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Foliar magnesium fertiliser remediates induced Mg deficiency in cation-rich vineyard soils

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ABSTRACT

Magnesium (Mg) is an essential plant macronutrient that influences various physiological processes, including photosynthesis and carbohydrate translocation. Magnesium deficiency in grapevines (*Vitis vinifera* L.) can impair vine performance, productivity, and fruit quality. High soil concentrations of the cationic nutrients potassium and calcium can reduce the uptake of Mg, which can induce Mg deficiency in grapevines, even with high soil Mg. This study compares the effectiveness of foliar-applied magnesium sulfate (MS) and chelated magnesium (MC) fertilisers for mitigating induced Mg deficiency symptoms associated with a cation-rich soil in the Columbia Basin growing region. An experiment was conducted in a commercial Mourvèdre vineyard block near Milton-Freewater, OR, USA, from 2023 to 2024, in which fertilisers were applied at three-week intervals between bloom and harvest. The severity of visible Mg deficiency symptoms was assessed, leaf nutrients were quantified, and fruit quality at harvest was analysed. MS significantly increased leaf Mg and decreased the severity of Mg deficiency symptoms compared to the control and MC. Fruit yield components and chemistry were not significantly altered by the fertiliser treatments. It is likely that the MS treatment was more effective at improving Mg deficiency due to the higher Mg dose compared to the MC fertiliser, which appeared similarly effective relative to the dose. The effect of MS was more pronounced when leaf Mg was below the regionally recommended whole leaf Mg threshold of 0.25 %, and the effect largely disappeared when leaf Mg increased above this threshold. These results justify the use of foliar applied magnesium sulfate fertiliser as a lower cost solution to correct induced Mg deficiency in cation-rich soils with poor Mg uptake. Moreover, this study verifies the recommended leaf Mg threshold and demonstrates the importance of leaf nutrient analysis over visual diagnosis for accurate diagnosis and correction of Mg deficiencies in grapevine.

KEYWORDS: grapevine, magnesium, nutrient deficiency, soil, fertiliser, foliar, chelated fertilizer

INTRODUCTION

Magnesium (Mg) is a critical plant macronutrient that contributes to plant function by regulating cellular enzymatic reactions, maintaining vacuolar homeostasis, promoting carbohydrate translocation, and forming the structural center of the chlorophyll molecule (Shaul, 2002; Verbruggen & Hermans, 2013). As such, the exogenous supply of magnesium is critical for vegetative and reproductive growth in agricultural crops like grapevine (*Vitis vinifera* L.). Mg deficiency causes a number of apparent and inconspicuous symptoms in grape leaves and fruit, such as reduced photosynthetic rate, interveinal chlorosis, foliar anthocyanosis, and reduced sugar translocation into ripening berries (Keller, 2020; Senbayram *et al.*, 2015). Severe Mg starvation and reduced carbohydrate production can have compounding effects on yield formation and, ultimately, vine productivity (Ahmed *et al.*, 2023; Engels *et al.*, 2023; Gransee & Führs, 2013).

In contrast to other macronutrients like nitrogen and phosphorus, Mg remobilisation from senescent leaves to woody storage tissue in grapevines is low, thus fertiliser is often required to supplement the supply of Mg from soil (Pradubsuk & Davenport, 2010; Schreiner *et al.*, 2006). Mg management in grapevines is guided primarily by leaf nutrient analysis instead of soil nutrient analysis. Leaf Mg concentrations are generally considered deficient below 0.25 % for proper grapevine function in the western United States (Christensen & Peacock, 2000; Moyer *et al.*, 2018; Skinkis & Schreiner, 2018).

Mg uptake is strongly influenced by the supply of other cations (*e.g.*, K, Ca). The suppression of Mg uptake by high concentrations of these nutrients in the soil is sometimes referred to as cation competition or antagonism (Gransee & Führs, 2013; White, 2023). Consequently, high soil K or Ca content can induce Mg deficiency, even when soil Mg is high (Zlámalová *et al.*, 2015). Additionally, ratios of K:Mg and Ca:Mg are used to determine whether K or Ca concentrations reduce Mg uptake and induce deficiency (Ramos & Romero, 2016; White, 2023). Because uptake is limiting but supply is not, induced Mg deficiency cannot be readily mitigated with soil-supplemented Mg fertiliser or other nutrients like P that may promote Mg uptake (Skinner & Matthews, 1990; Trolove *et al.*, 2008).

Mg deficiencies associated with low soil Mg can be corrected with soil-applied Mg fertilisers, of which magnesium sulfate (*e.g.*, epsomite or kieserite) is the most common (Christensen & Peacock, 2000; Trolove *et al.*, 2008). Foliar application of Mg fertiliser may be necessary when uptake is low and preferred as an alternative to large volumes of soil-applied fertiliser for correcting major deficiencies (Trolove *et al.,* 2008; Zlámalová *et al.*, 2015). Some formulations like magnesium sulfate can be applied to both soil and leaves, but others like magnesium disodium EDTA (*i.e.*, chelated magnesium) are formulated primarily for foliar application, often at higher cost. Foliar application of Mg is an effective treatment for improving leaf Mg concentration, but it may also mitigate other symptoms of Mg deficiency by increasing yield and improving fruit quality (Bai *et al.*, 2024; Trolove *et al.,* 2008; Zlámalová *et al.*, 2015).

