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Organic waste composts improve soil fertility and alter development of pathogenic dagger and pin nematode populations in a crown gall-diseased vineyard

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ABSTRACT

Compost application has many benefits for soil fertility and grapevine performance. Composts introduce new nutrient sources and exogenous microorganisms that enhance soil nutritional status and diversify microbial populations. This can lead to pathogen suppression by beneficial soil microbes through a variety of different mechanisms. Grapevine crown gall (GCG), induced by *Allorhizobium vitis*, has detrimental impacts on grapevine performance and crop quality. Plant-parasitic nematodes may increase the frequency and/or severity of soil-borne *A. vitis* infections because they induce wounds on roots through which the bacterium can easily enter the vine and establish systemic infection. Compost prepared from organic materials has reduced pathogenic nematode populations in soil of other perennial crop plants. Therefore, we hypothesized that organic compost application would improve soil fertility parameters, plant performance, crop quality, yield, and reduce the severity of *A. vitis* infection via reduction in pathogenic nematode soil populations. Three organic waste composts were applied in-row in a Chardonnay *(Vitis vinifera)* vineyard infected with *A. vitis* and plant-parasitic nematodes. After three years, all composts increased total carbon and nitrogen (%), organic matter (%), and phosphorus ($mg.kg^{-1}$ soil) content in soil. Compost containing peat moss decreased *Paratylenchus* population densities in soil, while vineyard waste compost only reduced *Ximphinema* population densities in one year. However, no meaningful changes in plant performance, crop quality, yield, or GCG severity were detected. Extreme winter and summer temperatures experienced during this study likely reduced grapevine performance overall and potentially decreased the impact of improved soil fertility and lower parasitic nematode populations on GCG disease.

KEYWORDS: compost, soil amendments, nematodes, crown gall, *Allorhizobium vitis*, grapevine, soil fertility

INTRODUCTION

The wine industry in British Columbia (BC), Canada, contributes $3.75 billion annually to the province's economy (Central Okanagan Economic Development Commission, 2023). The Okanagan Valley is the largest-producing cold-climate wine grape region in the province with over 900 vineyards (Province of British Columbia, 2022). Thus, diseases that affect the yield and quality of wine grapes severely threaten the industry's large economic impact.

Application of compost amendments is often promoted in the region to increase soil organic matter (OM) contents and thereby improve soil fertility and physical properties of coarse-textured soils. Compost amendments are also known to suppress plant diseases caused by a variety of different pathogens, including soil-borne bacteria (reviewed by Zinati, 2005) and plant-parasitic nematodes (Forge *et al.,* 2016). Composts promote soil microbial biodiversity and biological activity by introducing non-indigenous populations of microorganisms and new nutrient sources (Enwall *et al.,* 2007). These changes in soil microbial community structure and function can enhance nutrient availability and suppressive mechanisms performed by microbial populations, including antibiosis, competition for nutrients and colonization sites, and hyperparasitism, along with induced systemic and systemic acquired resistance in plants (reviewed by Raviv, 2016), which can lead to improved plant performance. Composts made up of various combinations of vineyard pruning and sheep manure applied to Pinot noir impacted microbial composition and functions, improved soil physiochemical properties, and increased the plant availability of several nutrients, including phosphorus and potassium (Tu *et al.,* 2025). Additionally, compost consisting of manure, vineyard debris, and pomace applied to a young Cabernet-Sauvignon vineyard also induced changes in microbial community structure, resulting in a decrease in pathogenic fungi in soil, increased plant nutrient uptake, and subsequent increased vegetative growth (Lucchetta *et al.,* 2023). Both studies resulted in improved vine performance, including higher pruning weights and vine yield, with several improvements to grape quality (Lucchetta *et al.,* 2023; Tu *et al.,* 2025).

Grapevine crown gall (GCG) is one of the most economically important diseases affecting grapevines *(Vitis vinifera)* worldwide (reviewed by Kuzmanović *et al.,* 2018) and is found throughout the Okanagan Valley. The disease is most severe in grape-growing regions where winter freezing occurs. Gall formation is initiated along the trunk by physical wounding, primarily caused by winter freezing, mechanical injury, or grafting. Nutrient and water transport within diseased vines is interrupted due to the presence of galls, resulting in reduced vine performance and crop quality, and/or vine death, especially if the graft union is affected (reviewed by Kuzmanović *et al.,* 2018).

The causal agent of GCG is the bacterium *Allorhizobium vitis* (formerly *Agrobacterium vitis*; Burr & Otten, 1999). Strains of *A. vitis* that cause gall growth in grape carry tumor-inducing (Ti) plasmids that possess virulence *(vir)* genes required for pathogenicity (Burr & Otten, 1999). *A. vitis* is typically introduced into vineyards *via* propagation material and can persist in soil for at least two years, even after diseased vines have been removed (reviewed by Kuzmanović *et al.,* 2018).

A. vitis is not considered a quarantine pathogen and there are currently no standardized protocols for detection or identification in place (reviewed by Kuzmanović *et al.,* 2018). Furthermore, the exchange of grapevine material is not subject to regulated phytosanitary control. This equates to a severe risk of disease manifestation upon planting in cold-climate grape-growing regions where disease pressure is high. Additionally, no commercial biological or chemical product is currently available in Canada for disease control. These facts, along with the systemic nature of *A. vitis*, renders GCG particularly difficult to manage within a vineyard. GCG in commercial vineyards is typically managed using cultural practices that aim to reduce vine injury (reviewed by Kuzmanović *et al.,* 2018). While these do not completely prevent disease occurrence, they can reduce physical symptoms.

Plant-parasitic nematodes are major grapevine pests that can build up in vineyard soil over time and can negatively impact grapevine productivity (reviewed by Nicol *et al.,* 1999). Parasitism by the northern root-knot nematode, *Meloidogyne hapla*, increased grapevine root infection by *A. vitis* (Süle *et al.,* 1995). While the effects of other types of plant-parasitic nematodes on *A. vitis* infection have not been examined experimentally, it is likely that root parasitism by nematodes other than *M. hapla* would also increase chances for *A. vitis* infection from the soil. Several groups of plant-parasitic nematodes are present in vineyards across BC (Forge *et al.,* 2021). Root-lesion nematodes (*Pratylenchus* spp.), dagger nematodes (*Xiphinema* spp.), and ring nematodes (*Mesocriconema* spp.) were present in more than 75 % of vineyards surveyed in a recent study, with pin nematodes (*Paratylenchus* spp.) seen in more than 50 % of vineyards surveyed (Forge *et al.,* 2021).

Enhancing beneficial soil microbial populations via compost has the potential to inhibit *A. vitis* and/or parasitic nematode establishment in the grapevine rhizosphere. Root lesion nematode parasitism was reduced in raspberry bushes grown in soils amended with poultry manure + greenhouse + yard waste compost compared to non-amended soil (Forge *et al.,* 2016). Since *A. vitis* infection of grapevine roots may be facilitated or influenced by root-parasitic nematodes (Süle *et al.,* 1995), it is possible that reducing soil nematode populations via compost application may reduce wound sites induced by parasitizing nematodes on roots, thereby reducing *A. vitis* infection.

Questions are often raised about whether or how composts may differ in their effects on soil-borne pathogens and overall vine performance. The objective of this study was to assess the effects of three different composts on plant-parasitic

nematode populations and the incidence of GCG in a cold-climate vineyard. We hypothesized that the three composts would similarly reduce plant-parasitic nematode populations in soil and the incidence of GCG, and thereby improve grapevine performance and crop quality in diseased vines.

MATERIALS AND METHODS

1. Vineyard site and experimental design

The experiment was conducted in a commercial vineyard with Chardonnay 99 (121) *(V. vinifera)* on SO4 rootstock planted in 2014 in Kelowna, British Columbia (Table 1). Vines were previously infected with GCG prior to the onset of this study as old gall growth was visible on most vines. Few studies have examined the difference in susceptibility between grapevine varieties and rootstocks. However, Chardonnay is considered to be more susceptible to GCG compared to other varieties (reviewed by Vizitiu *et al.,* 2012), while SO4 rootstock is relatively less susceptible to pathogenic *A. vitis* infection compared to other rootstocks, including Teleki 5C (Goodman *et al.,* 1993).

The semi-arid climate of the Okanagan Valley commonly includes freezing winters and hot, dry summers. The vineyard underwent standard winery management protocols, which included cane-pruning, leaf thinning (25-50 %) on both sides of the row (August), shoot-thinning to 4-8 shoots per cane with 3-5 shoots left on the crown, and vertical shoot positioning. Grapevines were trained using the double Guyot system. No cluster thinning was performed. Irrigation was reduced (though not to a true deficit) post-bloom and into veraison (May/June), then further reduced leading to harvest (early September). Irrigation was turned off during harvest (September/October).

The experiment was set up as a randomized complete block design of 24 plots total, with four treatments randomly allocated to four plots in each of six adjacent rows, which were designated as blocks. The four plots in each row-block consisted of five adjacent vines spanning an average distance of 7 m, with the inner three vines designated to be measurement vines, and the outer two vines considered guard vines. Plots were considered experimental units while the three individual measurement vines within them were considered subsamples. There were buffer zones of at least 10 vines between the last treatment plots and the ends of each row.

During the study period, the site experienced freezing temperatures reaching –20 °C or below in 2019 and 2020 (Figure S1). *V. vinifera* L. 'Chardonnay' buds have a cold hardiness threshold of about –24 °C (Rahemi *et al.,* 2021). Therefore, the vineyard site experienced severe bud death during the time of our study. In addition to cold winter temperatures, an unprecedented heat wave also occurred during the second year of our study (June 2021) where daily temperatures exceeded 40 °C (Figure S1). Grapevine photosynthesis is impaired at temperatures above 40 °C, with consequences for overall vine growth and health (reviewed by Venios *et al.,* 2020).

