Soil and Winegrape Quality in Biodynamically and Organically Managed Vineyards

Jennifer R. Reeve,[1]* L. Carpenter-Boggs,[1] John P. Reganold,[1]
Alan L. York,[2] Glenn McGourty,[3] and Leo P. McCloskey[4]

Abstract: Wines produced from biodynamically grown grapes have received increasing attention. Similar to organic agriculture, biodynamics eliminates synthetic chemical fertilizers and pesticides. The primary difference between the two farming systems is that biodynamics uses a series of soil and plant amendments, called preparations, said to stimulate the soil and enhance plant health and quality of produce. Whether these preparations actually augment soil or winegrape quality is unclear and controversial. A long-term, replicated, 4.9-ha study was initiated in 1996 on a commercial Merlot vineyard near Ukiah, California, to investigate the effects of these biodynamic preparations on soil and winegrape quality. The study consisted of two treatments, biodynamic and organic (the control), each replicated four times in a randomized, complete block design. All management practices were the same in all plots, except for the addition of the preparations to the biodynamic treatment. No differences were found in soil quality in the first six years. Nutrient analyses of leaf tissue, clusters per vine, yield per vine, cluster weight, and berry weight showed no differences. Although average pruning weights for both treatments in 2001 to 2003 fell within the optimal range of 0.3 to 0.6 kg/m for producing high-quality winegrapes, ratios of yield to pruning weight were significantly different ($p < 0.05$) and indicated that the biodynamic treatment had ideal vine balance for producing high-quality winegrapes but that the control vines were slightly overcropped. Biodynamically treated winegrapes had significantly higher ($p < 0.05$) Brix and notably higher ($p < 0.1$) total phenols and total anthocyanins in 2003. Biodynamic preparations may affect winegrape canopy and chemistry but were not shown to affect the soil parameters or tissue nutrients measured in this study.

Key words: biodynamic viticulture, organic farming, soil quality, winegrape quality

Prior to the organic agricultural movement, biodynamic agriculture was developed in the 1920s in response to concerns from farmers about the deteriorating soils and health of their farms (Steiner 1993). Similar to organic agriculture, biodynamics eliminates synthetic chemical fertilizers and pesticides. Biodynamics is a holistic approach that emphasizes soil building and high diversity of crops, animals, and wildlife habitat (Koepf et al. 1990); therefore, inputs from outside the farm are minimized and use of on-farm resources is optimized. In addition, biodynamic practitioners use a series of fermented manure, plant, and mineral-based preparations on soil, crops, and compost (Table 1). These substances are not claimed to act as fertilizers but are said to stimulate soil nutrient cycling and promote photosynthesis and optimal compost development (Koepf et al. 1990).

Organic and biodynamic farming practices are increasing worldwide. As of 2002, 1.5% of U.S. grape acreage was certified organic (Green 2003) and organic methods continue to spread in both certified and noncertified acreage. Approximately 500 ha of winegrapes are certified biodynamic in the United States (H.G. Courtney 2003, Josephine Porter Institute, personal communication).

Biodynamic wines have received growing attention in the past 10 years as some of the world's prestigious domaines have adopted the method. Growth in biodynamic viticulture has been particularly rapid in France, with 1000 ha of winegrapes cultivated biodynamically in 1993 and 15,000 ha in 1998 (Meunier 2001).

Biodynamic farming, with its strong emphasis on soil building, holds many benefits in terms of sustainability and soil quality (Reganold et al. 1993, Mäder et al. 2002). Whether the unique biodynamic preparations themselves have any additional benefits is controversial, however. Research of the preparations suggests that they may benefit soil quality and crop quality (Koepf 1993, Reganold 1995), although results are mixed.

[1]Department of Crop and Soil Sciences, Washington State University, Pullman, WA 99164; [2]Wholistic Estate Management, PO Box 760, Hopland, CA 95482; [3]University of California Cooperative Extension, 579 Low Gap Road, Ukiah, CA 95482; and [4]Enologix, 461 Seventh St. W., #1, Sonoma, CA 95476.

*Corresponding author [Email: jrreeve@wsu.edu]

Acknowledgments: Bonterra Vineyards, Jim Fetzer, Benziger Family Winery, The Land Institute, the Biodynamic Farming and Gardening Association of North America, and the Department of Crop and Soil Sciences at Washington State University supported this research. Special thanks go to Chad Boardman for managing the field site and to Paul Dolan, Bob Blue, and Dave Koball at Bonterra Vineyards. We also thank Mary Fauci, Debbi Bikfasy, Margaret Davies, and Eric Harwood for much-needed advice and assistance in the laboratory and Ron Bolton for assistance with numerous computer-related problems and questions.

Manuscript submitted February 2004; revised September 2004, January 2005, June 2005

Table 1 Main ingredients and recommended (unit) amounts of the biodynamic preparations 500 and 501 and barrel compost used per hectare of land or preparations 502 through 507 added per metric tonne compost.

Preparation	Main ingredient	Use	Unit volume (cm^3)	Unit mass (g)
500	Cow (*Bos taurus*) manure	Field spray	88.0	95.0
501	Finely ground quartz silica	Field spray	5.00	4.50
502	Yarrow blossoms (*Achilliea millefoilium* L.)	Compost	1.07	0.08
503	Chamomile blossoms (*Matricaria recutita* L.)	Compost	1.07	0.21
504	Stinging nettle shoots (*Urtica dioica* L.)	Compost	1.07	0.31
505	Oak bark (*Quercus robur* L.)	Compost	1.07	0.28
506	Dandelion flowers (*Taraxacum officinale* L.)	Compost	1.07	0.34
507	Valerian flower extract (*Valeriana officinalis* L.)	Compost	0.14	0.09
Barrel compost	Cow manure fermented with 502 to 507	Field spray	118	128

In studies comparing organic and biodynamic treatments differing only or primarily in use of the preparations, biodynamic plots developed greater soil biological activity, greater soil microbial diversity per unit respiration (Mäder et al. 2002), greater soil organic matter, soil organic N, microbial biomass, and microbial dehydrogenase enzyme activity, greater dehydrogenase per unit microbial biomass (Abel 1987, as translated by Koepf 1993), and greater microbial biomass and root growth (Goldstein 1986). Colmenares and de Miguel (1999) found that the preparations, sprayed on permanent grassland in Spain over 3.5 years, increased dry matter content in the absence of any fertilization. Neuhoff et al. (1999) found slightly higher yields of potatoes in biodynamic as opposed to organic plots in three consecutive years. Conversely, a study by Carpenter-Boggs et al. (2000a,b) that compared plots receiving biodynamic sprays with control plots was inconclusive, as were studies in Sweden (Pettersson et al. 1992) and Australia (Penfold et al. 1995).