The Columbia Basin is the largest grape-producing region in the Pacific Northwest and is characterised by a warmer growing season climate and lower precipitation in comparison to other grape-production areas in the region (Meinert & Busacca, 2000). The vineyard soils in the Columbia Basin generally have a slightly alkaline pH, low organic matter, high salt content, and high cation content (McIlquham, 2022). In particular, vineyard soils in the Walla Walla Valley American Viticultural Area of the Columbia Basin can have K, Ca, and Mg concentrations in excess of the regional recommended values (Table S1; Moyer *et al.*, 2018).

Mg fertilisation and the management of Mg deficiency in grapevines have been investigated, but these strategies have not been sufficiently applied to the cation-rich soils of the inland Pacific Northwest. Induced Mg deficiency in this region may delay ripening, reduce vine productivity, and affect wine quality. This is particularly problematic for varieties that are more susceptible to Mg deficiency and for those that ripen late in the region's truncated growing season. The present study evaluates the effectiveness of two common foliar Mg fertiliser formulations for mitigating the leaf and fruit symptoms of Mg deficiency in cation-rich soils.

MATERIALS AND METHODS

1. Experimental setup

1.1. Experimental site

The field experiment was conducted in a commercial vineyard located near Milton-Freewater, OR, USA, (45.9594° N 118.3730° W) from 2023 to 2024. Milton-Freewater is characterised as a cold semi-arid (Köppen-Geiger BSk), warm, and Winkler Region III growing region (Beck *et al.*, 2018; Jones *et al.,* 2010). This region has an average (1990-2020 normals) of 1860 growing degree days (base 10 °C) between 1 April and 31 October, average (1981-2010 normals) temperature of 17.3 °C from 1 April to 31 October, and average (1981-2010 normals) annual precipitation of 417 mm (National Oceanic and Atmospheric Administration, 2025). The soil at the experimental site is Freewater very cobbly loam and belongs to the Freewater series (Sandy-skeletal, mesic Fluventic Haploxerolls, somewhat excessively drained, neutral pH). It comprises very cobbly (*i.e.*, basalt clasts) loam from 0-10 cm depth, very gravelly loam from 10-50 cm, and extremely gravelly sand from 50-200 cm (United States Department of Agriculture Natural Resources Conservation Service, 2019). The vineyard block was planted in 2018 to *Vitis vinifera* L. cv. Mourvèdre (clone 04) grafted to Schwarzmann rootstock (*Vitis riparia* × *Vitis rupestris*). Rows were oriented north-south with 2.1 m between rows and 1.1 m between vines.

1.2. Experimental design

The experiment was organised as a randomised complete block design with four blocks extending down the vine rows; each block consisted of three four-vine panels across three rows. The treatments consisted of an untreated control (CON), a chelated magnesium (Versatile Magnesium, Wilbur Ellis; 3-0-6) treatment (MC), and a magnesium sulfate heptahydrate (Magriculture, Giles Chemical; 0-0-0) treatment (MS). The MC treatment was applied at maximum label rate of 2.35 L/ha (0.07 kg Mg/ha) using a total volume of 280 L/ha per application. The MS treatment was applied at a rate of 11.1 kg/ha (1.1 kg Mg/ha) using a total volume of 280 L/ha. In 2023, treatment application was initiated on 29 June and repeated at approximately three-week intervals on 18 July, 10 August, and 31 August. In 2024, treatment application was initiated on 24 May and repeated at approximately three-week intervals on 6 June, 26 June, 17 July, 7 August, and 28 August.

2. Nutrient analysis

2.1. Soil nutrient analysis

Soil samples were collected on 27 June 2023 prior to the first treatment application. A separate sample was collected for each treatment plot and each sample consisted of five subsamples. Subsamples were collected from within the vine row between the trunk and nearest drip emitter using a soil sampling probe to a depth of 0.5 m. Samples were immediately sent to a commercial laboratory (Kuo Testing Laboratories, Othello, WA, USA) for chemical analysis of pH, organic matter, and concentrations of NO_3-N, NH_4-N, P, K, Ca, Mg, and Na. Soil pH was determined using a 1:2 soil:H_2O mixture. K, Ca, Mg, and Na were extracted using ammonium acetate.

2.2. Leaf nutrient analysis

Leaf samples were collected for nutrient analysis at bloom (modified E-L stage 23) and veraison (modified E-L stage 35) in both years. Bloom samples were collected on 7 June 2023 and 12 June 2024. Veraison samples were collected on 8 August 2023 and 19 August 2024. A separate sample consisting of 20 whole leaves was collected for each treatment plot. Samples were then rinsed in the laboratory with 25 mL distilled H_2O to remove treatment residue, dried at room temperature in a fume hood, and then immediately sent to a commercial laboratory (Kuo Testing Laboratories, Othello, WA, USA) for chemical analysis of N, P, K, Ca, and Mg.

3. Magnesium deficiency

3.1. Magnesium deficiency symptom severity

The severity of leaf magnesium deficiency symptoms (*i.e.*, marginal to interveinal chlorosis and anthocyanosis) was monitored throughout the growing season each year. Severity was estimated as the percentage of symptomatic leaves per vine. Each four-vine panel was subsampled and rated on each date. Raw data were converted using the Horsfall-Barratt scale to midpoint percentage values for analysis (Horsfall & Barratt, 1945). In 2023, symptom severity was rated on 10 July, 24 July, 14 August, 31 August, and 25 September. In 2024, symptom severity was rated on 17 July, 31 July, 14 August, 28 August, and 11 September.

4. Fruit quality

4.1. Cluster metrics

Just prior to commercial harvest, four representative clusters were harvested per treatment replicate. The clusters were weighed and dissected to determine berry number and berry weight. Two subsamples of 200 berries each were used for analysis of primary and secondary fruit chemistry.