2. Confirmation of *A. vitis* infection

Fresh galls were collected from randomly-selected infected vines within the experimental block (non-treatment/control vines). *A. vitis* was isolated as described by Tolba and Zaki (2011). The *A. vitis* isolate was analyzed to confirm the presence of the virulent *virD2* gene (necessary for infection) *via* colony PCR using the *virD2* primer set (virD2-F and virD2-R) and DNA amplification conditions outlined by Johnson *et al.* (2013). The PCR reactions were carried out in 30 µL volumes containing 1X Standard *Taq* Reaction Buffer (New England Biolabs), 150 µM dNTPs, 0.4 µM of each primer, 1.25 unit of *Taq* polymerase (New England Biolabs), and approximately 1 µg of extracted template DNA. Colonies approximately 1 mm in diameter were transferred with a sterile pipette tip and diluted in 10 µL of water. *A. vitis* CG47 is *virD2* positive and was used as a positive control for colony PCR (Eastwell *et al.,* 1995).

TABLE 1. Vineyard information and compost application dates.

Coordinates	49° 82' N 119° 47' W
Year established	2014
Cultivar	Chardonnay 99
Rootstock	S04
Irrigation type	Drip
Compost application 2019	May, 21
Compost application 2020	June, 3 & 15*
Compost application 2021	May, 27
Compost application 2022	May, 3

*Weston compost applied June, 3, other composts applied June, 15.

A volume of 1 µL was transferred into the PCR reactions as template DNA. Samples were analyzed using electrophoretic separation in SYBR Safe (Thermo Fisher Scientific) stained 1 % *(w/v)* agarose gels.

Whole genome sequencing was then performed on this novel *A. vitis* strain (named W3) using Illumina MiniSeq and Nanopore MinION technologies (Weisberg lab, Department of Botany and Plant Pathology, Oregon State University). The hybrid de novo bacterial genome assembly tool Unicycler (version 0.5.1+galaxy0; Wick *et al.,* 2017) *via* the Galaxy Australia platform (The Galaxy Community, 2024) was used to generate a complete genome assembly using both the Illumina and Nanopore reads as inputs. The assembled genome was annotated on the Galaxy Australia platform using the Bakta tool (version 1.9.2; Schwengers *et al.,* 2021) and *A. vitis* strain NCPPB 3554 as the reference genome (BioProject number PRJNA300487; BioSample number SAMN04223557; Gan *et al.,* 2018). The 16S rRNA gene sequence was extracted from the annotated *A. vitis* strain W3 genome for BLAST analysis using National Center for Biotechnology Information's (NCBI) tool "blastn" (Standard Nucleotide BLAST; BLAST+ 2.16.0; Altschul *et al.,* 1990).

3. Compost application

Three types of compost were applied in this study: GlenGrow compost (City of Kelowna, BC), Weston compost (Superior Peat, Penticton, BC), and a compost supplied by Quail's Gate Estate Winery (QGEW; Kelowna, BC). Feedstocks for GlenGrow compost consisted of yard trimmings, such as grass and plant debris. Feedstocks for Weston compost consisted of peat and yard waste organics, including grass clippings, hedge trimmings, and arboricultural waste. Feedstocks for the QGEW compost consisted of vineyard and wine making waste, primarily grapevine debris and grape marc. Each compost was applied in-row and mixed with the surface layer of soil using a sterile rake. Each compost was live, fresh compost produced each year of application.

Total (%) nitrogen content (samples prepared using the combustion technique and analyzed using an elemental analyzer (modified from Carter & Gregorich, 2008 [p. 226]; Thermo Fisher Scientific, Inc., 2010) and OM content (%; samples prepared using an ashing furnace to heat samples to 450 °C for 16 h and measured using an analytical balance (modified from Kalra & Maynard, 1991 [p. 25])) were determined (BC Ministry of Environment, Analytical Chemistry Laboratory, Victoria, BC) for each compost prior to compost application (Table 2). The bulk density ($kg.m^{-3}$) of each compost was calculated prior to application using the mass per unit volume technique (Table 2; Agnew *et al.,* 2003).

TABLE 2. Compost application rates.

Compost	Bulk density (mg dry compost m^{-3})	Total N (%)	OM content (%)	Application rate ($kg.ha^{-1}$)	Mineral N input ($kg.ha^{-1}$)	Final OM input ($kg.ha^{-1}$)
2019						
GlenGrow	0.35	1.2	38	4.2×10^4	50	15.8×10^3
Weston	0.30	1.5	36	4.4×10^4	66	15.8×10^3
QGEW	0.35	1.3	67	2.4×10^4	30	15.8×10^3
2020						
GlenGrow	0.33	1.3	35	1.9×10^4	25	6.7×10^3
Weston	0.29	1.5	59	1.1×10^4	17	6.7×10^3
QGEW	0.22	0.6	17	4.0×10^4	22	6.7×10^3
2021						
GlenGrow	0.35	1.4	46	1.8×10^4	25	8.2×10^3
Weston	0.26	1.6	42	2.0×10^4	31	8.2×10^3
QGEW	0.20	0.9	43	1.9×10^4	16	8.2×10^3
2022						
GlenGrow	0.23	1.5	40	1.7×10^4	25	6.7×10^3
Weston	0.29	1.7	47	1.4×10^4	24	6.7×10^3
QGEW	0.34	0.7	28	2.4×10^4	18	6.7×10^3

Note: Composts were applied in the spring (May – June) of each year. The area of each plot was 14.7 m^2.
Abbreviations: OM – organic matter; QGEW – Quail's Gate Estate Winery.

Compost applications in the first year were normalized by OM content, with each compost applied at 23.2 kg OM per plot which approximated 15.8×10^3 kg OM.ha^{-1} vineyard. As the composts differed in percentage OM and nitrogen content, this OM-normalized application rate required application of different amounts of bulk compost and resulted in slightly different inputs of total nitrogen, with GlenGrow, Weston, and QGEW applications providing 50, 66 and 30 kg total N.ha^{-1}, respectively (Table 2). In spring of years 2-4 of the study compost treatments were re-applied at one-half of the rates used in the first year.

4. Bulk and rhizosphere soil collection

A composite soil sample was collected from the vine root zone of each plot in May and October of each year. Two cores (2 cm diameter × 30 cm depth sampling tube) were taken from within 20 cm of the base of the three measurement vines in each plot and combined (Table 3). One of the two cores from each vine was taken from under the drip irrigation on one side of the vine and one core was taken at a 90° angle away from the drip irrigation line. The samples were stored at 4 °C in polyethylene bags until subsamples were subjected to analyses of soil chemical parameters and nematode populations.

5. Soil chemical properties

A subsample of each composite bulk soil sample from each plot was sent to the BC Ministry of Environment, Analytical Chemistry Laboratory (Victoria, BC) for soil analysis in the spring of each year between 2020 and 2022 (Table 3). Several soil quality measurements, including pH (samples prepared using the 1:1 soil:water technique (modified from Carter & Gregorich, 2008 [p. 173])), total (%) carbon and nitrogen (samples prepared as described above), OM content (%; samples prepared as described above), and extractable elemental analysis (aluminum (Al), boron (B), calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorus (P), sulphur (S), and zinc (Zn); samples prepared using the Mehlich III extraction method and analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES; modified Carter & Gregorich, 2008 [p. 81]) were performed. C:N ratio was calculated by dividing total (%) carbon by total nitrogen (%).

6. Nematode analyses

Each composite soil sample was first passed through a 6 mm sieve to remove stones and root fragments. Nematodes were extracted from a 100 cm^3 subsample using a wet-sieving sucrose centrifugation procedure (Forge & Kimpinski, 2007). The plant-parasitic nematodes in each sample extract were then identified to genus level and counted using a gridded counting dish on an inverted microscope; free-living nematodes in each sample were also counted as a group. Nematode counts for each group were expressed as population densities, nematodes/100 cm^3 soil.

7. Visual assessment of GCG disease severity

GCG disease severity was assessed visually every year as an estimate of the percentage of trunk affected by new gall growth rounded to the nearest 10 %. New gall growth was defined as galls that were growing during the active growing season when the measurement was assessed. New galls were distinguishable from old galls in that they were still fleshy

TABLE 3. Data and sample collection dates.

	2019	2020	2021	2022
Soil collection – Spring	-	May, 4*	April, 14*	April, 13*
Soil collection – Fall	September, 19	October, 20	October, 28	October, 6
New gall growth estimate	July, 26	August, 6	August, 24	August, 10
Budbreak	- **	May, 6, 8, 10, 12	April, 29, May, 1, 3, 4, 7, 11	May, 3, 13, 16, 21
Shoot and cluster counts	- **	May, 28	May, 20	June, 6
Bloom	- **	June, 22, 24, 26, 29	June, 17, 19, 21	June, 27, July, 6, 8
Leaf greenness	July, 26	August, 6	July, 29	August, 10
Harvest	September, 30	October, 6	-	September, 21
Pruning weight	December, 17	January, 5 (2021)	-	-

* Bulk soil samples sent for analysis.

** Budbreak, shoot/cluster counts, and bloom were not performed until compost had been applied for one year because these are determined by the previous growing season.

and tended to be lighter in colour compared to the rest of the trunk. Old galls from previous growing seasons were not included in the estimation. Data collection dates are listed in Table 3.

