Balanced soil fertility management in wine grape vineyards

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Imbalances in the supply of nutrients can cause nutrient disorders (deficiencies, excesses, and toxicities) in grapevines. They can also decrease vineyard soil fertility, structure, and tilth, making a less hospitable environment for vines and cover crops.

The physical, chemical, and biological characteristics of soils often vary across a vineyard. Under cultivation, the fertility and tilth of some soils will decline more rapidly than others, which compromises uniformity in fruit development, complicates vineyard management, and increases operational costs.

Grape quality suffers, as do vineyard income and relations with buyers. These factors make it apparent that maintenance of a balanced nutrient supply is critical to sustained vineyard profitability.

Mineral nutrients are chemical ions required by plants for growth and development. They occur naturally in soils. Some mineral nutrients are required by grapevines in relatively large amounts, others in small amounts. These are the macronutrients and micronutrients, respectively (Table I). Macronutrients include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). Important micronutrients[A] are boron (B), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu).

[[A]Other micronutrients of higher plants (excluding mosses, ferns, and other primitive plant forms) include molybdenum (Mo) and chloride (Cl), but no deficiencies of these nutrients have been observed in grapevines. Chloride toxicity is a problem associated with many saline soils.]

Fertility refers to a soil's ability to supply mineral nutrients. A limited mineral nutrient supply causes grapevine deficiencies that include damaged tissues (rendering specific foliar symptoms), restricted vine growth, limited fruit production, delayed fruit maturation, diminished fruit quality, and increased susceptibility to various pests and diseases.

An excessive nutrient supply in the soil is also detrimental to balanced vine growth and fruit quality, and sometimes causes toxicity in plant tissues. Therefore, the basic goal of vineyard soil fertility management is to provide a supply of mineral nutrients that avoids both of these extreme conditions.

Historical approaches to managing vineyard soil fertility

The earliest methods for maintaining vineyard soil fertility did not consider the supply of individual mineral plant nutrients. Instead the focus was on maintenance of general soil fertility and health with soil amendments. Soil amendments are organic materials (usually agricultural wastes) and mined mineral materials.

Soil amendments continue to have a significant role in sustaining soil viability and long-term vineyard profitability. However, they often fail to provide sufficient nutrients to avoid grapevine deficiencies in soils with very low supplies of available nutrients or in soils with the capacity to absorb and adsorb large quantities of applied nutrients.

In recent years, soil amendment failures have increased as more vineyards are developed on marginal lands and many vineyard managers shun synthetic fertilizer inputs for philosophical, financial, or other reasons.

In the 1950s, after synthetic fertilizers became widely available, grapegrowers had the ability to target specific nutrient elements in their management of soil fertility. These fertilizers contained ample nutrients. Concentrated, large-dose applications can saturate a soil's nutrient absorption capacity, leaving excess nutrients available for uptake by plant roots.

Two large-dose application technologies, broadcast and band, were developed to make the most efficient use of synthetic fertilizers in the 1950s. Banded applications (shanked when the fertilizer band is placed below the soil surface) are appropriate for nutrients that are strongly adsorbed by soils. Broadcast applications are appropriate for all other nutrients.

In recent years, application of liquid, dissolved, or suspended fertilizer in irrigation water has become a common practice in vineyards. This technology, called fertigation, allows great flexibility in the timing of fertilizer applications.[3,48] In addition, it often increases the rate of nutrient uptake and the predictability of vine responses to fertilization compared to broadcast or banded applications.[3,30,41] Therefore, it is generally the most efficient fertilizer application method.

Avoidance of deficiencies is possible and correction of severe deficiencies is achievable with these fertilization technologies. A single nutrient approach to vineyard soil fertility management developed from them because they readily lent themselves to correction of specific mineral nutrient problems. The single nutrient approach was further refined with advances in laboratory testing of soils and plant tissues, and calibration of yield and growth responses to test values.

Balanced grapevine mineral nutrition

As effective as the single nutrient approach is for avoiding deficiencies, it does not easily lend itself to the maintenance of a balanced supply of plant nutrients in the soil. Rather, supplies of the applied nutrient in treated soil are usually excessive for a time immediately after fertilizer application, sometimes causing large changes in pH, spikes in salinity, and large shifts in soil chemical equilibria.[3,48]

These changes in the soil chemical environment are sometimes antagonistic to the uptake of other nutrients, creating nutrient imbalances.[1,6,48] They also are unfavorable for roots and certain beneficial soil microorganisms.

