# AG CHEMICAL AND CROP NUTRIENT INTERACTIONS – CURRENT UPDATE

Don M. Huber, Emeritus Professor, Purdue University

**ABSTRACT:** Micronutrients are regulators, inhibitors and activators of physiological processes, and plants provide a primary dietary source of these elements for animals and people. Micronutrient deficiency symptoms are often indistinct ("hidden hunger") and commonly ascribed to other causes such as drought, extreme temperatures, soil pH, etc. The sporadic nature of distinct visual symptoms, except under severe deficiency conditions, has resulted in a reluctance of many producers to remediate micronutrient deficiency. Lost yield, reduced quality, and increased disease are the unfortunate consequences of untreated micronutrient deficiency. The shift to less tillage, herbicide resistant crops and extensive application of glyphosate has significantly changed nutrient availability and plant efficiency for a number of essential plant nutrients. Some of these changes are through direct toxicity of glyphosate while others are more indirect through changes in soil organisms important for nutrient access, availability, or plant uptake. Compensation for these effects on nutrition can maintain optimum crop production efficiency, maximize yield, improve disease resistance, increase nutritional value, and insure food and feed safety.

## INTRODUCTION

Thirty+ years ago, U.S. agriculture started a conversion to a monochemical herbicide program focused around glyphosate (Roundup®). The near simultaneous shift from conventional tillage to no-till or minimum tillage stimulated this conversion and the introduction of genetically modified crops tolerant to glyphosate. The introduction of genetically modified (Roundup Ready®) crops has greatly increased the volume and scope of glyphosate usage, and conversion of major segments of crop production to a monochemical herbicide strategy. Interactions of glyphosate with plant nutrition and increased disease have been previously over looked, but become more obvious each year as glyphosate residual effects become more apparent

The extensive use of glyphosate, and the rapid adoption of genetically modified glyphosate-tolerant crops such as soybean, corn, cotton, canola, sugar beets, and alfalfa; with their greatly increased application of glyphosate for simplified weed control, have intensified deficiencies of numerous essential micronutrients and some macronutrients. Additive nutrient inefficiency of the Roundup Ready® (RR) gene and glyphosate herbicide increase the need for micronutrient remediation, and established soil and tissue levels for nutrients considered sufficient for specific crop production may be inadequate indicators in a less nutrient efficient glyphosate weed management program.

Understanding glyphosate's mode of action and impact of the RR gene, indicate strategies to offset negative impacts of this monochemical system on plant nutrition and its predisposition to disease. A basic consideration in this regard should be a much more judicious use of glyphosate. This paper is an update of information on nutrient and disease interactions affected by glyphosate and the RR gene(s), and includes recently published research in the European Journal of Agronomy and other international scientific publications.

## UNDERSTANDING GLYPHOSATE

Glyphosate (N-(phosphomonomethyl)glycine) is a strong metal chelator and was first patented as such by Stauffer Chemical Co. in 1964 (U.S. Patent No. 3,160,632). Metal chelators are used extensively in agriculture to increase solubility or uptake of essential micronutrients that are essential for plant physiological processes. They are also used as herbicides and other biocides (nitrification inhibitors, fungicides, plant growth regulators, etc.) where they immobilize specific metal co-factors (Cu, Fe, Mn, Ni, Zn) essential for enzyme activity. In contrast to some compounds that chelate with a single or few metal species, glyphosate is a broadspectrum chelator with both macro and micronutrients (Ca, Mg, Cu, Fe, Mn, Ni, Zn). It is this strong, broadspectrum chelating ability that also makes glyphosate a broad-spectrum herbicide and a potent antimicrobial agent since the function of numerous essential enzymes is affected (Ganson and Jensen, 1988).

Primary emphasis in understanding glyphosate's herbicidal activity has been on inhibition of the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) at the start of the Shikimate physiological pathway for secondary metabolism. This enzyme requires reduced FMN as a co-factor (catalyst) whose reduction requires manganese (Mn). Thus, by immobilizing Mn by chelation, glyphosate denies the availability of reduced FMN for the EPSPS enzyme. It also can affect up to 25 other plant enzymes that require Mn as a co-factor and numerous other enzymes in both primary and secondary metabolism that require other metal co-factors (Co, Cu, Fe, Mg, Ni, Zn). Several of these enzymes also function with Mn in the Shikimate pathway that is responsible for plant responses to stress and defense against pathogens (amino acids, hormones, lignin, phytoalexins, flavenoids, phenols, etc.). By inhibiting enzymes in the Shikimate pathway, a plant becomes highly susceptible to various ubiquitous soilborne pathogens (*Fusarium, Pythium, Phytophthora, Rhizoctonia*, etc.). It is this pathogenic activity that actually kills the plant as "the herbicidal mode of action" (Johal and Rahe, 1984; Levesque and Rahe, 1992, Johal and Huber, 2009). <u>If glyphosate is not translocated to the roots because of stem boring insects or other disruption of the vascular system, aerial parts of the plant may be stunted, but the plant is not killed.</u>

