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Sustainable weed management – What is it and how are we doing?

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Abstract

The topic of sustainability is popular in mainstream media and a common discussion theme, particularly for the agriculture discipline that serves the entire world. Individuals and corporations often have a desire to be sustainable in their practices, but the commentary on "being sustainable" can be confusing in terms of realistic practices. To define whether weed science is sustainable one must first identify the resource or object to be sustained. From a historical perspective, weed control in the United States over the past 40 yr has revolved around no-tillage row crop acres. The implementation of no-till or reduced till has undeniable benefits in sustaining natural resources, especially two of our most valuable resources: soil and water. While the overall trend toward chemical weed control has been shown to decrease agriculture's impact on the environment, depending solely on herbicides is not sustainable long term with the rise in herbicide-resistant weed species. We also consider the benefits and challenges associated with agronomic trends within the context of sustainability and expand consideration to include emerging technology aligned to human health and environmental stewardship. The key to improving farming is producing more and safer food, feed, and fiber on less land while reducing adverse environmental effects, and this must be accomplished with the backdrop of human population growth and the desire for an improved standard of living globally. Emerging technologies provide new starting points for sustainable weed management solutions, and the weed science community can initiate the conversation on sustainable practices and share advancements with our colleagues and community members. In addition to broadening the sustainability concept, targeted and relevant communication tools will support the weed science community to have successful and impactful discussions.

Introduction

As with any popular phrase, it is important to first define the key words within the expression. "Sustainability" is mentioned in all aspects of society and sectors of the economy, and depending on the application, it may be interpreted differently. Sustainability is defined by the Oxford English Dictionary as "the quality of being sustainable at a certain rate or level." Within the accepted definition of sustainability, or the verb sustain, the object to be maintained at a certain rate or level is not defined; rather, the object is defined within the context in which it is being used. In the 21st century, the word sustainability is typically used within the context of maintaining natural resources or ecosystems, such as how it is used in the 2011 publication: Sustainability and the U.S. Environmental Protection Agency (NAS-NRC 2011). In evaluating the sustainability of weed science or weed control, it is necessary to identify the objects or subjects that we strive to maintain at a certain rate or level.

At Corteva Agriscience, the definition of sustainability is *balancing environmental, economic, and social benefits to meet the needs of today and the future.* This is specifically rooted in the ability to effectively supply the growing food, feed, fuel, and fiber needs of the world via crop production that is cultivated on fewer acres each year. As fewer people are directly involved with the agriculture industry, it is necessary to share with each partner in our value chain the reason why decisions are made and products are used. In addition, this brings economic benefits to the grower, including but not limited to the ability to align with sustainable development goals of buying groups, provide insight to public inquiries, and improve the overall understanding and recognition of agriculture at the community level. Not only is it important to have a definition of sustainability and goals that align toward them, but it is also important to make the connection to the products our customers use to improve the lives of society around them. Through the alignment of

Table 1. Objective of the Weed Science Society of America in addressing some of the most important issues facing our modern world.[a]

Maximize crop yields and feed a growing population as cropland is lost to urbanization.
Eliminate aquatic weeds that cog our waterways and impact water quality.
Control invasive weeds that compromise biodiversity in our rangelands and wild areas.
Develop integrated weed management techniques for conventional and organic farming.
Reduce the impact of weeds on human health and allergies.
Develop new and improved integrated weed management strategies in response to climate change.
Manage weed resistance to herbicides.
Prevent soil erosion by optimizing the role of tillage in weed control.
Manage weeds that fuel devastating fires.

[a]Adapted from Fostering an Awareness of Weeds and Their Impact on the Environment (WSSA 2021).

sustainability goals and our ability to connect these at the grower level, Corteva Agriscience will help meet the needs of the growing world and help advance the progress of agricultural technology.

This article follows from a symposium held at the virtual 2021 Weed Science Society of America (WSSA) annual meeting. The primary objective of the symposium was to better understand the broad, confusing, and sometimes futuristic topic of sustainability within the context of weed management. Additionally, this symposium was successful in providing tangible examples of what we are doing now, and how WSSA members can maintain sustainability in their daily work as weed scientists. The symposium speakers were asked to reflect on the topic of sustainability and provide specific insights within the context of weed management, highlighting examples of sustainable practice and tools that are used now. This review will describe the transition to reduced tillage to improve soil quality and the impact of herbicide-resistant weeds, then connect human health to herbicide technology. To support the weed science community in an increasingly connected society that is more curious about agricultural production, this review will also provide guidelines to enhance our communication to the public and to our colleagues.

The WSSA has established a list of objectives (Table 1) that address important issues that impact agricultural and environmental systems around the world (WSSA 2021). Focusing in on the 21st century definition of sustainability, several objectives of the WSSA would fit within the definition of sustaining our natural resources or ecosystems such as elimination of aquatic weeds, control of invasive weeds, prevention of soil erosion, and wildfire weed management. Additionally, several objectives focus on the ability to feed a growing world population while facing climate change and dramatic increases in herbicide resistance.