4.2. Fruit chemistry

The two subsamples were submitted to a commercial laboratory (ETS Laboratories, Walla Walla, WA, USA). One sample was used to determine juice primary chemistry, including total soluble solids (TSS), pH, titratable acidity (TA), L-malic acid, tartaric acid, yeast assimilable nitrogen (YAN), and potassium, using mid-infrared spectroscopy and proprietary reference calibrations for each analyte (Minerva, ETS Laboratories, ISO 17025-accredited). The other subsample was used to determine berry secondary chemistry, including catechin, quercetin, tannin, polymeric anthocyanin, and total anthocyanin, with a proprietary extraction method in a wine-like solution and reverse-phase high performance liquid chromatography in accordance with Price *et al.* (1995).

5. Statistical analysis

Statistical analyses and figures were generated using R statistical software (v. 4.2.3; R Core Team, 2023). Data were assessed for normality and homoscedasticity with the Shapiro-Wilk test and Levene's test, respectively. Linear models were constructed using the *lme4* package (Bates *et al.*, 2015). All data, except for symptom severity, were analysed using a two-way analysis of variance (ANOVA) with treatment and year as the main factors. Symptom severity data were analysed by ANOVA with treatment, year, interaction of treatment and year, and interaction of treatment and date as the main factors. Means were generated and compared using the *emmeans* package (Lenth, 2025). Pairwise comparisons were conducted when there was a significant effect of the main factors and were subjected to Tukey's Honestly Significant Difference test for multiple comparisons. Figures were generated using the *ggplot2* package (Wickham, 2016).

RESULTS

1. Weather and phenological development

Weather data were accessed from a weather station (College Place, AgWeatherNet, Washington State University) approximately 10 km from the experimental site. In 2023, 1739 growing degree days (base 10 °C) accumulated from

1 April to 31 October, compared to the 30-year average of 1531. In 2024, 1592 growing degree days (base 10 °C) accumulated from 1 April to 31 October. Water year precipitation (1 October to 30 September) totaled 377 mm for 2023 and 347 mm for 2024, compared to the 30-year average of 323 mm.

Bloom (modified E-L stage 25) was observed on 4 June 2023 and 16 June 2024. Veraison (modified E-L stage 35) was observed on 10 August 2023 and 14 August 2024. Experimental harvest was conducted just before commercial harvest on 2 October 2023 and 11 October 2024.

2. Nutrient analysis

2.1. Soil nutrient analysis

Though soil samples were collected prior to treatment application, the soil chemical properties were analysed by treatment to assess whether pre-existing plot soil differences would have affected the uptake or dynamics of Mg in the vines. There was no significant difference amongst the treatment plots for soil pH, organic matter, NO_3-N, NH_4-N, P, K, Ca, and Mg (Table 1). Soil Na was significantly higher in the MC plots compared to the MS plots. Concentrations of K, Ca, and Mg were all above the regionally recommended thresholds, being 6, 28, and 132 % higher, respectively (Table S1). Consequently, base saturation for Mg was quite high at just over 21 %, which is considerably higher than the optimum range of 10-15 % recommended by White (2015). The average K:Mg and Ca:Mg values across all plots were 1.2 and 5.6, respectively.

2.2. Leaf nutrient analysis

There was no significant effect of the treatments on whole leaf concentrations of N, P, K, or Ca at bloom or veraison in both years (Table 2). Bloom Mg for MS was significantly higher than CON or MC in 2024, but not in 2023. The treatments had a significant effect on veraison Mg across both years, such that MS was significantly higher than CON but not significantly higher than MC (Figure 1A). The effect of MS on veraison Mg was more pronounced in 2024 than in 2023 (Table 2).

TABLE 1. Soil chemical properties.

Treatment	pH	Organic matter (%)	NO3-N (ppm)	NH4-N (ppm)	Olsen P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Na (ppm)
CON	6.67	2.68	16.6	7.3	32.8	506	2,290	420	24.7 ab
MC	6.62	2.83	20.6	7.1	29.8	559	2,405	438	28.8 b
MS	6.72	2.81	13.6	7.0	31.0	557	2,555	453	23.6 a
Standard error	± 0.07	± 0.27	± 3.6	± 0.8	± 2.4	± 41	± 73	± 16	± 1.2
Mean	6.67	2.77	16.9	7.1	31.2	541	2,417	437	25.7
TRT	*0.512*	*0.922*	*0.211*	*0.932*	*0.367*	*0.593*	*0.057*	*0.178*	*0.020*

Samples were taken on 27 June 2023 prior to the first treatment application. Data are means ($n = 4$). *P*-values for the analysis of variance are presented at the bottom of the table (*TRT*: treatment). Letter assignments indicate statistically significant differences ($p < 0.05$). CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

TABLE 2. Whole leaf nutrient concentrations.

Year	Treatment	Bloom					Veraison				
		N (%)	P (%)	K (%)	Ca (%)	Mg (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
2023	CON	3.71	0.37	1.32	2.32	0.27	2.45	0.25	1.00	2.52	0.25
	MC	3.56	0.45	1.34	2.23	0.23	2.78	0.32	1.11	3.08	0.28
	MS	3.24	0.42	1.55	1.94	0.20	2.58	0.28	1.00	2.82	0.31
2024	CON	3.41	0.38	1.64	1.82	0.22 a	2.00	0.27	1.29	2.38	0.27 a
	MC	3.24	0.36	1.74	1.86	0.24 a	1.95	0.26	1.21	2.34	0.29 a
	MS	3.31	0.46	1.77	1.83	0.32 b	1.93	0.31	1.36	2.32	0.38 b
Standard error		± 0.12	± 0.03	± 0.09	± 0.10	± 0.02	± 0.13	± 0.03	± 0.08	± 0.14	± 0.02
TRT		*0.108*	*0.082*	*0.105*	*0.173*	*0.475*	*0.549*	*0.323*	*0.905*	*0.226*	*0.005*
YEAR		*0.092*	*0.664*	*< 0.001*	*< 0.001*	*0.101*	*< 0.001*	*0.969*	*< 0.001*	*< 0.001*	*0.073*
TRT × YEAR		*0.231*	*0.083*	*0.568*	*0.182*	*0.001*	*0.338*	*0.195*	*0.194*	*0.138*	*0.424*