After a time (up to several weeks), the level of fertilizer nutrient decreases, most adverse side effects diminish, and the vine draws upon healthy soil with an adequate nutrient supply. Eventually, with continued removal from the soil by plants and leaching, and without intervention by vineyard management, the nutrient may become so depleted as to impair vine functions. Thus, the supply of nutrients is again out of balance.

Obviously, at no time during the growing season do grapevines take up only a single mineral nutrient. Rather, they take several mineral nutrients at rates that vary according to environmental conditions including nutrient availability in the soil, and the changing demands of their developing tissues and metabolic activity.[48]

Optimized soil fertility management must consider (and whenever possible anticipate) the changing needs of grapevines for all mineral nutrients.

Most vineyards are initially developed with an unbalanced supply of soil mineral nutrients, in which levels of one or more nutrients are low or high compared to the rest. There are several causes for these imbalances:

1) Mineral composition of the rocks that evolve into soil is not proportionate to vine mineral nutrient needs.

2) Soil forming processes release minerals from weathered rock at varying rates.[1,48]

3) Soils hold some available nutrients better than others and absorb or fix some nutrients more readily than others.

4) Plants remove some nutrients in greater quantities than others, more rapidly depleting the soil supply.

5) Previous agricultural practices affect the amount of nutrients added with fertilizers, soil amendments, and irrigation water, and the amount of nutrients lost with harvested crops, eroded soil, and irrigation water that moved below the root zone.

Balanced soil fertility management strives to maintain a supply of nutrients balanced relative to one another and needs of the grapevine during particular phenological periods. In addition to balancing the supply of mineral nutrients, a balanced nutrient approach to soil fertility management should provide vineyard managers with the ability to correct moderate deficiencies in season and give partial control of vine vigor.[B]

Table I. Major mineral nutrients of grapevines, mechanism of their movement in soils, and effects of nutritional disorders.[1]

Mineral Nutrient	Mineral Nutrient Type	Principal Soil Movement Mechanism[2]	Effects of Deficiency[3]	Effects of Excess[4]
N	Macronutrient	Mass flow & diffusion	Reduced vigor, small shoots and leaves, pale foliage, reduced yield	Excess vigor, enlarged leaves, reduced bud fruitfulness, reduced fruit set, *reduced root growth*
P	Macronutrient	Diffusion	Retarded growth, reduced bud fruitfulness reduced yield, restricted foliage growth, reddened or yellowed tissues between leaf veins	*Zinc deficiency*
K	Macronutrient	Diffusion & mass flow	Leaf chlorosis & death, early leaf fall, retarded shoot growth, reduced cluster size & number, uneven ripening, increased susceptibility to frost damage	High fruit pH, *decreased magnesium uptake*
Ca	Macronutrient	Mass flow & root interception	*Restricted shoot & root growth*	*Reduced potassium & magnesium uptake*
Mg	Macronutrient	Mass flow & root interception	Yellowing at leaf edges, sometimes extending inward between main veins	Reduced potassium uptake
S	Macronutrient	Mass flow	*Uniform chlorosis, retarded plant growth, nitrogen accumulation*	*Soil acidification*
B	Micronutrient	Mass flow	Very short internodes, mottled & patched chlorosis, poor or no fruit set, shot berries, shoot tip death	Toxicity: Dark brown speckles or necrosis on edges of older leaves, cupped & wrinkled young leaves
Zn	Micronutrient	Mass flow	Distorted, mottled apical leaves; stunted shoots; poor fruit set & shoot berries	*Inhibited root growth, young leaf chlorosis*
Mn	Micronutrient	Mass flow	Chlorosis bands on basal leaves & death, decreased cold hardiness	*Tissue injury, deficiency symptoms of other nutrients*
Fe	Micronutrient	Mass flow	Interveinal, creamy chlorosis on apical leaves; stunted shoots; reduced yield	*Reduced yield*
Cu	Micronutrient	Mass flow	*Short internodes, pale color, distorted young leaves*	*Reduced vigor, inhibited root growth or root damage*

[1] Effects in italics have not been documented in California vineyards.

[2] Source: Barber (1984).

