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Herbicides

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A minimum data set for tracking changes in pesticide use

2

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Chapter outline

A frequently asked but deceptively simple question often arises about pesticide use on a given farm or crop: Is pesticide use going up, down, or staying about the same?

Where substantial changes in pesticide use are occurring, it is also important to understand the factors driving change. These might include more or fewer hectares planted, a change in the crop mix, a higher or lower percentage of hectares treated, or higher or lower rates of application and/or number of applications. Or, it might arise from a shift to other pesticides applied at a higher or lower rate and/or lessened or greater reliance on nonpesticidal strategies and integrated pest management (IPM).

Questions about whether pesticide use is changing and why arise for a variety of reasons. Rising use typically increases farmer costs and cuts into profit margins. It generally raises the risk of adverse environmental and/or public health outcomes. It can accelerate the emergence and spread of organisms resistant to applied pesticides. If the need to spray more continues year after year for long enough, farming systems become unsustainable.

Lessened reliance on and use of pesticides, on the other hand, are typically brought about and can only be sustained by incrementally more effective prevention-based biointensive IPM systems (bioIPM).[1–3] Fewer pesticide applications and fewer pounds/kilograms of active ingredient applied reduce the impacts on nontarget organisms and provide space for beneficial organisms and biodiversity to flourish. Such

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systems reduce the odds of significant crop loss in years when conditions undermine the efficacy of control measures, leading to spikes in pest populations and the risk of economically meaningful loss of crop yield and/or quality.

Introduction

There are many ways to track changes in pesticide use:

- Pounds/kilograms of active ingredient applied per unit area.
- Number of applications made on a given acre/hectare in a crop year.
- Rate of application of a pesticide on a given crop.
- Number of different active ingredients required to control target pests and bring a crop to harvest.
- Expenditures on pesticide products and their application.

Tracking changes in pesticide use requires multiple metrics because no single metric will provide a reliable lens through which to evaluate pesticide use. For this reason, a Minimum Data Set (MDS) approach is recommended to answer questions dependent on an empirical accounting of pesticide use.

The metrics in an MDS will vary as a function of why pesticide use is of interest. Use trends have real-world consequences in three important ways. The first is in determining whether pest management systems are stable, improving, or in decline relative to the efficacy of control. Second, in the world of risk assessment, use is an essential variable in tracking actual and potential adverse effects on public health or the environment. Third, changes in pesticide use are key factors when identifying pest-management-system efficacy and effects on farm-level productivity and profitability, and hence economic sustainability and food security.

Tools and metrics are available to analyze each of the above real-world impacts, but with highly variable—and generally modest—precision.

To determine whether pest management systems are stable, it is not enough to just track changes in pounds/kilograms applied or the number of treatments made on a given field. This is because pesticides vary greatly in two ways that directly affect measures of use and efficacy: (1) rates of application, and (2) breadth of control, duration of control, and degree of control achieved by a given spray application.

One example: To replace a soil fumigant applied at 100 kg/hectare that controls several soil-borne insects and pathogens and some weeds, farmers sticking with a predominantly pesticide-based system may need to apply a dozen other pesticides at rates between 0.1 and 1.5 kg/hectare. Some products may need to be applied multiple times. Still, metrics based on kilograms applied will show a large reduction in use from 100 kg to fewer than 5. Does that mean the farmer has reduced reliance on pesticides? Not necessarily.

To accurately determine whether a change in a pest management system shifts reliance from pesticides to other control measures, it is necessary to quantify and then track three dimensions of pesticide efficacy: (1) how many target pests will a given application affect, (2) how long will susceptible target pests be controlled, and (3) the degree and reliability of control. Such efficacy-focused evaluations are available to one degree or another for many crop-pest-geographic regions but they vary significantly, even from farm to farm, as a function of many factors (e.g., soil type and health, irrigation methods, cropping patterns/rotations, cultural practices, plant genetics). While analytically challenging, each farmer's best guess at answers to these questions plays an important role in driving the selection of which pesticides they apply, when, and how.

Another key factor at the farm level is the cost of pesticide products plus their application. To the degree possible, farmers weigh efficacy versus cost when deciding which pesticides to use. Heavy weight tends to be placed on each farmer's recent, personal experience with how well the pesticides they applied last year worked. In cases where adequate control has been achieved in recent years at acceptable and/or comparable costs to known alternatives, farmers are generally reluctant to try something new, especially if alternatives are unproven in the area and/or more costly.

But if farmers are concerned about slipping efficacy, perhaps driven by the emergence and spread of resistant organisms or a new pest taking hold, they are more open to incorporating new pesticides into their control strategies. Then, tradeoffs between expected efficacy and cost must be evaluated to the extent possible and decisions made. In working through such decisions, farmers always must contend with some degree of uncertainty on the efficacy side, coupled with generally hard numbers on the cost side.

From the farmer's perspective—and society's—the most important metric is whether, year to year, a farmer needs more, less, or about the same pesticide-delivered "control power" to bring a crop to harvest. Control power encompasses the impacts of pesticides on target pests, whether through "kill" power (acute toxicity), effects on reproduction (insect pheromones, herbicide plant growth regulators targeting flowering or reproduction), metabolic disruption (through altering energy metabolism or blocking enzyme-controlled metabolic pathways), physical barriers (applying horticultural oils to protect fresh fruit from viral and bacterial pathogens), or biological controls (microbial biocontrol agents).

