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A Review of the Effect of Magnesium on Performance of Huanglongbing (HLB)-affected and Non-HLB-affected Citrus Trees

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Citrus production is one of the most important and valuable fruit industries worldwide, although production and area harvested have been declining in some of the biggest producing countries, mainly because of Huanglongbing (HLB), also known as citrus greening. Nutrients play an important role in defense mechanisms and have the potential to extend the productive life of HLB-affected citrus trees. Ensuring adequate magnesium (Mg) nutrition could be important in this context because of its role in photosynthesis and carbohydrate partitioning. This paper reviews how Mg affects citrus trees with and without HLB. Results from past research are inconsistent, most likely because those studies aimed to raise soil pH and overcome Mg deficiencies by using low-solubility Mg sources (e.g., dolomitic lime). In contrast, recent data using water-soluble Mg fertilizers show that Mg may affect vegetative growth (greater canopy volume and leaf Mg), fruit yield and fruit quality (greater juice acidity). While Mg applications can have positive effects on vegetative growth (e.g., canopy volume) and leaf Mg concentration, and either positive or negative effects on yield and juice quality, grove management including a balanced nutrition program seems to be optimal to address HLB. Adequate management of Mg and its interaction with other nutrients may help keep citrus trees in production despite HLB and a well-designed fertilization program may allow growers to partially overcome the effects of HLB on citrus growth and productivity.

Citrus (oranges, tangerines, lemons, limes and grapefruit) are the fruit trees with the highest global production, with more than 130 million tonnes (t) of fruit produced per year (FAO, 2019). In the US, Florida is the state with the highest citrus production, accounting for 57% of bearing citrus acreage and 45% of total production in 2016-2017 (FDACS and USDA, 2021). Citrus production in Florida occupied around 170,000 ha in 2020, a 52% reduction from about 350,000 ha in 1996 (USDA, 2020). Production in Florida was less than 3 million t in 2019-2020, down from a peak of 12.4 million t during the pre-HLB 1997-1998 season (FDACS and USDA, 2021). In just 5 years, from 2012 to 2017, the value of orange production in Florida declined by $330 million (FDACS and USDA, 2021). This reduction that occurred in the past 20 years has been ascribed to the devastating effects of citrus greening that is also called huanglongbing (HLB), hurricane damage and increasing urbanization (Ferrarezi et al., 2019; Kadyampakeni, 2012). A similar decline in area has been observed in Brazil whereas acreage increased in both China and India. Consequently, China and India have both increased orange production whereas US production has declined, although Brazil production has been stable in the last 15 years despite the severe loss in acreage. It is likely that HLB has played a major role in both production and area harvested dynamics in Florida and in other citrus producing countries.

Nutrients play an important role in plant development and defense mechanisms against diseases (García-Mina, 2012; Huber and Jones, 2013; Schumann et al., 2010) and nutrient applications can help citrus trees mitigate HLB symptoms (Handique et al., 2012; Morgan et al., 2016; Pustika et al., 2008; Rouse et al., 2012). Magnesium applications may increase or decrease disease severity, depending on plant species, disease type, environmental conditions, and the rate of Mg application (Datnoff et al., 2007; Spann and Schumann, 2009). Magnesium plays a very important role in phloem transport of photosynthesis products and its imbalance could lead to excessive accumulation of sugar, starch and amino acids in source tissues like leaves (Hermans et al., 2005; Cakmak and Kirkby, 2008; Huber and Jones, 2013). As HLB is a phloem-restrictive disease, a balanced nutritional approach including Mg could benefit the vegetative and productive performance of HLB-infected trees.

The objective of this paper is to review the effects of Mg applications on tree development, productivity and fruit quality variables in citrus trees infected and non-affected with HLB. The role of this divalent cation has been studied and documented, but there is limited information about its effects on HLB-affected citrus trees and most importantly, there is little information about which Mg rates are optimal in the HLB context.

Description of HLB and its interaction with citrus

One of the major reasons for the decrease in citrus production and cultivated area in Florida is HLB (Alvarez et al., 2016; Court et al., 2018; Kadyampakeni et al., 2015). Huanglongbing, “yellow dragon disease” in Chinese, was first reported in China in 1919 (Bové, 2006). The disease is now found in more than 40 countries in Asia, Africa, and America. HLB was first detected

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*Corresponding author. Email: dkadyampakeni@ufl.edu in Florida in 2005 although the vector was likely present as early as 1998 (Alvarez et al., 2010).