Recognizing that glyphosate is a strong chelator to immobilize essential plant micronutrients provides an understanding for the various non-herbicidal and herbicidal effects of glyphosate. Glyphosate is a phloem-mobile, systemic chemical in plants that accumulates in meristematic tissues (root, shoot tip, reproductive, legume nodules) and is released into the rhizosphere through root exudation (from RR as well as non-RR plants) or mineralization of treated plant residues. Degradation of glyphosate in most soils is slow or non-existent since it is not 'biodegradable' and is primarily by microbial co-metabolism when it does occur. Although glyphosate can be rapidly immobilized in soil (also spray tank mixtures, and plants) through chelation with various cat-ions (Ca, Mg, Cu, Fe, Mn, Ni, Zn), it is not readily degraded and can accumulate for years (in both soils and perennial plants). Very limited degradation may be a "safety" feature with glyphosate since most degradation products are toxic to normal as well as RR plants. Phosphorus fertilizers can desorb accumulated glyphosate that is immobilized in soil to damage and reduce the physiological efficiency of subsequent crops. Some of the observed affects of glyphosate are presented in table 1.

## TABLE 1. Some things we know about glyphosate that influence plant nutrition and disease.

1. Glyphosate is a strong metal chelator (for Ca, Co, Cu, Fe, Mn, Mg, Ni, Zn) – in the spray tank, in soil and in plants.
2It is rapidly absorbed by roots, stems, and leaves, and moves systemically throughout the plant (normal and RR).
3. Accumulates in meristematic tissues (root, shoot and reproductive) of normal and RR plants.
4. Inhibits EPSPS in the Shikimate metabolic pathway and many other plant essential enzymes.
5. Increases susceptibility to drought and disease.
6. Non-specific herbicidal activity (broad-spectrum weed control).
7. Some of the applied glyphosate is exuded from roots into soil.
8. Immobilized in soil by chelating with soil cat-ions (Ca, Co, Cu, Fe, Mg, Mn, Ni, Zn).
9. Persists and accumulates in soil and plants for extended periods (years) – it is not 'biodegradable.'
10. Desorbed from soil particles by phosphorus and is available for root uptake by all plants.
11. Toxic to soil organisms facilitating nutrient access, availability, or absorption of nutrients.
12. Inhibits the uptake and translocation of Fe, Mn, and Zn at very low, non-herbicidal rates.
13. Stimulates soilborne pathogenic and other soil microbes to reduce nutrient availability.
14. Reduces secondary cell wall formation and lignin in RR and non-RR plants.
15. Inhibits nitrogen fixation by chelating Ni for ureide synthesis and is toxic to *Rhizoiaceae*.
16. Reduces physiological availability and concentration of Ca, Cu, Fe, K, Mg, Mn, and Zn in plant tissues and seed.
17. Residual soil activity can damage plants through root uptake.
18. Increases mycotoxins in stems, straw, grain, and fruit.
19. Reduces photosynthesis ($CO_2$ fixation).
20. Accumulates in food and feed products to enter the food chain as an item of food safety.

### UNDERSTANDING THE ROUNDUP READY® GENE

Plants genetically engineered for glyphosate-tolerance contain the Roundup Ready® gene(s) that provide an alternate EPSPS pathway (EPSPS-II) that is not blocked by glyphosate. The purpose of these gene inserts is to provide herbicidal selectivity so glyphosate can be applied directly to these plants rather than only for preplant applications. As an additional physiological mechanism, activity of this duplicate pathway requires energy from the plant that could be used for yield. The RR genes are 'silent' in meristematic tissues where glyphosate accumulates so that these rapidly metabolizing tissues are not provided an active alternative EPSPS pathway to counter the physiological effects of glyphosate's inhibition of EPSPS. Meristematic tissues also are areas of high physiologic activity requiring a higher availability of the essential micronutrients needed for cell division and growth that glyphosate immobilizes by chelation.

Residual glyphosate in RR plant tissues can immobilize Fe, Mn, Zn or other nutrients applied as foliar amendments for 8-35 days after it has been applied. This reduces the availability of micronutrients required for photosynthesis, disease resistance, and other critical physiological functions.The presence of the RR gene(s) reduces nutrient uptake and physiological efficiency and may account for some of the 'yield drag' reported for RR crops when compared with the 'normal' isolines from which they were derived. Reduced

physiological efficiency from the RR gene is also reflected in reduced water use efficiency (WUE) and increased drought stress (table 2).

**It should be recognized that there is nothing in the glyphosate-tolerant plant that operates on the glyphosate applied to the plant. All the technology does is insert an alternative enzyme (EPSPS-II) that is not blocked by glyphosate in mature tissue. Thus, when glyphosate enters the plant, it is not selective; it chelates with a host of elements influencing nutrient availability, disease resistance, and the plant's other physiological functions for the life of the plant or until it is exuded into soil or groundwater through the roots.**

## TABLE 2. Some things we know about the glyphosate-tolerance (RR) gene(s).

1. Provides selective herbicidal activity for glyphosate.
2. Inserts an alternative EPSPS pathway that is not sensitive to glyphosate action.
3. Reduces the plant's physiological efficiency of Fe, Mn, Ni, Zn, etc.
4. Inactive (silent) in meristematic tissues (root and shoot tips, and reproductive tissues).
5. Reduces nutrient uptake and efficiency.
6. Increases drought stress.
7. Reduces N-fixation.
8. Lowers seed nutrient content.
9. Transferred in pollen to plants and from degrading plant tissues to microbes.
10. Generally causes a yield 'drag' compared with near-isogenic normal plants from which it was derived.
11. Has greatly increased the application of glyphosate.
12. Permanent in plants once it is introduced.