[3] Source: Christensen, et. al. (1978), Grant (1998), Marschner (1986), Mullins, et. al. (1992), Robinson (1992), Tisdale, et. al. (1985).

[4] Source: Barber (1984), Christensen, et. al. (1978), Marschner (1986), Robinson (1992), Tisdale, et. al. (1985).

[[B] The greatest part of vigor control comes from management of soil moisture and crop level, but fertilization, especially nitrogen fertilization, interacts with these.]

Requirements of a balanced nutrient approach

A balanced nutrient approach requires knowledge of soil nutrient supply, vine nutrient demand, vineyard nutrient economy, and vine nutrient uptake capabilities. It also requires fertilizer and application technologies.

Specific knowledge of the soil nutrient supply depends on estimates of the root zone size and its available nutrient content. The size of the root zone is a function of soil conditions and the extent of active roots, which change over the course of the growing season as soil moisture from winter rains is depleted and vines become increasingly dependent on moisture from irrigation.[50]

The changing and uncertain nature of root zone size greatly limits its usefulness for designing balanced nutrient fertilization programs. It does, however, indicate that broadcast and banded fertilizer applications are usually most useful early in the season, while the importance of fertigation increases as the season progresses.

Laboratory soil analyses provide a measure of available nutrients in the root zone, but analysis results are of limited use in determining the amount of fertilizer to apply because alone they do not indicate the total amount of nutrient accessible to the vines. They are, however, very useful for determining soil nutrient imbalances, such as high and low concentrations of competing ions, and the potential for nutritional disorders. They also indicate general soil chemical conditions, such as pH and salinity, which are considerations in fertilizer selection.

Grapevine demand for mineral nutrients corresponds mainly to vine biomass per acre. Obviously, a large vine biomass per acre, whether due to large vines or high vine density, will result in a larger nutrient requirement than low vine biomass.

It is the seasonal biomass — the new root, foliage, and fruit growth — that is the greatest determinant of vine nutrient demand.[8,9,10,11,33] The permanent vine biomass — the trunk, cordons, and old roots — begin the season as a source of nutrients, but they also exhibit a small demand for nutrients to be stored for the following season.

Table II.
Nutrient content of mature fruit.[1]

Nutrient	Nutrient content (lb/ton) Average	High	Low
N	2.92	4.12	1.80
P	0.56	0.78	0.44
K	4.94	7.38	3.18
Ca	1.00	1.86	0.34
Mg	0.20	0.32	0.10

[1] Source: Mullins, et. al. (1992)

Most of the nutrients garnered by new roots and foliage stay within the vineyard and are recycled, becoming available for vine use after decomposition.[33,57] In contrast, the harvested fruit represents a net nutrient loss (Table II).[33,57]

Nutrients contained in the fruit come from the soil and stored reserves in permanent parts of both the vine and soil, both of which need to be replenished for the following season to sustain consistent vine performance. It is this loss that figures most heavily in the seasonal fertilization rates of a balanced nutrient program.

Vegetative growth of roots and foliage is steady early in the growing season, and there is a corresponding increase in demand for nutrients (Table III).[8,9,10,11,33]

Shortly before bloom, vegetative growth and nutrient demand slows, but demand for nutrients sharply increases after the fruit sets, when reproductive growth becomes rapid.[8,9,10,11,26,33] A large portion (40% to 45%) of nitrogen taken up during this time will be removed from the vineyard in the harvested fruit and some (20% to 25%) will be stored in permanent structures for use during the following growing season.[8,9,11]

After fruit set, along with the general shifts in growth and nutrient demand, there is a change in the relative demand for specific nutrients (Table III). Instead of similarly increasing, after bloom the demand for specific nutrients diverges.

The demand for calcium and magnesium increases moderately, the demand for nitrogen and phosphorus increases more rapidly, and demand for potassium increases more dramatically.[8,9,10,11,33] [C]

[[C] Post bloom nitrogen uptake representing about 70% of the seasonal requirement.]

Differences among nutrients in seasonal demand figure heavily in the scheduling of fertilizer applications.