HLB is caused by the phloem-restrictive, gram-negative bacteria *Candidatus* Liberibacter spp. that is spread by its vector, the Asian citrus psyllid (ACP) (*Diaphorina citri*, Hemiptera: Liviidae). There are three known *Candidatus* Liberibacter species: *Candidatus* (Ca.) Liberibacter (L.) *africanus*, which affects citrus trees in Africa; Ca. L. *asiaticus*, also known as *C*Las, which affects citrus trees in Asia and America; and Ca. L. *americanus*, which affects citrus trees mainly in Brazil (Bové, 2006). The vector, ACP, is an insect that sucks phloem sap with a proboscis and infects citrus plants with the causal pathogen during the process. A young plant flush is needed for ACP eggs to be laid and to further develop into nymphs (Stansly et al., 2018).

Huanglongbing causes lower vegetative growth, smaller fruits with no symmetric size and poor color (greening) (Bové, 2006), root mortality, stunted branches, fruit drop, severe leaf defoliation, and finally plant mortality (Bassanezi et al., 2011; Graham et al., 2013; Kadyampakeni et al., 2014). According to Graham et al. (2013), four-year-old symptomatic HLB-affected *Citrus sinensis* 'Valencia' trees may lose up to 38% of root mass density (mg/cm^3 soil) compared to non-symptomatic trees. Furthermore, Johnson et al. (2019) reported that HLB may cause up to 50% root loss early in disease development and 70% when canopy decline starts in citrus. Regarding productivity, HLB had more severe effects on yields in late maturing varieties, like 'Valencia' compared to early and mid-season maturing varieties, like 'Hamlin', 'Westin', and 'Pera' in Brazil (Bassanezi et al., 2011). In addition to yields and vegetative growth, HLB may also affect fruit quality by decreasing sweetness (°Brix) and increasing acidity, similar to immature fruits (Bassanezi et al., 2009; Dagulo et al., 2010).

Currently, HLB has no cure, but important research efforts are under way to develop disease tolerant/resistant cultivars, formulate a chemical cure and establish alternative production practices that would optimize irrigation, plant nutrition and pest management to maintain productivity in affected groves. As recent evidence suggests that HLB symptoms in citrus can be reduced with an enhanced nutritional program (Handique et al., 2012; Kadyampakeni et al., 2016; Morgan et al., 2016; Rouse et al., 2012; Zambon et al., 2019), it is important to continue investigating and understanding the role of nutrients in this plant-disease relationship.

The role of Mg in citrus nutrition and HLB management

Nutrition plays an important role in the development of citrus plants. Nitrogen (N), phosphorus (P), and potassium (K) are very important components of plant structure and metabolism and micronutrients such as iron (Fe), zinc (Zn) and manganese (Mn) are key parts of enzymatic activities and, photosynthesis (Kadyampakeni et al., 2015; Obreza et al., 2008; Ramírez-godoy et al., 2018). Normally, nutrient management focuses on primary macronutrients, although micronutrients have received increasing attention lately, especially in HLB-affected citrus (Atta et al., 2018, 2020a; Uthman, 2019; Zambon et al., 2019). However, less attention is given to secondary macronutrients like calcium (Ca), sulfur (S), and magnesium (Mg). Magnesium is an important component of the chlorophyll molecule and it is linked to cell division and metabolism (Chen et al., 2018; Morton et al., 2010; Schumann et al., 2010). Magnesium is a bridging element for the aggregation of ribosome subunits, a necessary process for protein synthesis, and under deficiency or excessive concentrations, the ribosome subunits dissociate and protein synthesis stops (Chen et al., 2018). Besides enzyme regulation, Mg also regulates the cation-anion balance and cellular pH (Hawkesford et al., 2012). There are many interactions among Mg and nutrients uptake in the soil and plant, including synergisms and antagonisms that must be considered in a balanced nutritional approach (Anderson and Albrigo, 1971; Havlin et al., 2013; Quaggio et al., 1992; Zekri, 2016).

Nutrition also plays an important role in disease resistance, as pathogens affect plant physiology after infection. Pathogens can interfere with water and nutrient transport inside the plant, which can cause deficiencies induced by nutrient immobilization and root starvation (Schumann and Schumann, 2009), especially for secondary macronutrients like Mg.

