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Bob Hartzler
Iowa State University, hartzler@iastate.edu

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A reintroduction to soil applied herbicides

Bob Hartzler, professor and Extension weed specialist, Agronomy, Iowa State University

Although the growth regulator herbicides (2,4-D; dicamba, etc.) were responsible for ushering in the chemical era of weed control in the late 1940's, it was the introduction of the triazine, dinitroaniline and amide herbicides that transformed weed control in corn and soybean. These products were the backbone of weed control systems until the mid-80's when the introduction of ALS inhibitors and other postemergence products provided more consistent postemergence weed control. The introduction of glyphosate resistant crops in the late 1990's completed the transition from soil-applied to postemergence programs for the majority of Cornbelt farmers. The heavy reliance on glyphosate for over a decade has created a situation where soil-applied products will once again be an essential component of weed management systems due to herbicide resistance. This paper will discuss factors that influence the performance of soil-applied products for those who have little experience with these products, or simply need a refresher.

Preemergence herbicides are most effective when they are absorbed by weed seeds initiating the germination process; however, only a small portion of the applied herbicide actually is taken up by the intended target. The majority of herbicide degrades within the field, but a portion of the herbicide may be lost from the field due to leaching, runoff, or volatilization. The ultimate fate of an herbicide is largely dictated by adsorption of the herbicide molecules to soil colloids.

Herbicide adsorption to soil colloids

There are two pools of herbicides present in the soil: the larger pool is the herbicide bound to soil colloids, the smaller pool is the herbicide that is dissolved in the soil water. An equilibrium (the percentage of herbicide present in each pool) is maintained between these two pools, thus herbicide molecules are able to move back and forth (sorption:desorption) between the two pools as herbicide is lost from one of the pools. The equilibrium is determined primarily by the adsorptive capacity of the soil and the chemical characteristics of the herbicide. Since only the herbicide in the soil solution is available to plants, a basic knowledge of herbicide adsorption is essential to understand the behavior and performance of preemergence herbicides. Although adsorption places the majority of herbicide into a 'bank' where it cannot be immediately absorbed by weeds, it is critical since it maintains the majority of herbicide near the soil surface where weed seeds germinate, and adsorption protects groundwater from herbicide leaching through the profile.

Soil factors influencing adsorption

The adsorptive capacity of a soil is determined by its clay and organic matter content. For most Iowa soils, organic matter is responsible for the majority of herbicide binding. It is important to distinguish between the different types of soil organic matter found in soil. Herbicides bind to the highly degraded, stable forms of organic matter referred to as humic matter or humic acids. The humic acid content of a soil is usually closely related to the organic matter content. Crop residue present on the soil surface in conservation tillage systems or mixed within the soil profile by tillage is not involved in the binding of soil-applied herbicides.

Herbicide rates found on the product label take into account herbicide adsorption and are designed to insure that sufficient herbicide is present in the soil solution to control susceptible weeds. Rates of soil applied herbicides generally increase as clay and organic matter increase. For example, the recommended rate for Dual II Magnum increases approximately 10% for each 1% increase in soil organic matter. Many herbicide labels prohibit use on high organic matter soils, such as peats, due to inactivation of herbicide by excessive binding of the herbicide to the soil. Herbicides with a low margin of crop safety often prohibit use on soils with low adsorptive capacity due to the potential for crop injury due to high availability of the herbicide within the soil.

Soil pH influences binding of herbicides that are classified as basic chemical compounds (versus acidic or non-ionic compounds). These molecules have a neutral or positive charge depending on the soil pH. In neutral or basic soils ($pH \geq 7$) a basic herbicide will have a neutral charge, whereas under acidic soil conditions ($pH < 7$) the herbicide takes on a positive charge. Due to the positive charge on the molecule in acid soils, basic herbicides are more tightly bound to soil colloids in soils with a low pH. The triazine herbicides are the primary examples of herbicides with a basic nature. The metribuzin label warns that use of the product on soils with pH of 7.5 or higher may result in crop injury. The increased risk of injury in alkaline soils is due to the greater amount of herbicide in soil solution.

Herbicide factors influencing adsorption

The degree of soil adsorption of a herbicide is determined by its chemical characteristics. The sorption coefficient (K) is a measure of the tendency for an herbicide to be adsorbed by the soil. It is usually expressed either as K_d or K_{oc}. The K value for an herbicide will vary among soils due to the different binding capacity of soils. The K_{oc} is adjusted for the organic matter content of a soil, whereas the K_d takes into account binding to clay and organic matter. The K values determined on different soils or under different laboratory conditions will vary somewhat, but they are still very useful in predicting herbicide behavior.

