Soil and Environmental Health after Twenty Years of Intensive Use of Glyphosate

Opinion

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Glyphosate [N (phosphonomethyl)glycine], the active ingredient of formulated herbicides including Roundup™ and others, is the most widely used herbicide compound in the world for vegetation management in agricultural, urban/suburban, aquatic, publically-held, and recreational ecosystems. The herbicide became very popular for non-selective weed management used in burndown or knockdown applications in field preparation prior to implementing conservation tillage systems, including no- or zero-tillage practices, that were initiated as alternatives to intensive tillage methods of moldboard plowing and disking in the late 1970's. As agriculture shifted toward large-scale production of commodity crops on wide expanses of land, major crops were genetically engineered (GE) to resist the herbicidal action of glyphosate so that weed management could be streamlined by using only one herbicide to control all weed species present in fields thereby simplifying production practices for large-scale crop production systems. The first GE crops with glyphosate resistance included soybean (*Glycine max* [L.] Merr.), maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and canola (*Brassica rapa* L.), which were introduced and commercially planted in the mid-1990's. Subsequently GE varieties were released for sugarbeet (*Beta vulgaris* L.) and alfalfa (*Medicago sativa* L.). Meyers et al. [1] describes the continuing increase in use of glyphosate in the United States alone, from an annual usage of 2.72 to 3.62 million kg in 1987 prior to release of GE crops, to 81.6 to 83.9 million kg in 2007 when glyphosate-resistant crops were widely planted. By 2014, annual agricultural usage of glyphosate increased to about more than 108 million kg applied to the environment. Worldwide use is estimated to be 1.35 million metric tons in 2017 [2].

Despite the increasing frequency of glyphosate herbicide use, monitoring of residues in soils and the relative effects on the environment is not consistently practiced [3]. Glyphosate may be applied one to two times during crop production at doses between 0.6 to 0.9 kg ha^{-1} in the U.S. but applications may increase annually due to development of resistance to glyphosate by weeds [3]. Because glyphosate herbicides have been consistently applied to glyphosate-resistant crops in production fields over the past 20 years, it is not surprising that glyphosate is now detected in the environment. Indeed, glyphosate and its primary metabolite aminomethylphosphonic acid (AMPA) are now frequently detected in ground and surface waters and in some marine environments [4]. Based on a limited number of studies available, glyphosate residues detected in soils of crop production fields range from 25 to 1000 μg kg^{-1} soil [5-7]. Concentrations exceeding 1000 μg kg^{-1} of soil have been detected in silt loam soils of northeast Missouri U.S.A. more than one year after the last application (Kremer, unpublished data). As frequency of glyphosate application increases during the crop season and with annual use, residual concentration likely builds up and persists in soils because about 5% of the applied dose reaches the target weed while the remaining amount contacts the soil surface or is released by roots of plants intercepting the glyphosate, and from vegetative residues treated plants during decomposition [6-9].

The revelation of potential widespread soil persistence contradicts the assumed rapid immobilization, degradation, and sorption of glyphosate in soils, raising concerns about non-target effects on the environment. However considerable research over the past ten years has shown that characteristics in diverse soils combined with various crop management practices influence the activity of glyphosate and demonstrate that its association with soil colloids, organic matter and water may have potential adverse effects on plant nutrient availability, phytotoxicity to non-GE crops, and soil microbial diversity and function. The interacting factors that affect the potential activity of glyphosate likely differ depending on the particular soil and suggest that activity of this compound must be considered within the framework of a specific soil and the imposed management rather than relying on broad generalizations. The primary factors that influence glyphosate activity in the environment include: soil pH, soil mineralogy, soil texture, soil organic matter content and composition, soil phosphorus content, cation nutrient content and availability, soil oxygen status and compaction, soil microbial structural and functional diversity, and presence of herbicide formulation ingredients. Based on rigorous evaluations on fates of suspected glyphosate persisting in soils of glyphosate-resistant crop production fields, a body of research reported in peer-reviewed scientific journals reveals numerous potential adverse effects on environmental biological organisms and functions. Effects of glyphosate are briefly summarized as the following: altered respiration in some eukaryotic organisms due to disruption of cytochrome function within the electron transport system; immobilization of nutrients essential for metabolic processes in microorganisms and plants; disruption of microbial diversity in plant rhizospheres; increase in potential root phytopathogens and suppression of beneficial antagonistic bacteria; inhibition of mycorrhizal spore germination leading to poor host plant infection and establishment of the symbiosis; reduced infection of legume roots by rhizobia leading to reduced nodulation required for symbiotic nitrogen fixation; disruption of earthworm activity; and reduction in growth and reproduction of numerous aquatic organisms including *Daphnia* spp. [10] as well as sediment-inhabiting organisms [11].

