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Short Communication

Response of crop yields to magnesium fertilization: A meta-analysis in China

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Crop magnesium (Mg) deficiency is widespread in global agriculture, but limited assessment is available on how crop yield could respond to Mg fertilization at national or regional scale. This meta-analysis from 196 paired datasets evaluated the different yield responses of 49 crop species under Mg fertilization at the southern and northern region of China where 50% soils were Mg-deficient. The results showed that under Mg fertilization the crop yields were averagely increased by 19.2%, 11.3% and 16.6% in southern China, northern China and the whole country, respectively. Meanwhile, significantly greater yield increment of crop types under Mg fertilization ranked as vegetables (20.1%) ≈ fruits (19.6%) >cereals (6.5%). In conclusion, Mg fertilization is recommended to enhance yield and quality of fruit and vegetable crops in subtropical and tropical China and other similar countries.

Key words: Soil exchangeable magnesium, deficiency, yield increment, soil pH.

INTRODUCTION

Magnesium (Mg) is an essential macronutrient required for the normal growth and development of higher plants. It plays many various physiological and molecular roles in plants, such as being a component of the chlorophyll molecule, a cofactor for many enzymatic processes associated with phosphorylation, dephosphorylation, and the hydrolysis of various compounds, and a bridging element for the aggregation of ribosome subunits necessary for protein synthesis (Marschner, 2012). For example, numerous key chloroplast enzymes are strongly influenced by slight variations in Mg^{2+} levels in the cytosol and the chloroplast, indicating the significance of maintaining Mg homeostasis in plants (Shaul, 2002). However, Mg deficiencies in soil, crops and even human beings have been a widespread problem affecting crop productivity and quality (Aitken et al., 1999; Gerendas and Fuehrs, 2013) as well as the dietary Mg intake and hence the human health (White and Broadley, 2009).

Magnesium has a high hydrated radius and is less strongly adsorbed to soil colloids than by other cations. Therefore, Mg is highly prone to leaching, which is considered as the most important factor in decreasing Mg availability for roots (Hermans et al., 2004). In addition, the rate of Mg uptake can be strongly depressed by other cations, such as K^+, NH_4^+, Ca^{2+}, Mn^{2+}, H^+ and Al^{3+}, leading frequently to plant Mg deficiency (Marschner, 1995; Rengel and Robinson, 1990). Furthermore, with the introduction of high-yielding crops and the increasing use of nitrogen (N), phosphorus (P) and potassium (K) fertilizers, deficiency of Mg in light-textured soils was also increasingly observed in different parts of the world (Ding et al., 2006; Senbayram et al., 2015; Martinez et al., 2002; El-Fouly et al. 2010).

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Consequently, crops grown in Mg-deficient soils show obvious Mg deficient symposium such as chlorosis in older leaves due to the reasons of starch accumulation in the leaves, loss of plastic pigments from most plants and Mg translocated to actively growing sinks (Marschner, 2012). Generally, a moderate or serious Mg deficiency in soil could result in a reduced crop yield and quality. Therefore, an increase of crop yields after the application of Mg fertilizers such as Kieserite and Kainite has been reported round the world, although its importance has been overlooked in many decades by botanists and agriculturists who did not regard Mg deficiency in plants as a severe problem (Guo et al., 2015; Gerendas and Fuhrs, 2013). Meanwhile, limited crop types and sites have been studied for the yield response to Mg fertilization (Neuhaus et al., 2014; Orlovius and McHoul, 2015). Thus, it is hardly known how much crop yield could be increased by Mg fertilization at large spatial and temporal scales. Such information would be therefore very useful for farmers and policy makers to apply Mg fertilizer rationally and cost-effectively.