While a wide range of factors contribute to control power, tracking changes over time is reasonably straightforward and generally entails taking into account the efficacy of pesticide products in just a few families of chemistry. In many cases, at least qualitatively, the differences in efficacy across pesticide alternatives are known and widely accepted. For example, the spread of target pests newly resistant to a previously applied product is typically tracked and known, and can reduce the control power of pesticides. Shifts in the complex of pests in a given area and cropping system are often driven by pesticide control power, whereby populations of well-controlled pests decline over time and other, less susceptible pests fill ecological voids.

Pest management challenges become more difficult for farmers and their advisors as a function of the scope and scale of change needed or desired in relative reliance on pesticides for control versus nonchemical preventive practices. The challenges are more complex in areas where high-value fruits and vegetables are being grown in hot, humid, and wet areas where multiple weeds, insects, and plant pathogens can cause major crop damage within days, leading to sizable economic loss.

Evaluating the environmental and public health effects of pesticide use patterns entails another set of analytical challenges that often are well beyond the reach of current science. The serious, generally well-funded efforts over the last 20 years to sort out the effects of neonicotinoid insecticides on pollinators, or glyphosate-based herbicides (GBHs, including Roundup) on weed management and cancer rates, are contemporary examples.[4–8] But all assessments of the environmental and public health risks stemming from pesticide use must begin with accurate data on the extent of use of any pesticide or family of chemistry.

Data on the extent of use in a region over a defined period have a major and direct role in identifying levels of exposure as well as who or what organisms are exposed, in which environments, and at what life stages. Only then can the tricky challenge be tackled—estimating pesticide-induced adverse effects on organisms, populations, and ecosystems.

In the next section, 18 metrics are outlined that can be drawn upon to provide a robust assessment of changes in pesticide use. They fall into two categories:

- Changes in land area treated (acres/hectares) planted in a given crop, percentage of acres/hectares treated with a given pesticide, and number of acre-treatments (see the caption of Fig. 2.1 for information on how to convert from acre-treatments to hectare-treatments).
- Changes in the intensity of pesticide use on a given acre/hectare (rate of application, number of applications, rate per crop year).

Fig. 2.1 illustrates the way multiple metrics can be integrated to assess changes in the use of a single pesticide, pesticides targeting a type of pest (herbicides/weeds, insecticides/insects, fungicides/plant diseases, others), or all pesticides. Applications of the metrics are discussed, along with methods to access sources of use data for crops in the United States. The penultimate section of the chapter, "Glyphosate-based herbicide

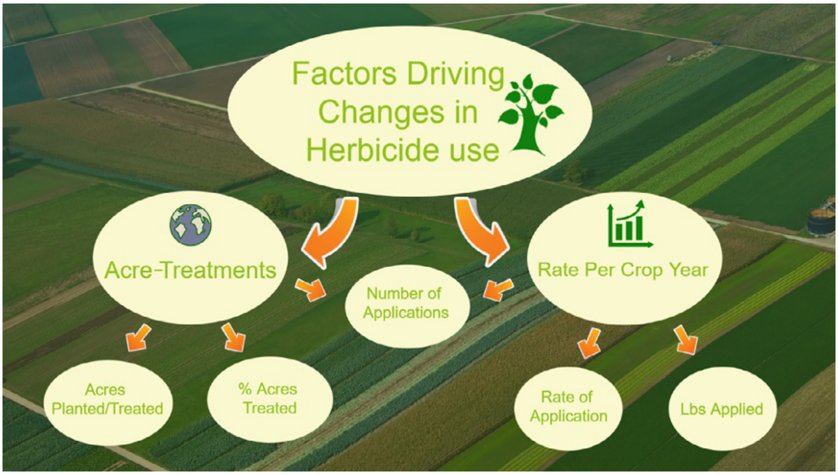

Fig. 2.1 Land-based (left side) and rate-based (right side) metrics that quantify herbicide use. Note that acre-treatments is a calculated variable that will not be converted into SI units for the purpose of this chapter. Multiply acre-treatment values by a conversion factor of 0.40686 to convert to hectare-treatments.

use on soybeans in the United States," is a case study in how the metrics can be applied to one important crop (soybeans) and type of pest (weeds).

Pesticide use metrics

Pesticide impacts on the environment and human health are a function of how widely and often a pesticide is applied (acre-treatments in Fig. 2.1) in addition to the rate at which it is applied (rate per crop year). A series of land-based metrics is needed to quantify the proportion of a crop treated and the number of times a given hectare is treated in a growing season. Rate-based metrics are dependent on the one-time rate of application on a crop coupled with the number of applications. The first seven metrics in Fig. 2.2 address land- and rate-based indicators.

PESTICIDE USE METRICS

Metrics by Active Ingredient:

1. Percent of Acres Treated
2. Number of Acres Treated
3. Acre Treatments
4. Rate per Application
5. Number of Application
6. Rate per Year
7. Pounds Applied

Metrics by High or Low Dose Chemistry:

8. Number Low-Dose Chemistry
9. Reliance Low-Dose Chemistry
10. Number High-Dose Chemistry
11. Reliance High-Dose Chemistry
12. Weighted Average Rate of Application

Metrics by Pesticide Type (Herbicide, Insecticide, Fungicide, Other):

13. Number of Active Ingredients
14. Number of Active Ingredients per Acre
15. Number of Acre-Treatments
16. Acre-Treatments per Acre
17. Pounds Applied
18. Pounds Applied per Acre

Fig. 2.2 The 18 pesticide use metrics, shown here in US units for consistency with the online database at http://www.hygeia-analytics.com/puds. Where possible without creating confusion, herbicide use values have been converted to SI units throughout this chapter.

