strength by providing planes of weakness in soil. Very large pores (biopores 0.5 to 5 mm diameter) enhance water infiltration rate and drainage and are primary conduits for air exchange.

Water-holding capacity. Soil water available for uptake by plants is stored in small (micropores, 0.0005 to 0.03 mm or 0.001 inch in diameter) and medium (mesopores, 0.03 to 0.075 mm or 0.003 inch) pores (Hamblin 1985). Degradation of soil structure may not necessarily reduce the frequency of these pores and absolute water-storage capacity may not be reduced. However, the probability of breaking pore continuity is great and water accessibility or flow may be reduced. Addition of composted organic matter to soil helps maintain the stability of the soil pores during water infiltration, which supports pore continuity and improves the water-holding capacity of the soil (Nemati et al. 2000a).

Soil water-storage capacity is enhanced by increasing numbers of micro- and macropores. These pore sizes correspond to the diameter of grass lateral and seminal roots. Stimulation of microbial activity in soil and the increase in the quality of the root environment obtained by addition of compost has the capacity to increase these water-storage pores. Many reports show that water-retention capacity of soils with high porosity is usually higher than the soils with low porosity (Aggelides and Londra 2000). Compost and compost residues themselves have some water-storage capacity, but this contribution is minor in relation to the capacity of soil pores.

Infiltration and hydraulic conductivity. After tillage, especially if tilled at the Lower Plastic Limit, soil generally has a large proportion of unstable large pores (tillage voids). Any disturbance, especially wetting or heavy traffic, causes these pores to collapse, particularly at the surface. However, if the soil has been treated with compost prior to tillage, then a larger proportion of these pores will persist through many wetting and drying cycles. Soils with a large proportion of macropores generally have higher infiltration rates and higher saturated hydraulic conductivity values. Without addition of compost, the infiltration rate and hydraulic conductivity of most tilled soils may decline to levels even lower than that present before tillage (Horton et al. 1994). Compost addition has little impact on the transmission properties of subsoils, even if tillage has penetrated to the subsoil, because of the difficulty of incorporating compost to this depth and the low microbiological activity.

Aggregate stability. Vineyard development and management generally has a deleterious effect on aggregate stability. Aggregate stability is related to the strength of the interaction between the components of the aggregate in relation to the magnitude of outside forces that may disrupt the aggregate. With stable aggregates the arrangement of solids and voids can be preserved when put under different stresses (Nemati et al. 2000b). Manure and other composted materials when added to the soil contribute to the development of water-stable aggregates (Aoyama et al. 1999). The proportion of stable aggregates is correlated with the size of the microbial population, suggesting that an increase in microbiological activity, resulting from compost addition, is responsible for the initial formation of soil aggregates (Diaz et al. 1994).

Addition of compost to soil is an effective treatment for increasing rhizosphere aggregate stability (Caravaca et al. 2001). Compost adds organic matter, particularly carbohydrates, to the soil, the factor most closely related to soil aggregate stability (Albiach et al. 2001). The end products of the breakdown of compost in soil are humic and fulvic acid (Wolf and Snyder 2003), but intermediate polysaccharide compounds are generated before reaching these stable configurations. Both intermediate and end products of compost decomposition act as glues to bond soil particles into aggregates and as a food source for microbes (Fortun et al. 1990). Stimulation of microbial activity creates many fungal hyphae, which also stabilize aggregate structure and which may be more persistent than polysaccharides (Wolf and Snyder 2003). Aggregate stability has been shown to be particularly correlated with the presence of glomalin (a glycoprotein present in fungal hyphae) in the soil (Wright and Upadhyaya 1998). Glomalin is involved in an important hypha-mediated stabilization of 1- to 2-mm soil aggregates (Rillig et al. 2002).

Biological activity. An increase in soil porosity aids in soil biological and biochemical activities, which lead to increased enzymatic activity. An important element of soil biological activity is the growth of fungi and bacteria, which are the leading soil organic matter decomposers. Byproducts of decomposition are enzymes that attack and break resistant bonds in the organic matter found in compost. The end product of organic matter decomposition is humus, an amorphous, colloidal, polymeric, dark-brown group of compounds. Humus contains a group of compounds referred to as humic acid, fulvic acid, and humin (Wolf and Snyder 2003).

The organic compounds that form polymers including the all-important fungal hyphae are part of the microbial food chain. The microorganisms that generate compounds and substances that stabilize soil structure also form part of the food substrate of other microorganisms. Biological activity in the soil must proceed at a pace for constant replenishment of the polymers and protein-producing hyphae as they are consumed (Rillig et al. 2003). Any sudden imbalance in biological activity, such as flooding soil for extended periods, can result in catastrophic deterioration to soil structure resulting from consumption of polymers and hyphae without replacement. Mycorrhizal fungi in particular are important components of the soil microbial population that are particularly susceptible to disruption by tillage and traffic.