In China, more than 50% of croplands are naturally low in soil available Mg content (Bai et al., 2004). Meanwhile, Mg deficiency in crops has become an urgent concern due to the overuse of chemical NPK fertilizers, introduction of high yield varieties and depletion of soil Mg pool after long-term crop harvest and no or bare application of Mg fertilizer (Cakmak, 2015; Guo et al., 2015). According to the biogeographic cycle of Mg in soil and plants (Marshner, 2012; Senbayram et al., 2015), we assumed that crop yield response to Mg fertilization could be greater (1) in the warmer and more humid southern China where Mg deficiency is more serious than that in the colder and less humid northern China; (2) in vegetables and fruits than cereal crops because the former received more intensive chemical N and K fertilizers (Guo et al., 2015). We therefore synthesized current evidence at a nationwide scale to assess their yield response of different agricultural crops under Mg fertilization in China. By comprehensive meta-analysis from peer reviewed publications, a total of 166 literatures related to the response of crop yields to Mg fertilization in China were collected from both the Chinese database (www.cnki.com) and international database (www.webofscience.com). The synthesized results could provide spatial and temporal evidence in promoting our better understanding of Mg fertilization on crop yield increment of crops in relation to climate region, crop type and growing history. Meanwhile, the expected results may offer an effective pathway of crop Mg biofortification to improve human health related to world-wide magnesium malnutrition (Grzebisz, 2011; White and Broadley, 2009).

RESULTS AND DISCUSSION

There were 196 pair datasets from 166 peer-reviewed publications that contained yield data with and without Mg fertilization. These datasets included 49 crop types: 9 cash crops such as tobacco, sugarcane and cotton, 4 cereal crops such as rice, maize, wheat and barley, 22 vegetables such as tomato, potato, radish and pepper, 10 fruits such as citrus, banana and grape, and 4 oil and tea crops like oilseed, peanut, soybean and tea, respectively. Among these crops, tobacco and citrus were mostly reported with 34 and 13 times, respectively. This indicated that soils in the southern China where tobacco and citrus are mostly grown had lower soil exchangeable Mg due to stronger weathered process under higher temperature and rainfall conditions than these in the northern China (Barker and Pilbeam, 2007; Bai et al, 2004). During last decades, typical symptoms of Mg deficiency as leaf interveinal chlorosis have been found in field crops in China (Fig. 1), partly due to long-term unbalanced chemical fertilization in China (Bai et al., 2004; Guo et al., 2015). Similar symptoms were also increasingly reported in other regions of the world (Canizella et al., 2015; Ndabamenye et al., 2013), indicating the necessity of Mg fertilization for food production and security (Cakmak, 2015; Gerendas and Fuehrs, 2013).

Overall, we found that Mg fertilization showed positive effect on crop yields in most studies (Fig. 2). Among the 196 paired datasets under Mg fertilization, 5.6% showed a negative yield increment of the tested crops including sugarcane, peanut, tobacco, citrus, radish, banana and soybean. The reason may be that incorrect method (for example foliar application with too much high concentration of Mg fertilizer) or overuse of Mg fertilizer in soil resulted in toxic damage to root and leaf, and perhaps also induce strong antagonism with other cations like potassium and calcium (Verbruggen and Hermans, 2013). In contrast, 94.4% datasets showed increased crop yields under Mg fertilization (Fig. 2). Nearly 70% datasets fall into the range of 0 to 20% for yield increment under Mg fertilization; and around 25% datasets showed that Mg fertilization can increase crop yield by more than 20% (Fig. 2). Overall, the averaged yield increment by Mg fertilization was 16.6% ± 3.19% with 95% confidence interval (CI).These positive yield increases were derived from an improved root growth, photosynthesis and translocation of photosynthates, and enzyme activities (Dechen et al., 2015; Marschner, 2012; Shaul, 2002). Such data indicated that Mg fertilization could be an effective approach to enhance crop productivity across the whole China (Bai et al., 2004).