8. Grapevine performance measurements

Budbreak (defined as the day that at least one leaf could be recognized clearly separated from the bud on half of the primary buds) was determined each spring *via* regression analysis of visual ratings taken at least three times within a two-week period. Bud fruitfulness (number of clusters per shoot) was estimated when shoots reached approximately 15 cm in length. Only primary shoots and clusters were counted. Bloom or anthesis was similarly estimated as with budbreak, as described by Voegel *et al.* (2023). Budbreak, bud fruitfulness, and bloom were measured after the first year of compost application because these are determined by the previous growing season (reviewed by Wilkie *et al.,* 2008). Leaf greenness (measured using a soil plant analysis development (SPAD) chlorophyll meter (Spectrum Technologies), and pruning weight (g)) were measured as described by Voegel *et al.* (2023). Due to extremely cold winters causing excessive bud damage and loss (Figure S1), fall pruning was not performed in 2021 and 2022 and thus pruning weight could not be determined for those years. Data collection dates are listed in Table 3.

9. Yield and berry quality measurements

Cluster counts, yield per vine (kg), crop load (yield per vine (kg)/pruning weight (kg)), average berry weights (g), and berry quality parameters (berry pH, total soluble solids (TSS; °Brix), and titratable acidity (TA; $g.L^{-1}$ tartaric acid) were measured. Berry analysis in 2019 was conducted by the Summerland Research and Development Centre (Carl Bogdanoff, AAFC, Summerland, BC), and was then performed by Mount Kobau Wine Services (Oliver, BC) for the remainder of the study (2020 and 2022; see Voegel *et al.* (2023) for method details for both services).

10. Data analysis

Visual GCG disease severity ratings, plant performance, yield, and berry quality measurements collected from individual treatment vines (subsamples) were averaged per plot (experimental unit), for a total of 24 experimental units. Response variables, except for count data and percent data, were tested for normal distribution using the Shapiro Wilk normality test and/or confirmed visually. If the data were not normally distributed, ordered quantile (ORQ) normalization was applied and the assumption of normality was tested again. If data were normally distributed, the Bartlett's test was applied to test homogeneity of variance. If data were not normally distributed following transformation, homogeneity of variance was tested using the Levene's test. Homogeneity of variance was also assessed visually in both cases.

All soil parameters that met the assumptions of normality and homogeneity of variance were analyzed using linear mixed-effect models (LMMs) to assess the effect of "compost treatment", "year", and "compost treatment × year" interaction. "Block number" was set as a random factor, as well as "plot" to account for repeated measures. Dates of budbreak and bloom were converted to a number with a common origin (1900-01-01) to allow for statistical analysis. Continuous vine performance and crop quality data that met the assumptions of normality and homogeneity of variance (bloom, budbreak, bud fruitfulness, SPAD values (leaf greenness), cluster yield (kg), average berry weight (g), berry TSS (°Brix), berry pH, berry TA ($g.L^{-1}$), pruning weight (kg), and crop load), were also analyzed using LMMs. Mixed-effect models were chosen to account for unbalanced data. Estimated marginal means were calculated for all LMMs to allow for pairwise comparison of treatment means with Tukey's method applied to adjust *p* values. Model diagnostic plots were created to ensure the models created met LMM assumptions.

Populations density data for *Xiphinema* and *Paratylenchus* nematodes contained many zero counts and were over-dispersed; therefore, they were subjected to a zero-inflated negative binomial generalized linear mixed effect model (ZINB-GLMM) to assess the effect of "compost treatment" and "sampling date". "Block number" and "plot" were set as random effects. Furthermore, each year's data (consisting of two sampling dates) were analyzed individually to assess the effect of compost treatment. Estimated marginal means were calculated to allow for pairwise comparison of treatment or sampling means using Tukey's method to adjust *p* values for all models.

Fresh gall growth (%) each growing season was analyzed using beta regression. Percent data were converted so that all values fit between 0 and 1 (beta distribution). Beta regression was applied using the "logit" link assessing the effect of "compost treatment" and "year", and "compost treatment × year". Estimated marginal means were calculated for pairwise comparison of treatment means with *p* value adjustment via Tukey's method.

Averaged grape cluster count data (clusters per vine; by plot) were rounded to the nearest whole number to maintain the nature of the data prior to data analysis. A negative binomial family GLMM was applied to the clusters per vine count data to assess the effect of "compost treatment", "year", and "compost treatment × year" interaction. "Block number" and "plot" were set as random effects in this model. A negative binomial family was specified as these data were over-dispersed. Estimated marginal means were calculated for pairwise comparison of treatment and year means using Tukey's method to adjust *p* values.

All analyses were performed using R statistical software (R version 4.2.3).

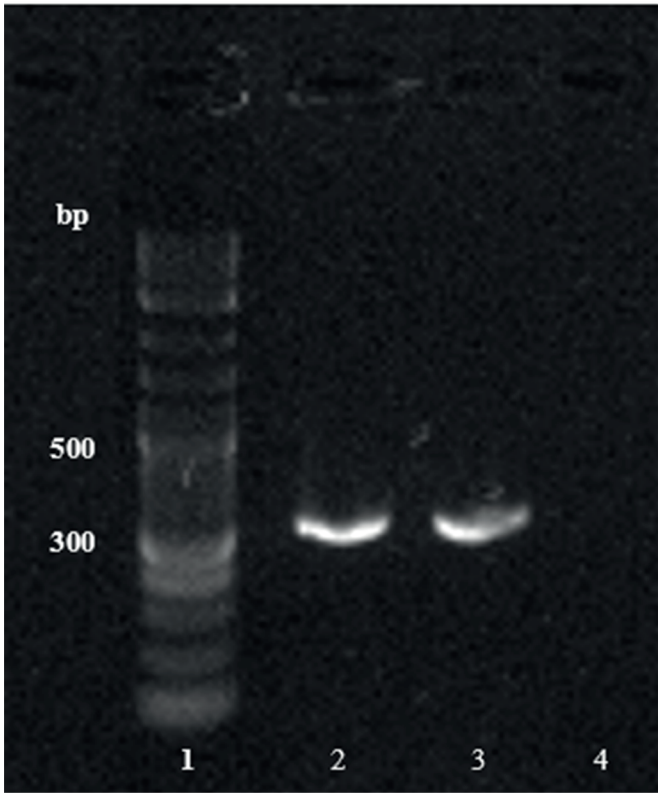


FIGURE 1. Agarose gel (1 % agarose *w/v*) following electrophoretic separation of PCR amplified products using the *virD2*-F/*virD2*-R primer set (Johnson *et al.,* 2013), confirming presence of virulence gene, *virD2* (lane 1: 1 direct load 100 base pairs low ladder (Sigma Aldrich); lane 2: W3; lane 3: positive control, *A. vitis* CG47; and lane 4: negative template control).

RESULTS

1. *A. vitis* isolate analysis

The assembled genome of *A. vitis* strain W3 was deposited into NCBI GenBank (accession number JBGRQX000000000). BLAST analysis of W3's extracted 16S rRNA gene sequence confirmed it belongs to the species *A. vitis.* Colony PCR using the *virD2*-F/*virD2*-R primer pair confirmed that *A. vitis* strain W3 carries the *virD2* gene, indicating virulence and confirming presence of GCG (Figure 1).

2. Soil analysis

Results from soil analysis of bulk soil samples are shown in Table 4, including differences between sampling years. Boron and sulphur had very few detectable values throughout the experiment; therefore, these measurements were not statistically analysed. Total nitrogen (%; p value < 0.001), total carbon (%; p value < 0.05), and OM content (%; p value < 0.05) in soil were higher in all compost-treated plots (with the exception of total nitrogen in QGEW-treated plots) compared to untreated control plots (Table 4). While there was an interaction between compost treatment and year for soil C:N ratio (p value = 0.02; Table 4), no differences between treatments alone were observed. Magnesium, phosphorus, potassium, and sodium soil content ($mg.kg^{-1}$) were also all higher in compost treated plots compared to untreated controls (p value < 0.05; Table 4). Soil calcium content ($mg.kg^{-1}$) was higher in GlenGrow and Weston compost-treated plots compared to untreated control plots and QGEW compost-treated plots (p value < 0.05; Table 4). Weston compost-treated plots had higher concentrations of iron ($mg.kg^{-1}$) in soil compared to QGEW compost-treated plots (p value < 0.01; Table 4). Soil pH was higher in GlenGrow compost-treated plots compared to Weston compost-treated plots (p value = 0.03; Table 4). No differences in soil copper, manganese, or zinc content ($mg.kg^{-1}$) were observed (p value > 0.05; Table 4). All soil chemical parameters showed differences between years (p value < 0.05; Table 4).