### INTERACTIONS OF GLYPHOSATE WITH PLANT NUTRITION

Glyphosate can affect nutrient efficiency in the plant by chelating essential nutrient co-factors after application since there is 100 to 1000 times more 'free' glyphosate in the plant than all of the unbound cat-ions. Chelation of Mn and other micronutrients after application of glyphosate is frequently observed as a 'flashing' or yellowing that persists until the plant can 'resupply' the immobilized nutrients. The duration of 'flashing' is correlated with the availability of micronutrients in soil. Symptom remission indicates a resumption of physiological processes, but is not an indicator of plant nutrient sufficiency since micronutrient deficiencies are commonly referred to as 'hidden hunger.' As a strong nutrient chelator, glyphosate can reduce physiological efficiency by immobilizing elements required as components, co-factors or regulators of physiological functions at very low rates. Thus, plant uptake and or translocation of Fe, Mn and Zn are drastically reduced (up to 80 %) by commonly observed 'drift' rates of glyphosate (<1/40 the herbicidal rate). This is reflected in reduced physiological efficiency, lower mineral nutrient levels in vegetative and reproductive tissues, and increased susceptibility to disease. Microbial and plant production of siderophores and ferric reductase in root exudates under nutrient stress are inhibited by glyphosate to exacerbate plant nutrient stress common in low-available micronutrient soils.

Glyphosate is not readily degraded in soil and can probably accumulate for many years chelated with soil cat-ions. Degradation products of glyphosate are as damaging to RR crops as to non-RR crops. Persistence and accumulation of glyphosate in perennial plants, soil, and root meristems, can significantly reduce root growth and the development of nutrient absorptive tissue of RR as well as non-RR plants to further impair nutrient uptake and efficiency. Impaired root uptake not only reduces the availability of specific nutrients, but also affects the natural ability of plants to compensate for low levels of many other nutrients. Glyphosate also reduces nutrient uptake from soil indirectly through its toxicity to many soil microorganisms responsible for increasing the availability and access to nutrients through mineralization, reduction, symbiosis, etc.

Degradation of plant tissues through growth, necrosis, or mineralization of residues can release accumulated glyphosate from meristematic tissues in toxic concentrations to plants. The most damaging time to plant wheat in ryegrass 'burned down' by glyphosate is two weeks after glyphosate application to correspond with the release of accumulated glyphosate from decomposing meristematic tissues. This is contrasted with the need to delay seeding of winter wheat for 2-3 weeks after a regular weed burn-down' to permit time for immobilization of glyphosate from root exudates and direct application through chelation with soil cat-ions. The Roundup® label for Israel lists recommended waiting times before planting a susceptible crop on that soil.

One of the benefits of crop rotation is an increased availability of nutrients for a subsequent crop in the rotation. The high level of available Mn (130 ppm) after a normal corn crop is not observed after glyphosate-treated RR corn. The lower nutrient availability after specific RR crop sequences may need to be compensated for through micronutrient application in order to optimize yield and reduce disease in a subsequent crop.

## THE INFLUENCE OF GLYPHOSATE ON SOIL ORGANISMS IMPORTANT FOR ACCESS, MINERALIZATION, SOLUBILIZATION, AND FIXATION OF ESSENTIAL PLANT NUTRIENTS

Glyphosate is a potent microbiocide and is toxic to earthworms, mycorrhizae (P & Zn uptake), reducing microbes that convert insoluble soil oxides to plant available forms (Mn and Fe, *Pseudomonads, Bacillus,* etc.), nitrogen-fixing organisms (*Bradyrhizobium, Rhizobium*), and organisms involved in the 'natural,' biological control of soilborne diseases that reduce root uptake of nutrients. Although glyphosate contact with these organisms is limited by rapid chelation-immobilization when applied on fallow soil; glyphosate in root exudates, or from decaying weed tissues or RR plants, contacts these organisms in their most active ecological habitat throughout the rhizosphere. It is not uncommon to see Cu, Fe, Mg, Mn, Ni, and Zn deficiencies intensify and show in soils that were once considered fully sufficient for these nutrients. Increasing the supply and availability of Co, Cu, Fe, Mg, Mn, Ni, and Zn have reduced some of the deleterious effects of glyphosate on these organisms and increased crop yields.

In contrast to microbial toxicity, glyphosate in soil and root exudates stimulates oxidative soil microbes that reduce nutrient availability by decreasing their solubility for plant uptake, immobilize nutrients such as K in microbial sinks to deny availability for plants, and deny access

to soil nutrients through pathogenic activity. Plant pathogens stimulated by glyphosate (table 3) include ubiquitous bacterial and fungal root, crown, and stalk rotting fungi; vascular colonizing organisms that disrupt nutrient transport to cause wilt and die-back; and root nibblers that impair access or uptake of soil nutrients.