Winegrapes could be the ideal crop for studying differences in soil and fruit quality resulting from management practices. There is a considerable body of knowledge on the subject because of the prestige and profitability of high-quality wine. A small but growing body of research has compared the effects of conventional versus biodynamic or organic practices on soil and winegrape parameters.

A study of Germany's Mosel Valley grapegrowing region showed differences from 50 to 300% in biological soil-quality parameters between biodynamic and conventional vineyards; biodynamic vineyards contained higher organic matter, dehydrogenase activity, microbial biomass, and earthworm populations (Gehlen et al. 1988). Bourguignon and Gabucci (2000) studied paired plots of winegrapes in France, either treated or untreated with the biodynamic preparations, and, although they found no differences in the surface soil, there were significantly more macro- and micronutrients and microbial activity in the subsoil of the biodynamically treated plots. A comparison study between organic and conventional vineyards (Lotter et al. 1999) showed that increasing soil biological activity through additions of organic matter significantly reduced effects of phylloxera infestations. Even though phylloxera populations were similar under both systems, fungal necrosis as a result of the damage was 70% lower under organic management.

Dupin et al. (2000) tested 91 commercially available organic and conventional white wines. Although 70% of the wines could be discriminated based on viticultural practices, the results were statistically nonsignificant. A long-term study comparing organic and conventionally grown grapes found few consistent differences in grape quality (Henick-Kling 1995). The differences detected appeared to relate to the crop load of the vine: organic vines brought a smaller crop to higher sugar and better color content in adverse years. In good growing seasons, however, there were no significant differences.

Although these studies highlight the beneficial effects of increased soil organic matter on soil quality, disease suppression, and possibly even grape and wine quality, any potential effects of the preparations cannot be differentiated when biodynamic practices are compared solely to conventional ones. Given recent interest in the biodynamic approach, and since no research has currently been published in a refereed journal on biodynamic versus organic methods when applied to viticulture, we began a long-term replicated field experiment in 1996 comparing biodynamic and organic winegrape production on a commercial vineyard in Mendocino County, California. Our objective was to determine whether any changes in soil and winegrape quality could be detected, using common measurements of soil and winegrape quality, as a result of using the biodynamic preparations. No conventional treatment was included in the study for additional comparison as the experimental site was located on a certified biodynamic farm and the grower would have had to remove hundreds of healthy vines to buffer the biodynamic and organic plots and the rest of the farm from the conventional plots.

Materials and Methods

Experimental site and management. The experimental area was 4.9 ha, part of a commercial vineyard (*Vitis vinifera* L. cv. Merlot, grafted onto 5C rootstock). The study area was part of 60-ha of biodynamic vineyards on a diversified 170-ha certified biodynamic farm called McNab Ranch, near Ukiah, California, which was certified organic from 1994 to 1996. It started its transition into biodynamics in 1996 and became fully certified biodynamic (Demeter, Junction City, OR) in 1997.

Four 0.6-ha replicate plots for each of the two soil-management systems were delineated in June 1996 in a randomized complete block design in the study area. Each plot contained about 50 rows (on average ~27 vines per row), with vines being trained (bilateral cordon) to a vertical shoot-position. The vines were planted in 1994 at a spacing of 1.83 m within rows and 2.44 m between rows, resulting in an average of 2233 vines/ha. Once the vines were established by 2000, each vine was maintained at 10 to 12 spurs (five to six spurs per arm) and yielded 20 to 24 shoots (two shoots per spur). Vines were suckered at 15 to 30 cm of shoot growth to maintain this shoot count. Although yields averaged about 14.6 t/ha between 1997 and 2000, they were reduced by thinning to a projected yield of 10.0 t/ha in 2001, 2002, and 2003 to improve grape quality.

The 114 cm average annual precipitation at the site is supplemented with an under-vine drip-irrigation system. Vines were irrigated regularly in years up to 2000 with 30.2 L water per vine per week being applied for 10 weeks during the growing season. From 2001, continuous irrigation was discontinued. In 2001, 30.2 L per vine was applied twice, once in August and once in September. There was no irrigation in 2002 and only one irrigation application of 37.8 L per vine at veraison in mid-August in 2003. In addition, a solid-set overhead sprinkler system was used for frost protection in the winter and for evaporative cooling in the summer. The extra water added to the soil annually by overhead sprinklers, when evaporative losses were accounted for, totaled another 5.1 cm of water annually.

The two treatments received identical soil and vine management practices throughout the experiment, except that the biodynamic preparations were only applied to the biodynamic plots (see Table 1). Soil on biodynamic plots annually received biodynamic spray preparation 500 in April about two weeks after budbreak and again at the end of October to early November, two to four weeks after harvest. Preparation 501 was applied to vines in May, 10 to 17 days prebloom, and barrel compost spray was applied together with preparation 500 to the soil but in the fall only. All preparations were stirred into water and applied at rates recommended by the Josephine Porter Institute (Woolwine, VA) (Table 1).

A cover crop of annual ryegrass (*Lolium multiflorum*) was sown in fall 1996 in both treatments and disked under to increase soil organic matter in spring 1997. In 1997, grape pomace and manure compost with or without the biodynamic preparations was applied to the biodynamic and organic plots, respectively, at a rate of 8 t/ha. In fall 1997 to 2000, an oat (*Avena sativa* cv. California red)-mustard (*Brassica* spp.)-clover (*Trifolium incarnatum* cv. Flame) interrow cover crop was planted in both treatments and turned under in spring of the following year. In 2001 to 2003, alternating rows of a subclover (*Trifolium subterraneum*, mixed cultivars) and wildflowers and an oat-mustard-clover green manure crop served as interrow cover crops in both treatments. These two cover-crop mixtures, the first used mainly to attract beneficial insects and the second mainly to fertilize the soil when turned under, were rotated with each other every other year.

Soil analyses. The soil in the study area was a Cole loam, drained (fine, mixed, thermic Pachic Argixeroll), formed in alluvium. In 1996 (before implementation of management treatments), soil profiles were examined in several places in each of the eight plots for morphological characteristics, including depth and thickness of soil horizons based on texture, gravel content, structure, and color. Soil profiles within each block were found to have similar morphological characteristics.