3. Soil nematode population analysis

Several genera of plant-parasitic nematodes with species known to parasitize grapevines were initially detected in the plots in May of 2019: *Xiphinema, Paratylenchus, Mesocriconema*, and *Pratylenchus*. Population densities of all four genera were initially very low (< 2 nematodes/100 cm^3 soil) in 2019 and increased through time thereafter for *Xiphinema* and *Paratylenchus* (Figure 2). Population densities of *Mesocriconema* and *Pratylenchus* remained low through 2022 and were omitted from further statistical analyses and discussion. Main-factor mean *Paratylenchus* population densities were lower in plots treated with the QGEW compost compared to plots treated with GlenGrow compost (p value = 0.02),

TABLE 4. Soil property measurements over three years (2020-2022) of compost treatment.

	n	N (%)	C (%)	C:N	OM (%)	pH	Al (mg kg^{-1})	Ca (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	K (mg kg^{-1})	Mg (mg kg^{-1})	Mn (mg kg^{-1})	Na (mg kg^{-1})	P (mg kg^{-1})	Zn (mg kg^{-1})
Compost																
Control	6	0.078^{b}	0.91^{c}	11.8:1^{a}	2.28^{b}	6.25^{ab}	569.4^{ab}	937.2^{b}	3.01^{a}	218.3^{ab}	92.3^{c}	81.0^{c}	76.1^{a}	11.5^{c}	40.3^{b}	17.4^{a}
GlenGrow	6	0.112^{a}	1.38^{ab}	12.1:1^{a}	3.06^{a}	6.62^{a}	530.6^{a}	1304.4^{a}	2.96^{a}	218.3^{ab}	184.4^{b}	152.6^{a}	69.3^{a}	14.8^{b}	92.3^{a}	17.7^{a}
QGEW	6	0.092^{b}	1.19^{b}	12.7:1^{a}	2.81^{a}	6.42^{ab}	533.3^{b}	907.8^{b}	2.71^{a}	201.1^{b}	262.2^{a}	112.6^{b}	68.8^{a}	17.9^{a}	76.1^{a}	14.6^{a}
Weston	6	0.111^{a}	1.44^{a}	12.9:1^{a}	3.19^{a}	6.22^{b}	588.3^{a}	1233.9^{a}	2.78^{a}	252.8^{a}	155.4^{b}	139.8^{a}	71.8^{a}	15.8^{ab}	68.5^{a}	17.4^{a}
SE*	-	0.01	0.11	0.54	0.18	0.13	16.7	82.8	0.23	15.4	0.2	9.6	5.0	0.9	12.0	1.2
df*	-	63	63	68	15	20	63	15	63	15	15	68	15	65	15	20
Year																
2020	24	0.094^{b}	1.05^{b}	10.9:1^{b}	2.66^{b}	6.30^{b}	600.8^{a}	1225.0^{a}	3.19^{a}	240.8^{a}	138.3^{b}	111.5^{b}	82.1^{a}	13.1^{b}	57.9^{b}	17.7^{a}
2021	24	0.091^{b}	1.24^{a}	13.5:1^{a}	2.80^{ab}	6.23^{b}	545.4^{b}	926.3^{b}	2.42^{b}	199.6^{b}	177.2^{b}	112.6^{b}	64.5^{b}	15.2^{a}	68.5^{b}	15.7^{b}
2022	24	0.109^{a}	1.40^{a}	12.7:1^{a}	3.04^{a}	6.60^{a}	520.0^{c}	1136.2^{a}	2.98^{a}	227.5^{a}	205.4^{a}	140.3^{a}	68.0^{b}	16.6^{a}	83.1^{a}	17.0^{ab}
SE*	-	0.01	0.10	0.34	0.15	0.05	8.3	51.8	0.17	6.0	16.2	7.5	3.2	0.7	5.4	0.6
df*	-	46	46	46	46	46	46	46	46	46	46	46	46	41	44	46
LMM Results**	df	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)
Compost	3	< 0.001 (16.9)	< 0.001 (15.3)	0.03 (3.5)	< 0.001 (12.0)	0.02 (4.2)	0.008 (5.7)	< 0.001 (12.8)	0.51 (0.8)	0.02 (4.8)	< 0.001 (38.6)	< 0.001 (33.2)	0.25 (1.5)	< 0.001 (34.3)	0.001 (8.8)	0.06 (3.0)
Year	2	< 0.001 (11.1)	< 0.001 (13.1)	< 0.001 (39.0)	0.02 (4.2)	< 0.001 (63.4)	< 0.001 (58.8)	< 0.001 (26.9)	< 0.001 (10.7)	< 0.001 (23.3)	< 0.001 (14.5)	< 0.001 (9.2)	< 0.001 (22.7)	< 0.001 (14.4)	< 0.001 (13.5)	0.043 (6.2)
Compost × Year	6	< 0.001 (5.5)	< 0.001 (4.6)	0.02 (2.9)	0.02 (3.0)	< 0.001 (7.6)	0.04 (2.5)	0.03 (2.7)	0.31 (1.2)	0.54 (0.84)	< 0.001 (10.6)	0.03 (2.6)	0.11 (1.8)	0.005 (3.5)	< 0.001 (4.9)	0.29 (1.3)

Note: Data are expressed as means per treatment (n = 18) or per year (n = 24) estimated from LMM analysis of non-transformed data. Treatments or years sharing the same letter within a column do not differ significantly (p value ≥ 0.05) according to estimated marginal means test.

* Standard errors (SE) of means derived from LMM and degrees of freedom (df) associated with SEs.

** Values are significant at a p value < 0.05 significance level.

Abbreviations: LMM – linear mixed-effect model; OM – organic matter; QGEW – Quail's Gate Estate Winery.

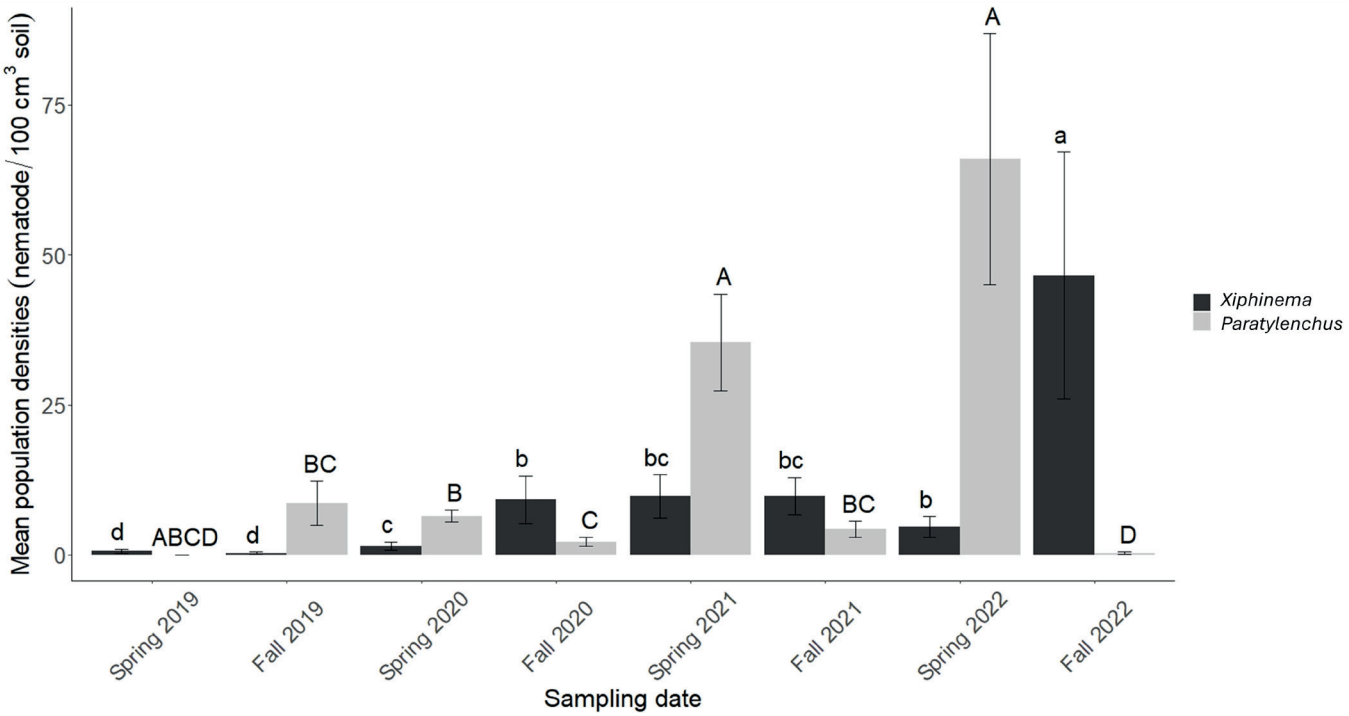


FIGURE 2. Mean (± SE) nematode population densities (nematodes/100 cm^3 soil) over four years (2019-2022). Data are expressed as means per sample date (n = 24). Dates sharing the same letter (lowercase for *Xiphinema* and uppercase for *Paratylenchus*) do not differ significantly (p value ≥ 0.05) according to zero-inflated negative binomial generalized linear mixed-effect model (ZINB-GLMM) and estimated marginal means test. Error bars represent standard errors (SE) of means derived from ZINB-GLMM.

Weston compost (p value = 0.03), and untreated control plots (p value = 0.03; Figure 3A). Mean *Paratylenchus* nematode counts fluctuated across sampling dates, with higher population densities in the spring compared to the fall in 2020, 2021, and 2022 (p value < 0.001; Figure 2). Main-factor mean *Xiphinema* population densities did not differ between compost treatments and/or untreated control plots overall, but they tended to be lowest in Weston compost-amended plots and at five of the eight sample dates. When sampling years were analyzed individually, *Xiphinema* population densities were lower in Weston compost-treated plots compared to QGEW treated plots (p value = 0.03; Figure 3B) in 2021, during the third year of this study. No differences in *Xiphinema* population densities were observed in 2019, 2020, or 2022. However, over the course of the experiment, *Xiphinema* counts (nematodes/100 cm^3 soil) increased across all treatments and varied between sampling dates (p value < 0.001; Figure 2), with higher *Xiphinema* population densities in fall compared to spring in 2022.

4. Analysis of the incidence of fresh gall growth

Fresh galls were more prevalent on vines growing in plots treated with Weston compost compared to plots treated with the QGEW compost (p value = 0.01) and untreated control plots (p value < 0.05; Table 5). Fresh gall growth also varied between sampling years, with lower gall growth in 2020 compared to 2019 and 2021 (Table 5).