Meanwhile, the effect of size of Mg fertilization on crop yields significantly varied in regional scale, years and crop types (Fig. 3). In the aspect of regional scale, the datasets were 140 from southern China while 56 were from northern China. The averaged crop yield increment of Mg fertilization was 19.2% ± 4.2% in southern China, whereas 11.3% ± 3.5% in northern China (Fig. 3a). Such findings were well fitted with our expectation because soil available Mg content was lower in southern China (generally lower than 150 mg/kg) than that in northern China (generally higher than 200 mg/kg) due to poor drainage or excessive leaching, low soil pH and high

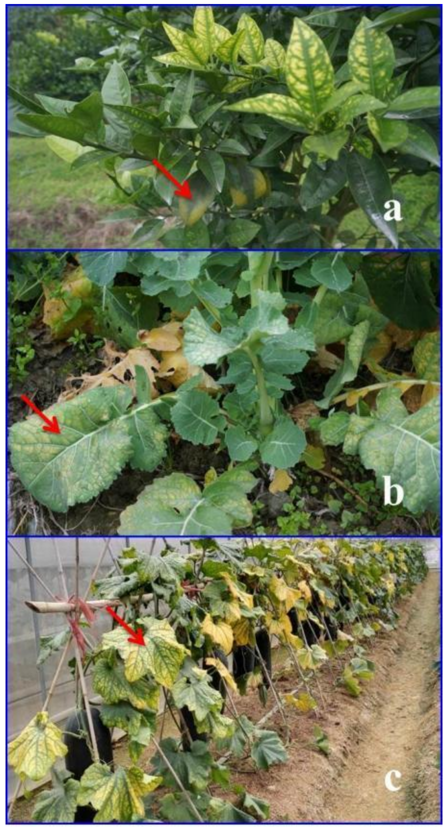

Figure 1. Symptom of Mg deficiency incitrus(a), oilseed (b), and wax gourd (c) grown in China.

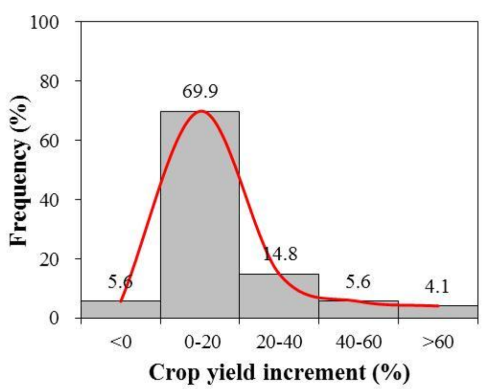

Figure 2. Frequency of crop yield increment under Mg fertilization in China.

temperature in southern China (Bai et al., 2004; Barker and Pilbeam, 2007).

The Chinese scientific community has paid more attention to Mg deficiency in crops after year 2000 (156 studies) than before 2000 (40 studies). On average, crop yield increment of Mg fertilization was 16.6% either before or after year 2000, but with a smaller 95% confidence interval for the latter years (Fig. 3b). This result indicated that Mg fertilization