Soil samples were also taken at 0 to 15, 15 to 30, and 30 to 45 cm from each of the designated plots in 1996. Each sample consisted of a composite of 10 subsamples, five taken from between the vines and five from the center of the rows. All subsamples were taken randomly from the inner 30 rows of each experimental plot and 7.6 m from row ends to minimize edge effects. Samples were shipped to Woods End Research Laboratory (WERL, Mt. Vernon, ME) from California by overnight mail. The samples were passed through a 2-mm sieve and stored at 4°C until analyses of the following biological, physical, and chemical properties according to recommended soil-testing procedures (Sims and Wolf 1995) unless otherwise specified: Soil pH was measured in a 1:2 w/v in water and $CaCl_2$; effervescence of free carbonates was tested with HCl; organic matter was determined using the Walkley-Black method; biological CO_2 respiration was measured after a one-week incubation at 34°C and expressed as C and total CO_2 output; water stable aggregates were measured as the dry mass of soil still aggregated after wet sieving (Kemper and Rosenau 1986); conductivity was measured using the saturated paste method; nitrate was measured using ion chromatography; and available P and reserve P were extracted with Bray P1 and P2 and measured by atomic absorption spectrometry. Chloride and sulfate were extracted with water and measured on a Waters HPLC (Waters, Milford, MA) fitted with an Alltech conductivity detector (model 650; Alltech Associates, Deerfield, IL), Alltech 335 SPCS suppressor, and a Hamilton PRP x 100 column, 4.1 x 150 mm, 10 µm (Hamilton Company, Reno, NV) with flow of 2.0 mL/min and a mobile phase of 1.7 mmol $NaHCO_3$, 1.8 mmol Na_2CO_3, and 0.1 mmol NaSCN, a sensitivity of 50 decisemens at 30°C. Exchangeable K, Na, Ca, and Mg were extracted with the modified Morgan

extractant and measured using atomic absorption spectrometry. Effective cation exchange capacity (CEC) was calculated from the measured cations.

These 1996 soil analyses revealed no significant differences between treatments (Table 2), which is essential at the start of such an on-farm experiment (Reganold 1988). These data also provide baseline data for monitoring soil changes during the experiment.

Soil samples were taken as described above at 0 to 15 cm in fall 1997, spring 2000, and fall 2001 and 2002. Samples were shipped to WERL for the following analyses: pH in H_2O and in $CaCl_2$; organic matter; total 7-day CO_2 output; water soluble aggregates; conductivity; nitrate; available P; exchangeable K, Na, Ca, and Mg; and total CEC. Soil respiration was measured in 2001 and 2002, using a Solvita Soil Life Index ranging from 0 to 5 (W.F. Brinton, WERL, 2003). In addition, in spring 2000 soil samples were analyzed by WERL for the following micronutrients: available Zn, Fe, Mn, and Cu extracted with 0.005 M DTPA and measured using atomic absorption spectrometry and boron was measured using the hot water method.

In the fall of 2002 additional soil biological characteristics were analyzed at Washington State University. Ammonium-N and NO_3^--N were measured in a filtered extract of 5.0 g soil in 25 mL 1 M KCl on a Latchat QuickCHem FIA+ 8000 series autoanalyzer (Latchat Instruments, Milwaukee, WI) using the salycilate method for NH_4 and the NH_4CL_2 method for NO_3. Readily mineralizable carbon (RMC), basal respiration (BR), and active microbial biomass by substrate-induced respiration (SIR) were measured according to Anderson and Domsch (1978). Ten grams of wet weight soil was brought to 23.6% moisture content and incubated at 24°C for 10 days. Total CO_2 released after 10 days was considered RMC. Vials were uncapped, covered with parafilm, and the following day recapped for 2 hr and the headspace CO_2 measured as BR. Vials were again uncapped, covered with parafilm, and the following day 0.5 mL of 30 g/L aqueous solution of glucose was added, rested for 1 hr before being recapped for 2 hr and headspace CO_2 measured for SIR . For all respiration tests, CO_2 was measured in vial headspace using a Shimadzu GC model GC -17A, with a thermal conductivity detector and a 168 mm HaySep 100/120 column (Shimadzu Scientific Instruments, Columbia, MD). Dehydrogenase enzyme activity was measured using 2.5 g dry weight soil and triphenyl tetrazolium chloride as substrate and phosphatase enzyme activity using 1.0 g dry weight soil and *p*-nitrophenyl phosphate as substrate (Tabatabai 1994). Dehydrogenase was measured as absorbance at 490 nm and phosphatase at 400 nm using a microplate reader (model EL311s; Bio-Tek Instruments, Winooski, VT). Potential ni-

Table 2 Means and standard errors (n = 4) from initial soil samples taken at the start of the experiment in 1996 at three depths (0–15, 15–30, and 30–45 cm) from biodynamic (BD) and organic plots before treatments were applied.

Soil property	BD (0-15 cm)	Organic (0-15 cm)	BD (15-30 cm)	Organic (15-30 cm)	BD (30-45 cm)	Organic (30-45 cm)
pH in H_2O	6.9 ± 0.10	6.9 ± 0.02	7.0 ± 0.07	6.9 ± 0.00	6.8 ± 0.05	6.8 ± 0.06
pH in $CaCl_2$	6.8 ± 0.08	6.8 ± 0.03	6.8 ± 0.05	7.6 ± 0.91	6.6 ± 0.05	6.7 ± 0.17
Organic matter (g/kg)	24 ± 1.5	24 ± 3.1	22 ± 1.2	20 ± 1.7	22 ± 5.2	18 ± 2.0
Biological respiration (g/kg C/wk)	15.0 ± 3.0	12.0 ± 4.9	11.0 ± 5.1	9.0 ± 3.6	10.0 ± 3.8	13.0 ± 4.6
Total CO_2 output (mg/kg/wk)	715 ± 162	589 ± 265	512 ± 243	369 ± 161	500 ± 244	488 ± 209
Water soluble aggregates (g/kg)	250 ± 30	300 ± 21	233 ± 24	290 ± 29	210 ± 21	217 ± 22
Conductivity (mmhos/cm)	0.4 ± 0.07	0.3 ± 0.07	0.2 ± 0.00	0.2 ± 0.03	0.2 ± 0.00	0.2 ± 0.09
Available phosphorus (mg/kg)	10.7 ± 2.7	10.3 ± 2.3	8.0 ± 0.0	10.7 ± 2.7	8.0 ± 0.0	8.0 ± 0.0
Nitrate (mg/kg)	30.7 ± 8.2	33.3 ± 6.8	12.0 ± 1.5	20.0 ± 9.1	15.0 ± 2.0	16.0 ± 4.5
Reserve phosphorus (mg/kg)	18.7 ± 4.7	24.3 ± 2.8	11.0 ± 3.0	17.7 ± 8.7	12.3 ± 3.0	13.3 ± 5.3
Chloride (mg/kg)	4.7 ± 0.9	4.7 ± 0.7	3.0 ± 0.6	4.3 ± 0.3	11.0 ± 6.7	7.33 ± 2.8
Sulfate (mg/kg)	32.3 ± 23.3	6.0 ± 1.5	4.0 ± 1.0	6.3 ± 2.4	5.7 ± 3.7	3.7 ± 0.3
Potassium (mg/kg)	194 ± 25	208 ± 12	210 ± 53	183 ± 25	147 ± 31	163 ± 14
Sodium (mg/kg)	52 ± 12	58 ± 14	62 ± 20	54 ± 16	67 ± 23	54 ± 15
Calcium (mg/kg)	2889 ± 386	2491 ± 157	2938 ± 320	2259 ± 401	2270 ± 346	2193 ± 135
Magnesium (mg/kg)	925 ± 66	839 ± 46	1168 ± 211	930 ± 179	1138 ± 139	1041 ± 42
Total CEC (cmol+/kg)	23.9 ± 1.7	20.9 ± 0.7	25.9 ± 3.8	21.1 ± 3.6	22.5 ± 3.3	22.3 ± 1.5