The objective of "prevent soil erosion by optimizing the role of tillage in weed control" provides an interesting intersection of the two perspectives of sustainability within the WSSA objectives. For example, to reduce soil erosion, no-tillage or reduced-tillage systems began gaining popularity in the United States during the 1980s and 1990s. The push for increasing no-tillage adoption began in the early 1980s with the support of several soil scientists such as Phillips et al. (1980). Starting from the soil, the basis of agriculture practices, that article highlighted advantages such as soil erosion reduction, an increase in usable land for crop production, reduction in energy requirements, an increase in planting and harvesting windows, more efficient use of soil water, and reduced investment in machinery. With the benefits in mind, no-till or reduced tillage also brings certain disadvantages within the sustainability of an agriculture system. Phillips et al. (1980) listed some of the disadvantages of no-tillage systems that included an increase in disease and insect pressure, an increase of required management skills, slower soil warming in the spring, and up to a 50% increase in pesticide use. A bolstered desire of the agriculture community to preserve soil resources in combination with advancements in planting equipment and advancements in selective herbicides led to an increase in no-till acreage starting in the 1980s. Estimates of no-tillage corn and soybean acreage in the United States reached 12.2 million in 1990 and 13 million hectares in 1995, respectively (CTIC 2021). One of the drivers behind the quick adoption of no-tillage systems in the 1980s and 1990s was the rapidly increasing number of herbicide active ingredients and sites of action becoming available from the crop protection industry (McDougall 2018).

While the sustainability benefits of no-tillage are undeniable, the use of the systems inherently eliminated an effective mechanical weed control tool available to farmers. At the same time there was also a rapid increase in the number of cases of unique herbicide-resistant weeds with an increase of global cases jumping from 25 in 1979 to 128 in 1990 (Heap 2021). Although it would be easy to assume a direct correlation between the increase in no-tillage adoption and increase in herbicide resistance, there is not a causal relationship. Herbicide usage on corn and soybean acreage peaked and plateaued in the early 1980s, whereas no-tillage acreage adoption had only begun at that point in time (Fernandez-Cornejo et al. 2014). Although the two events may not be directly correlated, the removal of tillage from the cropping systems favored chemicals becoming the primary and often the sole weed control tactic, which inherently increased the herbicide selection pressure in weeds. The increase in herbicide resistant weeds in the 1980s and 1990s was not sustainable, especially considering the decline or lack of discovery of new herbicide sites of action, with no new sites of action discovered between 1982 and 2020 (Heap 2021). Recent reviews provided excellent summaries of herbicide resistance as a key theme in sustainable weed control (e.g., Ganie et al. 2020; Kaundun 2020; Sleugh et al. 2020).

Rather than reimplementing the environmentally unsustainable practice of tillage for weed control, a change in technology occurred with the introduction of herbicide-resistant crops, and more specifically, the introduction of Roundup Ready® (glyphosate-resistant) crops in 1996. The introduction of glyphosate-resistant crops allowed for the continued growth of no-till corn and soybean acreage in the United States with acreage estimates reaching more than 19 million hectares by 2006 (CTIC 2021). The introduction of herbicide-resistant crops not only allowed no-tillage acreages to continue to increase, but also enabled a reduction in overall herbicide use and lowered energy input requirements (Green 2012). It has been argued though, that the introduction of glyphosate-resistant crops did not decrease herbicide use, with an increase in herbicide use in the United States in corn, cotton, rice, and wheat cropping systems from 1990 to 2010 (Kniss 2017). Interestingly, glyphosate-resistant varieties of rice and wheat were not available, so the increase in herbicide use intensity in these crops was independent of this herbicide-resistant offering. Uniquely from other crops grown in the United States, the overall herbicide use per hectare for soybean did not increase from 1990 to 2010, while having the highest adoption rate among the glyphosate-resistant crops (Kniss 2017; USDA-ERS 2020).

The benefits of herbicide-resistant crops extended well beyond just expanding environmental sustainability. Additional benefits of herbicide-resistant crops included increased and more consistent weed control, simplified weed control, and lower production cost (Green 2012). The distinct advantages of herbicide-resistant crops led to their rapid adoption, especially in soybean, with 68% of United States acreage being planted with herbicide-resistant soybean by 2001, which continued to climb to 94% by 2014 (USDA-ERS 2020). Although adoption of herbicide-resistant crops has climbed steadily with peaks of adoption occurring in corn and soybean around 2014, the trend of rapidly increasing herbicide-resistant weeds has also continued since their introduction (Heap 2021; USDA-ERS 2020). The number of unique cases of herbicide resistance in the world increased from 213 to 524 from 1996 to 2020 (Heap 2021). More specifically, cases of glyphosate-resistant weeds globally increased from one species in 1996 to 40 species in 2016, when additional herbicide-resistant soybean traits started emerging in the United States (Heap 2021). Since 2016, several new herbicide-resistant soybean traits have come onto the market, including events that confer resistance to dicamba and 2,4-D (Behrens et al. 2007; Wright et al. 2010). Despite the introduction of these new herbicide-resistant crops, global cases of herbicide-resistant weeds have continued to increase, including the recent identification of potentially dicamba- and glufosinate-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in Arkansas (Heap 2021; Norsworthy et al. 2021). Despite the overall success of herbicide-resistant crops over the past two decades and their contributions to environmental sustainability, the continued sole reliance on herbicides for weed control is not sustainable.