**TABLE 3. Some plant pathogens stimulated by glyphosate.**

| | |
|---|---|
| *Botryospheara dothidea* | *Gaeumannomyces graminis* |
| *Corynespora cassicola* | *Magnaporthe grisea* |
| *Fusarium species* | *Marasmius spp.* |
| *F. avenaceum* | *Monosporascus cannonbalus* |
| *F. graminearum* | *Myrothecium verucaria* |
| *F. oxysporum f.sp. cubense* | *Phaeomoniella chlamydospora* |
| *F. oxysporum f.sp. (canola)* | *Phytophthora spp.* |
| *F. oxysporum f.sp. glycines* | *Pythium spp.* |
| *F. oxysporum f.sp. vasinfectum* | *Rhizoctonia solani* |
| *F. solani f.sp. glycines* | *Septoria nodorum* |
| *F. solani f.sp. phaseoli* | *Thielaviopsis bassicola* |
| *F. solani f.sp. pisi* | *Xylella fastidiosa* |

*Clavibacter michiganensis* subsp. *nebraskensis* (Goss' wilt)

## HERBICIDAL MODE OF ACTION OF GLYPHOSATE

As a strong metal micronutrient chelator, glyphosate inhibits activity of EPSPS and other enzymes in the Shikimate metabolic pathway responsible for plant resistance to various pathogens. Plant death is through greatly increased plant susceptibility of non-RR plants to common soilborne fungi such as *Fusarium, Rhizoctonia, Pythium, Phytophthora*, etc. that are also stimulated by glyphosate (Johal and Rahe, 1984; Levesque and Rahe, 1992; Johal and Huber, 2009). It is very difficult to kill a plant in sterile soil by merely shutting down the Shikimate pathway (secondary metabolism) unless soilborne pathogens are also present. It is the increased susceptibility to soilborne pathogens, and increased virulence of the pathogens, that actually kills the plants after applying glyphosate. Disease resistance in plants is manifest through various active and passive physiological mechanisms requiring micronutrients. Those metabolic pathways producing secondary anti-microbial compounds (phytoalexins, flavenoids, etc.), pathogen inhibiting amino acids and peptides, hormones involved in cicatrisation (walling off pathogens), callusing, and disease escape mechanisms can all be compromised by glyphosate chelation of micronutrient co-factors critical for enzyme function. Genetic modification of plants for glyphosate tolerance partially restores Shikimate pathway function to provide a selective herbicidal effect.

## INTERACTIONS OF GLYPHOSATE WITH PLANT DISEASE

Micronutrients are the regulators, activators, and inhibitors of plant defense mechanisms that provide resistance to stress and disease. Chelation of these nutrients by glyphosate compromises plant defenses and increases pathogenesis to increase the severity of many abiotic (bark cracking, nutrient deficiencies) as well as infectious diseases of both RR and non-RR

plants in the crop production system (table 4). Many of these diseases are referred to as 'emerging' or reemerging' diseases because they rarely caused economic losses in the past, or were effectively controlled through management practices.

**Non-infectious (Abiotic) Diseases:** Research at Ohio State University has shown that bark cracking, sunscald, and winter-kill of trees and perennial ornamentals is caused by glyphosate used for under-story weed control, and that glyphosate can accumulate for 8-10 years in perennial plants. This accumulation of glyphosate can be from the inadvertent uptake of glyphosate from contact with bark (drift) or by root uptake from glyphosate in weed root exudates in soil. Severe glyphosate damage to trees adjacent to stumps of cut trees treated with glyphosate (to prevent sprouting in an effort to eradicate citrus greening or CVC) can occur through root translocation and exudation several years after tree removal.

**Infectious Diseases:** Increased severity of the take-all root and crown rot of cereals (*Gaeumannomyces graminis*) after prior glyphosate usage has been observed for over 20 years and take-all is now a 'reemerging' disease in many wheat producing areas of the world where glyphosate is used for weed control prior to cereal planting. A related disease of cereals, and the cause of rice blast (*Magnaporthe grisea*), is becoming very severe in Brazil and is especially severe when wheat follows a RR crop in the rotation. Like take-all and Fusarium root rot, this soilborne pathogen also infects wheat and barley roots, and is a concern for U.S. cereal production.

*Fusarium* species causing head scab are common root and crown rot pathogens of cereals everywhere; however, Fusarium head scab (FHB) has generally been a serious disease of wheat and barley only in warm temperate regions of the U.S. With the extensive use of glyphosate, it is now of epidemic proportions and prevalent throughout most of the cereal producing areas of North America. Canadian research has shown that the application of glyphosate one or more times *in the three years previous to planting wheat* was the most important agronomic factor associated with high FHB in wheat, with a 75 % increase in FHB for all crops and a 122 % increase for crops under minimum-till where more glyphosate is used. The most severe FHB occurs where a RR crop precedes wheat in the rotation for the same reason. Glyphosate altered plant physiology (carbon and nitrogen metabolism) increasing susceptibility of wheat and barley to FHB and increased toxin production, is also associated with a transient tolerance of wheat and soybeans to rust diseases.

The increased FHB with glyphosate results in a dramatic increase in tricothecene (deoxynivalenol, nivalenol, 'vomitoxins') and estrogenic (zaeralenone) mycotoxins in grain; however, the high concentrations of mycotoxin in grain are not always associated with *Fusarium* infection of kernels. Quite often overlooked is the increase in root and crown rot by FHB *Fusaria* with glyphosate and the production of mycotoxins in root and crown tissues with subsequent translocation to stems, chaff and grain. Caution has been expressed in using straw and chaff as bedding for pigs or roughage for cattle because of mycotoxin levels that far exceeded clinically significant levels for infertility and toxicity. This also poses a health and safety concern for grain entering the food chain for humans. The list of diseases affected by glyphosate (see reference No. 18) is increasing as growers and pathologists recognize the cause-effect relationship.