trification and aerobic N mineralization were measured as described by Schmidt and Belser (1994) using 10 g moist weight soil. Nitrate-N and NH_4^+-N after a 10-day incubation were measured on a Latchat QuickCHem FIA+ 8000 series autoanalyzer. All laboratory measurements were carried out in triplicate.

Earthworm populations were measured in Spring 2003 by randomly removing three 8000 cm^3 (20 cm x 20 cm x 20 cm) samples from separate rows in each plot a minimum of 10 m apart and then counting the number of earthworms.

Vine nutrition and winegrape analyses. Fifty mature leaves were randomly selected, sixth or seventh from the growing tip, from vertical shoots of average vigor in rows 15, 25, and 35 (16 to 17 leaves from each row) of each plot and 7.6 m from row ends to minimize edge effects. Leaf sampling followed recommended procedures as outlined by Campbell and Fey (2003). Samples were taken at veraison in the second week of September 2003. They were placed in marked paper sampling bags and shipped the same day by overnight mail to Cascade Analytical (Wenatchee, WA), where they were analyzed for total nitrogen, phosphorus, potassium, calcium, magnesium, boron, zinc, iron, copper, and manganese (WSALPT 1997).

Whole grape clusters were randomly sampled at harvest in 2000, 2001, 2002, and 2003 from shoots of average vigor in rows 14 to 16, 24 to 26, and 34 to 36 of each plot and 7.6 m from row ends to minimize edge effects. Enough samples were taken to fill a 7.6-L zip-lock freezer bag (about 10 to 12 clusters per bag). Sample bags were immediately placed in a refrigerator and delivered to the laboratory of Enologix (Sonoma, CA) the next morning. Winegrapes were analyzed for the following characteristics: Brix was determined by refractometer (Ough and Amerine 1988); total phenols were determined by the Folin-Ciocalteu method (Ough and Amerine 1988); and total anthocyanins were analyzed by pH shift and free anthocyanins by HPLC (Wulf and Nagel 1978, Ough and Amerine 1988).

Vine yield, cluster number, cluster weight, and berry weight were measured during harvest in 2001, 2002, and 2003 from three of the four blocks only. Ten to 20 typical vines for each vineyard plot are generally measured for this assessment (Kliewer and Casteel 2003). In our study, 10 contiguous vines approximately uniform in size in two adjacent rows (for a total of 20 vines per plot) were randomly selected in 2001 from the inner 30 rows of each treatment replicate in order to avoid an edge effect. The vines were tagged and their exact location noted on a field map, so that the same vines could be measured in 2001, 2002, and 2003 of this experiment. On the morning of fruit harvest, before harvesting the vines, a sample of 100 individual berries was randomly picked by hand from clusters from these same 20 vines for each plot, placed into a plastic zip-lock bag, and weighed. Average berry weight for each plot was calculated by dividing the total berry weight in each bag by 100. Then, each vine was hand harvested separately by cutting grape clusters with harvest knives and the total number of clusters per vine was recorded. The fruit was placed into small (16-kg capacity) plastic field lugs and weighed on a portable electronic scale; total cluster weight was recorded for each vine. Cluster weight was calculated by dividing total cluster weight per vine by the number of clusters per vine. Later in the winter, each vine was pruned and weighed separately by placing fresh prunings in bundles and weighing them on a portable electronic scale. Fruit yield to pruning weight ratios were then calculated for each vine in each treatment replicate.

Statistical analyses. The experiment was analyzed as a random complete block design (RCBD) with years as repeated measures. Data are presented by year when year-by-treatment interactions were present (significant). Test parameters measured in one year only were analyzed using a RCBD. Changes in soil over time were analyzed by combining treatment data and using year as the main factor. All statistics were measured using the SAS system for Windows version 8 ANOVA (SAS Institute, Cary, NC) and Fisher's protected LSD.

Results and Discussion

Soil quality. No consistent significant differences were found between the biodynamically treated and untreated plots for any of the physical, chemical, or biological parameters tested (Tables 3, 4, 5). Also, no differences were found in the more sensitive measures of microbial efficiency known as biological quotients: dehydrogenase activity per unit CO_2 respiration, dehydrogenase activity per unit readily mineralizable carbon, and respiration per unit microbial biomass (Table 5). Mäder et al. (2002) found significantly higher microbial efficiency in biodynamic compared to organic plots using this method. Carpenter-Boggs et al. (2000b) also investigated these quotients but found no differences between biodynamic and organic plots.

Our results are consistent with the literature in that responses to the use of the biodynamic preparations have been seen in some situations but not others. Contrary results are common in soils research and attention to the parameters and conditions in which treatments do or do not show effects often provide new hypotheses as to the reasons for such different observations.