Compost quantity. An important consideration is how much compost must be applied to soil to achieve a particular result and at what intervals. The amount of compost to apply for optimum effectiveness as an amendment is difficult to ascertain because organic matter sources differ in their effectiveness in stabilizing structural units (Nemati et al. 2000a,b). Organic matter amendment effectiveness is short-lived. Generally an annual application of compost is necessary to obtain a year-to-year effect on structural stability.

Improvement of physical properties by organic matter application appears to be linear in some situations (Aggelides and Londra 2000). However, adding more compost than needed can have adverse effects. For example, too much nutrient may be added, particularly nitrogen (N), and vine growth may be excessive. Often the salt load in compost is high and application of excessive amounts of compost can induce high salinity in the amended soil. Determining the optimum rate of compost to apply to vineyard soils as a conditioner will depend on site specific factors: moisture regime, soil type, and plant type. In many cases the upper limit of application may depend on the quality of the compost.

Compost Quality

The composition of compost determines the suitability of the material for a particular task and the maximum amount that can be applied. About half of most forms of commercial compost consist of carbon and much of the remaining half is O_2 and H_2. There are also lesser amounts of N, phosphorus (P), and a large variety of other constituents. The composition of these lesser constituents depends on the source materials used for manufacturing the compost. These constituents may include unusually high concentrations of chemical constituents such as soluble salts, plant nutrients (e.g., N), heavy metals or physical contaminants such as plastic waste, wood chips, sawdust, metal, and rock. In some cases constituents are added to target particular soil-amelioration requirements such as lime for acid soils.

Because the composition of compost is generally not under the control of the user, the material should be subjected to assay before use. Various protocols for assay of compost have been published or in the process of publication by a variety of authorities in various countries to try to regulate how compost composition is determined. In the United States, the USDA and the US Composting Council are working toward publishing a set of standards for compost analysis (Thompson 2001). Adoption and use of these standards will be a major step forward. However, at present, the most pressing need of compost users is to select the most appropriate test methods and interpret the test results to obtain the best results from compost use. In this section we describe the methods and interpretation criteria that we use to select the best possible compost for restoring optimum soil physical properties to surface soil after establishing vineyards.

Uncontrolled use of compost may give rise to problems caused by salinity, heavy metal content, nitrogen fixation, diminishment of O_2 in the rhizosphere, raised soil temperature, accumulation of phytotoxic substances like organic acids of low molecular weight, and pathogenic organisms (Garcia et al. 1992). The properties of immediate importance in judging compost quality for improving soil structural quality are maturity, salinity, sodicity, soluble N concentration (nitrate and ammonia), boron (B) concentration, heavy metal concentrations, and presence of pathogens.

Heavy metals. The source and quality of compost are important because some composted materials tend to have higher concentrations of heavy metals (i.e., municipal solid waste). In one study, Pinamonti et al. (1997) reported that municipal solid-waste compost used over a six-year period increased concentrations of zinc (Zn), copper (Cu), nickel (Ni), lead (Pb), cadmium (Cd), and chromium (Cr) in the soil and increased plant Pb and Cd in vegetation and fruits. Zn and Cu accumulate in the soil most readily (Baldwin and Shelton 1999), with others in the order Zn > Cu > Pb = Cd > Ni > Cr (Pinamonti et al. 1997). Depending on soil type, plant species, and compost quality, increased concentrations of Zn, Cu, and Pb have been recorded in soils and plants. Fewer reports have documented accumulation of Cd, Ni, and Cr.

Objections to using compost with high heavy metal contamination resides in risks to vines from heavy metal contamination of fruit and the threat to the survival of vines as well as the danger of contamination of the environment with these metals. Generally, critical levels for damage to vine health and fruit quality from heavy metal uptake have not been established specifically for vines. However, research on perennial tree crops and general experience indicates that vines cannot tolerate more than about 15 mg of Ni per kg of soil without damage (Daniel Roberts, personal communication, **XXXX**). Our standards for compost use in vineyards (Table 1) are based on the EPA 503 standard for environmental contamination (Thompson 2001).

Table 1 Proposed compost standards for restoring optimum soil structure after vineyard establishment (a compendium of criteria derived from CCQC 2001, Standards Australia 1997, Thompson 2001, Wilkinson 2001).