5. Grapevine performance, yield, and berry quality analysis

Leaf greenness (SPAD units) was higher in vines grown in Weston compost-treated plots compared to plots treated with QGEW compost (p value = 0.04) and untreated control plots (p value = 0.01; Table 6). While differences were detected between years, no other treatment effects were found for the other grapevine performance measurements taken (Table 6).

Berries collected from vines growing in plots treated with the GlenGrow (p value = 0.04) and Weston composts (p value = 0.04) had higher pH levels compared with berries collected from vines grown in untreated control plots (Table 7). No other treatment differences were observed between berry quality measurements; however, all yield and berry quality indices showed differences between years (Table 7).

DISCUSSION

The primary goal of this study was to determine if surface application of compost influences the abundance of plant-parasitic nematodes in soil and the incidence of GCG, as well as assess composts' effects on soil fertility parameters, plant performance, and crop quality in diseased vines. All three composts affected many soil fertility parameters. However, there appeared to be differences among the composts with respect to vine performance, crop quality, and pathogen suppression.

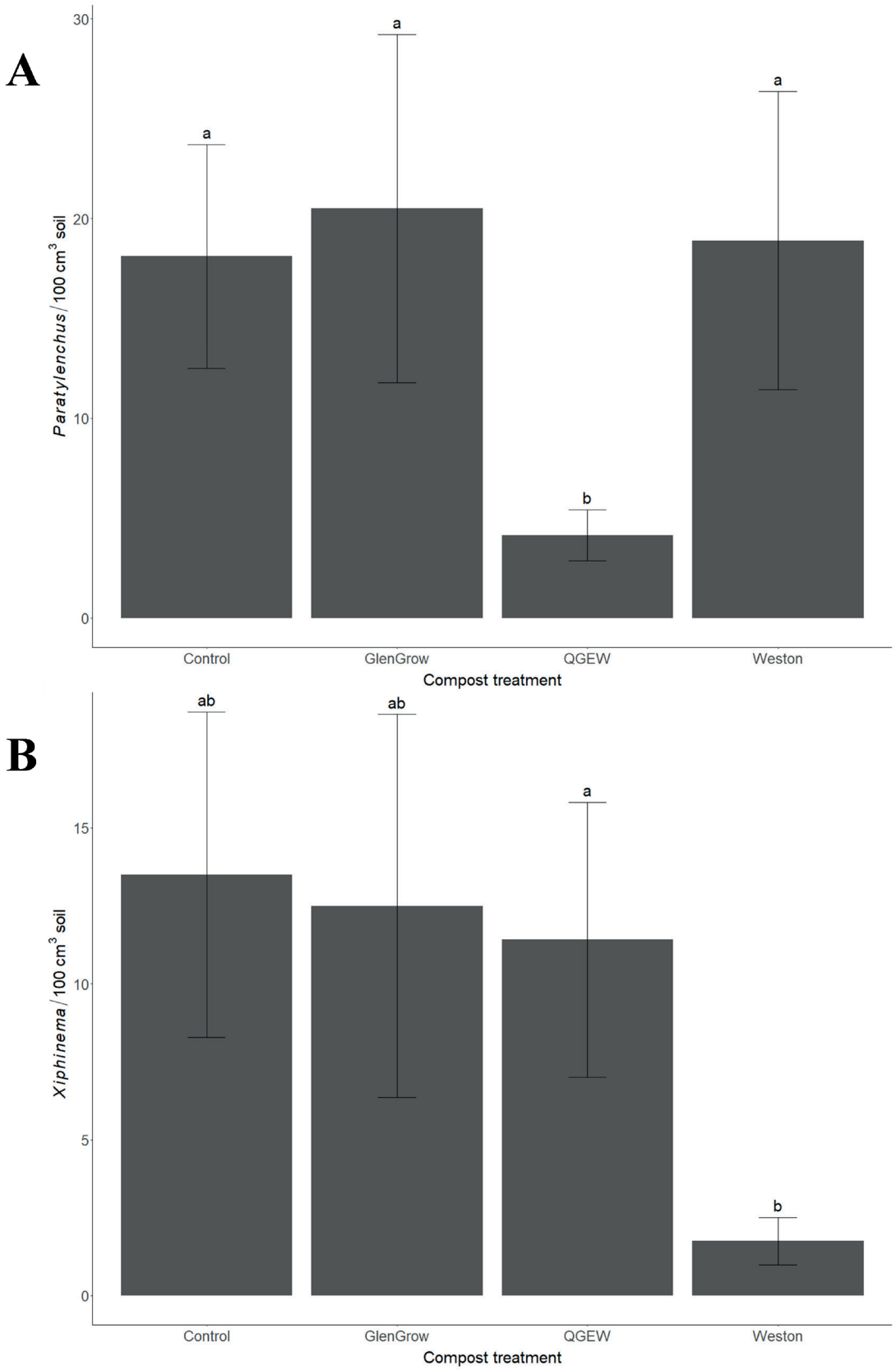


FIGURE 3. Mean (± SE) (A) *Paratylenchus* (pin nematode; (*n* = 192) and (B) *Xiphinema* (dagger nematode; *n* = 24) counts (nematodes/100 cm^3 soil) between compost treatments (untreated controls, GlenGrow, Weston, and Quail's Gate Estate Winery (QGEW) compost). A) *Paratylenchus* nematodes sampled twice per year between 2019 and 2022. B) *Xiphinema* nematodes sampled in 2021 (spring and fall). Treatments sharing the same letter do not differ significantly (*p* value ≥ 0.05) according to a zero-inflated negative binomial generalized linear mixed effect model (GLMM) and estimated marginal means test.

TABLE 5. Fresh gall growth over four years (2019-2022) of compost treatment.

	n	Fresh gall growth (%)
Compost		
Control	24	4.2[b]
GlenGrow	24	4.8[ab]
QGEW	24	3.8[b]
Weston	24	6.9[a]
SE*	-	0.2
df*	-	8
Year		
2019	24	5.5[a]
2020	24	1.4[b]
2021	24	8.5[a]
2022	24	4.3[ab]
SE*	-	0.2
df*	-	8
Beta Regression Results**	df	*p*
Compost	3	0.003
Year	2	< 0.001
Compost × Year	9	0.9

Note: Data are expressed as means per treatment (n = 24) or per year (n = 24). Treatments or years sharing the same letter within a column do not differ significantly (p value ≥ 0.05) according to estimated marginal means test.

* Standard errors (SE) of means derived from beta regression and degrees of freedom (df) associated with SEs.

** Values are significant at a p value < 0.05 significance level.

Abbreviations: QGEW – Quail's Gate Estate Winery.

Regular inputs of organic matter can support more diverse soil biota, which may suppress disease over time (Liu *et al.,* 2022), if microorganisms with inhibitory activity against *A. vitis* and/or plant-parasitic nematodes are able to thrive. All compost treatments increased OM content in soil (Table 4); however, only two composts influenced pathogenic nematode soil populations. *Paratylenchus* (pin nematodes) counts (nematodes/100 cm^3) were lower in plots treated with the QGEW compost compared to plots treated with the other two composts and untreated control plots (Figure 3A). *Paratylenchus* were found in 54 % of the 57 vineyards recently surveyed in the Okanagan Valley (Forge *et al.,* 2021). The implications of reduced *Paratylenchus* population densities are difficult to predict, however, as there is currently no evidence that they induce significant damage in grapevine or influence grapevine susceptibility to other pathogens such as *A. vitis.* As well, no previous studies have examined the effects of compost amendments on *Paratylenchus* populations.

Plots treated with Weston compost tended to have lower *Xiphinema* counts overall, but differences were only statistically significant in 2021, the third year of compost application (Figure 3B). Continued or increased Weston compost application may have a stronger effect on *Xiphinema* soil population densities. It is also important to note that compost in this study was applied to the soil surface, whereas the majority of studies of the influence of composts on plant-parasitic nematodes involved incorporating compost into the soil (for example, in Forge *et al.,* 2016); it seems likely that surface applications may require more time or greater application rates to drive significant changes in the soil profile.

In addition to physical soil properties, nematode populations are influenced by chemical soil properties (Dias-Arieia *et al.,* 2021), which did change significantly following compost application (Table 4). Different classifications of soil nematodes (plant-parasitic,

TABLE 6. Vine performance measures over four years (2019-2022) of compost treatment.

	n	Bud fruitfulness (# clusters/# shoots)	Budbreak	Bloom	Leaf greenness (SPAD units)	Pruning wt (g)
Compost						
Control	- *	1[a]	May, 18[a]	June, 25[a]	36.1[b]	449.8[a]
GlenGrow	- *	1[a]	May, 18[a]	June, 24[a]	36.7[ab]	464.8[a]
QGEW	- *	1[a]	May, 17[a]	June, 24[a]	36.3[b]	436.3[a]
Weston	- *	1[a]	May, 17[a]	June, 24[a]	37.7[a]	413.8[a]
SE*	-	0.2	0	0	1.0	0.07
df*	-	68	60	60	92	39
Year						
2019	24	-	-	-	37.8[b]	314.6[b]
2020	24	2[a]	May, 9[b]	June, 24[b]	34.5[c]	567.8[a]
2021	24	1[b]	May, 9[b]	June, 15[c]	41.0[a]	- ***
2022	24	0.5[c]	June, 2[a]	July, 4[a]	33.6[c]	- ***
SE**	-	0.1	0	0	0.4	0.02
df**	-	46	60	60	69	23
LMM Results**	df	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)
Compost	3	0.4 (1.0)	0.7 (0.5)	0.9 (0.2)	0.01 (5.1)	0.8 (0.4)
Year	2	< 0.001 (70.1)	< 0.001 (145.2)	< 0.001 (185.2)	< 0.001 (159.4)	< 0.001 (172.3)
Compost × Year	6	0.26 (1.3)	0.5 (0.9)	0.03 (2.5)	0.07 (1.9)	0.1 (2.3)

Note: Data are expressed as means per treatment* or per year (n = 24) estimated from LMM analysis of non-transformed data. Treatments or years that share the same letter within a column do not differ significantly (p value ≥ 0.05) according to estimated marginal means test.