Additional metrics are needed to gain deeper insight into how changes in one-time rates of application influence trends in overall use (metrics 8–12). This is because since the early 1980s, the pesticide industry has focused on identifying new modes of action that are highly specific to target pests and are usually effective at low per-hectare rates of application. Such active ingredients (AIs) typically target specific metabolic, biochemical, physiological, developmental, or reproductive processes in target pests. Several are applied at very low rates (e.g., 0.01 pound or less per acre or 0.0112 kg/hectare). Low-rate AIs bring down the overall pounds/kilograms per acre/hectare in a region or on a crop. Shifting cropland treated from one or a few relatively high-dose pesticides to low-dose ones reduces use measured in kilograms of AIs applied, but would appear as intensification of use relative to the metric number of acre/hectare-treatments required to achieve control.

Metrics 13–18 focus on the number and type of individual pesticides used on a given crop. The effects of annual use on farm production costs, the environment, the emergence and spread of resistant pests, and public health are driven by the total number, weight, environmental fate, and toxicity of the AIs applied. These metrics are needed to take into account how many different pesticides are required to bring a crop to harvest in a production cycle. They are tracked by three major categories: weeds (herbicides), insects (insecticides), and plant diseases (fungicides), referred to herein as H/I/F/O, with the "O" encompassing all other types of pesticides (e.g., desiccants, rodenticides, fumigants). The number and type of pesticides applied can be quantified per acre/hectare, on a field, across all fields on a farm, and/or in a county, state, or region, nationally or globally.

The 18 metrics constitute a robust MDS. When applied to a specified crop and region, the MDS metrics will yield multiple insights useful in answering the questions of whether and how pesticide use has changed. Note that acres are used in this metric list to be consistent with the online database, but units have been converted to SI in the tables, figures, and text of this chapter where possible.

1. *Percent of acres treated* is the percentage of the total acreage of a given crop that is treated one or more times with a given pesticide in an annual crop production cycle.
2. *Number of acres treated* is the number of acres of the crop treated one or more times with a given pesticide, calculated as the (percent acres treated) multiplied by (total crop acreage).

Those two metrics are needed to quantify the area treated with a given pesticide, but they fail to capture when a given acre/hectare is treated more than once in a season and do not account for differences in rates of application.

3. *Acre-treatments* takes into account the acres planted to a given crop in a region, the percent of acres treated one or more times, and the average number of applications made with each active ingredient applied. It is calculated as:

$$\text{Acre} - \text{treatments} = (\text{acres planted}) \times (\text{percent acres treated}) \times (\text{number of applications})$$

For example, if one-half of a farmer's soybean acreage is treated twice with a pesticide$_x$ and the rest once, the number of acre treatments on this farm with pesticide$_x$ would be 1.5 multiplied by the acreage of soybeans.

4. *One-time rate of application* is the average amount of active ingredient applied per acre/hectare on a given crop in a field, farm, region, or country.
5. *Number of applications* is the average number made with a specific active ingredient on a crop in a production cycle (usually a calendar year).
6. *Rate per crop year* is the average total rate of application per production cycle, and is calculated as (average one-time rate of application) multiplied by (average number of applications).
7. *Pounds applied* is the total pounds/kilograms of AIs per production cycle on a given crop. It is calculated for an individual pesticide by multiplying (acre treatments) by (average rate of application per crop year), or alternatively by (acres treated one or more times) multiplied by (rate per crop year).

The pounds of AIs applied per unit area is the most widely reported pesticide use metric. But application rates per acre/hectare vary by 100-fold or more. For this reason, a series of metrics that capture reliance on high- versus low-dose AIs is needed (focus below is on rates in pounds per acre).

8. *Number low-dose chemistry* is the number of AIs applied at a rate of $\leq$0.1 pound/acre.
9. *Reliance on low-dose chemistry* is the percent of acres treated with an AI applied at a rate of $\leq$0.1 pound/acre.
10. *Number high-dose chemistry* is the number of AIs applied at a rate of $\geq$1.0 pound/acre.
11. *Reliance on high-dose chemistry* is the percent of acres treated with an AI applied at a rate of $\geq$1.0 pound/acre.
12. *Weighted average rate of application* is the average rate per acre-treatment across all pesticides applied within a category (herbicides, insecticides, fungicides, and other), weighted by each pesticide's share of total acre-treatments.

Metric 12 is the best way to track the overall impact of changes in average rates of application. This indicator, coupled with trends in the average number of acre-treatments on any given acre, provides the most reliable empirical assessment of overall changes in the intensity of pesticide use on a given crop.

The last six metrics allow tracking changes in the use of a particular pesticide or category.

13. *Number of H/I/F/O applied* is the average number of different pesticide AIs used on a given crop in a specific region and year combination (e.g., number of different herbicide AIs applied on soybeans in Iowa in 2015).
14. *Number of H/I/F/O applied per acre* is the average number of AIs applied one or more times per acre. It is calculated as the sum of the percent of acres treated with each AI falling within a category (e.g., herbicides), divided by 100.
15. *Number of H/I/F/O acre-treatments* takes into account the number of applications per acre and the percent of acres treated. It quantifies the total number of acre-treatments with H/I/F/O AIs (e.g., a field treated twice with the same AI counts as one herbicide applied but two acre-treatments).
16. *H/I/F/O acre-treatments per acre* is the total number of acre-treatments divided by the number of acres planted.
17. *Pounds of H/I/F/O applied* is the sum of AI pounds applied across all agents within a type of pesticide in a given crop year/region combination.
18. *Pounds H/I/F/O applied per acre* is the total pounds applied divided by total acres planted.