Looking toward the future of weed control, it is important that the agriculture community seeks out methods that continue to sustain natural resources, and sustain effective and economical weed control. Although the answer of how to achieve this goal is not a single solution, weed scientists are looking toward nonchemical weed control methods such as harvest weed seed control and the use of machine learning, sensors, and robotics to complement and overcome the failures of our current chemical-dependent systems (Walsh et al 2018; Westwood et al. 2018). These methods, as well as an emphasis of the need to employ molecular biology to understand weed biology and control, has been highlighted as a research priority by the national and regional weed science societies by focused symposia and featured journal articles.

Herbicide Resistant Weeds: Rethinking Our Approach to Addressing Sustainable Solutions

The Herbicide Resistance Education Committee was initially formed to create resource materials for the agency and grower communities. However, through discussion with weed science and social science colleagues, the committee began to broaden its focus to consider how weed resistance to herbicides impacts other goals of sustainability such as soil conservation, soil health, and more (CAST 2012). The committee also began to discuss sustainability in the broader context articulated by the National Research Council (NAS-NRC 2010) and discussed in a CAST Commentary (CAST 2020), which includes economic and social science perspectives on agricultural sustainability. Activities now focus on developing the capacity to engage a broad range of stakeholders to facilitate a sense of community to address local resistance issues.

The U.S. Department of Agriculture–Animal and Plant Health Inspection Service (USDA-APHIS) sponsored a group of experts to write two journal articles, one on the state of the science regarding the evolution of herbicide-resistant weeds (Vencill et al. 2012) and a second on best management practices (BMPs) and recommendations to combat herbicide resistance (Norsworthy et al. 2012). The National Research Council, a division of the National Academy of Sciences, sponsored a summit in 2012 with the objective to bring the issue to the attention of a broad audience of scientists and decision makers through an overview of the BMPs and facilitated discussion (NAS-NRC 2012). The recommended BMPs were the basis for the U.S. Environmental Protection Agency's Office of Pesticide Programs Pesticide Registration Notice 2017-2 "Guidance for Herbicide Resistance Management Labeling, Education, Training, and Stewardship" (EPA 2017). An additional educational project created a set of training modules designed to provide background information and guidance to the production community on how to identify and mitigate resistance through integrated weed management (Soteres et al. 2011). The original group of committee members published the first series on agronomic crops. Subsequent subcommittees of experts produced modifications of the training modules for turf crops, non-crop land, and aquatics. All modules were made available to the general public and to educators on the WSSA website (https://wssa.net/wssa/weed/resistance/). The committee also began working with the United Soybean Board, National Cotton Council, and the industry-sponsored Take Action program to develop a series of infographics. These can be viewed at https://wssa.net/herbicide-resistance/wssa-infographics-on-herbicide-resistance-management/.

Building on insights and perspectives from the 2012 Herbicide Resistance Summit (NAS-NRC 2012), a second herbicide resistance summit was organized to facilitate a more unified understanding of herbicide resistance across the country, to understand different viewpoints on the subject, and, especially, to present a "call to action" for all stakeholders to contribute to solutions (WSSA 2014). With funding from the USDA and other organizations WSSA co-sponsored this event, which was hosted by the National Research Council. The presentations focused on the human dimensions of the "wicked problem" of herbicide resistance. A wicked problem is defined by sociologists as one without clear causes or solutions and is thus difficult or impossible to solve (Shaw 2016); therefore, the combined effort of the community of stakeholders is needed to address the problem. The presentations from the summit were developed into a s eries of papers published as a special issue of the journal *Weed Science* (Ward 2016). The "Call to Action" presentation and final paper in the series challenged all stakeholders to work together to address this "wicked problem" of herbicide resistance (Coble and Schroeder 2016).

WSSA, USDA-APHIS, and United Soybean Board partners recognized that more needed to occur to understand the diversity of local herbicide resistance issues and challenges that growers, managers, and decision makers were facing across the United States. Therefore, the WSSA Herbicide Resistance Education Committee developed an initiative in 2016 to organize stakeholder listening sessions in different regions of the country. These listening sessions led to the publication of three journal papers: the first summarized the outcomes and lessons learned; the second presented the methodology the committee used to conduct the sessions; and the third presented the critical next steps needed to address resistance (Schroeder et al. 2018a, 2018b; Shaw et al.