Element concentration	Symbol	Units	Critical value
General constituents and conditions			
Plastic or rock >0.5 inch	-	% dry mass	<5
Electrical conductivity	EC_{se}	dS/m	See below
Reaction	pH	-	5 to 7.5
Extractable calcium	Ca_{ex}	% dry mass	None
Extractable magnesium	Mg_{ex}	% dry mass	$<Ca_{ex}/2$
Extractable sodium	Na_{ex}	% dry mass	<1
Soluble ammonia nitrogen	NH_{4SE}	mg/L SE[a]	<300
Soluble nitrate nitrogen	NO_{3SE}	mg/L SE	<42
Soluble chloride	Cl_{SE}	mg/L SE	Under scrutiny
Soluble boron	B_{SE}	mg/L SE	<100
Carbon:nitrogen ratio	C:N	-	<20
Moisture	-	% dry mass	>25
Organic matter	OM	% dry mass	>25
Extractable heavy metals (EPA 503 standard)			
Arsenic	As	mg/kg dry mass	<41
Cadmium	Cd	mg/kg dry mass	<39
Cobalt	Co	mg/kg dry mass	<34
Chromium	Cr	mg/kg dry mass	<1200
Copper	Cu	mg/kg dry mass	<1500
Lead	Pb	mg/kg dry mass	<300
Mercury	Hg	mg/kg dry mass	<17
Nickel	Ni	mg/kg dry mass	<420
Selenium	Se	mg/kg dry mass	<35
Zinc	Zn	mg/kg dry mass	<2800
Derived parameters			
Maximum application rate	-	t/ac	See below
Sodium adsorption ratio	SAR_{SE}	-	<6

Examples: Maximum ton/acre of compost to apply if mixed with soil, based on EC measurement of salt: Max (ton/acre) = 42.3 $EC^{-0.7}$

EC_{se} (dS/m) of compost	1	5	10	20	30
Maximum rate t/ha (t/ac)	94 (42)	30.5 (13.6)	18.8 (8.4)	11.6 (5.2)	8.9 (3.9)

[a] SE: saturation extract

Salinity and boron. High salinity and B concentrations have toxic effects on vines. Based on the composition and maturity of composting materials, the phytotoxicity caused by salt concentrations, including B, in compost may cause severe damage to plants (O'Brien and Barker 1996a,b). Build up of high salt load in the soil profile, in addition to negatively affecting crop yield, may lead to the contamination of groundwater. Salinity is measured by electrical conductivity (EC). If the EC of the compost amendment is high, it may lead to soil salinization and result in N depletion, reduced nutrient cycling, and weakened crop growth (Stamatiadis et al. 1999). Salts can leach to lower depths in the soil, so a salinity problem induced by compost with high EC may go undetected with surface sampling. Sampling at greater depth will aid in discovering the effects of high EC compost, especially in soils of low buffering and cation exchange capacity (Stamatiadis et al. 1999).

The primary source of salt in compost is from use of animal waste in manufacturing the compost, although there are other sources of salt as well. Boron salts in municipal solid waste comes largely from gluing material. Leaching of the compost before application can be one solution for eliminating the high salt and B problems (Mamo et al. 1998).

The critical level of soluble B permitted in our recommendation for compost is shown in Table 1. We have not developed a critical level for salt, but instead use a sliding scale that restricts the amount of compost recommended, depending on salt level. Assuming that the compost is to be thoroughly mixed with surface soil, we base this decision on salinity, using the following formula as recommended by Standards Australia (1997):

$$M = 42.3\,EC^{-0.7} \qquad (1)$$

where M is the maximum amount (ton/hectare) of compost to apply at any one time to avoid salinity damage to young vines and EC is the electrical conductivity of a saturation extract of the compost.

The maximum rates of compost calculated from this relationship for hypothetical saturation electrical conductivity values of 1, 5, 10, 20, and 30 dS/m are shown in Table 1. Most commercial compost sold in the northern Bay Area of California has EC values of less than 20 dS/m and compost application rates of 11.2 t/ha (5 ton/acre) are common in newly developed vineyards. Other contaminants such as weed seeds, herbicide, and pesticide residues may also need to be monitored.

Sodicity. High concentrations of Na in soil may impact vine health but the most serious problems arising from Na in soil relate to soil physical quality. Elevated soil sodicity promotes soil susceptibility to seal formation, reduced infiltration rate, and a decrease in the hydraulic conductivity of the soil profile. To prevent importation of Na into soil, we recommend a maximum extractable concentration of less than 1% (dry mass) in compost (Table 1).