## SPECIAL NUTRIENT CONSIDERATIONS IN A GLYPHOSATE-DOMINANT WEED MANAGEMENT ECOLOGICAL SYSTEM

There are two things that should be understood in order to remediate nutrient deficiencies in a glyphosate usage program: 1) the effects of glyphosate on nutrient availability and function and 2) the effect of the RR gene on nutrient efficiency. With this understanding, there are four objectives for fertilization in a glyphosate environment – all of which indicate a more judicious use of glyphosate as part of the remediation process. These four objectives are to:

1. Provide adequate nutrient availability for full functional sufficiency to compensate for glyphosate and RR reduced availability or physiological efficiency of micronutrients (esp. Mn and Zn but also Cu, Fe, Ni).
2. Detoxify residual glyphosate in meristematic and other tissues, in root exudates, and in soil by adding appropriate elements for chelation with the residual glyphosate.
3. Restore soil microbial activity to enhance nutrient availability, supply, and balance that are inhibited by residual glyphosate in soil and glyphosate in root exudates.
4. Increase plant resistance to root infecting and reemerging diseases through physiological plant defense mechanisms dependent on the Shikimate, amino acid, and other pathways that are compromised by micronutrient inefficiency in a glyphosate environment.

**Meeting Nutrient Sufficiency:** Extensive research has shown that increased levels and availability of micronutrients such as Mn, Zn, Cu, Fe, Ni, etc can compensate for reduced nutrient efficiency and the inefficiency of RR crops. This need may not be manifest in high fertility or nutrient toxic soils for a few years after moving to a predominantly monochemical strategy. The timing for correcting micronutrient deficiencies is generally more critical for cereal plants (barley, corn, wheat) than for legumes in order to prevent irreversible yield and/or quality loss. Nutrient sufficiency levels from soil and tissue analysis that are considered adequate for non-GM crops may need to be increased for RR crops to be at full physiological sufficiency. Since residual 'free' glyphosate in RR plant tissues can immobilize most regular sources of foliar-applied micronutrients for 8-15 days, and thereby reduce the future availability of these materials, it may be best to apply some micronutrients 1-2 weeks after glyphosate is applied to RR crops.

The expense of an additional trip across the field for foliar application frequently deters micronutrient fertilization for optimum crop yield and quality. There are newly available micronutrient formulations (nutrient phosphites) that maintain plant availability without impacting herbicidal activity of the glyphosate in a tank-mix, and plants have responded well from these micronutrient-glyphosate mixes. Simultaneous application of some micronutrients with glyphosate might provide an efficient means to overcome deficiencies in low fertility soils, as well as mitigate the reduced physiological efficiency inherent with the glyphosate-tolerant gene and glyphosate immobilization of essential nutrients in the plant.

Under severe micronutrient deficiency conditions, selecting seed high in nutrient content or a micronutrient seed treatment to provide early nutrient sufficiency, establish a well-developed root system, and insure a vigorous seedling plant with increased tolerance to glyphosate applied later, has been beneficial even though excess nutrient applied at this time may be immobilized by glyphosate from root exudates and not available for subsequent plant uptake. Micronutrients such as Mn are not efficiently broadcast applied to soil for plant uptake because

of microbial immobilization to non-available oxidized Mn, but could be applied in a band or to seed or foliage.

**Detoxifying Residual Glyphosate:** Some nutrients are relatively immobile in plant tissues (Ca, Mn) so that a combination of micronutrients may be more beneficial than any individual one to chelate with residual glyphosate and 'detoxify' it in meristematic and mature tissues. Thus, foliar application of Mn could remediate for glyphosate immobilization of the nutrient; however, it may be more effective when applied in combination with the more mobile Zn to detoxify sequestered glyphosate in meristematic tissues even though Zn levels may appear sufficient. Gypsum applied in the seed row has shown some promise for detoxifying glyphosate from root exudates since Ca is a good chelator with glyphosate (one of the reasons that ammonium sulfate is recommended in spray solutions with hard water is to prevent chelation with Ca and Mg which would inhibit herbicidal activity).

Although bioremediation of accumulating glyphosate in soil may be possible in the future, initial degradation products of glyphosate are toxic to both RR and non-RR plants. This is an area that needs greater effort since the application of phosphorus fertilizers can desorb immobilized glyphosate to be toxic to plants through root uptake. Micronutrient seed treatment can provide some detoxification during seed germination, and stimulate vigor and root growth to enhance recovery from later glyphosate applications.