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2018). The information from these sessions has helped guide subsequent committee activities.

The listening session lessons led to WSSA and USDA-APHIS sponsorship of a group that included weed scientists, entomologists, sociologists, and economists to attend a workshop where they learned new approaches to help communities and organizations confront and address "wicked" problems. This continuing collaboration across disciplines led to a greater engagement between pest management organizations (weed scientists and entomologists) and resulted in a science policy tour in Iowa in 2019. Attendees on the tour included representatives from many stakeholder groups from local and national organizations. The workshop included science presentations but was more focused on establishing shared values, developing trust, and identifying key commonalities among the participants regarding pest resistance (Dentzman et al. 2020).

Currently, a community development project in the Pacific Northwest is in progress. In that region, herbicide resistance threatens to reverse soil conservation gains achieved through reduced tillage. Weed scientists and rural sociologists are working together to help communities to develop local solutions to herbicide resistance in their cropping systems. Using past research on community-based management, they created a pilot toolkit that supports communities of farmers to create their own approach to management. This illustrates an ideal example in which weed scientists can partner with other disciplines as our needs evolve and rethink our approach as new solutions are required. Toolkit stages include defining goals, creating an action plan, and establishing evaluation criteria. As of early 2021, 28 producers and other stakeholders were actively involved in three community groups. The group also made presentations on the approach at multiple conventions for wheat growers, reaching approximately 144 people (Dentzman and Burke 2021; also see reports posted on the WSSA website https://wssa.net/wssa/weed/resistance/). Personnel changes slowed efforts in 2021; however, a newly hired postdoctoral professional is currently organizing and reenergizing the communities. The toolkit for community organizations has evolved based on experience. They are facing challenges, including how to equalize the conversation between the farmer participants and the scientists, how to work with differing leadership styles in the three communities, the need to identify practices that farmers are willing to adopt, and finding the resources to incentivize adoption. Other new committee activities include plans to conduct focus group sessions with crop advisors from different regions and cropping systems in the United States. All activities are designed to bring together the groups that are addressing herbicide resistance to learn from each other and to discuss field-level solutions.

Committee members have also spent considerable effort reaching out to other organizations and professional societies to inform and engage new groups of stakeholders in the discussion. Several symposia have been presented at WSSA annual meetings; the most recent was a workshop at the 2020 annual meeting titled Building a Community to Battle the Wicked Problem of Herbicide Resistance. Additionally, members have organized sessions or presented at annual meetings of the Entomology Society of America, the tri-societies (i.e., American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America), the 2022 International IPM Symposium, American Association for the Advancement of Science, and National Academies of Science. Some of these audiences were not aware of resistance as a complex issue; the presentations have extended the conversation and are beginning to make more groups aware that pest resistance is a significant threat to overall goals of sustainability in our food production systems.

Herbicide resistance management, which is a component of effective weed management, must be part of overall sustainability objectives. The Herbicide Resistance Education Committee has learned that we need stakeholder engagement from local to national scales to be successful. Engagement across and between stakeholder groups, including federal agencies, academia, companies, growers, and crop advisor organizations, has never been higher in addressing the "wicked" problem of herbicide resistance. In particular, involvement of rural sociologists and economists in the project has broadened the perspective of the weed science committee. The human dimension of herbicide resistance evolution and management was a critical missing part of the conversation prior to their collaboration. Moreover, this partnership has the potential to change approaches to addressing multiple agricultural issues affecting sustainability beyond herbicide resistance. It is not possible to overstate the radical change in thinking that this collaboration has fostered. Because of the diversity of voices and perspectives involved in the conversation, more effective understandings are being developed by all; solutions that may appear simple from one perspective are often impossibly difficult from another perspective. We must work together to find common purpose and develop collaborations to address long-term management of herbicide-resistant weeds, preserve our conservation gains, and protect the environment in an economical and socially responsible manner.

Sustainable Innovation for Human Health and Environmental Stewardship

Development of safe and environmentally benign crop protection products benefits society and the planet. The significance of safe herbicide technology within the context of sustainable weed management should not be understated. Herbicides remain the most used and reliable method of weed control that is economically feasible, and their effectiveness is unmatched compared with other methods; however, their use introduces potential concerns. To provide safe herbicide technology, industry researchers must anticipate project failure and the discovery of safety risks during the development of novel chemistry. This is an important shift in considering and protecting the longevity of novel crop protection solutions, a necessary component in the sustainability of the technology. It is a laborious and continuous cycle to test and retest novel chemistries to ensure robust efficacy on the target weeds, but also to establish safety to the crop, environment, and human health to ensure the sustainability of the product. Applying modern approaches to predicting safety very early in the discovery and development process permits potential human, animal, or environmental concerns to be identified and further investigated before significant resources are expended, thus focusing research on sustainable solutions. Purposeful use of in silico (computer-based) and in vitro (laboratory-based without the full organism) tools to predict the environmental and human health safety profiles of candidate pesticides early in the development process allows developers to focus resources on safe chemistries while helping ensure that pest control solutions contribute to sustainable farming practices. Continual innovation in the development and implementation of in silico and in vitro methodologies to predict safety is supporting a new wave of discovering planet-friendly pest control options.