A simple description of the K value is that it is a ratio of the herbicide bound to soil colloids to the herbicide present in the soil solution.

$$K = \frac{\text{Herbicide (soil)}}{\text{Herbicide (water)}}$$

Thus an herbicide that has a high K value will have a high percentage of the herbicide bound to soil colloids, and thus less is dissolved in the soil solution where it would be available for absorption by plants. Herbicides with low K values have more of the herbicide in the soil solution, thus have greater availability to plants and are more mobile in the soil profile.

A second parameter that can influence herbicide behavior is an herbicide's water solubility; however, water solubility usually is relatively insignificant compared to the sorption coefficient. Initially this may not seem logical since the fraction of herbicide dissolved in soil water is responsible for herbicide activity. Consider that most herbicides are applied at a pound or less per acre and that an acre inch of water weighs approximately 220,000 lbs. For most herbicides, water solubility is not a limiting factor due to the large volume of water present in the soil compared to the low rate that herbicides are applied.

The sorption coefficient helps explain the performance of herbicides applied to the soil (Table 2). Both glyphosate and paraquat have very high K values compared to other herbicides. Neither product has significant soil activity since they are bound so tightly to soil colloids that they are unavailable to plants. The labels of both products state that the use of water containing soil sediments as a carrier will reduce performance due to inactivation of the herbicide by binding to the colloids.

Pendimethalin has a high K_{oc} compared to other preemergence herbicides, which explains why it requires more rainfall to provide consistent control than herbicides with lower sorption coefficients. Dicamba has one of the lowest sorption coefficients of commonly used herbicides. Although dicamba is registered for preemergence use in corn, applications made prior to germination of the corn seed have a relatively high risk of crop injury due to dicamba's mobility in the soil. Applications made before or shortly after corn planting may allow dicamba to reach the depth of the corn seed and be absorbed as the seed imbibes water and result in damage to the seedling.

Table 2. Chemical properties of several herbicides.

Common name	Tradename	K_{oc}	H_2O Solubility (ppm)
acetochlor	Harness	156	282
atrazine	Aatrex	100	35
dicamba	Banvel/Clarity	2	250,000
glyphosate	Roundup	24,000	10,500
mesotrione	Callisto	122	160
metolachlor	Dual	200	530
paraquat	Gramoxone	1,000,000	620,000
pendimethalin	Prowl	17581	0.33

Source: WSSA Herbicide Handbook; IUPAC Pesticide Properties Database

Environmental factors influencing adsorption Since adsorption is a physical process, temperatures within the range experienced in the field have little impact on binding of herbicides to soil colloids. Rainfall impacts herbicide performance by facilitating movement in the soil profile (leaching) and by influencing soil moisture content. As soil moisture decreases the film of water surrounding soil particles becomes thinner, resulting in less volume to dissolve herbicide molecules and greater adsorption to soil colloids. Preemergence herbicides are less active during periods when soil moisture is limiting.

Absorption by plants

To be effective, preemergence herbicides must be present in the soil solution surrounding weed seeds as the seed initiates germination. Thus, an herbicide must be positioned within the soil profile at the depth of weed establishment. Since most weeds have small seeds, the majority of seeds germinate in the upper inch of the soil profile. The term activation is commonly used to describe movement of a soil-applied herbicide from the soil surface into the soil profile. For most situations, a half inch rain is sufficient to move the chemical to the soil depth required for effective weed control. However, the rainfall required for activation will increase slightly with increasing adsorptive capacity of the soil and sorption coefficient of the herbicide. In addition, more rainfall will be needed in situations where an herbicide is applied to a very dry soil. With the exception of the dinitroaniline herbicides (pendimethalin, trifluralin), differences in the sorption coefficient (K) of commonly used preemergence herbicides are not sufficient to result in significant differences in the amount of rain required for activation.

Herbicide absorption from the soil is a passive process. The initial step in seed germination is imbibition of water from the soil. Herbicide molecules present in the soil solution are carried into the seed with the water. Since weeds are most vulnerable to preemergence herbicides just as they initiate germination, having the herbicide present in the germination zone at this time is critical. Herbicide applications made at planting generally are dependent upon rainfall within three to five days to ensure effective control of weeds that germinate shortly after planting and herbicide application.

A few preemergence herbicides can be absorbed by roots of emerged seedlings and provide control of established plants. This phenomenon typically occurs when weeds are able to establish due to dry conditions that minimize herbicide availability. Rain shortly after the weeds emerge releases herbicide bound to soil colloids into the soil solution, allowing absorption of the herbicide by the established weeds. It takes higher concentrations of herbicides to kill established weeds than a germinating seed, thus chemicals with low K values and the ability to translocate within the plant are more likely to kill established seedlings than herbicides without these characteristics. The bleaching herbicides (HPPD inhibitors) are promoted for their ability to control established plants through 'recharge', whereas amide type and dinitroaniline herbicides have little effect on emerged weeds. While the ability to control emerged weeds can on occasion improve weed control, this type of activity is much less consistent than an herbicide acting on a germinating seeds. Thus fields with escaped weeds should be monitored closely to determine the need for remedial control measures.