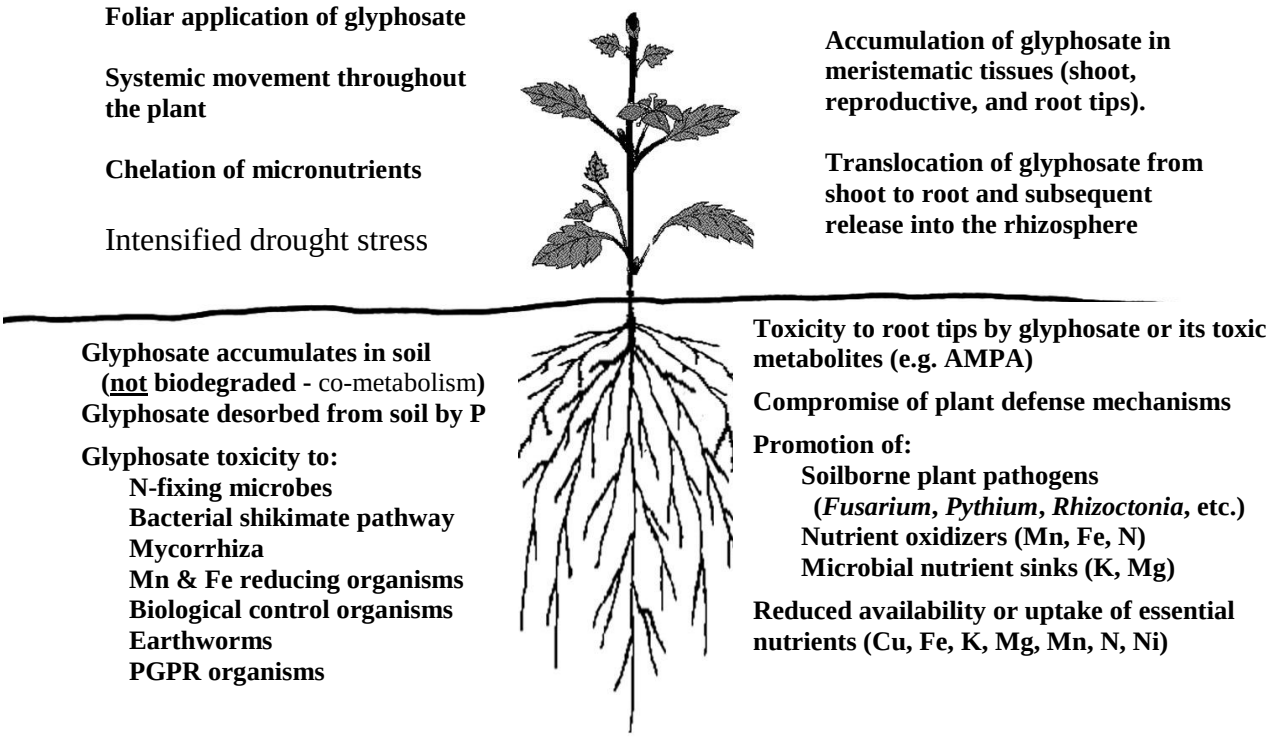
**Biological Remediation**: The selection and use of plants for glyphosate-tolerance that have greater nutrient efficiency for uptake or physiological function has improved the performance of some RR crops, and further improvements are possible in this area. Enhancing soil microbial activity to increase nutrient availability and plant uptake has been possible through seed inoculation, environmental modification to favor certain groups of organisms, and implementation of various management practices. There are many organisms that have been used to promote plant growth, with the most recognized being legume inoculants (*Rhizobia, Bradyrhizobia* species); however, glyphosate is toxic to these beneficial microorganisms. Continued use of glyphosate in a cereal-legume rotation has greatly reduced the population of these organisms in soil so that annual inoculation of legume seed is frequently recommended.

Biological remediation to compensate for glyphosate's impact on soil organisms important in nutrient cycles may be possible if the remediating organism is also glyphosate-tolerant and capable of over coming the soils natural biological buffering capacity. This would be especially important for nitrogen-fixing, mycorrhizae, and mineral reducing organisms, but will be of limited benefit unless the introduced organisms are also tolerant of glyphosate. Modification of the soil biological environment through tillage, crop sequence, or other cultural management practices might also be a viable way to stimulate the desired soil biological activity.

**Increasing Plant Resistance to Stress and Root-Infecting Pathogens:** Maintaining plant health is a basic requirement for crop yield and quality. Plant tolerance to stress and many pathogens is dependent on a full sufficiency of micronutrients to maintain physiological processes mediated through the Shikimate or other pathways that are compromised in a glyphosate environment. Sequential application(s) of specific micronutrients (esp. Ca, Cu, Fe, Mn, Zn) may be required to compensate for those nutrients physiologically lost through glyphosate chelation. Breeding for increased nutrient efficiency and disease resistance will be an important contributor to this objective.

## SUMMARY

Glyphosate is a strong, broad-spectrum nutrient chelator that inhibits plant enzymes responsible for disease resistance so that plants succumb from pathogenic attack. This also predisposes RR and non-RR plants to other pathogens. The introduction of such an intense mineral chelator as glyphosate into the food chain through accumulation in feed, forage, and food, and root exudation into ground water, could pose significant health concerns for animals and humans and needs further evaluation. Chelation immobilization of such essential elements as Ca (bone), Fe (blood), Mn, Zn (liver, kidney), Cu, Mg (brain) could directly inhibit vital functions and predispose to disease. The lower mineral nutrient content of feeds and forage from a glyphosate-intense weed management program can generally be compensated for through mineral supplementation. The various interactions of glyphosate with nutrition are represented in the following schematic:




**Schematic of glyphosate interactions in soil**

## SELECTED REFERENCES

1. Arregui, M.C., Lenardon, A., Sanchez, D., Maitre, M.I., Scotta, R., and Enrique, S. 2003. Monitoring glyphosate residues in transgenic glyphosate-resistant soybean. Pest Manag. Sci. 60:163-166.
2. Bernards, M.L. Thelen, K.D., Muthukumaran, R.J. and McCracker, J.L. 2005. Glyphosate interaction with manganese in tank mixtures and its effect on glyphosate absorption and translocation. Weed Sci. 53:787-794.