Since the soil in the experimental site was a fertile, alluvial Mollisol, compost was only applied once (in 1997) to the plots to avoid overvigor in the winegrapes. In most farming enterprises, the biodynamic method requires regular application of biodynamic compost, which is treated with specially fermented plant-based inoculants (preparations 502 to 507). There is evidence that the preparations alter the microbial community and end-product of the compost as a result (Carpenter-Boggs et al. 2000c). Soils receiving regular compost applications may be more likely to develop treatment differences because of different compost characteristics. Goldstein (1986) found differences in soil microbial biomass and root growth in wheat plots

treated with biodynamically treated as opposed to non-treated compost only and not with the biodynamic spray preparations alone.

In a review article, Raupp and König (1996) show that biodynamic preparations cause the greatest effect under poor yielding conditions, a small effect under medium yielding conditions, and no, or an inhibiting, effect under high yielding conditions. Yield conditions included available nutrients, soil, and climatic conditions. The plots at McNab Ranch had adequate available nutrients, good soil, and a suitable climate for growing grapes, and so may not respond to the biodynamic preparations in the same degree or way as a poor site.

Several changes were seen in the soil data as a result of the 1996 annual ryegrass green manure crop and the 1997 compost application. Organic matter spiked in 1997 and then fell back to precompost levels by 2000 (Tables 2 and 3). Calcium, Mg, total bases, and cation exchange capacity were all significantly higher in 1997 and then declined slowly through 2002. Available P and Na increased also in 1997, peaking in 2000, then declining again. Overall no change in P or K was found, however, and levels remained adequate for healthy vine growth (as discussed in next section). Conductivity was significantly higher in 1996 and lowest in 2000; no problems with salinity were indicated. In 2000 the soil was sampled in spring, which would likely account for the differences in that year.

Although some researchers (Nguyen et al. 1995, Penfold et al. 1995) have expressed concern that organic forms of agriculture may not adequately replace nutrients such as P and K, we did not observe declines in these nutrients over the duration of this study. Grapevines are less demanding nutritionally than most horticultural crops

Table 4 Means and standard errors (n = 4) of micronutrients in surface soil (0 to 15 cm) of biodynamic and organic plots analyzed in 2000.

Micronutrient (mg/kg)	Biodynamic	Organic
Copper	7.33 ± 0.63	6.33 ± 0.28
Manganese	28.33 ± 2.40	21.67 ± 2.03
Iron	80.33 ± 4.91	76.67 ± 5.70
Zinc	1.23 ± 0.03	1.27 ± 0.12
Boron	<0.01	<0.01

Table 3 Means and standard errors (n = 4) of soil analyses (0–15 cm) from biodynamic (BD) and organic plots conducted in 1997, 2000, 2001, and 2002.

	1997		2000		2001		2002	
Soil property	BD	Organic	BD	Organic	BD	Organic	BD	Organic
pH in H_2O	7.1 ± 0.04	7.2 ± 0.08	7.2 ± 0.09	7.1 ± 0.06	6.7 ± 0.04	6.7 ± 0.02	7.0 ± 0.0	7.2 ± 0.05
pH in $CaCl_2$	6.8 ± 0.07	6.8 ± 0.07	6.4 ± 0.03	6.3 ± 0.05	6.6 ± 0.13	6.7 ± 0.03	6.8 ± 0.08	7.6 ± 0.82
Organic matter (g/kg)	38 ± 1.2	36 ± 2.3	24 ± 0.3	25 ± 1.0	22 ± 1.7	23 ± 1.7	23 ± 1.5	23 ± 1.5
Solvita Soil Life Index (0-5)					3.5 ± 0.24	3.1 ± 0.14	3.5 ± 0.33	3.0 ± 0.47
Total CO_2 output (mg/kg/wk)			377 ± 68	501 ± 26	1062 ± 182	812 ± 72	1125 ± 250	850 ± 268
Water soluble aggregates (g/kg)	540 ± 11	580 ± 40	46 ± 20	60 ± 17	450 ± 77	457 ± 43	95 ± 07	187* ± 26
Conductivity (mmhos/cm)	0.2 ± 0.00	0.2 ± 0.00	0.09 ± 0.00	0.09 ± 0.01	0.15 ± 0.03	0.15 ± 0.02	0.18* ± 0.01	0.17 ± 0.01
Nitrate (mg/kg)	11.7 ± 0.3	11.0 ± 1.5	1.4 ± 0.4	1.7 ± 0.3	15.0 ± 2.1	14.0 ± 1.0	6.0 ± 0.5	6.7 ± 0.7
Available phosphorus (mg/kg)	22.3 ± 7.3	17.3 ± 2.6	37.5 ± 3.4	31.5 ± 2.0	17.5 ± 0.3	17.7 ± 1.0	12.5 ± 0.6	13.2 ± 1.3
Potassium (mg/kg)	202 ± 10	270*[a] ± 22	197 ± 9	177 ± 8	251 ± 73	198 ± 17	227 ± 9	245 ± 24
Sodium (mg/kg)	46 ± 2	72* ± 7	144 ± 77	55 ± 27	32 ± 1	33 ± 1	24 ± 2	22 ± 0
Calcium (mg/kg)	2356 ± 189	3867* ± 369	2407 ± 61	2375 ± 64	2213 ± 29	2273 ± 113	2034 ± 110	1993 ± 52
Magnesium (mg/kg)	1009 ± 56	1461** ± 67	692 ± 7	668 ± 15	718 ± 24	715 ± 17	656 ± 45	614 ± 24
Total CEC (cmol+/kg)	21.3 ± 1.1	33.3* ± 2.2	20.2 ± 0.6	19.9 ± 0.7	17.8 ± 0.3	17.9 ± 0.7	16.3 ± 0.9	15.8 ± 0.4

[a]Difference between means designated * and ** are significant at $p < 0.05$ and 0.01, respectively, within each year.

(Campbell and Fey 2003) and a single application of compost combined with a fertile soil was sufficient to maintain soil fertility for winegrape growing for several years. Although trace elements were very low in the surface soil (Table 4), no deficiencies were seen in the vines. It should be noted that surface soil testing (0 to 15 cm) does not reflect the minerals available in the subsurface (15 to 45 cm) and beyond to such a deep-rooted plant as winegrapes, whose roots can grow below 3.0 m where conditions allow (Campbell and Fey 2003).

Biodynamic practitioners often claim that earthworms increase after a farm is converted to biodynamics (Koepf et al. 1990). Earthworms are known to enhance soil structure, organic matter decomposition, and nutrient cycling (Edwards and Lofty 1977). Biodynamic plots had 39% more earthworms than organic plots; however, that was not a significant difference given the high variability among samples.