Herbicide degradation The persistence of an herbicide is typically described in terms of half-life ($t_{1/2}$), the time required for 50% of the herbicide present in the soil to break down. Herbicides begin to degrade as soon as they are introduced in the environment, but the rate of breakdown varies widely among chemicals and environmental conditions (Figure 1). In this example, the half-life for the chemicalwas 5 weeks under favorable conditions, but increased to 9 weeks under unfavorable conditions. The primary factors that influence degradation rate are soil characteristics, temperature and rainfall. Herbicides may be broken down by chemical or biological mechanisms, or both. Biological degradation is more responsive to environmental factors than chemical processes. The range of soil temperatures encountered during the growing season typically do not have a major influence on degradation rates, but extended dry periods can result in prolonged persistence of a herbicide.

Ideally a preemergence chemical could be applied in early spring and would control weeds until the crop canopy closes. After that it would dissipate quickly so that it would not interfere with future cropping plans or move into water resources or other areas where it is not wanted. Unfortunately, the dynamics of herbicide degradation and environmental variability prevent such a simple solution to weed management. The initial rate of degradation in spring is relatively rapid compared to degradation rates later in the season. This is due to a combination of greater initial herbicide availability and more favorable conditions for biological degradation in the spring (temperature, moisture) than occurs later in the season. Since herbicide degradation rates slow as the season progresses, a product that persists long enough to provide full-season weed control may pose a threat to susceptible rotational crops the following growing season.

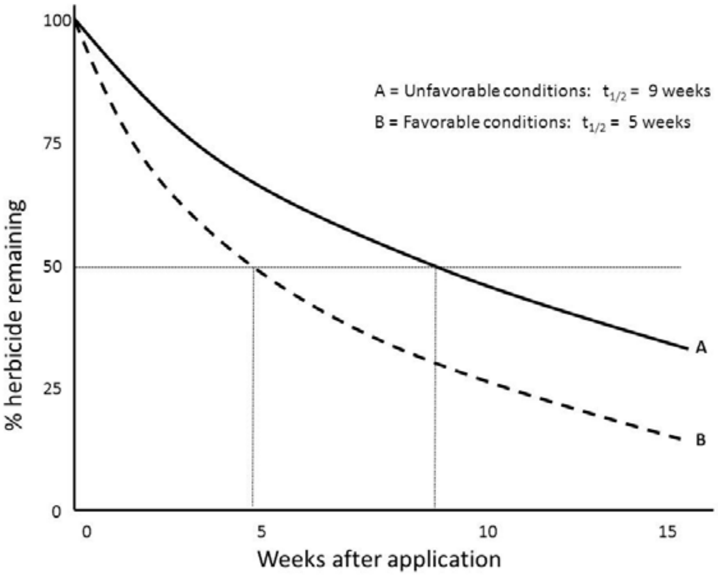

Figure 1.

Soil pH influences degradation rates of several herbicides that are used in Iowa corn and soybean production. The persistance of atrazine and chlorimuron increases with soil pH, and this limits their use in areas of the state with alkaline soils due to carryover risks to rotational crops. Atrazine degrades more rapidly when bound to soil colloids, thus the greater availability of atrazine in high pH soils increases the half-life of the chemical. Chlorimuron and other sulfonylurea herbicides are degraded by both chemical and biological processes in acidic or neutral soils, with chemical hydrolysis being the most important mechanism. In alkaline soils, only biological degradation is involved and the persistence is greatly increased.

Like atrazine, mesotrione binds to soil colloids less under alkaline conditions; however, mesotrione breaks down more rapidly when in solution than when bound to colloids. Thus, mesotrione is more persistent under alkaline conditions. The imidazolinone herbicides (Pursuit, Scepter) also have increased persistence in acid soils.

Application timing impacts on herbicide performance

Preemergence herbicides can be applied over an extended period of time, from fall applications made more than six months prior to crop planting, until after the crop has emerged. The primary influence of application timing is in determining the time period when the herbicide will be present at effective concentrations in the soil. Application timing also influences the probability of the herbicide being activated by rainfall before weeds become established.

Several preemergence herbicides are registered for fall applications. Fall applications are most appropriate for controlling winter annual weeds such as marestail/horseweed, field pennycress and henbit in no-till fields. Fall applications can also control early-emerging summer annuals; however, degradation of the product between application and establishment of the crop significantly reduces the length of in-season weed control. The only advantage of fall applications for in-season weed control is eliminating a field operation in the spring, thus the benefit of this strategy should be carefully evaluated. The potential success of this approach increases as one moves north in the state due to the longer winter which reduces the time the herbicide is vulnerable to degradation.