Applying the metrics

GBHs are by far the most heavily used pesticides in history as measured by pounds/kilograms of AI applied, both in the United States and globally.[9] The introduction of glyphosate-tolerant crops in 1996 allowed for postemergence, over-the-top applications on soybeans and cotton, and, soon thereafter, on corn, alfalfa, and sugar beets. This resulted in dramatic increases in the land area and total pounds/kilograms of glyphosate and GBHs sprayed beginning in 1998 and peaking around 2015.

Overuse triggered the emergence of weed phenotypes that required higher rates of GBH application and/or multiple applications to achieve acceptable levels of control. Incremental increases in glyphosate-imposed selection pressure on weed populations eventually triggered the emergence of resistant weeds. Continued use then assured the spread of resistant weed seeds, and more and more serious resistant-weed challenges for farmers. As a direct result, herbicide use intensity in US soybean production has risen dramatically in recent years, increases that are obvious when changes are tracked with the 18 pesticide use metrics.

Sources of pesticide use data for US crops

Use data provide the foundation for tracking changes. The primary public sources on US crops are:

- The US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) pesticide use data by crop, chemical, and state.[10]
- California Pesticide Use Reporting (PUR) data by crop, chemical, product, and county.[11]
- Periodic reports issued by the US Environmental Protection Agency (EPA).[12]
- The US Geological Survey (USGS) database of pesticide use by crop, chemical, and county.[13]

Since 1990, USDA pesticide use surveys have been reasonably complete for major field, fruit, vegetable, and grain crops. Funding shortfalls have, in recent years, reduced the number of crops surveyed annually, thereby creating longer gaps between years with survey data. From the early 1970s to 1990, the USDA conducted three surveys that were limited to major crops and regions. By drawing on these data for the crops that account for the most pesticide use in the last half-century in the United States, long-term use trends can be tracked through the Pesticide Use Data System (PUDS) (https://hygeia-analytics.com/puds).

Data are compiled and reported by USDA for H/I/F/O by AI and crop, and at the national and state levels. States accounting for about 85% or more of national crop acreage in a given year are surveyed by NASS. Each crop-year table in an NASS report, accessible via the PUDS, includes the percentage of surveyed acres treated, the average one-time rate of application, the average number of applications, the rate per crop-year (average rate multiplied by average number of applications), and the pounds of AI applied. Over many years, NASS has conducted its surveys with a consistent methodology, producing the highest quality publicly accessible data on trends in use by US farmers. Since 1990, NASS has surveyed major grain and row crops on a nearly annual basis. Vegetable crops are surveyed in even years, fruit crops in odd years.

High-quality detailed data have been collected by the California Department of Food and Agriculture since the 1980s via the PUR system.[11] The availability of detailed, location-specific use data in California is a major reason why epidemiologists have been able to conduct sophisticated studies of the linkage between pesticide use and exposure as well as adverse health outcomes (e.g., see von Ehrenstein et al.[14]).

Use data periodically released by the EPA are valuable because they include information on nonagricultural use, and because they draw upon both USDA surveys and proprietary data provided to the agency by pesticide registrants and private firms.

The USGS data are available for only a few major row crops at the county level, and are drawn largely from USDA pesticide-use reports.

In addition to publicly accessible sources, several consulting firms have compiled proprietary datasets. While private survey data are often more detailed and complete than government data, gaining access to private survey data can cost hundreds of thousands of dollars per year, and is hence not an option for most analysts.

Changes in glyphosate-based herbicide use in the United States

Two data sources are drawn upon for tracking trends in glyphosate use in this chapter. The first is the detailed tables from the 2016 paper "Trends in glyphosate herbicide use in the United States and globally."[9] The second is the EPA's periodic ranking of the most heavily applied pesticides in the US agricultural sector (i.e., Grube et al.[15]).

Table 2.1 shows trends in agricultural and nonagricultural use of GBHs from 1974 through 2014. Of the estimated 635,000 kg of AI applied in 1974, 363,000 were on farms and ranches and 272,000 were outside agriculture, for a 57% to 43% split.

The data show some striking changes. From 1974 to 2001, Monsanto's Roundup brands were the only GBHs sold in the United States. By 1982, the total kilograms applied had risen to 3.5 million, 5.6-fold higher than in 1974. The share accounted for by agricultural use rose to 64% in 1982 and nonfarm use fell to 36%.

After 1982, growth in sales and kilograms applied continued at a slower but still significant pace through 1990, a year when the total kilograms applied reached 5.8

Table 2.1 Glyphosate active ingredient use in the United States, 1974–2014.

	1974	1982	1990	1995	2000	2005	2010	2012	2014
Glyphosate use (1000 kg)	635	3538	5761	18,144	44,679	81,506	118,298	118,753	125,384
Agricultural	363	2268	3357	12,474	35,720	71,441	106,963	107,192	113,356
Nonagricultural	272	1270	2404	5670	8958	10,065	11,335	11,562	12,029
Share agricultural	**57.2%**	**64.1%**	**58.3%**	**68.8%**	**79.9%**	**87.7%**	**90.4%**	**90.3%**	**90.4%**
Share nonagricultural	**42.8%**	**35.9%**	**41.7%**	**31.3%**	**20.0%**	**12.3%**	**9.58%**	**9.74%**	**9.59%**

Notes: Data in thousands of kilograms of glyphosate active ingredient.
Table from Benbrook C. Trends in glyphosate herbicide use in the United States and globally. *Environ Sci Eur* 2016; **28**(1):3; data from the National Agriculture Statistical Service pesticide use data and the Environmental Protection Agency pesticide industry and use reports.

million, 1.6-fold higher than in 1982. Sales and kilograms applied grew faster for nonagricultural use, shifting the agricultural to nonagricultural shares to 58% and 42%.