The world of product safety science reached a tipping point in 2007 with publication of the National Academy of Sciences report on "Toxicity Testing in the 21st Century: A Vision and a Strategy" (NAS-NRC 2007). Outlined in that report was a framework to bring cutting-edge innovations into safety assessments with the long-term goal of sustainable innovation. Since then, significant multisector efforts have occurred to develop models and platforms aligned to turning this vision into a reality. What once seemed like an apparent mirage grows closer to reality as the research community explores a combination of in silico and in vitro approaches to advance toxicity testing methodologies.

Toxicity is a function of intrinsic hazard and exposure; in the toxicologist's fundamental dogma, attributed to Paracelsus, "the dose makes the poison." Some chemicals that are toxic at high concentrations are required nutrients at lower concentrations (e.g., vitamin D; Alshahrani and Aljohani, 2013). Indeed, certain commonly ingested dietary components contain hazardous substances but are overall associated with improved health when part of a balanced diet. For example, roasted coffee contains small amounts of acrylamide, which at high doses has been reported to cause cancer, but drinking coffee has been shown to actually reduce several types of cancer and overall cancer rates (Bagdonaite et al. 2008; Grosso et al. 2017; Herman et al. 2019; Sado et al. 2017).

Developers of pesticides have great economic incentive to identify the potential hazards of a candidate pesticide very early in the discovery and development process. A significant investment (cost ~$300 million; time ~12 yr per molecule) is required to discover and develop a new crop-protection active ingredient (Sparks and Lorsbach 2017; Sparks et al. 2019). Contributing to this cost is the multitude of regulatory agencies that oversee the approval of pesticides and the complexity this brings to their development. There is a regulatory aspect to every step in the development of a new crop-protection product; a product undergoes more than 100 studies to support the human health and environmental safety assessments required for registration, which is often more assessments than required for pharmaceuticals (Swanton et al., 2011). Such studies include assessments of the active ingredient, exposure to the formulation, safe re-entry to fields, persistence, and metabolism in the environment (i.e., soil/water), groundwater leaching potential, impact on pollinators and birds, residues in harvested products, etc. (EPA 2022). Product fate and behavior must be understood throughout their lifecycle and use.

Within this context, there has been an evolution in the safety assessment of pesticides from reactive to proactive to predictive (Figure 1). The path forward includes consideration of the balance between biological efficacy and favorable human health and environmental safety profiles. Corteva Agriscience is doing this through its Predictive Safety Center with the goal of 1) designing solutions to enrich the lives of growers and customers; 2) optimizing and prioritizing research and development investments by predicting downstream challenges; and 3) de-risking and maximizing the probability of safety and regulatory success for the pipeline. At Corteva Agriscience, a combination of in silico models and in vitro assays are used to screen molecules and assess their safety at earlier stages in the discovery process. The endpoints for a safety assessment cover different disciplines across the areas of human health and environmental safety, including mammalian toxicology, ecotoxicology, environmental fate and metabolism, and exposure. In silico and in vitro screening results serve two purposes: first, to provide a relative ranking for discovery molecules from a safety perspective based on the overall safety profile, which informs the decision-making on selection of candidate molecules; and second, to identify potential areas of concerns for the molecules, which may provide information for structure-activity relationship analysis that leads to molecule optimization and re-design.

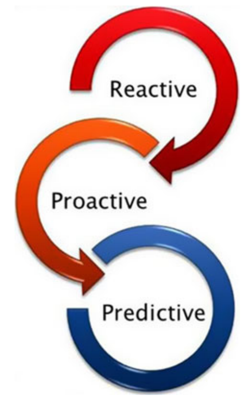

Figure 1. Evolution of safety assessment in the product discovery and development process.

One approach for predicting the toxicity of candidate pesticides involves developing transcriptomic profiles from cultured cells exposed to compounds known to cause specific adverse effects in vivo and developing a transcriptomic "fingerprint" for each adverse effect. The presence of this transcriptomic fingerprint from the same cell lines after exposure to a candidate pesticide can then be used to provide an indication of potential risk (Johnson et al. 2020). Depending on the level of predictability of a specific transcriptomic fingerprint for the adverse effect, the candidate pesticide can be deprioritized or further tested in higher-tier, more definitive assays (either in vitro or in vivo) for that particular adverse effect early in the development process. In this manner, an early indication for the potential risk allows limited resources to be allocated efficiently. Alternatively, analogues of molecules that are found to possess beneficial pesticidal activity, but are predicted to have hazard, can be designed based on in vitro and in silico approaches that are predicted to maintain the beneficial activity while eliminating the hazard (Figure 2).