Magnesium role in the soil-plant interface and in citrus with HLB

Magnesium is absorbed by plants as exchangeable Mg in the clay-organic matter complex (Weil and Brady, 2017) and roots take it up mainly by mass flow (Havlin et al., 2013). Magnesium root absorption takes place in the apical root zone, as opposed to K whose absorption takes place primarily in the basal zone (Morton et al., 2010, Hawkesford et al., 2012). Once the plant absorbs Mg, it is distributed into different organs. In Tarocco orange of southern Italy, Roccuzzo et al. (2012) found that 22% of the annual citrus Mg uptake goes to fruit production, 51% to abscised leaves and 19% to pruning material. This partitioning may be variety-dependent however, as Morton et al. (2010) observed rootstocks that absorb more Mg than others. Seedy citrus varieties may have higher Mg requirements than seedless ones (Zekri, 2016) as seeds represent a tenth of fruit dry biomass but a fifth of Mg fruit content (Camp, 1947). Mineralization of organic residues and composting may help recover Mg from abscised leaves and pruned biomass by making it available again for the plant, but the availability of this recycled Mg will depend on many factors like climate, soil, and management.

Magnesium is involved in starch decomposition and sucrose formation in citrus fruits (Zhou et al., 2018) and Mg-deficient citrus trees have poor fruit quality (Smith, 1966), i.e., smaller fruits with lower acidity and soluble solids content (Quiñones et al., 2012). Magnesium deficiency promotes the accumulation of starch in citrus leaves because carbohydrate export via the phloem is inhibited. Also, Mg deficiency impairs the lignification of vascular organs in roots, affecting water and nutrient flow from roots to aboveground biomass, while also leading to cell wall lignification of vascular cambium and spongy parenchyma cells (Huang et al., 2019). This generates a lower concentration of carbohydrates in sink organs such as roots and higher concentration of carbohydrates in the leaves (Arbona and Gómez-Cadenas, 2012; Hawkesford et al., 2012). Cakmak and Kirkby (2008) suggest that the role of Mg in phloem-loading process seems to be cultivar-specific and the accumulation of carbohydrates in Mg-deficient leaves is caused directly by Mg deficiency stress. As HLB restricts phloem movement and promotes accumulation of carbohydrates in leaves and depletion in roots (Etxeberria et al., 2009; Hawkesford et al., 2012; Huber and Jones, 2013), this high carbohydrate concentration in leaves could provide a favorable environment for pathogens and pests and even dilute the concentration of other nutrients used for plant defense, like Ca (Huber and Jones, 2013). In fact, Mg and K are used to improve phloem movement of carbohydrates, Zn, B, Mn, and other nutrients that are applied foliar in HLB-affected citrus (Rouse et al., 2012).

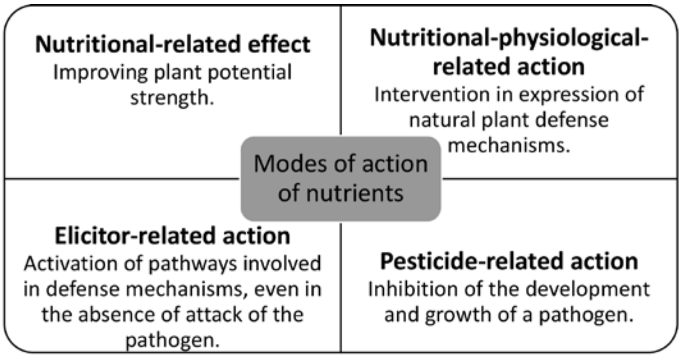

Fig. 1. Different levels of action of nutrients in plant defense mechanisms. Adapted from García-Mina (2012).

Interestingly, HLB-infected citrus trees have less Mg in leaves and roots compared to non-infected trees (Morgan et al., 2016; Zambon et al., 2019; da Silva et al., 2020; Shahzad et al., 2020). Zambon et al. (2019) found that HLB-affected 'Valencia' grafted on 'Carrizo' rootstock had around 20% less Mg leaf concentration and almost 50% less Mg root concentration compared to non-affected trees in a greenhouse experiment, whereas 'Valencia' grafted on 'Swingle' rootstock had almost 40% less Mg root concentration compared to HLB-free trees in a field trial. Da Silva et al. (2020) found that HLB-affected citrus plants had less Mg concentration in the sap extract compared to healthy plants. Reduced root growth, either due to HLB or Mg deficiency, can affect Mg uptake, exacerbate Mg deficiency and decrease the uptake of other nutrients (Camp, 1947; Hawkesford et al., 2012; Morgan et al., 2016; Shahzad et al., 2020). Therefore, both the upward and downward movement of nutrients inside the plant are affected by Mg levels, which could potentially accelerate physiological damage, especially for trees affected by HLB.