From 1990 to 1995, agricultural sales and kilograms applied more than tripled and nonagricultural use more than doubled. Total kilograms applied rose to 18 million, up 3.1-fold in just 5 years.

Beginning in the 1996–2000 period, agricultural glyphosate use began its decade-long run of spectacular, unprecedented growth, as farmers rapidly adopted the Roundup Ready seed and herbicide system. In 2000, farmers and ranchers applied 36 million kg, an absolute increase of 23 million since 1995, or a 2.9-fold increase. The rate of growth in nonagriculture sales and pounds applied was much lower, rising only by about 50% over 5 years. The agricultural to nonagricultural split moved to 80% and 20%.

Just the increase in the kilograms applied by farmers and ranchers in the 5 years from 1996 to 2000—23 million kg—exceeded by a wide margin the total growth in the preceding 25+ years that GBHs had been on the market.

While growth in the early years of the adoption of Roundup Ready seeds was unprecedented by any measure, it pales in comparison to the magnitude of growth in absolute agricultural sales and GBH kilograms applied from 2001 to 2005 and 2006 to 2010. The last US patents that prevented other pesticide companies from entering the GBH market lapsed in 2000, so since around 2001 it has been necessary to focus on total use of GBHs, not just Roundup brands.

From 2001 to 2005, agricultural and ranch use of GBHs nearly doubled from 36 million kg to 71 million kg. Meanwhile, nonagricultural use increased by just over 1 million kg, or just 12%. As a result, there was another sizable shift of agricultural relative to nonagricultural uses: 88% to 12%.

Rapid growth in GBH sales and kilograms applied persisted for 5 more years; for agricultural and ranch applications, this amounted to 107 million kg in 2010, an absolute increase of 35 million. This shifted the agricultural to nonagricultural shares to 90% and 10%, a split that has remained largely unchanged to 2020.

Monsanto successfully petitioned the EPA to approve tolerances and labels covering most agricultural and nonagricultural uses by 1982, a year when the total glyphosate use was 3.5 million kg. By 2014, as Table 2.1 shows, the total kilograms applied had risen to 125 million, a 35-fold increase in 22 years. No pesticide in history comes close to matching the sustained upward trajectory in glyphosate and GBH sales and pounds applied in the United States and globally.

EPA rankings of the most heavily applied pesticides

A series of reports issued by the EPA on the sale and use of pesticides in the United States provides a second data series and perspective on the growth in glyphosate. The reports list by year and rank order (1–25) the most heavily applied AIs on farms and ranches, along with the EPA's best estimate of total agricultural pesticide applications. They draw heavily on the USDA's periodic surveys, as does the trend analysis. The rankings were computed by the EPA every 2 years from 1993 through 2009 as well as in 1987 and 2012. Table 2.2 records the rapid rise and staying power of glyphosate relative to other widely used pesticides.

Table 2.2 Glyphosate's rise to the top, Parts I and II.

Part I—EPA rankings of the top pesticides by year in the US agricultural sector, 1987–2001													
("Range" is in million kilograms active ingredient applied) (see "Notes")													
		1987		**1993**		**1995**		**1997**		**1999**		**2001**	
Active ingredient	**Type**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**
Glyphosate	H	17	3–4	11	7–9	7	11–14	5	15–17	2	30–33	1	39–41
Atrazine	H	1	32–34	1	32–34	1	31–33	1	34–37	1	34–36	2	34–36
Metam sodium	Fum	15	2–4	8	11–14	3	22–24	3	24–26	3	27–29	3	26–28
Metolachlor-S	H									12	7–9	9	9–11
Acetochlor	H					11	10–12	7	14–16	4	14–16	4	14–16
Dichloropropene	Fum	4	14–16	6	14–16	5	17–20	6	15–17	11	8–9	8	9–11
2,4-D	H	5	13–15	7	11–14	6	14–16	8	13–15	6	13–15	5	13–15
Trifluralin	H	6	11–14	9	9–11	10	10–13	10	10–11	9	8–10	12	5–7
Propanil	H	13	3–4	15	3–5	17	3–5	22	3–4	18	3–5	17	3–4
Dicamba	H	23	2–3	16	3–5	18	3–5	16	3–5	22	3–4	24	2–3

Part II—Glyphosate stays at the top. EPA rankings of the top pesticides by year in the US agricultural sector, 2001–12													
		2001		**2003**		**2005**		**2007**		**2009**		**2012**	
Active ingredient	**Type**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**	**Rank**	**Range**
Glyphosate	H	1	39–41	1	58–60	1	67–76	1	77–86	1	95–104	1	122–132
Atrazine	H	2	34–36	2	34–36	2	30–34	2	32–36	2	13–31	2	29–34
Metam sodium	Fum	3	26–28	3	20–23	3	16–21	3	22–26	3	14–18	6	14–18
Metolachlor-S	H	9	9–11	6	13–15	5	11–16	4	12–17	6	11–15	3	15–20
Acetochlor	H	4	14–16	5	14–16	6	11–15	5	11–16	7	10–15	7	13–17
Dichloropropene	Fum	8	9–11	7	9–11	4	13–17	6	11–15	4	12–17	4	15–19

Continued

Table 2.2 Continued

Part II—Glyphosate stays at the top. EPA rankings of the top pesticides by year in the US agricultural sector, 2001–12													
		2001		2003		2005		2007		2009		2012	
Active ingredient	Type	Rank	Range	Rank	Range	Rank	Range	Rank	Range	Rank	Range	Rank	Range
2,4-D	H	5	13–15	4	14–16	7	10–14	7	10–15	5	11–15	5	14–18
Trifluralin	H	12	5–7	11	4–5	14	3–5	17	2–4	18	1–3	19	1–3
Propanil	H	17	3–4	18	2–3	18	1–3	18	1–3	17	1–3	17	1–3
Dicamba	H	24	2–3			22	0.5–2	—	0.5–2	25	0.5–2	18	1–3

Notes: "H" is herbicide; "Fum" is fumigant. (—) indicates that the pesticide did not make the 25 most commonly used pesticides ranking in the given year. Data does not include sulfur and petroleum oil.
Source: Data from US Environmental Protection Agency Pesticide Industry Sales and Usage Reports, accessible at https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2006-and-2007-market-estimates.