A grapevine's ability to take up nutrients normally increases early in the season as temperatures warm, metabolic activity increases, and transpiration increases.[8,9,10,11] Early season increases in nutrient uptake correspond well with increases in mineral nutrient demand. After bloom, uptake fails to keep pace with demand and much of the needed nutrients, particularly nitrogen, phosphorus, and potassium, are remobilized and transferred from roots and shoots.[8,9,10,11,26,33,35]

Nutrient uptake is frequently limited by factors that restrict movement of nutrients in the soil and factors that limit root growth and function.[1] Common environmental factors that may limit nutrient uptake include prolonged cool temperatures early in the season, restricted soil drainage, soil compaction, and presence of soil-borne pest populations capable of damaging roots.[1,10] Until these conditions are corrected, the effectiveness of soil-applied fertilizers will be limited, as will the success of a balanced mineral nutrition program.

Nutrient uptake can be artificially restricted through irrigation practices that reduce soil moisture and impose water stress on grapevines, such as regulated deficit irrigation (RDI). Although movement in the soil and uptake of all nutrients are affected by soil moisture status, some, such as potassium, are affected more than others.[54,55] The impact of soil moisture on nutrient uptake is an important reason to impose moderate rather than severe water stress during fruit ripening.

For unknown reasons, about 30 days after harvest, potassium uptake abruptly diminishes.[9] In contrast, nitrogen and phosphorus uptake continues until the onset of leaf fall.[8,9] During this time about 30% of the seasonal nitrogen requirement is taken up, and most of this (65% to 75%) is stored in the woody tissues of the vine.[11] Uptake and storage of nitrogen and phosphorus are enhanced when active leaves are maintained as long as possible.

The ability of vineyard management to apply fertilizers several times during the growing season to the active part of the root zone is critical to a balanced nutrition program. Development of drip irrigation and fertigation technologies has made this possible.[D]

[[D] Simultaneous application of multiple nutrients is possible with foliar fertilization technology. However, the low capacity of foliar tissues to absorb nutrients greatly limits fertilizer uptake (and the longevity of the

Table III. Percent increase in nutrient content of grapevines and vegetative organs above budbreak levels, and fruit above fruit set levels during a growing season.[1]

Phenological Period	Nitrogen (N)			Phosphorus (P)			Potassium (K)			Calcium (Ca)			Magnesium (Mg)		
	Vine	Vegetation	Fruit	Vine	Vegetation	Fruit	Vine	Vegetation	Fruit	Vine	Vegetation	Fruit	Vine	Vegetation	Fruit
6-inch shoots	15	15		12	12		23	23		8	8		8	8	
Start of bloom	32	32		62	62		109	109		34	34		50	50	
End of bloom	63	57		121	112		187	166		80	76		104	96	
End of rapid shoot growth	100	70	381	186	140	398	347	204	570	151	134	327	187	154	343
Veraison	165	95	1020	274	175	989	534	202	1459	225	199	562	318	253	800
Harvest	166	67	1463	263	139	1264	597	137	2063	249	222	570	382	308	917
Post harvest	103	103		163	163		269	269		234	234		374	374	
Start of leaf fall	129	129		222	222		272	272		264	264		443	443	
End of leaf fall	80	80		103	103		134	134		61	61		163	163	

[1] Sources: Conradie (1980), Conradie (1981).

corresponding response of the vine). Even repeated foliar applications are inadequate, if not cost-prohibitive, for some macronutrients.]

Another technological requirement involves the fertilizers themselves. They must be highly soluble so that they remain dissolved in irrigation water and, after reaching the root zone, remain readily available to vines. An array of liquid fertilizers has been developed to meet these needs (Table IV).

Other fertilizer considerations

Fertilizers have chemical characteristics other than their nutrient content, some of which can effect changes in soil chemistry. Consideration of these characteristics in a balanced fertigation program is essential to the maintenance of a healthy root zone, particularly with drip irrigation because of the small, intense root zone it creates.

The equivalent acidity or basicity of a fertilizer refers to its potential to decrease or increase soil pH, respectively.[5,48] The influence of fertilizer on soil pH may be either advantageous or disadvantageous.

For acid or alkaline soils, properly selected fertilizers may be used to advantage by promoting soil neutralization. However, on these same soils, improperly selected fertilizers may intensify existing pH problems.[21,34] On near-neutral soils, fertilizers should be selected to maintain neutral pH. Fertilizer-induced changes are more of a concern for sandy soil than clay soil due to differences in their lower buffering capacity (such as the capacity to resist changes in pH).

