Glyphosate Interactions with Micronutrients and Plant Diseases

Glyphosate is the most widely used pesticide in the world. As has happened with other pesticides that attained widespread use, concerns over unintended consequences resulting from its use have arisen. In addition to articles appearing in trade journals and the popular press, an entire issue of a scientific journal (Journal of European Agronomy) was devoted to this topic: *Glyphosate interactions with physiology, nutrition, and diseases of plants: Threat to agricultural sustainability?* (Yamada et al. 2009). This paper will provide an overview of the controversy regarding negative impacts of glyphosate on crop production

Interactions with micronutrients Shortly after the introduction of glyphosate resistant (GR) soybean, questions arose whether these varieties or glyphosate applications to them altered manganese (Mn) relations compared to conventional soybean varieties. It is well documented that certain cations, including Mn, can reduce the performance of glyphosate when they are present in water used as a carrier for the herbicide application. The complexes formed between glyphosate and metal cations are not absorbed as efficiently as free glyphosate, resulting in reduced weed control. Although the majority of research investigating the effect of glyphosate on mineral nutrition has focused on Mn, glyphosate would interact similarly with other metal cations (e.g. calcium, iron, magnesium).

Mn efficiency of soybeans with Roundup Ready trait Some of the first reports of Mn-related problems with GR soybean were reported by researchers at Purdue University in 2001 (Dodds et al. 2001). They found that growth of a GR variety on a Mn-limiting soil was inhibited more severely by Mn deficiency than a conventional variety. On a non-limiting soil there was little difference in growth of the two varieties. The research was repeated in 2002 using additional varieties, and some, but not all, GR varieties were found to be more sensitive to Mn-deficieny than conventional varieties (Dodds et al. 2002). Researchers at Kansas State University found similar results in that some RR varieties, but not all, were more responsive to MN than conventional soybean (Loeker et al. 2010).

Research in California found no evidence that the GR trait affected Mn relations (Rosolem et al. 2009). Research in Brazil found 1 out of 3 GR varieties had lower Mn concentrations in new leaves than the non-GR parental line, but the other two varieties did not respond differently than the parental line (Zobiole et al. 2010).

A cursory evaluation of the literature could lead to the conclusion that GR varieties are less efficient at Mn absorption/utilization than conventional varieties. However, studies that included more than one GR variety found that not all varieties show this response, thus it is likely that factors other than the GR trait are responsible for differences in Mn nutrition in those varieties that exhibited Mn deficiency.

Interactions of glyphosate and Mn within soybean
A second issue with glyphosate and Mn is related to interactions between the two compounds in the plant, rather than the characteristics of GR varieties. An injury response often seen following glyphosate application to GR soybean is chlorosis in newly emerged leaves. These symptoms are similar to those attributable to Mn deficiency, so it has been implied that glyphosate may interfere with Mn relations within the plant. Glyphosate is poorly metabolized by plants and accumulates in growing points, and can accumulate at

concentrations capable of forming complexes with Mn or other metal cations. Thus, it is theoretically possible that glyphosate could tie up Mn within plant tissue.

Zobiole et al. (2010) reported that glyphosate applications decreased Mn and other nutrient concentrations in GR varieties, providing support for the proposed negative interaction. They also reported significant reductions in shoot and root biomass due to the glyphosate applications, something that is normally not observed. However, the majority of research has not identified differences in Mn absorption, accumulation and availability between glyphosate-treated and non-treated GR soybean (Bott et al. 2008; Rosolem et al. 2009; Nelson 2009).

If glyphosate was reducing availability of Mn, it is logical that supplemental Mn could overcome the induced deficiencies. Ebelhar and Hart (2006) in Illinois were unable to prevent chlorosis associated with glyphosate by supplementing soybean with additional Mn, nor prevent yield loss associated with high glyphosate rates (2X to 4X). Rosolem et al. (2009) stated that glyphosate injury symptoms in GR soybean have been misinterpreted as Mn deficiency. While the chlorosis that appears following glyphosate application mimics Mn deficiency, the symptom has been attributed to accumulation of AMPA in new soybean leaves (Reddy et al. 2004). AMPA is the primary degradation product of glyphosate.

Interactions of glyphosate with Mn in the soil

It has been speculated that glyphosate may interfere with Mn relations by reducing its availability in the soil via chelation (complexes formed between a metal ion and an organic compound). It has also been suggested that glyphosate could reduce the availability of soluble Mn by affecting the activity of microorganisms that control the oxidation-reduction status of Mn within the soil.