* Sample size varied for different vine performance variables. Bud fruitfulness, budbreak, and bloom variables, n = 18. Leaf greenness, n = 24. Pruning wt, n = 12.

** Standard errors (SE) of means derived from LMM and degrees of freedom (df) associated with SEs.

*** Vines were not pruned in 2021 and 2022 due to bud damage caused by winter freezing.

**** Values are significant at a p value < 0.05 significance level.

Abbreviations: LMM – linear mixed-effect model; QGEW – Quail's Gate Estate Winery; wt – weight.

bacterivores, fungivores, and omnivore-predators) exhibit different reactions to fertilization (Qi *et al.,* 2023). *Paratylenchus* population densities increased in soil fertilized with nitrogen compared to unfertilized soil in a study by Sarathchandra *et al.* (2001), which differed from the findings here. *Xiphinema* nematode populations have been negatively correlated with ammonium, but positively correlated with boron (Shokoohi *et al.,* 2024).

No reductions in visual GCG symptoms were observed (Table 5), despite a reduction in *Paratylenchus* populations. Weston compost-treated plots had a higher incidence of fresh gall growth compared to vines grown in untreated control plots (Table 5). This does not support our hypothesis that a reduction in plant-parasitic nematodes would reduce GCG. It is possible that *Paratylenchus* spp., unlike *M. hapla* (Süle *et al.,* 1995), do not facilitate *A. vitis* infection in grape from soil, which is reasonable as *Paratylenchus* do not likely cause significant damage to grapevine roots. The difference in fresh gall growth between the untreated controls and the Weston compost-treated plots was small (less than 3 %; Table 5). Given the considerable amount of old gall growth from previous growing seasons and high frequency of vine death, there was little fresh gall growth observed during the current study. Older vines that survive the first few years of *A. vitis* infection tend to combat disease symptoms better and grow almost "normally" (Thomson, 1986). However, we were able to isolate virulent *A. vitis* bacteria from fresh galls growing on vines in the same planting area and from the same nursery material as the vines included in this study (Figure 1). Therefore, *A. vitis* was present and causing disease.

TABLE 7. Yield and berry quality measurements over four years (2019-2022) of compost treatment.

	n	Cluster yield (kg)	Clusters/vine	Crop load	Average berry wt (g)	Berry TSS (°Brix)	Berry pH	Berry TA ($g.L^{-1}$ tartaric acid)
Compost								
Control	24	2.01[a]	19[a]	6.0[a]	1.19[a]	19.1[a]	3.00[b]	9.10[a]
GlenGrow	24	2.12[a]	19[a]	6.1[a]	1.21[a]	19.1[a]	3.07[a]	9.09[a]
QGEW	24	2.42[a]	20[a]	6.7[a]	1.30[a]	18.9[a]	3.03[ab]	9.70[a]
Weston	24	2.21[a]	19[a]	6.9[a]	1.20[a]	19.2[a]	3.07[a]	9.02[a]
SE*	-	0.3	0	1.2	0.05	0.7	0.06	0.51
df*	-	15	64	44	63	68	68	68
Year								
2019	24	2.53[a]	21[a]	8.5[a]	1.29[a]	21.8[a]	3.17[a]	7.97[b]
2020	24	2.42[a]	21[a]	4.4[b]	1.29[a]	18.1[b]	3.03[b]	9.00[a]
2021**	24	-	-	- ***	-	-	-	-
2022	24	1.62[b]	15[b]	- ***	1.09[b]	17.4[c]	2.93[c]	10.7[c]
SE*	-	0.2	0	0.5	0.03	0.2	0.02	0.24
df*	-	46	40	23	46	46	46	46
LMM Results**	df	*p* (F)	*p* (F)*****	*p* (F)	*p* (F)	*p* (F)	*p* (F)	*p* (F)
Compost	3	0.6 (0.7)	> 0.05 (0.1)	0.66 (0.5)	0.05 (3.4)	0.68 (0.5)	0.03 (4.1)	0.59 (0.7)
Year	2	< 0.001 (21.2)	< 0.001 (13.1)	< 0.001 (75.1)	< 0.001 (37.8)	< 0.001 (112.9)	< 0.001 (132.7)	< 0.001 (85.9)
Compost × Year	6	0.5 (0.9)	> 0.05 (0.6)	0.3 (1.3)	0.8 (0.6)	0.04 (2.5)	0.2 (1.5)	0.008 (3.4)

Note: Data are expressed as means per treatment (n = 24) or per year (n = 24) estimated from LMM analysis of non-transformed data. Treatments or years sharing the same letter within a column do not differ significantly (p value ≥ 0.05) according to estimated marginal means test.

* Standard errors (SE) of means derived from LMM and degrees of freedom (df) associated with SEs.

** Clusters were not harvested in 2021.

*** Vines were not pruned in 2021 and 2022 due to bud damage caused by winter freezing.

**** Values are significant at a p value < 0.05 significance level.

***** Clusters/vine analyzed by generalized linear mixed-effect model.

Abbreviations: LMM – linear mixed-effect model; QGEW – Quail's Gate Estate Winery; TA – titratable acidity; TSS – total soluble solids; wt – weight.

Predictably, soil fertility parameters improved following compost application. In addition to increased OM content, compost treatment resulted in higher total carbon and nitrogen content in soil (Table 4) compared to untreated control plots. Nitrogen is crucial for plant development and vigour and can influence grape juice and wine composition (Gatti *et al.,* 2018). There were no effects of composts on vegetative growth or crop load. Weston and GlenGrow composts both increased nitrogen content in soil, but only the Weston compost induced an increase in SPAD chlorophyll meter values compared to untreated controls (Table 6). SPAD measurements estimate leaf nitrogen concentration and chlorophyll content, which are indicative of photosynthetic capacity (Porro *et al.,* 2001). SPAD values only differed by approximately 1.6 SPAD units between vines grown in Weston compost-treated plots compared to untreated

controls, corresponding to small changes in leaf nitrogen content, based on conversion rates determined in another grape variety (Ates & Kaya, 2021). The differences in values may not have been large enough to induce significant changes in other areas of plant performance. A longer period of compost application may lead to a larger change in leaf nitrogen content and overall plant performance.

Phosphorus is another essential plant macronutrient that is important for initiating flower growth, as well as root, seed, and fruit development (Skinner *et al.,* 1988). Extractable soil phosphorus content was higher in all compost-treated plots compared to untreated controls (Table 4). While ideal ranges can vary between regions, an adequate range for wine grape production is between 35-80 $mg.kg^{-1}$ soil (Lanyon *et al.,* 2004) to support an ideal balance of vegetative and reproductive growth. Mean soil extractable phosphorus content for all treatment plots, including untreated controls, fell within this range except for GlenGrow compost-treated plots, which exceeded this range but did not affect crop load, yield, or pruning weights (Tables 7 and 8).

Potassium plays a vital role in vine growth, mainly due to contributions in phloem transport and photosynthesis (reviewed by Liesche, 2015). Potassium deficiency in grape is common and it can have a negative impact on grape yield and quality (Rogiers *et al.,* 2020). Potassium in berries is crucial for acid balance and colour (Walker & Blackmore, 2012). High extractable soil potassium concentrations can lead to higher concentrations of potassium in grape juice which has been associated with higher pH values in grape juice (Dundon *et al.,* 1984). While soil extractable potassium content was higher in all compost-treated plots compared to untreated controls (Table 4), higher berry pH values were only found in berries harvested from vines grown in GlenGrow and Weston compost-treated plots compared to those collected from untreated control plots (Table 7). The ideal pH range of grape juice for white wines is 3.0-3.3 (Iland, 2000) and the berries from all compost-treated plots and untreated control plots fell within this range. However, berries from untreated control plots were at the lowest end of this range. Compost application may therefore be a useful tool to ensure and maintain ideal berry pH because adjusting pH during the wine making process can be costly (Walker & Blackmore, 2012). Potassium is also involved in maintaining cellular membrane potential by regulating the movement of ions and sugars (reviewed by Rogiers *et al.,* 2017). During ripening, potassium and sugar both accumulate within berries. The application of potassium fertilizers increased sugar content and decreased acid content in grapevine (Wang *et al.,* 2024). However, despite the increased soil potassium content achieved following compost application, there were no differences in berry TA or TSS (Table 7). This may be because, while higher levels of potassium ions were present in the soil, it may not have been taken up by the vines.

While soil nutrient concentration increased following compost application, significant changes in plant performance and crop quality were not observed. This may be because nutrients may not have been readily taken up by the vines, even if more nutrients were present in the soil following compost application. Cation exchange capacity (CEC) and soil base saturation percentage (BSP) were not determined in conjunction with elemental analysis, limiting our knowledge of the plant availability of several key nutrients (calcium, magnesium, potassium, and sodium). Boron and sulphur were rarely detected in soil at the study site. Boron deficiencies result in stunted growth, shoot tip necrosis, reduced flowering, and/or premature flowering, leading to decreased yield and cluster quality (Peacock & Christensen, 2005). Sulphur is an essential macronutrient integral for plant growth and development as it has roles in the formation of proteins, energy metabolism, and the promotion of root growth and seed formation (Considine & Foyer, 2015). A deficiency in boron and sulphur, therefore, also could have impacted plant performance and cluster yields in this study.