Most adverse effects have been reported at mg kg^{-1} concentrations although some studies report effects on specific environmental organism structure and diversity at glyphosate concentrations in the range of 10 µg kg^{-1}. However, because glyphosate tends to persist within the upper few mm of the soil profile [12] or concentrated within the root zone of plants exposed to the herbicide to over 4000 µg kg^{-1} soil [7], glyphosate concentrations are considerably higher in these restricted soil microhabitats and may not only pose contamination risks due to surface erosion and leaching [7] but also significantly affect soil microbial processes. Furthermore, adverse effects of adjuvants and other glyphosate herbicide formulation components may increase toxicological consequences. Concern about the considerable amounts of glyphosate and AMPA present in soil following many years of glyphosate-resistant GE crop production has prompted some action to determine whether negative effects on production of non-GE crops might result. This was addressed in a recent study under controlled conditions that found that the minimum concentrations causing phytotoxicity on the most sensitive plant species were 80 mg kg-1 and 40 mg kg-1 for glyphosate and AMPA, respectively [13]. Even though it was concluded that the likelihood of injury of the test plants from glyphosate or AMPA residues was low, increased monitoring for these residues in cropping systems where glyphosate is used frequently and at high doses is merited [13].

Although glyphosate use has increased nearly 15-fold since 1996 [14] when glyphosate-resistant GE crops were first introduced, it is only within the last 5 to 10 years that assessment of its detrimental effects on soil and environmental health have become the focus of intensive research efforts. Recent findings that glyphosate tends to accumulate and persist in restricted zones of soils and sediments and in rhizospheres [5-7,11,12] emphasizes the need to evaluate environmental effects within these specific microhabitats relative to more traditional investigations of such chemicals amended in “bulk” or root-free homogenous soils and expressing concentrations on a “furrow-slice” basis (i.e., using 908,000 kg of soil per ha). For a full understanding of effects of potential glyphosate accumulation in soils, long-term studies on persistence are needed on sites receiving annual application and on those that are no longer under GE cropping systems to determine the extent of any carryover of residual glyphosate and AMPA. Because soils are diverse within landscapes and among geographic regions, glyphosate fates and effects need to be studied over a range of characteristics to validate assumptions that glyphosate and AMPA are highly retained in fine textured soils and are more biologically available in coarse or sandy soils. Finally, as known for soil health assessment, management imposed on agroecosystems is a major factor affecting the manner in which soil properties behave and influence amendments such as pesticides. Therefore it is imperative that long-term studies of glyphosate include agricultural management variations. For example, soils receiving excessive phosphorus fertilizers are likely to exhibit higher unbound and active glyphosate concentrations compared to soils low in phosphorus. An overall better understanding of such factors is essential in improving more sustainable weed management. Rotations to non-GE crops and to non-glyphosate herbicides as well as including cover crops in the crop production system may likely overcome long-term adverse effects of glyphosate and AMPA residues. Implementation of such practices can restore soil microbial diversity that may not only enhance potential degradation of glyphosate and AMPA residues but also restore microbial community balance required for optimum nutrient cycling, pathogen suppression, plant growth promotion, and increased soil and environmental health.

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