Nitrogen. Production of premium wine requires extreme regulation of N application to avoid excessive vegetative growth of the vines. Avoiding addition of excess organic N that can be mineralized into plant-usable nitrate or ammonium is desirable. Phytoxicity from excess ammonium in the soil is also a concern when amending soils for growth of premium winegrapes. O'Brien and Barker (1996a) have shown serious plant damage shortly after adding immature compost high in ammonia but severity of damage declined with time. Compost high in organic N is problematic because it may mineralize into nitrate and leach causing nitrate pollution in groundwater (Wolkowski 2003). As compost ages, nitrate is increased at the expense of ammonium (O'Brien and Barker 1996a), and at maturity compost for use in new vineyards should have less than 300 mg/kg ammonium-derived N in the saturation extract but also less than 42 mg/L nitrate-derived N.

Maturity. The composting process requires a certain period of time and a specific set of conditions (temperature, humidity, and aeration) for the composted material to reach "maturity" (Garcia et al. 1992). Maturity means that the composted material has reached a certain degree of physical, chemical, and biological stability (Iannotti et al. 1993). Compost maturity refers to the degree of humification of the material such that C:N ratio, ammonium level, and salt concentrations of the material are within specific ranges.

Application of immature compost can result in lower nutrient availability or phytotoxicty due to the high C:N ratio, excess ammonium, lower O_2 concentration, and redox potential due to rapid decomposition of the compost, increase in the mobility of trace metals, and the presence of phenolic substances or organic acid such as acetic acid, propinoic acid, and *n*-butyric acid. These adverse characteristics of immature compost decrease over time, and sufficient aging of compost before application allows for dissipation of any plant growth-inhibiting factors (O'Brien and Barker 1996a).

Decomposition of immature compost mixed with soil can induce anoxic conditions as the microbial biomass uses oxygen from soil pores to break down the undecomposted plant residues. The anaerobic conditions lead to production of compounds such as hydrogen sulfide (H_2S) and nitrite (NO_2) as decomposition proceeds (Mathur et al. 1993). Immature composts with a high C:N ratio can cause N draw down in the soil (Butler et al. 2001). Other problems include phytotoxicity due to the presence of organic acids as the intermediate by-products of continuing decomposition. Acetic acid and phenolic compounds, in particular, may inhibit root growth and reduce yields.

Indices of compost maturity have been established based on simple parameters (Garcia et al. 1992, Smith and Hughes 2001): water soluble carbohydrates (<0.1%), content of carbohydrates soluble in hot water (biodegradability index, <2), water soluble C (<0.5%), ratio of cation exchange capacity to total organic C (>3.5), water soluble C: total N ratio (<0.3), and water soluble C: water soluble N ratio (<2).

Following the recommendations of the California Compost Quality Council (CCQC 2001), we have elected to use the C:N ratio as an initial test of compost maturity (see Table 1).

Organic and pathogenic contaminates. Contaminates in compost include pesticides, herbicides, fecal coliform, pathogens and weed seeds. Pesticide residues may remain in finished compost. Organic matter plays a major role in the binding of pesticides in soil (Bollag et al. 1992). The risk of subsoil and groundwater contamination from compost leachates, contaminated with pesticides, is a consideration to make when determining suitability of compost (Ertunç et al. 2002).

Herbicides that have been known to persist in composted organic materials are picloram and/or clopyralid herbicides (Burkhart and Davitt 2002). Levels of herbicides in the compost have been found at high enough concentrations to cause crop damage and loss. Due to herbicide resistance to degradation they have been observed in the soil more than two years following compost applications. Conditions that promote herbicide degradation are those that encourage the microbial populations which break down clopyralid and other herbicides (Burkhart and Davitt 2002).

Compost use may pose a danger to human and animal health from pathogens that may remain in the composted products (Pietronave et al. 2004). Composting is an aerobic thermophilic process and temperatures reached are sufficient to kill enteric pathogens and weed seeds (Pietronave et al. 2004). However, composting is not a precise sterilization process, so some pathogens may be reduced to low levels during the thermophilic stage and re-grow later. We have not developed criteria for organic and pathogenic contaminants in our use of composts in viticulture, but there are compelling reasons to scrutinize these contaminants as use of compost becomes more refined.

Conclusions

Production of winegrapes is highly mechanized and vineyard soils are susceptible to physical deterioration. Processes such as coalescence, slaking, dispersion, compaction, and pulverization degrade favorable soil structure and introduce physical limitations to vine growth. Compost has a beneficial effect on physically degraded soil, provided it is applied in conjunction with careful tillage. Application of compost for restoration of favorable soil structure following vineyard development has been shown to be particularly beneficial for early vine growth provided the compost is free of undesirable constituents. The factors dictating compost quality include: maturity, salinity, sodicity, N, heavy metal concentrations, weed seeds, herbicides, pesticides, and pathogens. Standards for these factors applicable to improving vineyard soil physical properties are proposed.

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