In addition, grapevine performance at the study site was negatively impacted overall by extreme weather conditions and reductions in solar irradiance during veraison experienced during the study (Figures S1 and S2). These climatic events also may have contributed to differences in measurements taken between years as every measured variable in this study showed differences between years of collection. Bud fruitfulness, SPAD chlorophyll meter values, clusters per vine, and cluster yield were all lower in 2022 compared to 2019 (Tables 6 and 7). Average berry weights were also lower in 2022 compared to 2019 and 2020 (Table 7). Temperatures as low as –28 °C were recorded in December 2022; therefore, this field site likely had lower plant performance and crop quality in subsequent growing seasons. Pruning weights differed between the two years they were collected (Table 6), and crop load was lower by approximately 50 % in 2020 compared to 2019 (Table 7). Additionally, budbreak and bloom were both delayed by several weeks in 2022 (Table 6). Berry TSS and pH decreased over the years from 2019 to 2022, while berry TA increased (Table 7), indicating that grapes harvested in 2022 had a lower ripeness level than those at harvested in 2019, which likely impacted the flavour of the wine produced from these grapes.

Compost feedstock input will vary to some degree year to year, even when following a compost feedstock recipe (reviewed in Rynk *et al.,* 2021). Therefore, it is expected to see differences in soil fertility parameters between sampling years. Different compost inputs will affect the number and diversity of microbes in each compost during maturation, and microbial interactions during that process will further change population dynamics (Narihiro *et al.,* 2004). In turn, organic amendments affect soil microbial composition and activity in the soil to which they were applied (Liu *et al.,* 2022). These changes in microbial populations can affect the availability of nutrients in the soil (reviewed by Philippot *et al.,* 2023). The populations of plant-associated microorganisms and their effect on soil properties (and *vice versa*) also can be altered by changes in climate (reviewed by Mekala & Polepongu, 2019).

CONCLUSION

In conclusion, several key soil fertility parameters were improved, and *Paratylenchus* population densities were reduced in organic compost-treated plots compared to untreated controls. Additionally, *Xiphinema* population densities were lower in a compost treatment during one year of the study. Nonetheless, none of the compost treatments reduced incidence of GCG as hypothesized. Further study into relationships between plant-parasitic nematodes and *A. vitis* infection in grape is needed.

A limiting factor in this study was that the soil microbial community and its metabolic activities were not investigated. This information could provide insight into the balance of beneficial and pathogenic microbes in the soil, and the effect on the processes in the soil, including nutrient availability. Thus, future studies should examine the effect of organic compost application on the soil microbiome in vineyards infected with both GCG and plant parasitic nematodes to examine how microbial functions in the soil were impacted. Future studies should also test the effect of compost on newly planted vines into *A. vitis*-infected soil. Compost may have more pronounced effects on initial infection of young vines than on the established vines examined in this study.

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REFERENCES

Agnew, J. M., Leonard, J. J., Feddes, J., & Feng, Y. (2003). A modified air pycnometer for compost air volume and density determination. *Canadian Biosystems Engineering / Le Genie Des Biosystems Au Canada*, *45,* 6.27 – 6.35.

Altschul, S. F., Gish, W., Miller, W., Myers, E. W., & Lipman, D. J. (1990). Basic local alignment search tool. *Journal of Molecular Biology*. *215*(30), 403-410. https://doi.org/10.1016/S0022-2836(05)80360-2

Ates, F., & Kaya, O. (2021). The relationship between iron and nitrogen concentrations based on Kjeldahl method and SPAD-502 readings in grapevine (*Vitis vinifera* L. cv. 'Sultana Seedless'). *Erwerbs-Obstbau*, *63*, 53–59. https://doi.org/10.1007/s10341-021-00580-8

Burr, T. J., & Otten, L. (1999). Crown gall of grape: Biology and disease management. *Annual Review of Phytopathology*, *37*(1), 53–80. https://doi.org/10.1146/annurev.phyto.37.1.53

Carter, M. R., & Gregorich, E. G (Ed.). (2008*). Soil sampling and methods of analysis* (2nd ed., pp 81, 173, 226). Canadian Society of Soil Science.

Central Okanagan Economic Development Commission. (2023). *Viticulture*. COEDC. https://www.investkelowna.com/key-sectors/viticulture/

Considine, M. J., & Foyer, C. H. (2015). Metabolic responses to sulfur dioxide in grapevine (*Vitis vinifera* L.): Photosynthetic tissues and berries. *Frontiers in Plant Science, 6*, 60. https://doi.org/10.3389/FPLS.2015.00060

Dias-Arieira, C. R., Ceccato, F. J., Marinelli, E. Z., Boregio Vecchi, J. L., de Oliveira Arieira, G., & de Melo Santana-Gomez, S. (2021). Correlations between nematode numbers, chemical and physical soil properties, and soybean yield under different cropping systems. *Rhizosphere*, *19,* 100386. https://doi.org/10.1016/j.rhisph.2021.100386

Dundon, C. G., Smart, R. E., & McCarthy, M. G. (1984). The effect of potassium fertiliser on must and wine potassium levels of Shiraz grapevines. *American Journal of Enology and Viticulture*, *35*, 200–205. https://doi.org/10.5344/ajev.1984.35.4.200

Eastwell, K. C., Willis, L. G., & Cavileer, T. D. (1995). A rapid and sensitive method to detect *Agrobacterium vitis* in grapevine cuttings using the polymerase chain reaction. *Plant Disease*, *79*(8), 822–827. https://doi.org/10.1094/PD-79-0822

Enwall, K., Nyberg, K., Bertilsson, S., Cederlund, H., Stenström, J., & Hallin, S. (2007). Long-term impact of fertilization on activity and composition of bacterial communities and metabolic guilds in agricultural soil. *Soil Biology and Biochemistry*, *39*(1), 106–115. https://doi.org/10.1016/j.soilbio.2006.06.015

Forge, T. A. & Kimpinski, J. (2007). Nematodes. In E.G. Gregorich & M. R. Carter (Eds.), *Soil sampling and methods of analysis (*2nd ed.*,* pp. 415-425). CRC Press.

Forge, T., Kenney, E., Hashimoto, N., Neilsen, D., & Zebarth, B. (2016). Compost and poultry manure as preplant soil amendments for red raspberry: Comparative effects on root lesion nematodes, soil quality and risk of nitrate leaching. *Agriculture, Ecosystems and Environment*, *223*, 48–58. https://doi.org/10.1016/j.agee.2016.02.024

Forge, T., Munro, P., Midwood, A. J., Philips, L., Hannam, K., Neilsen, D., Powers, T., & Zasada, I. (2021). Shifting prevalence of plant-parasitic nematodes in orchards and vineyards of the Okanagan Valley, British Columbia. *Plant Health Progress*, *22*(2), 113–121. https://doi.org/10.1094/PHP-10-20-0079-RS

Gan, H. M., Lee, M. V. J., & Savka, M. A. (2018). High-quality draft genome sequence of the type strain of *Allorhizobium vitis,* the primary causal agent of grapevine crown gall. *Microbiology Research Announcements. 7*(9), e01045-18. https://doi.org/10.1128/mra.01045-18

Gatti, M., Squeri, C., Garavani, A., Vercesi, A., Dosso, P., Diti, I., & Poni, S. (2018). Effects of variable rate nitrogen application on cv. Barbera performance: vegetative growth and leaf nutritional status. *American Journal of Enology and Viticulture*, *69*(3), 196–209. https://doi.org/10.5344/ajev.2018.17084

Goodman, R. N., Grimm, R., & Frank, M. (1993). The influence of grape rootstocks on the crown gall infection process and on tumor development. *American Journal of Enology and Viticulture*, *44*(1):22–26. https://doi.org/10.5344/ajev.1993.44.1.22

Iland, P. (2000). *Techniques for chemical analysis and quality monitoring during winemaking*. Patrick Iland Wine Promotions.

Johnson, K. L., Zheng, D., Kaewnum, S., Reid, C. L., & Burr, T. (2013). Development of a magnetic capture hybridization real-time PCR assay for detection of tumorigenic *Agrobacterium vitis* in grapevines. *Phytopathology*, *103*(6), 633–640. https://doi.org/10.1094/PHYTO-10-12-0267-R

Kalra, Y. P., & Maynard, D. G. (1991). *Methods manual for forest soil and plant analysis: Information Report NOR-X-319* (pp. 20, 25). Forestry Canada.