In general, nitrogen and phosphorus fertilizers have the greatest effect on soil pH.[48] Of these two nutrients, nitrogen fertilizers are commonly of greatest concern because they are applied to a larger portion of the root zone, and acidity from them persists longer in the soil. Among nitrogen fertilizers, those containing nitrogen in the form of ammonium and urea are acidifying, while those in the nitrate form are nearly pH-neutral.

The salt index indicates the potential of a fertilizer to increase the salinity of a soil.[32,48] In general, higher analysis fertilizers (those with a high nutrient content) will have less effect on soil salinity than a lower analysis fertilizer does when used to apply the same amount of nutrient per acre. Also, the salt index increases with fertilizer solubility in water.

Fertilization of salt-affected soils are a great concern, because they are frequently associated with poor internal drainage. However, salt loading in any soil may decrease the rate of water infiltration, damage young roots, and inhibit beneficial soil microorganisms. With careful fertilizer selection and application scheduling, soil salinization from fertigation will be negligible except possibly in a very small volume of soil at the edge of the wetted zone or where wetted zones coalesce.[18]

Additional specific information about fertilizers suitable for injection into drip irrigation systems, along with their most effective use, are available from several sources.[3,4,28,41,48]

Designing a balanced fertilization program: Fertilizer materials

Equipped with essential knowledge and technology, we are ready to design a basic balanced fertilization program. This program assumes a deep, well-drained, fertile soil of medium texture (fine sandy loam to silt loam), neutral pH, low salinity, and no nutrient excesses. The character of this soil changes little with depth, with the exception that the surface soil contains more mineral nutrients than the subsoil. Also, there are no unusual conditions that would inhibit nutrient uptake by grapevines.

Examples of these conditions can be found on Yolo series soils in the Napa Valley, Tokay series soils in the Lodi area, Sierra series soils in the Shenandoah Valley, and Arbuckle and Still series soils near Paso Robles.[42,43,44,45]

The program also assumes the following: 1) mature, bilateral, cordon-trained vines that had well-nourished, well-balanced growth during the previous season and went dormant with sufficient stored mineral nutrients in permanent parts of the vines; 2) soils that have been managed for mineral nutrient conservation, with minimum surface runoff and soil erosion due to the presence of a grass cover crop, and efficient irrigations; 3) Irrigation water that contains low levels of nutrients and salts.

The target yield for the current season is about six tons per acre of optimum quality fruit. Regulated deficit irrigation (RDI), in which moderate water stress is maintained during fruit ripening, will be practiced for enhanced fruit and wine quality. The basic program is structured around key grapevine phenological events.

Balanced fertilization programs are usually initiated with some nutrients applied at comparatively high rates to compensate for initial imbalances in soil nutrient supply. Still, it is important that most, if not all, nutrients are included in the program from the beginning of the season.

Without the inclusion of most nutrients, the soil under the drip emitter would soon become loaded with the recently applied fertilizer nutrients, and a new nutrient imbalance would develop.[E] Nutrient interactions in the soil, in which some nutrients either depress or stimulate uptake of other nutrients, intensify the effects of nutrient loading.[1,48]

[[E]For example, on a sandy loam soil, in less than two years, I made a significant shift in the soil nutrient equilibrium with frequent fertigated applications of 8-8-8 fertilizer. This was not a balanced program and soil levels of calcium and magnesium, which were formerly high, became very low relative to potassium. The soil pH had also decreased significantly.]

Determination of fertilization rates begins with consideration of nitrogen, because it is the nutrient most often in limited supply in soil, most often lost to leaching and volatilization, and most often responsible for detrimental under- or over-fertilization effects in vineyards.

In the basic program, the seasonal total target nitrogen is the product of the targeted yield and the nitrogen content of fruit, which is about 18 pounds per acre (6 tons/acre x 3 lbs. N/ton). Six tons of fruit will also contain about 3.5 lbs. phosphorus, 30 lbs. potassium, 6 lbs. of calcium, and 0.6 lb. magnesium.

Although fertigation is normally the most effective method of fertilizer application, actual fertilizer use efficiency can be quite low.[56] For this reason, fertilizer application rates often need to exceed replacement of nutrients in the harvested fruit to fully satisfy plant nutrient demand.

Selection of fertilizer formulations is used to achieve the desired ratio of nitrogen forms. Fertilizer formulation selection is also used to determine application rates and ratios of nutrients other than nitrogen.