Bloom (50 % capfall) samples were collected on 7 June 2023 (prior to the first treatment application) and 12 June 2024. Veraison (50 % berry color change) leaf samples were collected on 8 August 2023 and 19 August 2024. Data are means ($n = 4$). *P*-values for the analysis of variance are presented at the bottom of the table (*TRT*: treatment). Letter assignments indicate statistically significant differences ($p < 0.05$). CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

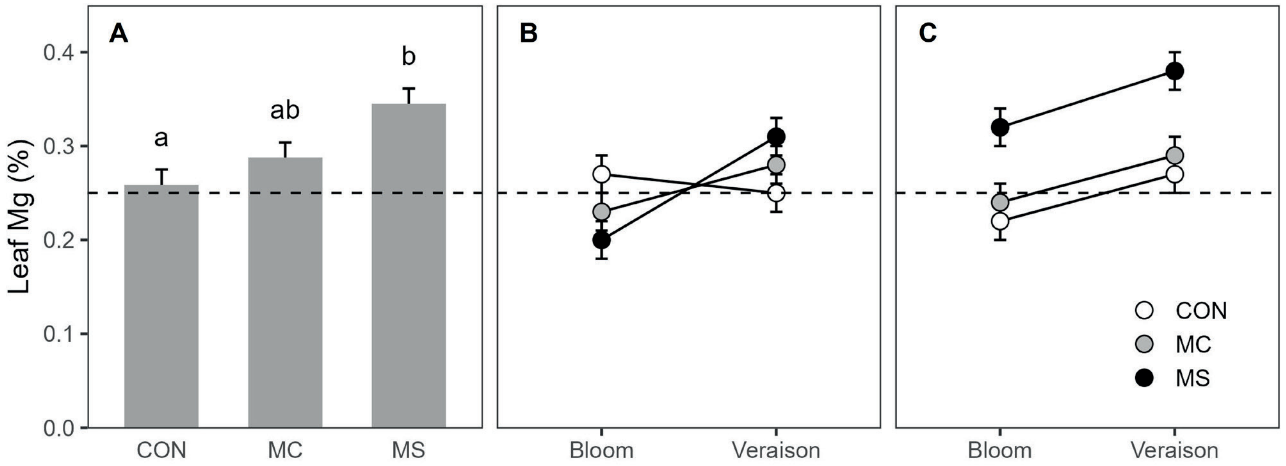

FIGURE 1. Leaf magnesium concentration at veraison.

Veraison leaf Mg concentration across 2023 and 2024 (A); data are means (*n* = 8) ± one standard error. Leaf Mg concentrations in 2023 (B) and 2024 (C); data are means (*n* = 4) ± one standard error. Letter assignments indicate statistically significant differences ($p < 0.05$). The horizontal dotted line indicates the recommended minimum Mg sufficiency level for whole leaf samples collected at veraison (Moyer *et al.*, 2018). CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

Leaf Mg increased from bloom to veraison for MC and MS in both years but decreased marginally for CON from bloom to veraison in 2023 (Figures 1B and 1C). In 2024, leaf Mg for all treatments increase from bloom to veraison, but MS was significantly higher than CON and MC. Leaf Mg for MS increased successively at each sampling time from bloom in 2023 to veraison in 2024. Veraison leaf Mg exhibited a linear relationship with the amount of Mg applied (kg/ha), but the relationship was more pronounced and stronger ($R^2 = 0.97$, $p = 0.073$) in 2024 (Figure 3).

3. Magnesium deficiency

3.1. Magnesium deficiency symptom severity

Across sampling dates, there was a significant treatment effect on magnesium deficiency symptom severity (Table 3). In 2023, all treatments were significantly different from each other, CON having the highest average symptom severity and MS the lowest. In 2024, MS was significantly lower than the other treatments. Symptom severity was lower in 2024 than in 2023 for all treatments. Deficiency symptoms were present by bloom in 2023 (Figure S1) and continued to increase for CON and MC but remained relatively stable for MS after veraison (Figure 2A). By harvest, MS was significantly lower than the other two treatments. Symptom onset and progression was delayed in 2024 and severity increased for all treatments up until harvest (Figure 2B). On the last two sampling dates, MS was significantly lower than the other two treatments. There was a linear relationship between symptom severity and Mg application rate (Figure 3). The slopes were similar in 2023 and 2024, but the y-intercept was lower in 2024 and the relationship was more robust in 2024 ($R^2 = 0.98$, $p = 0.063$).

4. Fruit quality

4.1. Yield components

Though there is visual evidence that Mg deficiency was severe enough to, in part, reduce fruit set (Figure S1), the treatments did not have a significant effect on cluster mass, number of berries per cluster, or berry mass (Table 4). Cluster mass in both years, berries per cluster in 2024, and berry mass in 2023 were highest for MS. Cluster mass and berries per cluster were lower in 2024, but berry mass was similar in both years. Whole vine yield and cluster number per vine were not determined due to the variation in cluster number between vines.