Another important approach to predicting the toxicity of candidate pesticides uses in silico models based on quantitative structure-activity relationships informed by knowledge of adverse outcome pathways and chemical hazards databases. Essentially, this approach uses previous knowledge of toxicity along with chemical structural information to develop in silico models to predict the toxicity of novel chemicals. Similarly, in silico models, such as GastroPlus, can be used to predict exposure through an understanding of likely bioavailability and metabolic processing in vivo (GastroPlus 2022). Together these in silico approaches predict hazard and exposure, which together predict risk.

Adoption of the predictive safety assessment approach early in the discovery process enables technology developers to design and develop sustainable actives with favorable human health and environmental safety profiles (Herrera et al. 2021). One successful example on how to achieve sustainable solution through the predictive approach is the development of Rinskor™ (florpyrauxifen-benzyl ester) rice herbicide at Corteva Agriscience. A predictive soil-persistence screen guided the optimization of this chemistry by introducing a methoxy group on the phenyl ring of the picolinate scaffold without reducing the high level of herbicidal activity. Rinskor™ possesses highly desirable safety

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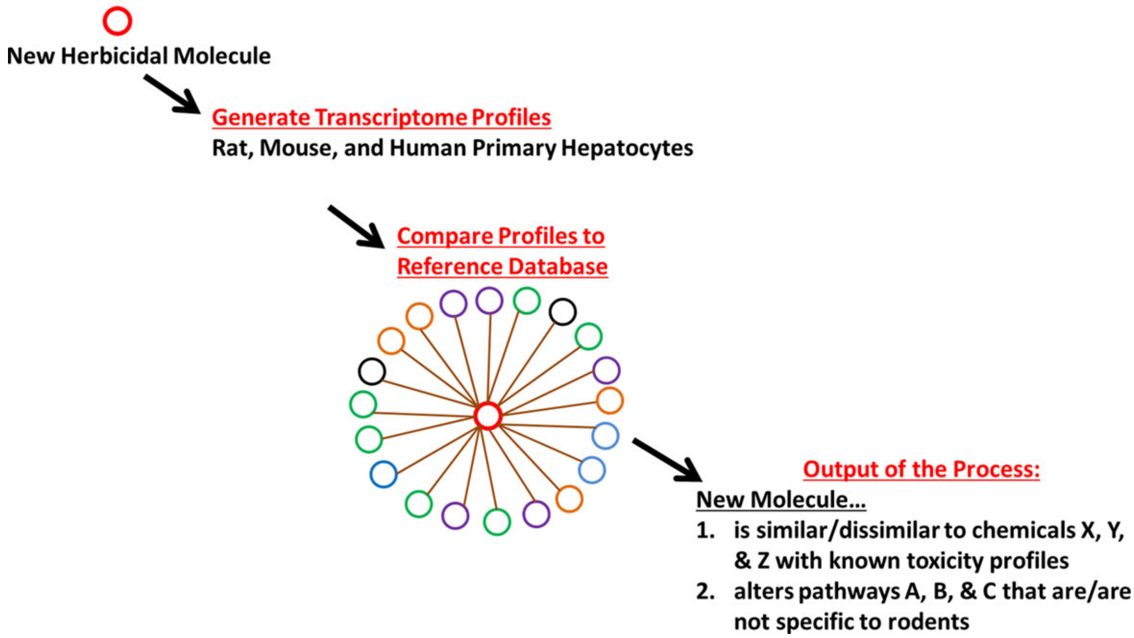

Figure 2. A transcriptomic profiling-based assessment process used to indicate potential risk with limited resources. Molecules with beneficial pesticidal activity, but are predicted to have hazard, can be designed based on in vitro and in silico predictive approaches to maintain the beneficial activity and eliminate hazard.

characteristics including 1) low persistence in soil, water, and plants; 2) a favorable human toxicity profile compared with current market alternatives; 3) low toxicity to nontarget organisms such as birds, insects, fish, and other aquatic organisms; and 4) very low application rates (10 to 30 g active ingredient/hectare) leading to a low exposure risk to farmers and applicators. Due to this outstanding safety profile, Rinskor™ was the winner of the 2018 Green Chemistry Challenge Award, sponsored by the U.S. Environmental Protection Agency's Office of Chemical Safety and Pollution Prevention in partnership with the American Chemical Society's Green Chemistry Institute and other members of the chemical community.