Glyphosate is a strong chelater of divalent metals (Mn, Ca, Mg), thus it could temporarily tie up these nutrients. However, glyphosate would not specifically target Mn, but rather would interact with the most prevalent cations in the vicinity of the roots. In Iowa soils, the majority of glyphosate would likely interact with the highly abundant Ca and Mg rather than Mn, and also with organic matter.

Manganese is absorbed by plants in the reduced state (Mn^{2+}). High soil pH limits Mn availability due to oxidation to the Mn^{4+} state under alkaline conditions. While the specific physiological mechanisms are poorly understood, many plants are able to absorb Mn from soils with limited Mn availability. This is accomplished either via associations between the plant and Mn-reducing bacteria, or alteration of the pH of the rhizosphere via root exudates (Rengel and Marschner, 2005).

Glyphosate is similar to most herbicides in that when it enters the soil it differentially affects soil microorganisms (Kremer, 2005). Thompson and Huber (2007) reported that glyphosate application to GR soybean altered the balance of Mn reducing and oxidizing bacteria associated with soybean roots in a manner that suggested that Mn would be immobilized in the soil. However, published data documenting reduced soil availability of Mn due to the activity of glyphosate on soil microorganisms is lacking. Furthermore, there have been no documented reports of Mn crop deficiency symptoms in Iowa. Mn deficiency symptoms occur in some regions of the Cornbelt, and these areas are where interactions between glyphosate and Mn nutrition have been reported.

Interactions with plant diseases Interactions between herbicides and plant diseases are well documented, with both positive and negative responses (Altman and Campbell, 1977; Johal and Huber, 2009). Glyphosate is known to predispose many plants to pathogens due to its inhibition of the shikimic acid pathway (Holliday and Keen, 1982). Phytoalexins, which are compounds produced by plants to defend against pathogens, are products of this pathway. GR crops gain their resistance to glyphosate by insertion of a gene for an insensitive target site (EPSPS). Since glyphosate does not bind to the transgenic enzyme, the shikimic acid pathway functions normally and the effects of glyphosate on phytoalexin accumulation in plants should be minimal in GR crops.

Other mechanisms for glyphosate affecting disease development have been proposed, including increasing soil pathogen populations or immobilizing micronutrients involved in disease resistance (Johal and Huber, 2009). Glyphosate applications to GR crops alter the types and quantity of compounds released from crops roots into the rhizosphere, including the exudation of glyphosate. These changes in exudates can have a dramatic impact on the microbes found in the root zone.

An increase in colonization of GR soybean roots by *Fusarium* following treatment with glyphosate has been documented in greenhouse studies (Kremer, 2003; Sanago et al. 2000). However, based on field research it was concluded that SDS development was influenced by cultivar susceptibility independent of the GR trait or glyphosate use (Nijiti et al. 2003; Sanogo et al. 2001).

Mn plays an important role in plants' disease defense mechanisms (Thompson and Huber, 2007). It has been proposed that glyphosate interferes with absorption and utilization of Mn, thus increasing a plants susceptibility to disease. However, the majority of research has not found reductions in Mn concentrations within plants following glyphosate applications (Bott et al. 2008; Rosolem et al. 2009; Nelson 2009).

Powell and Swanton (2008) reviewed research that has evaluated interactions between glyphosate and diseases caused by *Fusarium*. Their conclusion was that field research has not documented a causative link between glyphosate and an increase in diseases caused by *Fusarium* spp. However, they also stated that it is impossible to rule out the link between the two.

Summary

Glyphosate has been described as 'The Herbicide of the Century' due to its high level of effectiveness. Three factors contribute to its efficacy: 1) interference with an important metabolic pathway; 2) highly efficient translocation within plants, and 3) slow metabolism by plants. These factors, combined with the large margin of crop safety provided by the GR trait, has resulted in unparalleled use of glyphosate in Iowa and other areas with similar cropping systems.

Much of the concern regarding glyphosate is related to its effects within the rhizosphere. The persistence of glyphosate is dependent upon soil characteristics and environmental conditions, with half-lives reported from 14.2 days (Zablotowicz et al. 2009) to 45-60 days (Feng and Thompson, 1990). It is well documented that the presence of glyphosate in soil can significantly impact microbial populations. Due to the complexity of the processes that occur within the root zone, it is impossible to completely rule out negative effects of glyphosate on mineral nutrition or disease development in GR crops. However, results from field research and our widespread experience with glyphosate on GR crops for over a decade do not indicate widespread negative impacts of glyphosate on these factors.

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