4.2. Fruit chemistry

There were no significant treatment effects on fruit chemical attributes (Table 5). In 2023, TSS, berry sugar, glucose + fructose, and anthocyanins trended higher for MS. In 2024, TSS, berry sugar, glucose + fructose, pH, and anthocyanins trended higher for CON. Fruit was harvested at a later maturity (*i.e.*, TSS) in 2024 compared to 2023, which is reflected in the significant year effect for all attributes except TA and pH.

DISCUSSION

The coincidence of Mg deficiency and high soil cation (K, Ca, Mg) content at the study site indicates induced Mg deficiency, whereby the abundance of K and Ca suppresses the uptake of Mg. Amongst U.S. winegrowing regions, the San Joaquin Valley, southwestern U.S., and inland Pacific Northwest have high soil cation concentrations that could induce Mg deficiency (Smith *et al.*, 2019). Soil nutrient concentrations (Table 1) indicate that K, Ca, and Mg are higher than regionally recommended values for grapevine (Moyer *et al.*, 2018).

TABLE 3. Magnesium deficiency symptom severity.

Year	Treatment	Symptomatic leaves (%)
2023	CON	47.1 c
	MC	40.1 b
	MS	32.8 a
2024	CON	19.6 b
	MC	22.2 b
	MS	8.6 a
Standard error		± 1.7
TRT		*0.002*
YEAR		*< 0.001*
TRT × DATE		*< 0.001*
TRT × YEAR		*0.014*

Data are means across sampling dates (*n* = 20-24): 10 July, 24 July, 14 August, 31 August, 25 September in 2023 and 17 July, 31 July, 14 August, 28 August, 11 September in 2024. *P*-values for the analysis of variance are presented at the bottom of the table (*TRT*: treatment). Letter assignments indicate statistically significant differences ($p < 0.05$). CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

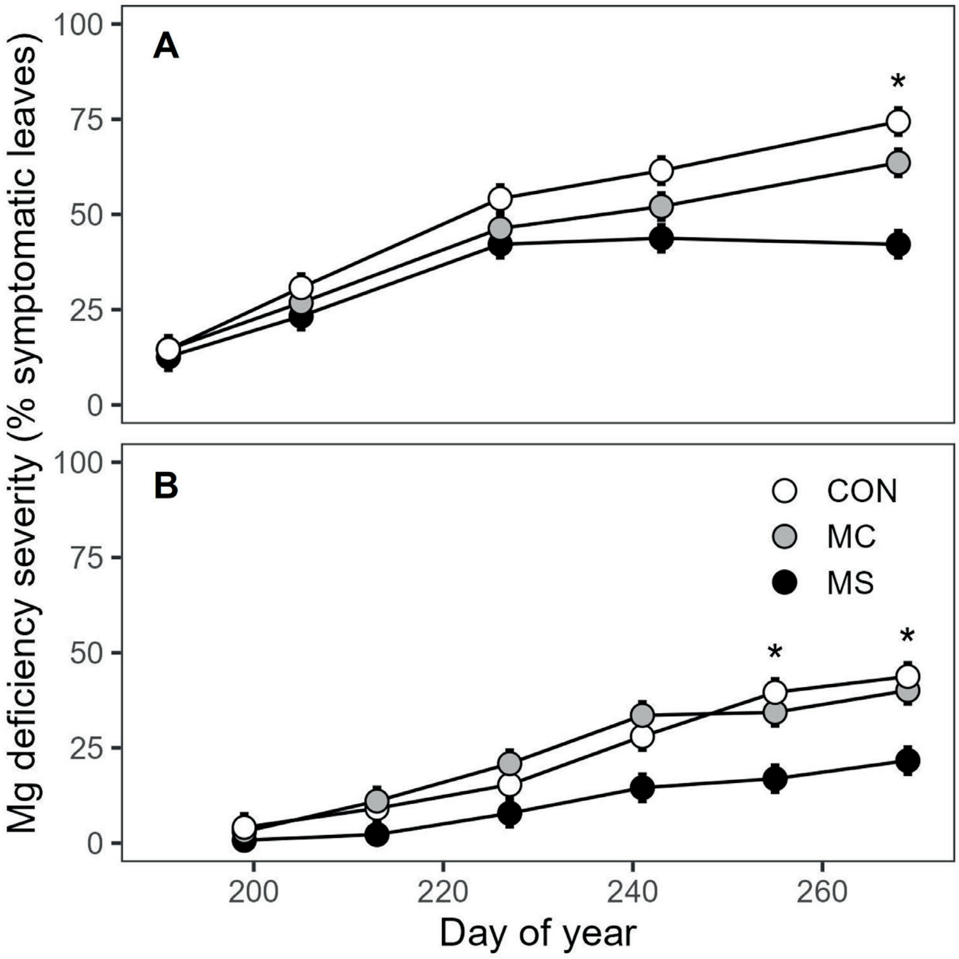

FIGURE 2. Magnesium deficiency symptom severity.