3. Bellaloui, N., Reddy, K.N., Zablotowicz, R.M., Abbas, H.K., and Abel, C.A. 2009. Effects of glyphosate application on seed iron and root ferric (III) reductase in soybean cultivars. J. Agric. Food Chem. 57:9569-9574.
4. Bott, S., Tesfamariam, T., Candan, H., Cakmak, I., Roemheld, V., and Neumann, G. 2008. Glyphosate-induced impairment of plant growth and micronutrient status in glyphosate-resistant soybean (*Glycine max* L.). Plant Soil 312:185-194.
5. Cakmak, I., Yazici, A., Tutus, Y., and Ozturk, L. 2009. Glyphosate reduced seed and leaf concentrations of calcium, magnesium, manganese, and iron in non-glyphosate resistant soybean. European J. Agron. 31:114-119.
6. Comeau, A., Pageau, D., Voldeng, H., and Brunelle, A. 2005. Micronutrients: essential for early canopy establishment in bread wheat. EECCO poster, Ottawa, Canada.
7. Datnoff, L.E., Elmer, W.H., and Huber, D.M. 2007. Mineral Nutrition and Plant Disease. APS Press, St. Paul, MN, 278 pages.
8. Duke, S.O., Rimando, A.M., Pace, P.F., Reddy, K.N., and Smeda, R.J. 2003. Isoflavone, glyphosate, and aminomethylphosphonic acid levels in seeds of glyphosate-treated, glyphosate-resistant soybean, J. Agric. Food Chem. 51:340-344.
9. Eker, S., Ozturk, L, Yazici, A., Erenoglu, B., Roemheld, V., and Cakmak, I. 2006. Foliar-applied glyphosate substantially reduced uptake and transport of iron and manganese in sunflower (*Helianthus annuus* L.) plants. J. Agric. Food Chem. 54:10019-10025.
10. Fernandez, M.R., Selles, F., Gehl, D., DePauw, R.M., and Zentner, R.P. 2005. Crop production factors associated with Fusarium head blight in spring wheat in eastern Saskatchewan. Crop Sci. 45:1908-1916.
11. Fernandez, M.R., Zentner, R.P., Basnyat, P., Gehl, D., Selles, F., and Huber, D.M. 2009. Glyphosate associations with cereal diseases caused by *Fusarium* spp. in the Canadian Prairies. European J. Agron. 31:133-143.
12. Ganson, R.J. and Jensen, R.A. 1988. The essential role of cobalt in the inhibition of the cytosolic isozyme of 3-deoxy-D-arabino-heptulosonate-7-phosphate synthase from *Nicotiana silvestris* by glyphosate. Arch Biochem. Biophys. 260:85-93.
13. Gordon, W.B. 2007. Does (the) glyphosate gene affect manganese uptake in soybeans? Fluid J. Early Spring:12-13.
14. Hernandez, A., Garcia-Plazaola, J.I., and Bacerril, J.M. 1999. Glyphosate effects on phenolic metabolism of nodulated soybean (*Glycine max* L. Merril). J. Agric. Food Chem. 47:2920-2925.
15. Huber, D.M., Leuck, J.D., Smith, W.C., and Christmas, E.P. 2004. Induced manganese deficiency in GM soybeans. North central Fert. Exten. Conf., November 2004, Des Moines, IA.
16. Huber, D.M. and Haneklaus, S. 2007. Managing nutrition to control plant disease. Landbauforschung Volkenrode 57:4:313-322.
17. Johal, G.R. and Rahe, J.E. 1984. Effect of soilborne plant-pathogenic fungi on the herbicidal action of glyphosate on bean seedlings. Phytopathology 74:950-955.
18. Johal, G.R. and Huber, D.M. 2009. Glyphosate effects on diseases of plants. European J. Agron. 31:144-152.
19. Johnson, W.G., Davis, V.M., Kruger, G.R., and Weller, S.C. 2009. Influence of glyphosate-resistant cropping systems on weed species shifts and glyphosate-resistant weed populations. European J. Agron. 31:162-172.