Although improvements in predicting the safety of chemicals advances sustainable innovation, it also could reduce animal testing. However, embracing new technologies is highly variable among regulatory agencies. Thus, reduced animal testing, enabled by improved prediction of safety using in silico and in vitro tools, is likely to progress gradually. The safety assessment community is moving in the right direction, but dramatic reductions in animal use cannot be expected in the short term unless there is widespread acceptance of alternatives by regulatory agencies (Burden et al. 2015). That said, an immediate side benefit of a detailed understanding of the mechanisms by which pest control chemicals exert their activity is that these data are useful in predicting the likely cross-resistance potential within target pest species. This permits new active ingredients to be chosen early in the development process that are likely to be durable in commercial use and improve the durability of existing products with differing modes of action or resistance mechanisms (Rauzan and Lorsbach, 2021). This should result in newer and safer pesticides remaining efficacious for longer periods of time, extending their environmental and human health benefits. Predictive safety tools and approaches have already contributed to sustainable innovation in the weed control industry and continual technical advances will build on this strong start.

Communicating Our Role in Sustainability

With these sustainable weed management topics in mind, it is imperative for weed scientists to have the skill and confidence to engage and build trust with other scientists and community members while sharing the important impact that weed management has on agriculture and food production. More than ever before, today's consumers want to know where their food comes from and how it was produced (Sabio and Spers 2022). This interest goes beyond the basic food labels or country of origin labeling. Consumers are engaged and informed, and they want to know whether their food was responsibly produced and sustainably sourced. They also bring their personal passions to their food decisions, with concerns ranging from whether packaging is recyclable, how much plastics are used, what chemicals were used and how much, what farming practices were used, impact on soil erosion, water quality and wildlife, and whether workers were protected.

As agriculture professionals and subject matter experts, we have an opportunity to communicate how our industry and farmers across the world are using responsible and sustainable products and practices to produce a safe, abundant, and nutritious food supply while protecting our natural resources. Plugging into that growing consumer interest, we can keep the pathway open to continue helping farmers feed the world and keep our planet healthy. We ensure the future of our industry by telling our story and leading the narrative about sustainable agriculture in an honest, open, and relevant manner.

Farmers and producers want us to do this. They want us, as fellow colleagues in the agriculture industry, to lift their voice and share their knowledge. For many years, farmers were hesitant of telling their story or sharing photos from their farm in fear of public scrutiny or false accusations. That has changed. Farmers are opening their doors and tractor cabs, offering farm tours, and sharing their experience on social media—all to show the public how safely food is produced and to shape the conversation in the marketplace.

Table 2. Communication tactics to lead the narrative about sustainable agriculture in an honest, open, and relevant manner.

Goal	Action step
Share what you know with those closest to you first	Listen, share, and answer questions about what you do every day with close family and friends to increase your comfort level and influence when it comes to sustainability communications.
Ask questions to identify your shared values	Update your social media profile; include information that relates to sustainability and common values. Invite others to engage in conversations about your shared interests.
Prepare for your communications by crafting your authentic message in advance	Prepare for a future opportunity to share and explain your key message point. Write it out, practice it and rewrite it until it comes naturally in your own voice
Baby step into social media	Take 10 min regularly to find and follow organizations and associations that use social media to advance science-based messages about agricultural sustainability. For example, Weed Science Society of America is on Facebook @Wssaweedsnow and on Twitter @Worldofweeds. LinkedIn is also a platform that many organizations use.

Just as farmers around the world are finding ways to share their stories in ways that fit their personality, farm, and passion, there are many opportunities for us as agricultural professionals to share our role in advancing agricultural sustainability. This doesn't mean you need to add professional communicator to your job title. It means finding ways that fit your interests, passions, and available time.

Here are four simple ways to start (Table 2):

1. *Share what you know with those closest to you first*

Effective communications start with knowing your audience. Figure 3 illustrates the level of influence we have with groups of people.

Our communications are most effective and influential with people whom we already have a close, personal relationship. With each additional layer of distance in your relationship, it is more challenging to influence the people within that group. You may need to use broadcast communication methods, such as speaking at events and social media channels. These tactics are potentially less influential in changing deep-seated beliefs, but still important to the overall effort.

Action step: *Listen, share, and answer questions about what you do every day with close family and friends to increase your comfort level and influence when it comes to sustainability communications.*

2. *Ask questions to identify your shared values*

As today's society is more and more segmented, it is our shared values that bring us together to build trust and foster collaboration. Taking time to identify the values that are important to the person with whom you are communicating is key. The first step is understanding their point of view, and then determining what information you can share that addresses not only their position on a specific issue, but also their deeper values. Ask questions to seek common ground. For example, if you are communicating with a fellow parent, you can open the conversation with a statement about how you care about the safety of children or your desire to buy healthy food for your family. Or maybe you share a love of nature, parks, or scenery and want to see them preserved.

Action step: *Update your social media profile. Include information that relates to sustainability and common values. Invite others to engage in conversations about your shared interests.*

3. *Prepare for your communications by crafting your authentic message in advance*

What's your core belief about sustainability? Perhaps, it's the ability to advance sustainable tools and technologies to ensure the long-term economic, environmental, and social viability of our global food system. It's how we will feed our planet and protect its natural resources for generations to come.