Magnesium deficiency symptom severity in 2023 (A) and 2024 (B). Data are means (*n* = 4) ± one standard error. An asterisk (*) indicates a significant treatment effect ($p < 0.05$). CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

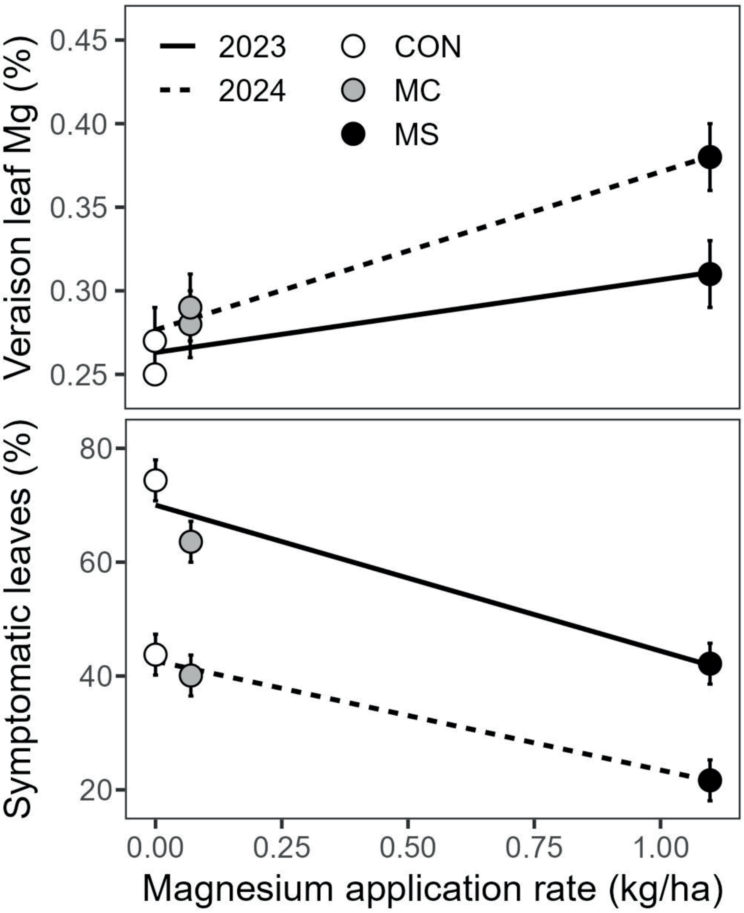

FIGURE 3. Linear relationships between magnesium application rate, leaf magnesium concentration, and magnesium deficiency symptom severity.

Linear relationships between magnesium application rate, leaf magnesium concentration, and magnesium deficiency symptom severity. Data are means ($n = 4$) ± one standard error. The final sampling dates (25 September 2023 and 25 September 2024) were used for symptomatic leaves data. The linear relationships between veraison leaf Mg and magnesium application rate are described by the equations $y = 0.04x + 0.26$ ($R^2 = 0.60$, $p = 0.297$) and $y = 0.09x + 0.28$ ($R^2 = 0.97$, $p = 0.073$) in 2023 and 2024, respectively. The linear relationships between symptomatic leaves and magnesium application rate are described by the equations $y = -25.6x + 70.0$ ($R^2 = 0.85$, $p = 0.177$) and $y = -19.2x + 42.0$ ($R^2 = 0.98$, $p = 0.063$) in 2023 and 2024, respectively. CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

TABLE 4. Yield components at harvest.

Year	Treatment	Cluster mass (g)	Berries per cluster	Berry mass (g)
2023	CON	349	195	1.70
	MC	343	188	1.72
	MS	357	185	1.83
2024	CON	289	158	1.73
	MC	268	157	1.67
	MS	301	166	1.73
Standard error		± 23	± 11	± 0.07
TRT		*0.565*	*0.934*	*0.388*
YEAR		*0.002*	*0.004*	*0.428*
TRT × YEAR		*0.902*	*0.694*	*0.578*

Data are means ($n = 4$). *P*-values for the analysis of variance are presented at the bottom of the table (*TRT*: treatment). Letter assignments indicate statistically significant differences ($p < 0.05$). CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

TABLE 5. Fruit chemistry at harvest.

Year	Treatment	TSS (°Brix)	Berry sugar (g)	Glucose + fructose (g/L)	TA (g/L)	pH	Potassium (mg/L)	Tannin (mg/L)	Anthocyanins (mg/L)
2023	CON	21.9	0.37	225	4.9	3.52	1,762	337	702
	MC	21.4	0.37	221	5.4	3.46	1,738	351	654
	MS	22.9	0.42	238	5.1	3.48	1,725	347	805
2024	CON	27.6	0.48	295	4.6	3.54	1,425	460	1,158
	MC	26.7	0.45	285	5.2	3.46	1,412	525	1,094
	MS	26.6	0.46	284	5.1	3.43	1,375	562	1,116
Standard error		± 0.6	± 0.02	± 21	± 0.3	± 0.05	± 58	± 25	± 42
TRT		*0.278*	*0.336*	*0.241*	*0.161*	*0.100*	*0.671*	*0.097*	*0.107*
YEAR		*< 0.001*	*< 0.001*	*< 0.001*	*0.393*	*0.806*	*< 0.001*	*< 0.001*	*< 0.001*
TRT × YEAR		*0.144*	*0.369*	*0.304*	*0.842*	*0.624*	*0.967*	*0.209*	*0.151*

Data are means ($n = 4$). *P*-values for the analysis of variance are presented at the bottom of the table (*TRT*: treatment). Letter assignments indicate statistically significant differences ($p < 0.05$). CON: Control; MC: chelated magnesium; MS: magnesium sulfate.

However, the calculated ratios of K:Mg and Ca:Mg can explain more precisely why Mg deficiency may occur in grapevines planted in the study region. The average Ca:Mg value of 5.6 falls within the recommended range of 2 to 10, and the average K:Mg value of 1.2 falls above the recommended range of 0.30 to 0.45 (Ramos & Romero, 2016). Despite an ostensibly high soil Ca content, it seems that excess soil K is the primary antagonist reducing Mg uptake and leaf concentrations.