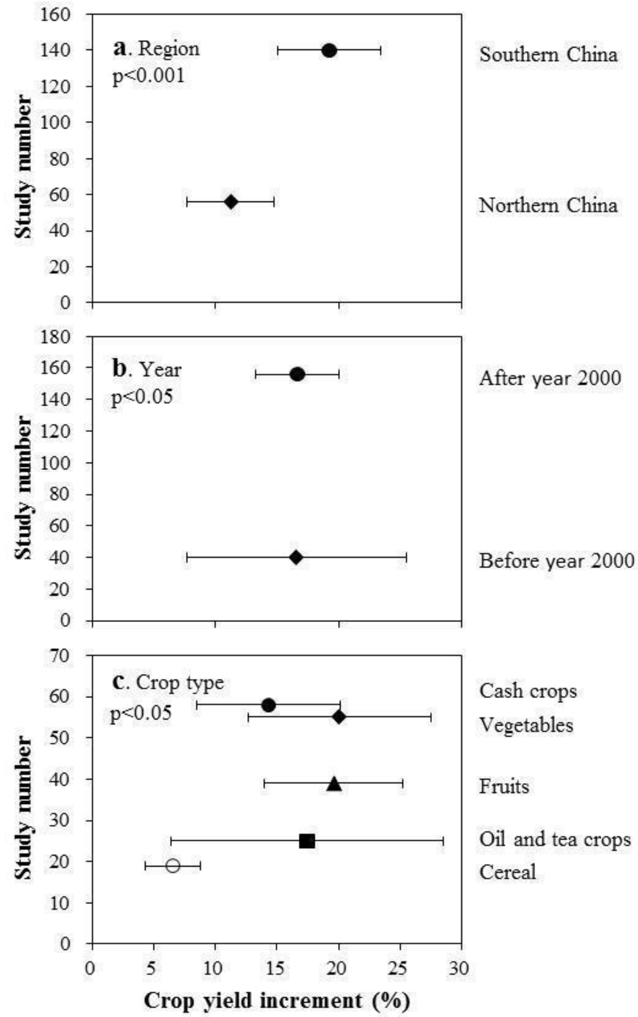

Figure 3. Variationof crop yield increment under Mg fertilization between region (a), year (b) and crop type (c) in China. Error bars represent 95% confidence intervals. Significant differences between categories are indicated by *P* values based on randomization tests.

on crop yield increment was becoming more effective and reliable in recent two decades (Guo et al., 2015). Furthermore, the effect of size of Mg fertilization on crop yield increment significantly differed among crop types (Fig. 3c). On average, crop yield increment under Mg fertilization was 6.5, 14.3, 17.4, 19.6 and 20.1% for cereals, cash crops, oil and tea crops, fruits and vegetables, respectively. Such differences were partly due to their genetic sensitivity and tolerance to Mg deficiency (Marschner, 2012; Shaul, 2002).

In addition, it's well known that sufficient K and/or Ca fertilizers have been used for high quality of products in vegetable and fruits producing systems. Thus, another reason would be that excessive K or Ca in soil might depress Mg uptake by crop root and thereafter its translocation to shoot parts (Ding et al., 2006; Tikhomirova, 2011; Barker and Pilbeam, 2007).

Finally, crop yield increment of Mg fertilization was closely related to soil properties (Fig. 4). The results showed that the crop yield increment was significantly declined from 18.6% to 8.1% with the increasing of initial soil exchangeable Mg content (Fig. 4a). This indicated that soil exchangeable Mg content is a useful index to apply Mg fertilizers (Bai et al., 2004). In addition, crop yield increment was more pronounced in soils with pH <7.0 than that with pH > 7.0 (Fig. 4b). This result is well consistent with the distribution of soil available Mg and soil pH while soil acidification is always accompanied with cation loss including Mg leaching (Gransee and Fuhrs, 2013; Tikhomirova, 2011). In contrast, soil organic matter had little effect on crop yield increment under Mg fertilization (Fig. 4c). These results indicated that a soil with lower exchangeable

Mg content (Fig. 4a) and lower pH value (Fig. 4b), rather than lower soil organic matter could respond more effectively to Mg fertilization. In addition, soils with high available K, N and Ca might also induce crop Mg deficiency because of their antagonism (Tikhomirova, 2011; Ding et al., 2006; Osemwota et al., 2007), indicating the necessity of supplying Mg fertilizer to such soils for a balanced nutrient uptake and finally a higher crop yield.

CONCLUSION

This study provided the first overall and integrated meta-analysis to address the effect of Mg fertilizers on yield increment of crops grown across China. In general, low exchangeable Mg in soil and soil acidification are two major soil factors to result in Mg deficiency in almost all major crops in China. Overall, Yield increment under Mg fertilization was more remarkable and reliable in southern China than in northern China; and yield increment of fruit and vegetable crops with Mg fertilization was more substantial than cereal crops. Fruit and vegetable crops especially grown in southern China are thus highly recommended to supply Mg fertilizers for both high yield and high quality.

More research is also guaranteed to evaluate the benefits of Mg fertilization on Mg biofortification of plant edible parts for sustaining normal human health.

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