In contrast, increasing Mg concentrations beyond the optimal level may cause accumulation in vacuoles, which could cause negative effects under drought stress, e.g., photosynthesis inhibition (Hawkesford et al., 2012). A balanced and constant nutrition of Mg is crucial to prevent deficiencies or excess and allow for appropriate plant development and performance.

As Mg affects the expression of plant defense mechanisms, adequate Mg nutrition may help the plant battle against the disease by promoting carbohydrate movement and restoring phloem function in citrus trees affected with HLB (García-Mina, 2012; Rouse et al., 2012; Huber and Jones, 2013) García-Mina (2012) defines and differentiates levels of action for nutrients in plant defense mechanisms (Fig. 1). He emphasizes the importance of understanding how, when and why nutrients are helpful to fight against pathogens and diseases, although the mechanisms responsible for these benefits remain unclear in many studies. According to García-Mina (2012), the role of Mg in citrus is mainly nutritional-physiological-related, i.e., it affects the expression of natural plant defense mechanisms when the plant is attacked by the pathogen. However, Mg may have deeper interactions with disease response in citrus, as Mg can complement or antagonize other minerals and its exchangeable content in soils or tissue may affect the incidence of plant diseases (Huber and Jones, 2013).

Application of Mg in citrus

In the pre-HLB period, Mg was mainly applied in citrus to correct deficiencies (Koo and Calvert, 1965; Smith, 1966; Koo, 1971; Lavon et al., 1999). A Mg deficiency may appear when soil exchangeable Mg is low, when soil K and/or Ca exchangeable content are high or when soil pH is low (Obreza and Morgan, 2008). For a Mehlich 3 extraction, less than 25 mg/kg of exchangeable soil Mg is considered to be low in Florida (Obreza and Morgan, 2008). Values considered as low, medium or high for Mg among different soil extractants in Florida can be found in Table 1.

Applications of dolomite can correct Mg deficiencies while also increasing soil pH in acidic soils of the United States, Africa and Australia (Smith, 1966). When soil pH is about 4.5–5, the use of dolomite to raise pH to 6.0–6.5 should increase the availability of Mg. Although this practice was recommended in the past, growers are now opting to acidify soils instead of raising soil pH in the HLB context. Morgan and Graham (2019) found that bicarbonates and high soil pH may be exacerbating the negative effects of HLB in Florida citrus, so they achieved higher yields and higher juice quality by acidifying irrigation water and decreasing soil pH. Therefore, growers should carefully choose their Mg material to avoid raising soil pH to a level that aggravates HLB symptoms. If soil pH is in the optimum range, soil applications of magnesium sulfate/Epsom salt ($MgSO_4$), langbeinite or Sul-Po-Mag ($K_2SO_4.2MgSO_4$) and chelates may correct Mg deficiencies (Havlin et al., 2013; Zekri, 2016) and may be better options than dolomite. Soil applications of soluble Mg may require about six months to increase citrus leaf Mg concentrations (Esteves, 2022), whereas less soluble forms like dolomite may require two years (Koo, 1971; Smith, 1966). In addition, maintaining an adequate soil Ca:Mg ratio when fertilizing with Mg is critical, as this ratio should be lower than 10:1 for most crops according to Havlin et al. (2013).

In addition to selecting the right Mg source, using the right Mg application rate is key to correct soil and/or plant deficiencies, which will depend on many factors such as plant and soil Mg concentrations as well as soil pH. Koo (1971) tested three different Mg rates to correct Mg deficiency in citrus: after 3 years, the highest rate (269 kg·ha^{-1} MgO equivalent) corrected visual deficiencies whereas deficiency symptoms were still visible in the two other rates (67.2 kg·ha^{-1} and 168 kg·ha^{-1} MgO equivalent). Atta et al. (2020) and Esteves (2022) tested 45 kg·ha^{-1} Mg and 101 kg·ha^{-1} Mg, respectively, in similar studies with different cultivars and different sites and found significantly higher soil Mg and leaf Mg concentrations with HLB-affected trees. For Florida citrus, Zekri (2016) and Obreza et al. (2008) recommend applying Mg at a rate equal to 20% of the N rate (the recommended N rate is between 135 and 224 kg·ha^{-1}) when the soil levels of this nutrient are medium to low. When leaves already show deficiencies, foliar applications of magnesium nitrate $[Mg(NO_3)_2]$ may correct the nutrient deficit (Zekri, 2016).