Vine nutrition and winegrape analyses. Analysis of leaves showed no differences between treatments (Table 6). Most nutrients were within recommended ranges (Table 6). The exceptions were K, Cu, and Mn, which were all low, and N, which was somewhat high. However, samples were taken at veraison, when ripening fruit becomes a sink for nutrients, especially K (Conradie 2005). No deficiency symptoms were seen in the vines at any time.

There were no differences in yield, cluster count, cluster weight, and berry weight (Table 7); however, it must be noted that yields in all plots were thinned to an expected yield of 10.0 t/ha. Disease pressures, which could have further modified yields, were minor in all blocks.

Although average pruning weight for the biodynamic treatment in 2001 to 2003 was notably higher ($p < 0.1$) than the organic treatment (Table 7), pruning weights for both treatments fell within the optimal range of 0.3 to 0.6 kg/m for producing high-quality winegrapes (Kliewer and Casteel 2003). The average yield to pruning weight ratio of 4.97 for the biodynamic treatment in 2001 to 2003 was significantly lower ($p < 0.05$) than the average ratio of 6.39 for the organic treatment. Annual ratios of yield to pruning weight varied from 4.46 to 5.26 for the biodynamic treatment and 6.27 to 6.47 for the organic treatment in 2001, 2002, and 2003 (Table 7). As there were no significant year-by-treatment interactions, the statistics in Table 7 are presented for the combined means.

The yield to pruning weight ratio gives a good indication of the balance between fruit and vegetative growth. Caspari (1997) reports that, although a yield to pruning

Table 5 Means and standard errors (n = 4) of biological parameters measured in soil (0 to 15 cm) of biodynamic and organic plots in the fall 2002.

Soil biological property[a]	Biodynamic	Organic
Dehydrogenase (µg TPF/g soil)	1.32 ± 0.24	1.30 ± 0.12
Alkaline phosphatase (µg *p*-nitrophenol/g soil)	110 ± 8.0	114 ± 9.0
Acid phosphatase (µg *p*-nitrophenol/g soil)	116 ± 9.0	137 ± 19.0
Readily mineralizable C (RMC) (µg C/g soil/10 d)	42.74 ± 3.63	41.60 ± 8.34
Microbial respiration (BR) (µg C/g soil/h)	0.91 ± 0.02	0.97 ± 0.04
Microbial biomass (SIR) (µg C/g soil)	466 ± 19.0	494 ± 19.0
Nitrate-N (µg/g soil)	6.36 ± 0.45	6.25 ± 1.25
Ammonium-N (µg/g soil)	1.95 ± 0.33	1.05 ± 0.20
Aerobic N mineralization (µg NH_4^+-N/g soil)	30.25 ± 1.59	30.31 ± 2.72
Potential nitrification (µg NO_3^+-N/g soil)	154.42 ± 1.22	157.35 ± 2.04
Earthworms/m^2 in top 20 cm	267 ± 47.0	192 ± 3.0
Dehydrogenase/RMC	0.032 ± 0.007	0.037 ± 0.010
Dehydrogenase/BR	0.432 ± 0.235	0.364 ± 0.167
Dehydrogenase/SIR	0.003 ± 0.001	0.003 ± 0.000
SIR/RMC	11.05 ± 0.71	13.66 ± 2.98

[a]Abbreviations: TPF: triphenyl formazan; RMC: readily mineralizable carbon; BR: basal respiration; SIR: substrate-induced respiration.

Table 6 Means and standard errors (n = 4) of tissue analysis on second mature leaves, sixth or seventh from the growth tip, at veraison from biodynamic and organic plots in 2003. Optimal ranges for Merlot leaf tissue nutrients represent lab analyses and data compiled since 2000 from Cascade Analytical, Washington State University, Oregon State University, and University of California, Davis (L.L. Mrachek, Cascade Analytical, Wenatchee, WA, personal communication).

Tissue nutrient	Optimal range	Biodynamic	Organic
Nitrogen (g/kg)	4.9 – 15.1	21.9 ± 0.7	23.2 ± 0.5
Phosphorus (g/kg)	1.0 – 3.6	1.7 ± 0.1	1.7 ± 0.1
Potassium (g/kg)	10.0 – 20.1	7.4 ± 0.8	6.6 ± 0.5
Calcium (g/kg)	12.5 – 30.1	25.4 ± 0.6	25.7 ± 0.9
Magnesium (g/kg)	2.0 – 12.6	7.3 ± 0.5	6.9 ± 0.6
Boron (mg/kg)	25.0 – 99.0	36.0 ± 2.3	36.0 ± 1.7
Zinc (mg/kg)	15.0 – 52.0	19.0 ± 1.9	22.0 ± 5.2
Iron (mg/kg)	30.0 – 101.0	90.0 ± 2.9	107.0 ± 10.4
Copper (mg/kg)	5.0 – 21.0	3.0 ± 0.0	3.0 ± 0.0
Manganese (mg/kg)	60.0 – 201.0	58.0 ± 5.2	53.0 ± 1.2

weight ratio of 5:1 to 6:1 is appropriate for most varieties, a lower yield to pruning weight ratio is required for varieties such as Pinot noir and Merlot (as in this study). In Mendocino County, ratios of 4 to 6 designate that vines are ideally balanced with an appropriate amount of photosynthetic area for the fruit load and that the fruit will probably be of the highest quality. Vineyards with values less than 4 are characterized by high shoot vigor, low fruit yields, and excessive vine growth, with fruit sometimes having undesirable "veggie" flavors; vineyards with values greater than 6 have high fruit yields in proportion to the amount of vine growth (overcropping), with fruit often lacking intensive flavors. Too low or too high ratios of yield to pruning weight can affect wine quality with off flavors, lack of extraction, high pH, and other problems (McGourty et al. 2001). These ranges of yield to pruning weight ratios suggest that the vines under biodynamic management were better balanced than the organic vines, which were slightly overcropped. Although we do not know why this result occurred, Colmenares and de Miguel (1999) have similarly shown a stimulation of vegetative growth in pastures by the biodynamic preparations.

Winegrape chemical analyses indicate a few differences between treatments. Biodynamically grown grapes had significantly higher Brix sugars in 2003 (Table 8) than the organic grapes. Total phenols ($p = 0.06$) and total anthocyanins ($p = 0.06$) were notably higher ($p < 0.1$) for the biodynamically grown grapes. Based on the fruit composition data, there is little evidence the biodynamic preparations contribute to grape quality. The differences observed were small and of doubtful practical significance. Whether treatment differences become more pronounced over time, or whether these results are an artifact of natural variation, would be of interest to evaluate through continued monitoring of the site.