Early preplant applications (EPP) are made several weeks ahead of planting. This strategy increases the probability that the herbicide will be moved into the soil profile by rainfall before annual weeds begin to germinate compared to at planting applications. EPP generally require higher use rates than applications made at planting to provide equivalent periods of weed control. The difference in length of control between EPP and at planting applications is magnified when planting is delayed due to wet springs. A factor to consider with EPP treatments is the impact of final seedbed preparation and planting operations on the distribution of the herbicide within the soil profile. In systems where tillage is used to prepare the seedbed after the EPP has been made, improper tillage can either leave a streaky pattern of herbicide across the field or place the herbicide too deep within the profile, effectively diluting the chemical to non-effective concentrations. Planters that move significant amounts of soil from the row can displace the herbicide, leaving an unprotected strip within the row for weeds to establish.

Preemergence applications made within a few days of planting provide the greatest likelihood of full-season weed control since the herbicide is placed in the field when it is needed. It is important to provide the crop with an even start with weeds, so any emerged weeds present at planting should be killed as close to planting as possible. The primary disadvantage of at planting applications is the need for timely rainfall to activate the herbicide. Assuming soils have reached temperatures favorable for germination at planting, failure to receive activating rainfall within three to five days of application may allow early germinating weeds to escape control. In no-till where burndown herbicides are used to kill established weeds rather than tillage, the window for rainfall is narrower due to the lack of soil disturbance to kill weeds that have initiated germination but have yet to emerge. Fields should be monitored closely when limited rainfall following application increases the likelihood of escapes. Rotary hoeing can be effective at reducing control failures due to lack of timely rain, but this tillage operation needs to be completed before weeds have emerged to be most effective.

Many preemergence herbicides allow application after the crop has emerged, but some products prohibit this use due to foliar activity that can result in crop injury. Preemergence herbicides applied after planting extend the period of weed control later into the growing season than applications made earlier in the season. This extended control can be valuable for weeds with prolonged emergence periods such as waterhemp. Since these applications are often made during peak weed emergence periods, lack of activating rain soon after application can result in inconsistent performance.

Crop injury

In the era of Roundup Ready crops, farmers have become accustomed to herbicides that have a large margin of crop safety. Although most preemergence herbicides used today have less risk of significant injury than some that were used in the past, there is the potential for adverse crop response with many products. The factors that influence this risk are: 1) crop tolerance to the herbicide, 2) soil characteristics, and 3) environmental conditions.

Each herbicide has a specific margin of safety on an individual crop, and ratings of crop tolerance to herbicides are provided by most land grant universities. Certain herbicide formulations include a safener that enhances tolerance. 'Safened' products include Dual II Magnum, Harness, Balance Flexx, etc. There can be varietal differences within a crop, but these differences are usually relatively small compared to the other factors that determine crop response.

The adsorptive capacity of a soil often influences crop response due to increased availability of the herbicide in soils with a low affinity for herbicides. Some products recommend not using the product on soils with low adsorptive capacity due to injury risk. The rate structure specified on herbicide labels is designed to avoid overwhelming the crops tolerance mechanisms, but variability of soil types within a field often makes it difficult to adjust rates accurately according to soil type.

Environmental conditions influence both the availability of the herbicide and a crop's tolerance mechanisms. Excess soil moisture increases the availability of the herbicide by increasing the amount of herbicide in soil solution. Herbicide selectivity normally is achieved by differential metabolism: the crop is able to metabolize the herbicide more rapidly than weeds, thus the weed dies due to toxic concentrations accumulating within the plant, whereas the crop detoxifies the herbicide before it is harmed by the herbicide. When a crop is under stress due to weather, disease, exposure to other chemicals, or other factors its ability to metabolize the herbicide may be compromised. A reduced rate of metabolism can allow the herbicide to reach toxic concentrations within the plant.

Determining the impact of injury on yield potential is difficult. Since preemergence herbicides cause injury early in the season, plants often have time to recover from the setback and yields will not be reduced unless significant stand loss occurs.

Summary

Preemergence herbicides will play an increasingly important role in weed management due to the evolution of glyphosate resistant weeds, either to reduce the risk of these weeds invading fields or to manage resistant populations. The keys to successful preemergence weed control are: 1) select a product that is effective against the weeds present in the field, 2) select a rate that is appropriate for the target weeds and soil properties of the field, and 3) apply the herbicide uniformly across the field and at an appropriate time. The availability of the herbicide within the soil profile determines the effectiveness of weed control and the risk of crop injury. Thus, knowing the soil characteristics of the field and the adsorptive characteristics of the herbicide is critical in diagnosing problems with performance of soil-applied herbicides.