In 1987, the first year EPA issued its ranking, glyphosate was 17th, at 3–4 million kg applied. No. 1 was the corn herbicide atrazine, 32–34 million, or 10 kg of atrazine for every kilogram of glyphosate. Six years later, glyphosate was No. 11, at 7–9 million, and atrazine remained No. 1, at 32–34 million. Glyphosate entered its rapid growth phase in the late 1990s and rose steadily to No. 1 by 2001, at 39–41 million, and atrazine fell to No. 2, at 34–36 million.

In the next 11 years, the amount of glyphosate applied almost tripled while atrazine declined modestly. In 2018, glyphosate exceeded 136 million—5 kg for every kilogram of atrazine.

Glyphosate-based herbicide use on soybeans in the United States: A case study

Dramatic changes have occurred in herbicide use on soybeans in the United States since the early 1990s. This case study describes trends in herbicide use metrics from 1991, a few years before the introduction of herbicide-tolerant crops, through 2018, the most recent year for which use data are available from the USDA. Units relied on in this section include acres/hectares, kilograms of active ingredient applied, and combinations of these units of measure.

Land area treated metrics

Table 2.3 covers the change in hectares of soybeans planted from 1991 through 2018 and the percent of hectares treated one or more times with any herbicide, GBH or non-GBH. The dramatic upward shift in reliance on GBHs stands out, as does the near doubling of hectares planted over this 27-year period. These data are displayed graphically in Fig. 2.3.

The total soybean hectares planted increased by ~50% from 1991 to 2018 while hectares treated with a GBH increased 27-fold, from 1.2 million in 1991 to a high

Table 2.3 Change in soybean hectares planted and herbicide use in the United States, 1991–2018.

	1991	1994	1997	2000	2003	2006	2009	2012	2015	2018
Soybean hectares planted	23.9	24.9	28.3	30.1	29.7	30.6	31.3	31.2	33.5	36.1
Percent soybean hectares treated										
All herbicides	206%	258%	252%	185%	155%	142%	179%	216%	274%	343%
Glyphosate-based herbicides	5%	15%	28%	62%	86%	96%	97%	98%	97%	87%
Nonglyphosate herbicides	201%	243%	224%	123%	69%	46%	82%	118%	177%	256%

Notes: Data downloaded from the Pesticide Use Dataset (https://hygeia-analytics.com/puds) and converted into hectares. Percentages above 100% indicate that hectarage was treated with a given herbicide more than once in the growing season.

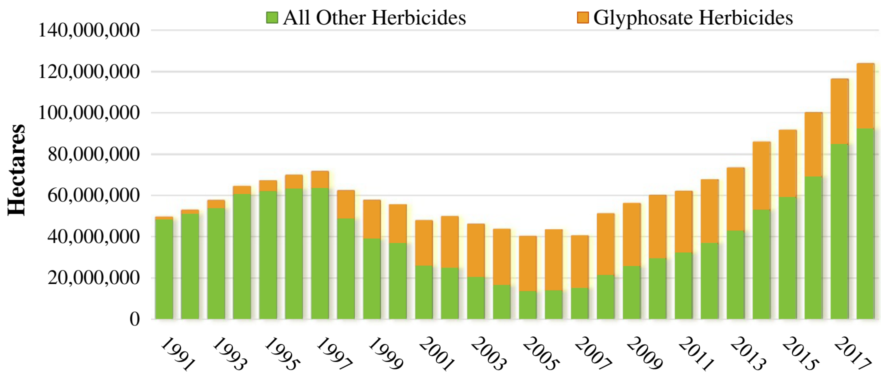

Fig. 2.3 US soybean hectares treated with glyphosate and all other herbicides, 1991–2018.

of 33 million in 2014. So, in terms of the total number of soybean hectares sprayed with a GBH one or more times, peak glyphosate use at 98% of total hectares planted occurred in 2012, then fell to 87% by 2018. Other indicators of peak glyphosate use occurred in other years, as evident in the following tables and figures.

In the early years of Roundup Ready technology (seeds genetically engineered to tolerate postemergence, over-the-top applications of a GBH), many farmers achieved acceptable to excellent weed control with a single application. But repeated use year after year triggered changes in weed communities and a loss of efficacy against some species, forcing farmers to make a second application and, on many farms, incrementally increase the rate applied per hectare.

Table 2.4 adds another metric—number of applications—to the appraisal of changes in soybean herbicide use. It reports the total hectares planted, the percent of hectares treated with a GBH one or more times, the percent of hectares treated with

Table 2.4 Change in soybean hectares planted and herbicide use in the United States, including acre-treatments, 1991–2018

	1991	1994	1997	2000	2003	2006	2009	2012	2015	2018
Soybean hectares planted	23.9	24.9	28.3	30.1	29.7	30.6	31.3	31.2	33.5	36.1
Percent soybean acres/hectares treated										
Glyphosate-based herbicides	5%	15%	28%	62%	86%	96%	97%	98%	97%	87%
Nonglyphosate herbicides	201%	243%	224%	123%	69%	46%	82%	118%	177%	256%
Millions of herbicide acre-treatments[a]										
Glyphosate-based herbicides	2.96	9.24	25.5	59.9	91.4	123.5	126.0	124.9	114.5	113.0
Nonglyphosate herbicides	120.3	154.2	162.1	92.5	51.8	36.0	65.8	96.9	153.9	251.7

[a] Multiply acre-treatments by the conversion factor of 0.40686 to convert them to hectare-treatments.