Grapevine Mg deficiency in cation-rich soils is not effectively corrected by soil-applied Mg fertiliser; therefore Mg must be delivered more directly by foliar application (Gransee & Führs, 2013). In the present study, a magnesium sulfate fertiliser applied at three-week intervals from bloom to harvest effectively increased leaf Mg, reduced visible Mg deficiency symptoms, but did not significantly or consistently influence fruit chemical attributes. In addition to the cation-rich soils suppressing vine Mg uptake, several other factors likely influenced the severity of Mg deficiency and the observed effects of foliar Mg fertiliser, namely phenotype, plant Mg dynamics, and practical aspects of foliar Mg fertiliser application.

Mg uptake and deficiency is influenced by both rootstock and scion characteristics, though variability among rootstocks is better documented than that of scion (*i.e.*, *V. vinifera*) varieties. Rootstocks with *V. riparia* parentage, such as SO4 (*V. berlandieri* × *V. riparia*), Schwarzmann (*V. riparia* × *V. rupestris*), 101-14 MGt (*V. riparia* × *V. rupestris*), and 44-53 M (*V. riparia* × (*V. cordifolia* × *V. rupestris*)), are more likely to reduce Mg uptake or exhibit Mg deficiency (Bettiga, 2003; Gautier *et al.*, 2020; Livigni *et al.*, 2019; Pouget & Delas, 1982; Rahemi *et al.*, 2022). The Schwarzmann rootstock in the present study could have contributed to the Mg deficiency symptoms observed here. Morel *et al.* (2024) observed low K and Mg concentrations compared to 46 other rootstocks, though it appears that the average leaf Mg concentration (~0.5 %) was higher than in the present study. The scion variety Mourvèdre has been described as sensitive to K/Mg balance and prone to deficiencies of these two cationic nutrients, but the empirical source of this information is unclear (Garcin *et al.*, 2023; Wolf, 2008). Anecdotally, other Mourvèdre plantings on different rootstocks in the Columbia Basin region exhibit similar Mg deficiency symptoms whereas adjacent plantings of other varieties do not. Though Keller (2020) does not list it amongst cultivars prone to Mg deficiency (*e.g.*, Barbera, Zinfandel), Mourvèdre appears prone to visible symptoms of Mg deficiency (*i.e.*, interveinal chlorosis or anthocyanosis) irrespective of the effects on leaf physiology, reproductive development, and fruit quality.

The treatments in this study had various effects on the dynamics of leaf Mg within and across growing seasons. Unlike other plant macronutrients, leaf concentrations of Ca and Mg tend to increase significantly between bloom and veraison (Pradubsuk & Davenport, 2010; Schreiner *et al.*, 2006). This trend was generally observed here. Only the MS treatment, however, improved leaf Mg across years from 2023 to 2024. This is noteworthy because the postharvest remobilisation of Mg from leaf blades to storage organs (*e.g.*, trunk, roots) is relatively low in grapevines compared to other macronutrients (Pradubsuk & Davenport, 2010; Schreiner *et al.*, 2006). Still, the high leaf Mg in 2024 for MS may have been driven by the remobilisation of Mg from these storage organs which directly accumulate Mg between veraison and harvest (Pradubsuk & Davenport, 2010; Schreiner *et al.*, 2006). In cation-rich vineyard soils, grapevine storage organs are likely an important, albeit small, reservoir to supplement exogenous Mg.

Previous investigations of foliar Mg fertiliser application to grapevines present variable leaf Mg status, fruit yield, and fruit quality responses. Rupp *et al.* (2002) observed no effect of multiple foliar magnesium sulfate applications at 24 kg Mg/ha on yield or fruit quality, but the effect on leaf Mg status was not reported. Bai *et al.* (2024) and Zlámalová *et al.* (2015) applied foliar magnesium sulfate fertiliser multiple times per season (over one and three seasons, respectively) and observed up to 32 and 11 % increases in fruit yield, respectively. Zlámalová *et al.* (2015) achieved this yield increase with approximately one-third of the kg Mg/ha/application used in the present study; the rate (kg/ha) of Mg applied by Bai *et al.* (2024) is unknown.

Several studies compared the effectiveness of different Mg fertiliser application methods including soil application, foliar application, and injection (Májer, 2004; Trolove *et al.*, 2008; Zatloukalová *et al.*, 2011). Májer (2004) observed no effect of a single foliar application, but did see yield increase (up to approximately 60 %) for soil applied Mg fertiliser at multiple rates and with or without additional foliar applications. Trolove *et al.* (2008) did not observe any differences in fruit quality (*i.e.*, TSS) amongst soil, foliar, or injected Mg fertiliser. Zatloukalová *et al.* (2011) also observed an increase in yield (16 % compared to untreated control) from soil applied but not foliar-applied Mg fertiliser, despite high leaf Mg (> 0.25 %) for all treatments. The effectiveness of Mg fertiliser, whether applied to soil or leaves, is ultimately a result of fertiliser dose and the associated improvement in leaf Mg status.

The magnesium sulfate treatment improved leaf Mg and Mg deficiency symptoms more than the chelated magnesium treatment, but this does not necessarily indicate that magnesium sulfate is more effective or efficient. The linear relationships presented in Figure 3 demonstrate that the two treatments were similarly effective in proportion to the Mg dose. Like the product used in the present study, commercially available chelated Mg fertilizers may be limited by application rate restrictions. The chelated Mg fertilizer used in this study was applied at the maximum allowable rate. The mass of Mg per application for MC was roughly 7 % of that for MS. Thus, the effect of the MS treatment is practically significant insofar as it may reduce the number of applications required to improve leaf Mg. The chelated magnesium fertilizer used here was also more expensive. The cost per treatment application was similar, but the cost per mass Mg was nearly 20-fold higher for the chelated magnesium product. Any purported improvement in uptake for the chelated product did not outweigh the cost nor application rate limits. Additional work is warranted to investigate varying rates of both magnesium sulfate and a chelated magnesium fertilizer that can be applied at higher rates.