Table IV. Selected liquid fertilizers suitable for injection into drip irrigation systems.[1]

Name	Analysis	Type	Acidifying in Soils
Ammonium Nitrate	20-0-0	Basic	Acidifying
Urea	23-0-0	Basic	Acidifying
Urea Ammonium Nitrate or UAN-32	32-0-0	Basic	Neutral
Ammonium Polyphosphate	10-34-0	Basic	Acidifying
Ammonium Thiosulfate	12-0-0-26(S)	Basic	Acidifying
Calcium Nitrate or CN-9	9-0-0-11 (Ca)	Basic	Neutral
Calcium Ammonium Nitrate or CAN-17	17-0-0-8.8 (Ca)	Basic	Mildly acidifying
Calcium Thiosulfate or Thiocal	0-0-0-10(S)-6(Ca)	Basic	Mildly acidifying[2]
Potassium Nitrate	2.3-0-8	Basic	Neutral
Potassium Chloride	0-0-10 or 12	Basic	Neutral
Potassium Chloride	4-0-10	Basic	Neutral
Potassium Sulfate	0-0-6 or 8	Basic	Neutral
Potassium Sulfate or ESP	1-0-8-2.5(S)	Basic	Neutral
Potassium Carbonate	0-0-30	Basic	Alkalizing
Potassium Thiosulfate, KTS, or K-MEND	0-0-25-17	Basic	Mildly acidifying[2]
Magnesium Sulfate	0-0-0-14(S)-10(Mg)	Basic	Neutral
	2-7-17-11(S)	Blended	Acidifying
	3-10-10-2(S)	Blended	Acidifying
	3-11-17 or 18	Blended	Acidifying
	5-0-8	Blended	Acidifying
	6-2-10	Blended	Acidifying
	6-2-13-4(S)	Blended	Acidifying
	8-4-8	Blended	Acidifying
	8-8-8-2(S)	Blended	Acidifying
	10-0-10	Blended	Acidifying
	12-0-9	Blended	Acidifying
	15-4-5-3(S)	Blended	Acidifying

[1] Sources: Burt (1998), Christensen (1995), Mid Valley Agricultural Services (2002), Western Fertilizer Handbook (1998).

[2] Neutral until acted upon (oxidized) by sulfur oxidizing bacteria (*Thiobacillus* sp.)

Prior to bloom, rapid development of full canopy is our primary vineyard management goal. Achieving this goal assures adequate leaf area for fruit ripening before the developing fruit becomes the main sink for vine resources.

Prebloom nutrient uptake from the soil is often limited by cool weather, cool soils, and limited transpiration. Much of the prebloom demand (20% to 30% of N demand) for mineral nutrients is met by reserves remobilized from the permanent vine structure.[7,8,9,10,11,12,15]

Still, in many vineyards, the demand for nitrogen exceeds the stored supply. Supplemental nitrogen from an external source is needed. A basic fertilization program includes nitrogen to meet this need, plus small amounts of other nutrients (particularly phosphorus and potassium) to balance the applied nitrogen and to build soil levels in anticipation of a surge in their demand following bloom (Table V).[F]

[[F]In this example soil fertility program, fertilizers will be applied through the drip irrigation system. Under some conditions it may be more desirable to apply nitrogen as dry fertilizer to the vine row. Under other conditions, the requirement may be met with the nitrogen contained in applied soil amendments or incorporated legume cover crops.]

The prebloom portion of the balanced fertilization program will use two fertilizers (Table V). Most of the nitrogen is supplied as nitrate (calcium nitrate, CN-9), which is pH-neutral, while a much smaller amount is supplied as ammonium in the N-P-K formulation 3-10-10. The small amount of applied ammonium may increase vine response to nitrogen fertilizer.[38,52] The N-P-K fertilizer also contains a micronutrient package.

Calcium nitrate and N-P-K fertilizers are incompatible because the calcium in the former will react with the phosphorus in the latter to form solid calcium phosphates.[3,17] Therefore, two fertilizer storage tanks are required — one for each fertilizer. Also, it is best to inject the fertilizers independently during separate irrigation events, with a complete flushing of the irrigation system in between.