20. King, C.A., Purcell, L.C., and Vories, E.D. 2001. Plant growth and nitrogenase activity of glyphosate-tolerant soybean in response to foliar glyphosate applications. Agron. J. 93:79-186.
21. Kremer, R.J., Means, N.E., and Kim, S. 2005. Glyphosate affects soybean root exudation and rhizosphere microorganisms. Inter. J. Environ. Anal. Chem. 85:1165-1174.
22. Kremer, R.J. and Means, N.E. 2009. Glyphosate and glyphosate-resistant crop interactions with rhizosphere microorganisms. European J. Agron. 31:153-161.
23. Laitinen, P., Ramo, S., and Siimes, K. 2005. Glyphosate translocation from plants to soil – does this constitute a significant proportion of residues in soil? Plant Soil 300:51-60.
24. Larsen, R.L., Hill, A.L., Fenwick, A., Kniss, A.R., Hanson, L.E., and Miller, S.D. 2006. Influence of glyphosate on Rhizoctonia and Fusarium root rot in sugar beet. Pest Manag. Sci. 62:1182-1192.
25. Levesque, C.A. and Rahe, J.E. 1992. Herbicide interactions with fungal root pathogens, with special reference to glyphosate. Ann. Rev. Phytopathol. 30:579-602.
26. Nilsson, G. 1985. Interactions between glyphosate and metals essential for plant growth. In: Grossbard E. and Atkinson, D. (eds.) The Herbicide Glyphosate. Butterworth, London. Pp 35-47.
27. Ozturk, L., Yazici, A. Eker, S., Gokmen, O., Roemheld, V., and Cakmak, I. 2008. Glyphosate inhibition of ferric reductase activity in iron deficient sunflower roots. New Phytol. 177:899-906.
28. Reddy, K.N., Hoagland, R.E., and Zablotowicz, R.M. 2000). Effect of glyphosate on growth, chlorophyll, and nodulation in glyphosate-resistant and susceptible soybean (*Glycine max*) varieties. J. New Seeds 2:37-52.
29. Reddy, K.N. and Zablotowicz, R.M. 2003. Glyphosate-resistant soybean response to various salts of glyphosate and glyphosate accumulation in soybean nodules. Weed Sci. 51:496-502.
30. Reddy, K.N., Rimando, A.M., and Duke, S.O. 2004. Aminomethylphosphonic acid, a metabolite of glyphosate, causes injury in glyphosate-treated, glyphosate-resistant soybean. J. Agric. Food Chem. 52:5139-5143.
31. Reichenberger, L. 2007. Missing micronutrients: Using glyphosate is complicating the uptake of some minor nutrients. The Furrow pp. 22-23.
32. Rodrigues, J.J.V., Worsham, A.D., and Corbin, F.T. 1982. Exudation of glyphosate from wheat (*Triticum aestivum*) plants and its effects on interplanted corn (*Zea mayes*) and soybean (*Glycine max*). Weed Tech. 30:316-320.
33. Tesfamariam, T., Bott, S, Cakmak, I., Roemheld, V., and G. Neumann. 2009. Glyphosate in the rhizosphere – role of waiting times and different glyphosate binding forms in soils for phytoxicity to non-target plants. European J. Agron. 31:126-132.
34. de Vendomois, J.S., Roullier, F., Cellier, D., and Seralini, G-E. 2009. A comparison of the effects of three GM corn varieties on mammalian health. Int. J. Biol. Sci. 5:706-726.
35. Waltz, E. 2009. Battlefield; Papers suggesting that biotech crops might harm the environment attract a hail of abuse from other scientists. Nature 461/3:27-32.
36. Yamada, T., Kremer, R.J., Camargo e Castro, P.R., and Wood, B.W. 2009. Glyphosate interactions with physiology, nutrition, and diseases of plants: Threat to agricultural sustainability? European J. Agron. 31:111-113.
37. Zablotowicz, R.M. and Reddy, K.N. 2007. Nitrogenase activity, nitrogen content, and yield responses to glyphosate in glyphosate-resistant soybean. Crop Prot. 26:370-376.

38. Zobiole, L.H.S., Oliveira, R.S. Jr., Huber, D.M., Constantin, J., Castro, C., Oliveira, F.A., Oliveira, A. Jr. 2009. Glyphosate reduces shoot concentration of mineral nutrients in glyphosate-resistant soybeans. Plant Soil 321:4 (Plant Soil: doi:10.1016/0014-5793(83)80888-6).
39. Zobiole, L.H.S., Oliveira, R.S. Jr., Kremer, R.J., Constantin, J., Bonato, C.M., and Muniz, A.S. 2010. Water use efficiency and photosynthesis as affected by glyphosate application to glyphosate-resistant soybean. Pesticide Biochem. Physiol. (In Press).
40. Zobiole, L.H.S., Bonini, E.A., Oliveira, R.S. Jr., Kremer, R.J., and Ferrarese-Filho, O. 2010. Glyphosate affects lignin content and amino acid production in glyphosate-resistant soybean. Acta Physiol. Plant. (In Press).
41. Zobiole, L.H.S., Oliveira, R.S., Kremer, R.J., Constantin, J., Yamada, T., Castro, C., Oliveira, F.A., and Oliveira, A. Jr. 2010. Effect of glyphosate on symbiotic $N_2$ fixation and nickel concentration in glyphosate-resistant soybeans. Applied Soil Ecol. 44:176-180.
42. Zobiole, L.H.S., Oliveira, Jr., R.S., Kremer, R.J., Muniz, A.S., and Oliveira Jr., A. 2010. Nutrient accumulation and photosynthesis in glyphosate resistant soybeans is reduced under glyphosate use. J. Plant Nutr. (In Press).
43. Zobiole, L.H.S., Oliveira Jr., Constantin, J., R.S., Kremer, R.J., Biffe, D.F. 2010. Amino application can be an alternative to prevent glyphosate injury. J. Plant Nutr. (In Press).
44. Zobiole, L.H.S., Oliveira Jr., Visentainer, J.V., Kremer, R.J., Yamada, T., Bellaloui, N. 2010. Glyphosate affects seed composition in glyphosate-resistant soybean. J. Agric. Food chem.. (In Press).