Ultimately, the effect of Mg fertilization on fruit chemistry was small and inconsistent. Fruit quality and reproductive productivity (*i.e.*, yield) are the primary economic concerns for Mg deficiency in grapevines. The majority of studies referenced here reported little impact of Mg fertilization on fruit quality, namely TSS, despite clear impacts on yield and leaf Mg status (Ruhl *et al.*, 1992; Rupp *et al.*, 2002; Trolove *et al.*, 2008; Zatloukalová *et al.*, 2011; Zlámalová *et al.*, 2015). MS was slightly more effective at improving fruit ripening by improving TSS by 1 °Brix in 2023, the same year that average leaf Mg at bloom (0.23 %) was just below the regionally recommended threshold of 0.25 % (Moyer *et al.*, 2018). At all other sampling times, average leaf Mg across treatments was above this threshold. Májer (2004) observed an improvement in fruit yield when leaf Mg was increased from 0.2 to just above 0.25 %, which was achieved primarily by soil-applied Mg fertilizer over three seaons. Indeed, Trolove *et al.* (2008) reported no differences in fruit quality across various Mg fertilizer application methods and formulations over two seasons, but leaf Mg values were low (< 0.25 %) for all treatments. Gluhić *et al.* (2009) reported leaf Mg values above 0.3 % over one season of study, but did not report about the effects of fertilization on vine productivity or fruit quality.

There is some inconsistency in Mg deficiency recommendations across grape producing regions in the western U.S. While petioles are used more commonly in the U.S. for diagnosing nutrient deficiencies, nutrient concentrations of leaf blades exhibit lower variability, particularly for Mg (Christensen & Peacock, 2000; Davenport *et al.*, 2012; Schreiner & Scagel, 2017; Wolf, 2008). In Oregon, petiole Mg values were indistinguishable between vines with and without Mg deficiency symptoms, but leaf blade values were different (Schreiner & Scagel, 2017). The leaf blade Mg sufficiency threshold recommended for wine grapes in Oregon is the same (*i.e.*, 0.25 %) as the whole leaf (*i.e.*, combined blade and petiole) recommendation for wine grapes in Washington (Skinkis & Schreiner, 2018). The critical values are similar for grapes in California, where petiole Mg below 0.2 % indicates a deficiency and petiole Mg values above 0.3 % are sufficient (Christensen, 2005; Christensen & Peacock, 2000). Tissue-specific thresholds will likely improve the accuracy of diagnosing Mg deficiency, though, because the concentration of Mg in petioles is higher than in leaf blades (Baby *et al.*, 2021; Davenport *et al.*, 2012).

MS exerted some influence on fruit ripening in 2023 when leaf Mg was deficient (< 0.25 %) and did not have a similar effect compared to CON and MC in 2024 when leaf Mg indicated that vines were not Mg deficient. Though this trend is subtle, it upholds the regional recommendations for whole leaf Mg at bloom and veraison by demonstrating that foliar Mg fertilization above the deficiency threshold provided no benefit to fruit quality. The presence of visible Mg deficiency symptoms should not replace leaf nutrient analysis for diagnosing Mg deficiency, particularly with Mourvèdre and other varieties that are prone to visible Mg deficiency symptoms. Tissue Mg increases later in the season (*i.e.*, at veraison) and may fall above the sufficiency threshold despite the presence of Mg deficiency symptoms that may have agreed with deficient Mg values earlier at bloom.

Conditions of the present study limit interpretation, particularly with respect to vine productivity and ripening. There was high variability in crop load between vines, which precluded a reliable measurement of vine yield.

An assessment of productivity is limited to changes at the cluster level (*e.g.*, berry number, berry mass) which were not significantly influenced by the treatments despite some small numeric differences. Differences in crop load could have been obscured by the high variability at the cluster and vine level. Crop load is a primary factor that determines grape ripening and maturity; therefore, a higher crop load with magnesium fertilization could explain the lower TSS value for the fertilizer treatments in 2024 (Verdenal *et al.*, 2022). Additional study including quantification of vine yield, lower variability among vines, and more severe Mg deficiency would be useful to determine whether the application of magnesium sulfate, which clearly improves leaf Mg, provides a real economic benefit (*i.e.*, improved yield).

CONCLUSION

Foliar applied magnesium sulfate fertilizer, in comparison to an untreated control and chelated Mg fertilizer, effectively increased leaf Mg and reduced the visible symptoms of Mg deficiency in Mourvèdre exhibiting evidence of reduced uptake due to soil cation competition. The magnesium sulfate was likely more effective than the chelated Mg fertilizer because of application rate limitations, which restricted the Mg supply from the chelated Mg fertilizer to about 7 % of the Mg supply from magnesium sulfate applications. There was little to no impact of Mg fertilization on yield components or fruit chemistry, which was likely due to leaf Mg values above the regionally recommended threshold at veraison in both years. This study demonstrates that foliar applied magnesium sulfate fertilizers are low-cost and effective at correcting Mg deficiency in cation-rich soils. Additionally, it confirms the regionally recommended minimum threshold of 0.25 % for whole leaf Mg and suggests that presence of visible Mg deficiency symptoms (*i.e.*, interveinal chlorosis or anthocyanosis) should not substitute for leaf nutrient analysis.

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