Table 7 Means and standard errors (n = 9) for vine data of biodynamic (BD) and organic plots for 2001, 2002, and 2003 with year as repeated measure.

	2001[a]		2002		2003		Combined means	
Vine property	**BD**	**Organic**	**BD**	**Organic**	**BD**	**Organic**	**BD**	**Organic**
Average clusters/vine	34.7 ± 2.7	38.9 ± 1.2	26.6 ± 2.2	26.0 ± 2.4	29.8 ± 1.6	28.5 ± 0.3	30.4 ± 2.2	31.1 ± 1.9
Yield/vine (kg)	4.28 ± 0.60	5.34 ± 0.15	4.38 ± 0.58	4.76 ± 0.34	5.11 ± 0.44	4.75 ± 0.34	4.59 ± 0.54	4.95 ± 0.29
Average cluster wt (kg)	0.12 ± 0.01	0.14 ± 0.01	0.16 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.00	0.15 ± 0.01	0.16 ± 0.01
Average berry wt (g)	1.21 ± 0.00	1.33 ± 0.03	1.09 ± 0.03	1.06 ± 0.04	1.09 ± 0.07	1.06 ± 0.05	1.13 ± 0.05	1.16 ± 0.04
Pruning wt (kg/m)	0.49 ± 0.02	0.50 ± 0.04	0.57 ± 0.02	0.47 ± 0.02	0.57 ± 0.01	0.47 ± 0.02	0.55† ± 0.02	0.48 ± 0.03
Yield/pruning wt ratio	5.26 ± 0.40	6.47 ± 0.45	4.46 ± 0.58	6.39 ± 0.79	5.19 ± 0.54	6.27 ± 0.53	4.97 ± 0.51	6.38*± 0.59

[a]Means are shown by year for the reader's interest. The appropriate statistics are shown on the combined means as there was no year-by-treatment interaction.

†Differences between means designated † are notably different at $p < 0.1$.

*Differences between means designated * are significant at $p < 0.05$.

Table 8 Means and standard errors (n = 4) for grape chemistry data at harvest of biodynamic (BD) and organic plots in 2000, 2001, 2002, and 2003.

	20 Sept 2000		22 Sept 2001		7 Oct 2002		15 Oct 2003	
Winegrape property	**BD**	**Organic**	**BD**	**Organic**	**BD**	**Organic**	**BD**	**Organic**
Brix	24.00 ± 0.14	24.15 ± 0.10	24.87 ± 0.13	25.33 ± 0.33	26.23 ± 0.08	25.80 ± 0.21	25.88* ± 0.09	25.55 ± 0.17
Total phenols (mg/kg)	2395 ± 88	2372 ± 46	3371 ± 60	3206 ± 160	2728 ± 27	2796 ± 61	3529† ± 37	3440 ± 35
Total anthocyanins (mg/kg)	1117 ± 91	1017 ± 29	995 ± 4.0	983 ± 25	1108 ± 18	1092 ± 10	1337† ± 14	1272 ± 13
Free anthocyanins (mg/kg)	846 ± 25	870 ± 16	1037 ± 139	933 ± 119	903 ± 17	862 ± 19	1049 ± 16	1020 ± 20

*Differences between means designated * are significant at $p < 0.05$ within each year.

†Differences between means designated † are notably different at $p < 0.1$ within each year.

Conclusions

No differences in soil quality at 0 to 15 cm were found between biodynamically treated and untreated plots. Also, no differences were found in microbial efficiency as measured by biological quotients. That is consistent with other studies in that effects of biodynamic preparations have been recorded in some situations but not in others. The effects of a single application of compost and an annual rye green manure crop on soil parameters in this study could be detected for several years, suggesting that only minimal compost application and limited use of green manure crops on fertile soils is needed to achieve lasting benefits in a lower-yield, high-quality winegrape system such as in this study.

Leaf tissue analyses showed no differences between treatments. In addition, most plant nutrients were within recommended ranges and deficiency symptoms were not seen in the vines at any time. Yield, cluster count and weight, and berry weight showed no difference between treatments, and disease pressure was minor in all blocks. Although average pruning weights for both treatments in 2001 to 2003 fell within the optimal range of 0.3 to 0.6 kg/m for producing high-quality winegrapes, ratios of yield to pruning weight were significantly different and suggested that the biodynamic treatment had ideal vine balance for producing high-quality winegrapes but that the organic vines were slightly overcropped.

Biodynamic grapes in 2003 had significantly higher Brix and notably higher total phenols and total anthocyanins. These differences, however, were small and of doubtful practical significance.

The biodynamic preparations were the only factor different between the management treatments in this study and may have caused the observed differences in ratios of yield to pruning weight as well as the small differences in winegrape chemistry. If so, the mechanism (or mechanisms) responsible for the few differences seen in this study is not known.

Continued monitoring of grape chemistry at this site would be worthwhile to determine whether differences in winegrape chemistry and canopy between biodynamic and organic treatments seen in the study will continue over time. In order to fully determine whether the high quality of biodynamic wines reported in the press is a result of the use of the biodynamic preparations or simply a matter of viticultural or enological practices, an evaluation of wine made from the two treatments would be necessary.

Literature Cited

Anderson, J.P.E., and K.H. Domsch. 1978. A physiological method for the quantitative measurement of microbial biomass in soil. Soil Biol. Biochem. 10:215-221.

Bourguignon, C., and L. Gabucci. 2000. Comparisons of chemical analysis and biological activity of soils cultivated by organic and biodynamic methods. *In* IFOAM 2000: The World Grows Organic. Proceedings of the 6th International Congress on Organic Viticulture. H. Willer and U. Meier (Eds.), pp. 92-99. Stiftung Okologie & Landbau, Bad Dürkheim, Germany.

Campbell, A., and D. Fey. 2003. Soil management and grapevine nutrition. *In* Oregon Viticulture. E.W. Hellman. (Ed.), pp. 143-161, Oregon State University Press, Corvallis.

Carpenter-Boggs, L., J.P. Reganold, and A.C. Kennedy. 2000a. Biodynamic preparations: Short-term effects on crops, soils and weed populations. Am. J. Altern. Agric. 15:110-118.

Carpenter-Boggs, L., A.C. Kennedy, and J.P. Reganold. 2000b. Organic and biodynamic management: Effects on soil biology. Soil Sci. Soc. Am. J. 64:1651-1659.