Kuzmanović, N., Pulawska, J., Hao, L., & Burr, T. (2018). The ecology of *Agrobacterium vitis* and management of crown gall disease in vineyards. In S. B. Gelvin (Ed.), *Agrobacterium Biology: From Basic Science to Biotechnology* (pp. 15–54). Springer. https://doi.org/10.1007/82_2018_85

Lanyon, D., Cass, A., & Hansen, D. (2004). The effect of soil properties on vine performance, CSIRO Land and Water Technical Report No. 34/04. In *CSIRO Land and Water*. https://doi.org/10.4225/08/586be7e218029

Liesche, J. (2015). How regulation of phloem transport could link potassium fertilization to increased growth. *Tree Physiology*, *36*(1), 1–5. https://doi.org/10.1093/treephys/tpv120

Liu, X., Shi, Y., Kong, L., Tong, L., Cao, H., Zhou, H., & Lv, Y. (2022). Long-term application of bio-compost increased soil microbial community diversity and altered its composition and network. *Microorganisms*, *10*(2). https://doi.org/10.3390/microorganisms10020462

Lucchetta, M., Romano, A., Alzate Zuluaga, M. Y., Fornasier, F., Monterisi, S., Pii, Y., Marcuzzo, P., Lovat, L., & Gaiotti, F. (2023). Compost application boosts soil restoration in highly disturbed hillslope vineyard. *Frontiers in Plant Science*, *14*, 1289288. https://doi.org/10.3389/fpls.2023.1289288

Mekala, S., & Polepongu, S. (2019). Impact of climate change on soil microbial community. In A. Varma, S. Tropathi, & R. Prasad (Eds.), *Plant Biotic Interactions: State of the Art* (pp. 31–41). Springer. https://doi.org/10.1007/978-3-030-26657-8_3

Narihiro, T., Abe, T., Yamanaka, Y., & Hiraishi, A. (2004). Microbial population dynamics during fed-batch operation of commercially available garbage composters. *Applied Microbiology and Biotechnology*, *65*(4), 488–495. https://doi.org/10.1007/s00253-004-1629-z

Nicol, J. M., Stirling, G. R., Rose, B. J., May, P., & Van Heeswijck, R. (1999). Impact of nematodes on grapevine growth and productivity: Current knowledge and future directions, with special reference to Australian viticulture. *Australian Journal of Grape and Wine Research*, *5*(3), 109–127. https://doi.org/10.1111/j.1755-0238.1999.tb00295.x

Peacock, W. L., & L. P. Christensen. (2005). Drip irrigation can effectively apply boron to San Joaquin Valley vineyards. *California Agriculture, 59*(3), 188–91. https://doi.org/10.3733/ca.v059n03p188

Philippot, L., Chenu, C., Kappler, A., Rillig, M. C., & Fierer, N. (2023). The interplay between microbial communities and soil properties. *Nature Reviews Microbiology*, *22*(4), 226–239. https://doi.org/10.1038/s41579-023-00980-5

Porro, D., Dorigatti, C., Stefanini, M., & Caschini, A. (2001). Use of SPAD meter in diagnosis of nutritional status in apple and grapevine. *Proceedings of the International Society for Horticulture, Acta Horticulturae 564: IV International Symposium on Mineral Nutrition of Deciduous Fruit Crops.* https://doi.org/10.17660/ActaHortic.2001.564.28

Province of British Columbia. (2022). Crop production: Grapes. *AgriService BC* https://www2.gov.bc.ca/gov/content/industry/agriculture-seafood/animals-and-crops/crop-production/grapes

Qi, Y., Sub, X., Peng, S., Tan, X., & Zhou, S. (2023). Effects of fertilization on soil nematode communities in an alpine meadow of Qinghai-Tibet plateau. *Frontiers in Ecology and Evolution*, *11*, 1122505. https://doi.org/10.3389/fevo.2023.1122505

Rahemi, A., Rahemi, A., Fisher, H., Dale, A., Taghavi, T., & Kelly, J. (2021). Bud dormancy pattern, chilling requirement, and cold hardiness in *Vitis vinifera* L. 'Chardonnay' and 'Riesling'. *Canadian Journal of Plant Science*, *101*(6), 871–885. https://doi.org/10.1139/cjps-2020-0332

Raviv, M. (2016). Compost as a tool to suppress plant diseases: Established and putative mechanisms. *Proceedings of the International Society for Horticulture, Acta Horticulturae 1146: I11 International Symposium on Organic Matter Management and Compost Use in Horticulture.* https://doi.org/10.17660/ActaHortic.2016.1146.2

Rogiers, S. Y., Coetzee, Z. A., Walker, R. R., Deloire, A., & Tyerman, S. D. (2017). Potassium in the grape (*Vitis vinifera* L.) berry: Transport and function. *Frontiers in Plant Science, 8*, 1–19. https://doi.org/10.3389/fpls.2017.01629

Rogiers, S. Y., Greer, D. H., Moroni, F. J., & Baby, T. (2020). Potassium and magnesium mediate the light and CO2 photosynthetic responses of grapevines. *Biology*, *9*(7), 1–19. https://doi.org/10.3390/biology9070144

Rynk, R., Schwarz, M., Richard, T. L., Cotton, M., Halbach, T., & Siebert, S. (2021). Compost feedstocks. In R. Rynk, G. Black, J. Gilbert, J. Biala, J. Bonhotal, M. Schwarz, & L. Cooperband (Eds.), *The Composting Handbook: a how-to and why manual for farm, municipal, institutional and commercial composters* (pp. 103-157). Elsevier. https://doi.org/10.1016/B978-0-323-85602-7.00005-4

Sarathchandra, S. E., Ghani, A., Yeates, G. W., Burch, G., & Cox, N. R. (2001). Effect of nitrogen and phosphate fertilisers on microbial and nematode diversity in pasture soils. *Soil Biology and Biochemistry, 33*, 953-964. https://doi.org/10.1016/S0038-0717(00)00245-5

Schwengers, O., Jelonek, L., Dieckmann, M. A., Beyvers, S., Blom, J., & Goesmann, A. (2021). Bakta: rapid and standardized annotation of bacterial genomes via alignment-free sequence identification. *Microbial Genomics, 7*(11), 000685. https://doi.org/10.1099/mgen.0.000685

Shokoohi, E., & Masoko, P. (2024). Association of plant-parasitic nematodes and soil physiochemical properties in tomatoes in Turfloop, Limpopo Province, South Africa. *Horticulturae, 10*(4), 328. https://doi.org/10.3390/horticulturae10040328

Skinner, P. W., Cook, J. A., & Matthews, M. A. (1988). Responses of grapevine cvs Chenin blanc and Chardonnay to phosphorus fertilizer applications under phosphorus-limited soil conditions. *VITIS - Journal of Grapevine Research*, *27*, 95-109. https://doi.org/10.5073/vitis.1988.27.95-109

Süle, S., Lehoczky, J., Jenser, G., Nagy, P., & Burr, T. J. (1995). Infection of grapevine roots by *Agrobacterium vitis* and *Meloidogyne hapla*. *Journal of Phytopathology*, *143*(3), 169–171. https://doi.org/10.1111/j.1439-0434.1995.tb00253.x

The Galaxy Community. (2024). The Galaxy platform for accessible, reproducible, and collaborative data analyses: 2024 update, *Nucleic Acids Research*, *52*: W83-W94. https://doi.org/10.1093/nar/gkae410

Thermo Fisher Scientific, Inc. (2010). *Organic elemental analysis: Flash 2000 elemental analyzer operating manual, Revision D*. Thermo Fisher Scientific.

Thomson, J. A. (1986). The potential for biological control of crown gall disease on grapevines. *Trends in Biotechnology*, *4*(8), 219–224. https://doi.org/10.1016/0167-7799(86)90265-9

Tolba, I. H., & Zaki, M. F. (2011). Characterization of Agrobacterium vitis isolates obtained from galled grapevine plants in Egypt. *Annals of Agricultural Sciences*, *56*(2), 113–119. https://doi.org/10.1016/j.aoas.2011.06.001

Tu, Q., Li, Y., Ding, W., Zhou, S., Huang, Y., Liu, S., Min, X., Zhang, J., Li, J., & Yuan, C. (2025). Mixed vineyard prunings and sheep manure compost: Creating changes in vineyard soil dominant microbiota to impact fruit quality. *Applied Soil Ecology, 208*, 105973. https://doi.org/10.1016/j.apsoil.2025.105973

Venios, X., Korkas, E., Nisiotou, A., & Banilas, G. (2020). Grapevine responses to heat stress and global warming. *Plants*, 1754. https://doi.org/10.3390/plants9121754

Vizitiu, D. E., Dejeu, L. C., Radulescu, I., & Popescu, C. F. (2012). Preventing and limiting the spread of crown gall in vineyards. *Scientific Papers, Series B, Horticulture*, *LVI*:203–210.

Voegel, T. M., McGonigal, P., Douglas, C. W. J., & Nelson, L. M. (2023). Transient heat therapy has few effects on grapevine performance in the Okanagan Valley, British Columbia, Canada. *American Journal of Enology and Viticulture*, *74*, 0740001. https://doi.org/10.5344/ajev.2022.21011

Walker, R. R., & Blackmore, D. H. (2012). Potassium concentration and pH inter-relationships in grape juice and wine of Chardonnay and Shiraz from a range of rootstocks in different environments. *Australian Journal of Grape and Wine Research*, *18*(2), 183–193. https://doi.org/10.1111/j.1755-0238.2012.00189.x

Wang, J., Lu, Y., Zhang, X., Hu, W., Lin, L., Deng, Q., Xia, H., Liang, D., & Lv, X. (2024). Effects of potassium-containing fertilizers on sugar and organic acid metabolism in grape fruits. *International Journal of Molecular Sciences, 25*(5), 2828. https://doi.org/10.3390/ijms25052828

Wick, R. R., Judd, L. M., Gorrie, C. L., & Holt, K. E. (2017). Unicycler: Resolving bacterial genome assemblies from short and long sequencing reads. *PLOS Computational Biology, 13*(6), e1005595. https://doi.org/10.1371/journal.pcbi.1005595

Wilkie, J. D., Sedgley, M., & Olesen, T. (2008). Regulation of floral initiation in horticultural trees. *Journal of Experimental Botany, 59*(12), 3215-3228. https://doi.org/10.1093/jxb/ern188

Zinati, G. M. (2005). Compost in the 20th century: A tool to control plant diseases in nursery and vegetable crops. *HortTechnology*, *15*, 61–66. https://doi.org/10.21273/HORTTECH.15.1.0061