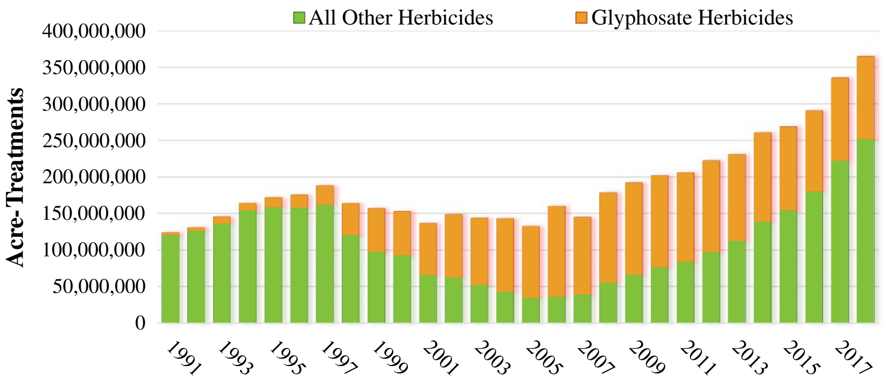

Fig. 2.4 Acre-treatments of glyphosate and all other herbicides on US soybeans, 1991–2018.

herbicides other than glyphosate, glyphosate acre-treatments and other herbicide acre-treatments, and glyphosate and other herbicide acre-treatments as a percent of total acre-treatments. Recall that multiplying acre-treatment values by a conversion factor of 0.40686 will give you the hectare-treatments.

The acre-treatments data are plotted in Fig. 2.4, with GBHs versus other herbicides. The average number of GBH applications rose from 1 in 1991 to 1.7 in 2006 and then fell back to 0.81 in 2018 (Table 2.5). This was associated with a rise in acre-treatments from 2.96 million to 113 million (1991 to 2018), or 38-fold (Table 2.4). The change in acre-treatments is one of the most important metrics when tracking changes in farmer reliance on a GBH or any other pesticide. Peak GBH acre-treatments as a percent of total herbicide acre-treatments occurred in 2006 at 77% and fell to 31% in 2018.

Table 2.5 Average application rate, number of applications, and rate per crop year, glyphosate and all other herbicides, 1991–2018.

	1991	1994	1997	2000	2003	2006	2009	2012	2015	2018
Average one-time application rate (kg/hectare)										
Glyphosate herbicides	0.897	0.583	0.684	0.762	0.821	0.890	0.963	1.039	1.092	1.004
All other herbicides	0.626	0.474	0.465	0.426	0.415	0.380	0.314	0.287	0.327	0.406
Average number of applications										
Glyphosate herbicides	1.00	1.00	1.30	1.30	1.45	1.70	1.68	1.65	1.43	0.810
All other herbicides	1.01	1.03	1.03	1.02	1.03	1.05	1.04	1.06	1.05	1.10
Average rate per crop year (kg/hectare)										
Glyphosate herbicides	0.897	0.583	0.889	0.991	1.19	1.51	1.61	1.72	1.56	0.81
All other herbicides	0.631	0.489	0.480	0.433	0.426	0.398	0.326	0.304	0.345	0.448

Application rate per acre metrics

The pounds/kilograms of any pesticide applied is a function of acre-treatments and the average rate of application on those acre-treatments. Table 2.5 reports the average one-time rate of application of glyphosate and all other herbicides, the average number of applications of glyphosate and all other herbicides, and the rate per crop year for glyphosate and all other herbicides. The rate of GBH application during this 27-year period rose 12% while that of other herbicides fell 35%. Even more startling, the peak glyphosate rate per crop year was in 2012, when the rate per year for GBHs was 91% higher than in 1991 while the rate per crop year for other herbicides fell 52% over the same period.

Table 2.6 combines the data on land area treated and rate per application to show trends over time in the amount of AI applied. Glyphosate use rose 41-fold. Other herbicides declined rapidly from 1997 through 2006, but then rose 751% by 2018. Glyphosate's share of the total herbicide kilograms applied peaked in 2006 at 89%, and fell to 52% in 2018. That share is likely to keep falling for several years as a result of slipping efficacy and the spread of glyphosate-resistant weeds.

Factors driving change in soybean herbicide use

The meteoric rise of GBH use on soybeans in the United States drove most of the changes in herbicide use metrics through about 2010. Since then, two additional trends have exerted significant influence on use patterns: an increase in the number of active ingredients required to achieve acceptable control (metric 13 in Fig. 2.2), and changes in the weighted average of rates of application (metric 12).

The spread of glyphosate-resistant weeds has required farmers to apply other herbicides, increase rates of application, or use nonchemical tactics. Roughly in order of impact when adopted, but not of prevalence, on US row crop farms, these tactics include diversified crop rotation, added tillage, preventing weeds that escape control from going to seed, planting cover crops, and changing planting and harvest timing. The surest way to reduce reliance on herbicides is to incorporate multiple nonchemical strategies into integrated weed management. This approach has appropriately been labeled the use of "many little hammers" by Iowa State University researchers.[16, 17]

Table 2.6 Kilograms applied, glyphosate and all other herbicides, 1991–2018.