Carpenter-Boggs, L., J.P. Reganold, and A.C. Kennedy. 2000c. Effects of biodynamic preparations on compost development. Biol. Agric. Hortic. 17:313-328.

Caspari, H. 1997. Sustainable viticulture: Current world trends. HortResearch Publication, Horticulture and Food Research Institute of New Zealand. http://www.hortnet.co.nz/publications/science/c/caspari/viti.htm (accessed 10 August 2004).

Colmenares, R., and J.M. de Miguel. 1999. Improving permanent pasture's growth: An organic approach. Cahiers Options Méditer. 39:189-191.

Conradie, W.J. 2005. Partitioning of mineral nutrients and timing of fertilizer applications for optimum efficiency. *In* Proceedings of the Soil Environment and Vine Mineral Nutrition Symposium. P. Christensen and D. Smart (Eds.), pp. 69-81. American Society for Enology and Viticulture, Davis, CA.

Dupin, I., U. Fischer, and P. Schlich. 2000. Differentiation of wines produced by organic or conventional viticulture according to their sensory and profiles and aroma composition. Abstr. Am. J. Enol. Vitic. 51:299.

Edwards, C.A., and J.R. Lofty. 1977. Biology of Earthworms. Halsted Press, New York.

Gehlen, P., J. Neu, and D. Schröder. 1988. Soil chemical and soil biological properties of conventionally and organically managed vineyards at the Mosel River. Wein Wissen. 43:161-173.

Goldstein, W. 1986. Alternative crops, rotations and management systems for the Palouse. Ph.D. dissertation. Washington State University, Pullman.

Green, C. 2003. USDA Organic Farming Statistics and Social Science Research. Economic Research Service, USDA, Washington, DC.

Henick-Kling, T. 1995. Summary of effects of organic and conventional grape production practices on juice and wine composition. Special report, New York Agricultural Experiment Station, Geneva. 69:67-75.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. *In* Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. 2d ed. A. Klute (Ed.), pp. 425-442. Soil Science Society of America, Madison, WI.

Kliewer, W.M., and T. Casteel. 2003. Canopy management. *In* Oregon Viticulture. E.W. Hellman (Ed.), pp. 177-184. Oregon State University Press, Corvallis.

Koepf, H.H. 1993. Research in Biodynamic Agriculture: Methods and Results. Bio-Dynamic Farming and Gardening Assn., Kimberton, PA.

Koepf, H.H., B.D. Pettersson, and W. Schaumann. 1990. Biodynamic Agriculture an Introduction: Practical Applications of the Bio-Dynamic Method. Anthroposophic Press, Hudson, NY.

Lotter, D.W., J.Granett, and A.D. Omer. 1999. Differences in grape phylloxera-related grapevine root damage in organically and conventionally managed vineyards in California. HortScience 34:1108-1111.

Mäder, P., A. Fleissbach, D. Dubois, L. Gunst, P. Fried, and U. Niggli. 2002. Soil fertility and biodiversity in organic farming. Science 296:1694-1697.

McGourty, G.T., R. Elkins, S. Tylicki, and J. Nosera. 2001. An evaluation of 7 Cabernet Sauvignon clones in Lake County. Report for the Lake County Wine Grape Commission, University of California at Davis. http://ucce.ucdavis.edu/files/filelibrary/1524/5356.pdf (accessed 10 Aug 2004).

Meunier, M. 2001. Biodynamic wine and its progress in different countries. Aust. Grapegr. Winem. 444:77-78.

Neuhoff, D., D.G. Schulz, and U. Köpke. 1999. Yield and quality of potato tubers: Effects of different intensity and kind of manuring (biodynamic or organic). *In* Organic Agriculture: The Credible Solution for the 21st Century. Proceedings of the12th International IFOAM Scientific Conference. D. Foguelman and W. Lockeretz (Eds.), pp. 142-146. IFOAM, Tholey-Theley, Germany.

Nguyen, M.L., R.J. Hayes, and K.M. Goh. 1995. Nutrient budgets and status in three pairs of conventional and alternative mixed cropping farms in Canterbury, New Zealand. Agric. Ecosyst. Environ. 52:149-162.

Ough, C.S., and M.A. Amerine. 1988. Methods for Analysis of Musts and Wines. Wiley & Sons, New York.

Penfold, C.M., M.S. Miyan, T.G. Reeves, and T. Grierson. 1995. Biological farming for sustainable agricultural production. Aust. J. Exp. Agric. 35:849-856.

Pettersson, B.D., H.J. Reents, and E. von Wistinghausen. 1992. Düngung und Bodeneigenschaften: Ergebnisse eines 32-jährigen Feldversuches in Järna, Schweden. Institut für Biologisch-dynamische Forschung, Darmstadt, Germany.

Raupp, J., and U.J. König. 1996. Biodynamic preparations cause opposite yield effects depending upon yield levels. Biol. Agric. Hortic. 13:175-188.

Reganold, J.P. 1988. Comparison of soil properties as influenced by organic and conventional farming systems. Am. J. Altern. Agric. 3:144-155.

Reganold, J.P. 1995. Soil quality and profitability of biodynamic and conventional farming systems: A review. Am. J. Altern. Agric. 10:36-44.

Reganold, J.P., A.S. Palmer, J.C. Lockhart, and A.N. Macgregor. 1993. Soil quality and financial performance of biodynamic and conventional farms in New Zealand. Science 260:344-349.

Schmidt, E.L., and L.W. Belser. 1994. Autotrophic nitrifying bacteria. *In* Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties. R.W. Weaver et al. (Eds.), pp. 159-177. Soil Science Society of America, Madison, WI.

Sims, J.T., and A. Wolf (Eds.). 1995. Recommended Soil Testing Procedures. Northeast Regional Publication. Bulletin 493. Agricultural Experiment Station, University of Delaware, Newark.

Steiner, R. 1993. Agriculture: Spiritual Foundations for the Renewal of Agriculture. Anthroposophic Press, Hudson, NY.

Tabatabai, M.A. 1994. Soil enzymes. *In* Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties. R.W. Weaver et al (Eds.), pp. 775-833. Soil Science Society of America, Madison, WI.

WSALPT. 1997. Western States Laboratory Proficiency Testing Program Soil and Plant Analytical Methods, Version 4.00. Colorado State University, Fort Collins.

Wulf, L.W., and C.W. Nagel. 1978. High-pressure liquid chromatographic separation of anthocyanins of *Vitis vinifera*. Am. J. Enol. Vitic. 24:42-49.