In your role, you may have a slightly different perspective and insights. Can you verbalize them? Take time to think through your authentic core beliefs—what you want others to know about sustainability.

Draw upon your values, background, and role. Ask yourself:

- What do you know for sure? For example, a statement such as "Crop protection has a place in achieving the high yields we need to feed a growing world population."
- How can you translate what you know for others?
- What is your passion point?
- How can you make sustainability part of your personal brand?

Action step: *Prepare for a future opportunity to share and explain your key message point. Write it out, practice it, and rewrite it until it comes naturally in your own voice.*

4. *Baby step into social media*

Social media can be both a wonderful and intimidating platform for communication. There are several easy entry points that will help increase your comfort level when using it for communicating about sustainability issues. Simply "following" and "liking" are easy ways to amplify sustainability messaging in the marketplace and uplift messaging that will engage others. You can help to build the following and the strength of the voice of organizations and influencers who are shaping a positive narrative of agricultural sustainability.

Action step: *Take 10 minutes regularly to find and follow organizations and associations that use social media to advance science-based messages about agricultural sustainability. For example, WSSA is on Facebook @Wssaweedsnow and on Twitter @Worldofweeds. LinkedIn is also a platform that many organizations use.*

In summary, you play an important role in building trust with consumers and other stakeholders and in ensuring the long-term viability of our industry. Use these simple tactics to start.

Conclusions

Establishing a comprehensive review on historical, current, and future components of sustainable weed management is an astounding task. In light of the cultural interest in sustainability,

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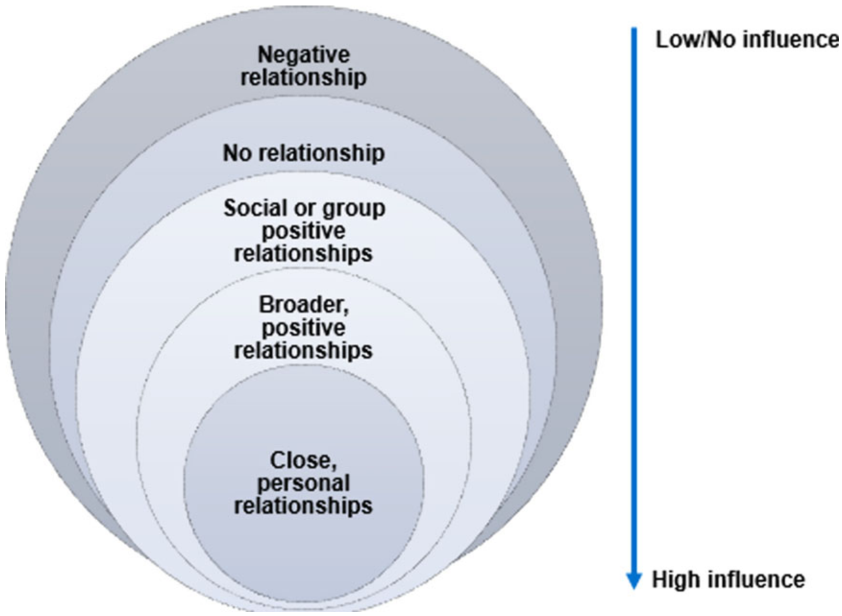

Figure 3. Correlation between influence and the strength of various types of relationships. The highest influencers tend to be people or groups that individuals have the closest relationships with and who possess the most credibility (Belanche et al. 2021).

the goal of this symposium review was to launch the conversation on sustainable weed management and highlight the significant focus of the discipline to provide sustainable solutions for global crop production. It is imperative to examine the multifaceted aspects of sustainable weed management practices and expand to consider sustainability within all aspects of agriculture. New technologies are a necessary component of sustainable weed management practices, but it is also imperative to understand the many practices within the discipline that are sustainable, such as crop rotation, reduced tillage practices, integrated weed management approaches, using multiple modes of action to combat herbicide-resistant weeds, and more. Finally, all weed scientists connect with the public, and we hope that providing some insight on thoughtful and impactful communication will help them understand the concerns of the public and help spread the word of sustainable weed management, particularly those who are passionate about food systems and agriculture.

This is a call to action for all weed scientists to think critically and make the connection between their research project and sustainability, both in conversation with the public and other scientists. By examining the many dimensions of multi- and cross-discipline collaborations and taking initiative to think creatively and critically, weed scientists can better position our sustainable approach to agriculture and expand the impact of our research. It is particularly important for today's students to reflect on their research objectives and consider the impact of their work on sustainable crop production and be prepared to highlight this significance when communicating their work. By addressing the impact of our research on the environment, humans, agriculture economics, and beyond, we can provide broad insight to others on how weed scientists understand and work to address these diverse needs.

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