Following bloom, the emphasis in fertilizer nutrients shifts slightly from nitrogen to potassium as the nutrient demand in the fruit greatly increases. The relative amounts of calcium nitrate and N-P-K fertilizers scheduled for application between bloom and veraison reflect this shift in nutrient demand. Potassium applied during this time may increase cane wood density and winter hardiness.

Generally, no fertilizer applications are required between veraison and harvest. However, if ripening appears delayed or variable, fertilizers may be beneficial. Potassium is frequently beneficial during this time, as the ripening fruit has continuing demand that is met mainly by a supply remobilized from vegetative organs.[53]

Post-harvest fertilizer amounts are similar to post-bloom. Irrigate to maintain active leaves as long as possible during autumn to enhance nutrient uptake and storage.

Designing a balanced fertilization program: Application timings

Some researchers have recommended application of fertilizers in very frequent, low doses to maintain a continuous, moderate nutrient supply in the soil solution and to maximize fertilization efficiency.[2,37] This frequent, light dose strategy works very well for vines on sandy soils managed for maximum production, but is not consistent with production and quality objectives in many other instances.

For most vineyards with low vine biomass per acre or soils with large moisture holding capacities, irrigations are delayed in the spring and applied infrequently during the growing season. Under these conditions, fertigations will also be infrequent.

In the sample program, the two prebloom fertilizers will be applied in separate irrigation events, both of which will last only long enough to fully charge the irrigation system, inject the fertilizer, and flush the system. CN-9 will be applied in the first irrigation, 3-10-10 in the second.

Between bloom and veraison, apply fertilizers in three applications in the following sequence: 3-10-10, CN-9, 3-10-10. Apply post-harvest fertilizers in the reverse order of pre-bloom (3-10-10 followed by CN-9), to gain maximum benefit from fertilizer potassium. Post-harvest irrigations, particularly the first, will be longer in duration than pre-bloom irrigations to fully wet the root zone.

Table V. Basic balanced fertigation program.

Application Period	Fertilizer Formulation	Fertilizer/ Acre	Ammonium	Nitrate	N	P	K	Ca	Mg	S
		gal	lb/ac	lb/ac	lb/ac	lb/ac	lb/ac	lb/ac	lb/ac	lb/ac
Prebloom	3-10-10-3(S)	7	2.1	0.0	2.1	3.1	5.8	0.0	0.0	2.1
	CN-9	4	0.3	4.1	4.4	0.0	0.0	5.4	0.0	0.0
	Subtotal	11	2.4	4.1	6.5	3.1	5.8	5.4	0.0	2.1
Post bloom	3-10-10-3(S)	10	3.0	0.0	3.0	4.4	8.3	0.0	0.0	3.0
	CN-9	2	0.1	2.0	2.2	0.0	0.0	2.7	0.0	0.0
	Subtotal	12	3.1	2.0	5.2	4.4	8.3	2.7	0.0	3.0
Post harvest	3-10-10-3(S)	13	3.9	0.0	3.9	5.7	10.8	0.0	0.0	3.9
	CN-9	3.5	0.2	3.6	3.8	0.0	0.0	4.7	0.0	0.0
	Subtotal	16.5	4.1	3.6	7.7	5.7	10.8	4.7	0.0	3.9
SEASONAL TOTAL		40	9.7	9.7	19.4	13.1	24.9	12.7	0.0	9.0

Modifications to basic program

The basic fertilizer program described above is appropriate for average vineyard conditions, but can be adapted to other conditions if appropriately modified.

Increase basic program application rates for vineyards on soils of lower fertility.[7] However, increasing fertigation rates alone may not be sufficient for soils of very low fertility, particularly for soils low in phosphorus or potassium.[17,48] Some soils have a large capacity to absorb these nutrients, and large quantities of fertilizer are required to saturate the soil's adsorption capacity.

Over time, with continued phosphorus and potassium fertigation, the volume of soil beneath the drip emitter will become saturated, but more rapid nutrient availability may be possible with shanked applications of dry fertilizer adjacent to the vine row. Correction of deficiency may require dry fertilizer application rates as high as one pound phosphorus or three pounds potassium per vine.[6,17]

Cover crops compete with grapevines for nutrients, requiring increases in vineyard fertilizer application rates.[22,23,47] Also, when environmental conditions early in the growing season limit foliage growth, the rate of growth some times can be stimulated with applications of nitrate-nitrogen (5 to 10 gal. CN-9 per acre).