Interactions between Mg and other elements may also lead to deficiencies due to interactions and competition for uptake and exchange sites by other cations. High salinity, the use of fertilizers high in potassium salts and manure may aggravate Mg deficiency (Zekri, 2016). In apples, Vang-Petersen (1980) concluded that symptoms of Mg deficiencies were more dependent on the leaf

Table 1. Soil test interpretations used in Florida for three extraction methods (Obreza and Morgan, 2008).

		Soil test interpretation		
Extractant	Nutrient	Low	Medium	High
Mehlich 1	Mg	< 15	15–30	> 30
Mehlich 3	mg/kg	< 25	25–33	> 33
Ammonium acetate (pH 4.8)		< 14	14–26	> 26

K:Mg ratio than leaf Mg concentration alone, as K competes with Mg and the concentration of K in the plant depends on the K:Mg in the growth medium. As a result, recommendations for K:Mg ratios are higher for fruit crops like citrus (2:1) as opposed to field crops (< 5:1) or vegetables (3:1) (Havlin et al., 2013).

The effects of Mg inputs on citrus growth, yield and fruit quality

Past research conducted on Mg application in citrus evaluated different variables like yield and fruit quality, mostly before HLB. Now that HLB has become widespread, new research is needed to determine if guidelines on Mg nutritional requirements must be adjusted.

Yield. Citrus yield response to Mg applications is inconsistent (Table 2), although many experiments that did not find significant results with Mg application used dolomitic limestone and low-solubility Mg sources. Calvert (1970) did not find any response on dolomitic limestone applications in 'Cleopatra' mandarin because soil Mg levels were already adequate, although the low solubility of dolomitic limestone might have also played an important role. In central Florida, Koo (1971) obtained a higher yield (36.8 t of fruit/ha) with a 168 kg·ha^{-1} MgO equivalent treatment compared to 67 and 269 kg·ha^{-1} MgO equivalent, but soil Mg concentration was not correlated to fruit production or quality. Although he did not find statistically significant differences in yield response due to Mg sources, there was a trend of higher average values with the most soluble sources. Koo (1971) concluded that the optimal Mg rate could be lower than 168 kg·ha^{-1} MgO equivalent on soils not severely depleted in Mg, but this experiment was done before HLB was reported in Florida.

In a commercial grove where HLB was detected during the 2005–06 season, Rouse et al. (2012) monitored orange tree (*C. sinensis*) varieties 'Hamlin' and 'Valencia' that were managed with soil and foliar application of many nutrients, including a combination of foliar (0.84 kg·ha^{-1}) and soil (9.6 kg·ha^{-1}) Mg applications. Yields slightly increased through time and varied between 45.7 to 73.1 t·ha^{-1} for 'Hamlin' sweet orange and 34.2 to 62.2 t·ha^{-1} for 'Valencia' sweet orange between 1999 and 2012, while Florida's average tended to decline and ranged from 27.9 to 43.3 t·ha^{-1} during the same period (Fig. 2). Yields seemed to be sustained by the application of nutrients described by Rouse et al., (2012) and Singerman (2016), although the total annual cost per hectare of this nutritional program (including soil and foliar fertilizations) was around $1121. This would become an additional expense that growers have to make to maintain grove productivity (Rouse et al., 2012).

Esteves et al. (2021) established a split-plot experiment in central Florida comparing the effects of a 101 kg·ha^{-1} Mg treatment to a grower standard treatment receiving 56 kg·ha^{-1} Mg across three N levels (168, 224, 280 kg·ha^{-1} N), in triplicate plots per combination of N and Mg fertilization. They found no significant difference between the Mg and grower standard treatments at the higher N rates (224 and 280 kg·ha^{-1} N), although Mg fertilization increased yields relative to the grower standard at the lowest N rate of 168 kg·ha^{-1} (Esteves et al., 2021). This suggests that N could also be playing a role and that a single nutrient may not address a complex disease, although a more balanced and holistic approach may be effective. These results are based on two years of data and may become more evident with a longer experiment.

Table 2. Compilation of results obtained in different experiments with application of magnesium (Mg) in citrus.