	1991	1994	1997	2000	2003	2006	2009	2012	2015	2018
Millions of kilograms applied										
Glyphosate herbicides	1.11	2.18	7.2	19.8	30.6	43.4	48	52	52	46
All other herbicides	30.5	29.6	30.5	15.9	8.7	5.5	8.4	11.2	20.4	41.3
Percentage of total kilograms applied										
Glyphosate herbicides	4%	7%	19%	55%	78%	89%	85%	82%	72%	52%
All other herbicides	96%	93%	81%	45%	22%	11%	15%	18%	28%	48%

As Roundup Ready technology rapidly gained soybean sector market share from 1996 through the early 2000s, the rise in reliance on GBHs drove the decline in the use of nearly all other herbicides registered for use on soybeans. Ease of use and efficacy, achieved at prices comparable to herbicide-based options, drove the rapid rise in the use of GBHs on Roundup Ready soybeans.

Table 2.7 gives percent change indices in core glyphosate-soybean use metrics through 2018, with 1996 as the base year (when glyphosate-tolerant crops were introduced). The greater the change from the baseline, the larger a parameter's effect on the total pounds applied. By 2018, the parameters with the greatest to least effect on glyphosate use were acres/hectares treated (248%), average one-time rate of application (42%), acres/hectares planted (39%), and number of applications (32%).

Conclusions and research challenges

The answer to the question "Is pesticide use going up, down, or staying the same?" will vary depending on the metric chosen and how the metric is applied. An MDS of metrics is recommended as a starting point. The 18 metrics outlined in this chapter provide different and useful insights into what is driving changes in pesticide use for a given crop across time and space. Additional data and more refined models and research strategies will be required to deepen understanding of the factors driving changes in pesticide use and the consequences of such changes.

From the farmer's perspective, the two key factors are the degree and reliability of control and the cost of weed management systems. On conventional row-crop farms in

Table 2.7 Percent change of core soybean metrics from 1996 baseline, 1996–2018.

	1996	1999	2002	2005	2008	2011	2014	2017	2018
Soybean acres/hectares planted	0%	15%	15%	12%	18%	17%	30%	40%	39%
Percent acres/hectares treated									
Glyphosate herbicides	0%	148%	232%	264%	287%	291%	289%	244%	248%
All other herbicides	0%	−46%	−66%	−81%	−71%	−56%	−35%	−4%	5%
Average number of applications									
Glyphosate herbicides	0%	18%	27%	35%	53%	51%	37%	33%	32%
All other herbicides	0%	0%	0%	2%	3%	4%	5%	5%	9%
Average one-time rate of application									
Glyphosate herbicides	0%	10%	17%	20%	33%	43%	52%	43%	42%
All other herbicides	0%	−11%	−8%	−6%	−30%	−38%	−34%	−23%	−14%

the United States, herbicides bear most of the weed-management burden. Accordingly, farmers need accurate, timely information on how well their herbicide programs are working and whether costs are rising, falling, or stable.

Two unmistakable indicators of weed management problems are erratic efficacy and rising cost. The dominant cause for both is usually the emergence and spread of resistant weed phenotypes. Regrettably for US farmers, the response by industry to the emergence of glyphosate-resistant weeds has been to engineer additional herbicide-resistant genes into corn, soybean, and cotton varieties. This strategy is akin to pouring gasoline on a fire in the hope of putting it out. The consequences are evident in the recent, sharply upward trends in the number of herbicides required to bring a soybean crop to harvest, the pounds/kilograms applied and expenditures per acre, and rising environmental and public health problems stemming from herbicide use.

The upward trend in herbicide use cannot go on forever. But what comes next and what will begin to shift reliance from herbicides to prevention-based integrated weed management remains to be seen. Refinements in the ability to track changes in herbicide use and nonchemical control strategies will assist in accelerating positive change, as will a better understanding of the factors driving how farmers respond to changes in weed pressure and control problems.

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EMERGING ISSUES IN ANALYTICAL CHEMISTRY
BRIAN F. THOMAS, SERIES EDITOR

HERBICIDES

Chemistry, Efficacy, Toxicology, and Environmental Impacts

ROBIN MESNAGE AND JOHANN G. ZALLER
EDITORS

The use of herbicides is an essential pillar of modern agricultural production systems. Weeds, if uncontrolled, would reduce crop yield and result in massive economic damage. Recently, the reliance on herbicides as the only weed control strategy has been linked to the development of weed resistance. To combat resistant weeds, farmers are advised to use a mix of several herbicides and to increase herbicide application rates. Although risk assessments of herbicides are mandatory, adverse effects are not always correctly predicted from the current battery of regulatory tests. As a result, the toxicity of herbicides on human health and the environment has become a controversial topic.

Herbicides: Chemistry, Efficacy, Toxicology, and Environmental Impacts addresses contemporary debates on herbicide toxicology. The reader is offered a comprehensive overview of this complex topic, presented by internationally recognized experts of different scientific disciplines. The information will feed the discussion on the use of herbicides in modern agricultural and other systems and their nontarget effects on human health and overall biodiversity in various ecosystems. The book covers these matters in concise language appropriate to engage both researchers and informed persons responsible for legislative, environmental, and public health matters.

KEY FEATURES

- Offers a comprehensive overview of herbicide science in modern agricultural systems, covering a brief history, the present state, and potential alternatives
- Addresses the complex problems that can arise from herbicide use and misuse, weed resistance, genetically modified crop farming, the role of coformulants, analytical strategies and monitoring, pollution, and human health issues
- Uses recent examples on many herbicides, and, with a focus on glyphosate, demonstrates the topical nature of this issue by including regulatory principles

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