Although fertilization of low fertility soils must be aggressive, care must be exercised not to over-fertilize. Seasonal nitrogen application, even for very low-vigor vineyards, should rarely, if ever, exceed 50 pounds per acre to avoid excessive foliage, decreased fruitfulness, delayed fruit maturation, and diminished fruit quality.[13,15,33,46]

To avoid toxicity, the concentration of nitrogen in the drip system should never exceed 1000 ppm.[28] Excessive fertilizer potassium applied late in the ripening period may increase fruit pH to undesirable levels.[20,31] For all nutrients, frequent, small-dose fertilizer applications are less likely to create undesirable side effects than infrequent, large-dose applications.

Low soil magnesium (Mg less than 25 ppm or Mg less than 10% of the exchangable cations) requires special application considerations. Fertilizer magnesium, like fertilizer calcium, reacts with N-P-K fertilizers to form solid magnesium phosphates and consequently, must be kept separate from them in storage and during injection. Currently, magnesium sulfate is the only cost-effective, high-analysis magnesium fertilizer suitable for supplying large amounts of magnesium through a drip system. It is sold as a highly soluble dry material.

Some soils may have very high fertility due to fertilizer residues from previous use, such as intensive farming of vegetable crops. Some irrigation waters may be high in nitrogen and may serve as the primary source of that nutrient.

Vineyards with small vines and low vine densities will have a low nutrient requirement. In these and other instances where there is an ample available supply of one or more nutrients, the corresponding nutrients in the basic fertilizer program should be lowered or, occasionally, eliminated.

The basic program may be altered to advantage for soils of high pH (*i.e.* alkaline soils). As mentioned earlier in this article, some nitrogen sources are acidifying. Examples include UN-32 and most N-P-K blends. Over time, use of acidifying fertilizers will decrease soil pH and neutralize soil alkalinity.

Saline soils require careful fertility management. Use only fertilizers with low salt index values (such as high analysis fertilizers), and apply them in frequent, small doses to avoid contributing to the existing salinity.

A continuous, balanced supply of micronutrients is required during the growing season. Regular applications assure their availability, and fertigation is a very effective technology for their application in non-alkaline soils. In soils with no significant micronutrient deficiencies, apply micronutrients roughly in ratios found in grapevine tissues.[1,6,40] The ratio I currently use is 1: 1: 1: 4: 0.25, representing boron: zinc: manganese: iron: copper.

Low micronutrient levels in soil where there is a history of deficiency should be balanced by fertilization programs emphasizing higher application rates. To avoid toxicity, rarely, if ever, apply more than one pound of boron per acre per year.[36]

Soil fertility program quality assurance

As with any vineyard management program, balanced soil fertility management requires monitoring and measuring to assure desirable performance. The basic quality assurance measure is vine appearance.

Internodes should be of normal length and diameter, and leaves should be normal in size and color. If they do not look normal, and assuming other management inputs have been applied correctly and vines are not suffering from other stresses, the program needs to be adjusted by applying either more or less fertilizer.

During bloom several nutrients reach peak concentrations in leaf tissues, making it a convenient time for analyzing nutrient status. Viticultural researchers have developed criteria for evaluating bloom leaf tissue status for deficiencies of most nutrients and excesses for a few nutrients.[6,40] These criteria, in conjunction with observations of vine and environmental conditions, may be used for fertility management program adjustments.

Soil samples collected from the vine row are also of value in soil fertility program quality assurance. A minimum panel of analyses for soil fertility quality assurance includes pH, salinity, concentrations of available nutrients, and percent base saturation.

While samples collected and analyzed at the beginning of the season indicate initial soil conditions and initial nutrient imbalances, samples collected late in the growing season represent the cumulative effects of the program. Late season soil analysis is particularly important for monitoring fertigation effects on acid, alkaline, and saline soils.

Uncorrected nutrient imbalances make vines more prone to pests, diseases, and winterkill.[14,39,51,55] They also result in fruit of low or high pH, high volatile acidity, low ratio of tartrate to malate, poor color, low phenolics, stuck fermentations, production of undesirable compounds (such as hydrogen sulfide and ethyl carbamate) and off flavors.[6,16,19,20,24,25,31,40,46,49] Certainly, avoidance of these is an important measure of soil fertility management program quality. Consistent, balanced growth of foliage and fruit is the ultimate measure of program success. ■

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