Authors	Scion and rootstock	Mg source and MgO (%)	MgO equivalent rate	Yield	CAV[z]	TC[y]	LAI[x]	Leaf Mg concentration	Brix	Acidity
Esteves et al., 2021	Valencia on Swingle citrumelo	$MgSO_4$ (16%)	101 kg·ha^{-1} Mg/year	NS[w]	+[v]	NS	--[u]	+	NS	+
Atta, 2019	Hamlin on Cleopatra and Hamlin on Swingle	MgO_3S_2 (7%)	75 kg·ha^{-1} /year	--	NS	--	+	+	--	--
Quaggio et al., 1992	Valencia on Rangpur lime	calcitic (6%) and dolomitic (20%) limestones	0, 3, 6, and 9 t·ha^{-1}	--	--	--	--	--	+	+
Koo 1971	Valencia orange on rough lemon	$MgSO_4$ (27%) MgO (91%) $MgCO_3$ (20%)	67, 168, and 269 kg·ha^{-1} /year	+	--	--	--	+	NS	NS
Calvert, 1970	Temple on Cleopatra mandarin	dolomitic limestone	0–51 kg·ha^{-1} at 1st, 4th, 6th, and 10th year	NS	NS	NS	--	NS	NS	NS
Weir, 1969	Valencia on sour orange	kieserite ($MgSO_4$)	1.81 and 3.63 kg/tree/year	NS	--	--	--	+	--	NS
Koo & Calvert, 1965	Marsh grapefruit on rough lemon rootstock	magox-90 (91.5%), seawater magnesia (93%), magnesia-65 (66%), magnesium sulphate (27.5%), and langebeinite (18%)	0.27, 0.91, 1.54 kg/tree/year	--	--	--	--	+	--	--

[z] CAV = canopy area/volume.
[y] TC= trunk circumference.
[x] LAI= leaf area index.
[w] NS = no significant results.
[v] + = increased
[u] Blank cells (--) = either no data available or not measured.

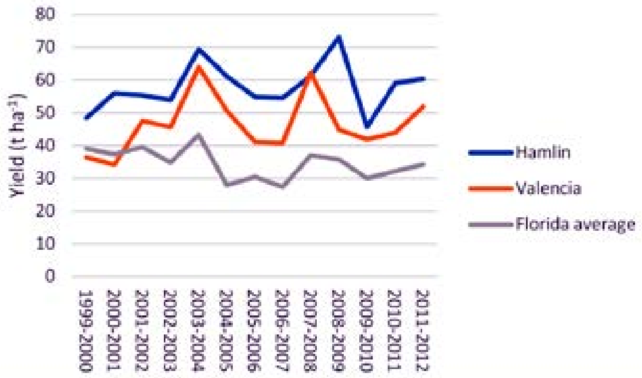

Fig. 2. Total yield by season and citrus (Citrus sinensis) variety from the Orange Hammock Grove in Hendry County, FL compared to Florida's average yield. Adapted from Rouse et al. (2012).

Vegetative Growth. Variables like trunk measurements, tree height and canopy values are used as indicators of vegetative growth in citrus (Calvert, 1970; Obreza et al., 1993). Calvert (1970) reported a non-significant increase in trunk circumference, tree height, tree width and tree canopy area with Mg applied as dolomitic limestone on pre-HLB Temple oranges on 'Cleopatra' mandarin rootstock (Table 2).

Esteves et al. (2021) documented the effect of Mg on canopy volume and TCSA on HLB-affected citrus trees and found a greater canopy volume with the Mg treatment relative to the grower standard when N was supplied at a rate of 168 $kg{\cdot}ha^{-1}$ N. Atta et al. (2020b) found significantly higher leaf area index (40%) in the Mg treatment compared to the control (Table 2).

As HLB restricts phloem movement (Hawkesford et al., 2012; Huber and Jones, 2013), supplying Mg may promote phloem movement (Rouse et al., 2012) and improve vegetative growth. Despite the benefits of Mg fertilization, the seven-year old trees from Esteves et al. (2021) had similar canopy volumes to two-year old trees measured before HLB became widespread (Obreza et al., 1993). Smaller canopy volumes could be due to HLB-driven increases in defoliation and branch stunting that reduce vegetative growth drastically (Bové, 2006; Graham et al., 2013; Kadyampakeni et al., 2014) or because the planting density of the experiment was three times higher compared to commercial groves.

Leaf Mg concentration

The response of citrus tree leaf nutrient concentration to Mg application depends on many factors, including soil exchangeable Mg content, prior leaf Mg concentration, soil and plant interactions with other nutrients and Mg source and rates. Weir (1969) found a significant increase in leaf Mg concentration with kieserite application, a magnesium sulfate mineral with about 25% MgO and 20% S (Table 2). Koo and Calvert (1965) reported a significant increase in grapefruit (*Citrus ×paradisi*) leaf Mg concentration with Mg application of oxides and sulfates and no effect on other plant or soil variables, although none of the tested sources had a low solubility (e.g., dolomite, carbonate). Koo (1971) observed a significant increase in leaf Mg concentration among sources and rates for trees that were initially Mg-deficient, with $MgCO_3$ being slower in correcting the deficiency compared to $MgSO_4$ and MgO (Table 2). The highest rate (269 $kg{\cdot}ha^{-1}$) was also faster at correcting Mg deficiency compared to the other two rates tested (67 and 168 $kg{\cdot}ha^{-1}$). In contrast, Calvert (1970) found no significant difference in leaf Mg concentration when dolomite was applied.

Some of these early Mg experiments used dolomite as a Mg source to raise soil pH and control leaf Mg deficiencies. Dolomite is less soluble than other Mg sources and citrus trees may take several years to respond to fertilization treatments (Camp, 1947; Koo, 1971). Interestingly, Koo and Calvert (1965) observed that Mg may become less available at high pH, regardless of source and rate, highlighting the critical role soil pH and its management play for Mg uptake in citrus trees.

The effect of Mg nutrition may also be influenced by the scion and rootstock combination. Leaf Mg was significantly increased by Mg nutrition in 'Hamlin' grafted on 'Swingle', but it was not clearly influenced in 'Hamlin' grafted on 'Cleopatra' (Atta, 2019). Esteves et al. (2021) found higher leaf Mg with Mg fertilization in 'Valencia' grafted on 'Swingle', regardless of N application rates (Table 2), although yields increased with Mg fertilization only at the lowest N rate, suggesting that the link between leaf Mg and yield is not straightforward, at least not at recommended N rates or above.

Leaf Mg reference levels vary according to location and may also differ depending on variety, rootstock and tree age (Table 3; Menino, 2012). The reference levels given by Rodriguez et al. (1961) and Jorgensen et al. (1978) are based on previous work done by Reuther et al. (1954) and Chapman (1960), more than 50 years ago. More recent studies report lower values, with critical levels of Mg equal to 0.3% (Liu et al., 1984) or 0.13% (Shimizu et al., 1985). In contrast, Quaggio et al. (1992) reported slight Mg deficiencies in 'Valencia' trees with leaf Mg concentration below 0.35%, which is within the optimum level reported by Koo et al. (1984) for Florida citrus prior to HLB. Given the devastating impacts HLB has on citrus physiology and growth, cultivar-specific and site-specific critical nutrient tissue concentrations should be developed to better understand the functions and interactions of individual nutrients in HLB-affected plants (Menino, 2012).

Furthermore, leaf Mg guidelines established either before HLB or in locations where HLB has not been reported yet must be updated. For example, the most recent study cited in Table 3 took place in Spain in 2010, a country where HLB is not yet present. In addition, there is no agreement on Mg excess and/or toxicity values, as some are still reported as uncertain. Finally,

Table 3. Leaf magnesium reference concentrations (%) for citrus in five different locations.

Authors	Country	Citrus variety	Deficient (less than)	Low	Normal (optimum)	High	Excess (more than)
Rodriguez et al., 1961	Brazil	Citrus	0.15	0.16–0.29	0.30–0.60	0.70–1.10	1.20[z]
Embleton et al., 1978	California, USA	Valencia Late orange	0.16	0.16–0.25	0.26–0.60	0.70–1.10	1.20[z]
Jorgensen et al., 1978	Australia	Citrus	0.16	0.16–0.25	0.25–0.60	0.6–1.20	1.20[z]
Koo et al., 1984	Florida, USA	Citrus	0.20	0.20–0.29	0.30–0.49	0.50–0.70	0.70
Quiñones et al., 2010	Spain	Citrus	0.15	0.15–0.24	0.24–0.45	0.46–0.90	0.90

[z] Uncertain values.

nutrient guidelines should be revised based on a balanced nutrition approach rather than individual nutrients taken in isolation. Lower Mg:Ca ratios may indicate Mg absorption and translocation to the leaf, and it could be a useful indicator if it correlates well to yields or fruit quality.

Fruit quality

Citrus fruit quality is evaluated with variables like Brix (i.e., total soluble solids), acidity, the Brix:acidity ratio, kg solids per hectare and kilograms juice per hectare. According to Koo (1988), soil applications of Mg slightly increase juice quality variables such as Brix, Brix:acidity ratio, fruit size and weight, and decrease rind thickness.

Carbohydrates are the most prevalent compound in citrus juice, accounting for about 80 % of total soluble solids (TSS) (Kimball, 1999). Carbohydrates increase with soil applications of N, Mg and Fe and decrease with K (Koo, 1988). Quaggio et al. (1992) found that Mg increases TSS in citrus juice and Koo (1971) found a non-significant increase in TSS with Mg. In contrast, Esteves et al. (2021) found no significant difference in TSS concentration with Mg application (Table 2), although TSS content was higher in the Mg treatment compared to the control, with all treatments above the minimum threshold of 11 established by the USDA for Grade A pasteurized orange juice (Kimball, 1999).

Acids, mainly citric and malic acids, are the second most abundant solids in citrus juice (Kimball, 1999; TETRA PACK, 2004). The Brix:acidity ratio is an indicator of fruit maturity and it measures the balance between the sweet and sour sensation of juice (Kimball, 1999; TETRA PACK, 2004). Since sour and sweet flavors compete for the same receptor sites in the tongue, the ratio between Brix and acidity is more important than the specific amount of each (Kimball, 1999). Previous studies report mixed effects of Mg on juice acidity, as Mg can either increase juice acidity (Moss and Higgins, 1974; Quaggio et al., 1992) or show no effect (Calvert, 1970; Koo, 1971; Koo, 1988; Weir, 1969). As Mg deficiency can decrease acidity and soluble solids (Quiñones et al., 2012), Mg applications can increase the acidity in oranges, possibly through a reduction in Ca uptake (Moss and Higgins, 1974; Quaggio et al., 1992). Vang-Petersen (1980) also found a reduction in Ca uptake due to Mg application in apple trees. However, Weir (1969) found no effect of Mg applications on ‘Valencia’ fruit juice acidity whereas Koo (1988) reported that Mg increased the Brix:acidity by increasing the Brix content. Esteves et al. (2021) found mixed results: a greater percent acidity and lower Brix:acidity ratio with Mg fertilization relative to the unfertilized control in the first year, compared to a non-significant decrease in juice acidity with Mg fertilization relative to the control in the second year (Table 2). The Brix:acidity ratio was compliant with USDA standards for unsweetened Grade A pasteurized orange juice in Florida for both years, although the acceptable Brix:acidity ratio varies among states (Kimball; 1999), highlighting that the effect of Mg fertilization on this indicator must be evaluated locally.

Future trends in managing nutrition of HLB-affected citrus

The citrus industry can take multiple paths to address issues related to nutrition and HLB. As the development of tolerant and/or resistant varieties to HLB is underway, plant breeders should develop rootstocks and scions that are resistant and tolerant against HLB and have high nutrient uptake to maximize benefits for improving plant immunity, growth and overall performance. Meanwhile, research that improves our understanding of nutrient placement and delivery mechanisms (foliar, soil application, trunk injection) along with water management practices and plant physiology should be prioritized to improve nutrient use efficiency and environmental quality in the mid- to long-term.

In addition, research should determine the nutritional requirements of emerging citrus varieties under endemic HLB conditions while considering the management of soil health, soil organic matter and soil organisms. The interaction between nutrients in the soil and plant related to the heterogeneity of soils and the responses obtained in the HLB era warrants further investigation not only in Florida, but also in other citrus producing regions.

Finally, despite promising results in terms of vegetative growth and yields, research on Mg fertilization in HLB-affected citrus trees should consider fruit quality variables like Brix:acidity ratio and consumer preference surveys to ensure the quality of juice and fruit produced is acceptable to fruit buyers, processing industries and consumers. Because interactions among nutrients are complex, determining the optimal ratios of Mg among nutrient management programs is key to ensure balanced nutrition in HLB-affected trees.

Conclusion

Although past research conducted on the effects of Mg application in citrus was mostly focused on using dolomitic lime to raise soil pH, the extent of HLB-affected areas illustrates the need to focus future research on soil – plant – disease interactions, not only with Mg cycling but with the other nutrients as well. This is critical as Mg applications can have positive effects on vegetative growth (e.g., canopy volume) and leaf Mg concentration and either positive or negative effects on juice quality. However, adjusting the supply of a single nutrient may not be optimal, and a holistic grove management that includes a balanced nutrition seems more promising to address HLB. Adequate management of Mg and its interaction with other nutrients may help keep citrus trees in production despite HLB, as a well-designed nutritional program may allow growers to partially overcome the effects of HLB disease on citrus growth and productivity.

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