PERSPECTIVE

The Future of Weed Science

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Abstract

Agricultural scientists, farmers, ranchers and the agriculture industry remain confident of their basic faith in the possibility of continued increasing production through the intelligent use of ever more efficient agricultural technology and research. Increasing production has been and remains the accepted way to achieve the moral obligation of feeding a growing population. Given that weeds are an obstacle to increasing food production, but not necessarily the only one, managing weeds in an integrated way is an important factor to consider in global agriculture. In this essay, I pose a number of questions concerning agriculture's moral justifications and ethics, as concerns of widespread human impacts and environmental harm of agriculture are felt, along with public fear of technology and food quality standards.

Keywords: Ecology, Ethics, Agricultural ethics, Integrated Weed Management, Herbicides, Pesticides, History, Island Empire, Values, Weeds

Introduction

We can, of course, be deceived in many ways.

We can be deceived by believing what is not true, but we certainly are also deceived by not believing what is true.

…………………….Kierkegaard - *Works of Love*.

I have chosen to begin with a topic that does not immediately relate to climate and weed management but, in my view, affects global food security. Those familiar with my writing will not be surprised that my topic is agricultural ethics (Zimdahl and Holtzer, 2018; Zimdahl, 2018; 2022). Nevertheless, it is a philosophical reflection on the future of weed science and agriculture. My presentation is a challenge to you. My comments on the future directions of weed research and technology will follow a consideration of what agricultural ethics is.

Agriculture Ethics

Universities routinely include ethical study in the curriculum for medicine, law, business, and the environment. Agriculture, the essential human activity and the most widespread of human interactions with the environment, does not. The agricultural science curriculum lacks consideration and study of the effects of agriculture on society and the environment. Ethics has not been institutionalized in Colleges of Agriculture, agricultural professional organizations, or the agribusiness industry. That is not to say there are no professional ethical standards.

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Many assume agriculture has an adequate ethical foundation. The assumption is not questioned. There has been too little investigation and too little critical thinking about the lack of and need for an ethical foundation.

Agriculture has scientific challenges: achieving sustainability, maintaining production, pesticide and antibiotic resistance, invasive species, loss of biodiversity, biotech/GMOs, and pollution. Those involved in agriculture believe that the development and use of more energy-dependent technology is always good and that more will be better. It will address the need for production, address the problems caused by the unintended consequences of present technology, and alleviate public concern.

I do not mean to imply that we should abandon science and technology. We humans, the earth's dominant species, are not just figures in the landscape — *we are shapers of the landscape* (Bronowski, 1973, p.19). Having achieved this power, we should think carefully about whether what we do is desirable. Although all involved in agriculture know what they are doing, they should think about what they may be undoing.

The moral imperative is to produce food and fibre to benefit all humanity. Production is what must be sustained. Agriculture's producers, suppliers, and researchers, regardless of their employer, should ask if production is a sufficient criterion for judging the consequences of all agricultural activities. *Does increasing production justify everything agriculture does? Does it achieve sustainable production practices? Does the quest to increase production solve or even address agriculture's moral dilemmas?*

Agricultural scientists have assumed that as long as their research and the resultant technology increased food production and availability, they and the end users were somehow exempt from negotiating the moral bargain that is the foundation of the modern democratic state (Thompson, 1989).

It is unquestionably a moral good to feed people. Therefore, it is assumed that anyone who questions agriculture's morality or the results of its technology simply doesn't understand the importance of what is done and how it is done. It is assumed that agricultural practitioners are technically capable and that the good results of their technology will make them morally astute.

When those involved in agriculture claim credit for improving production and keeping food costs low, they must also accept society's right to hold them responsible for problems often regarded as externalities. They need to ask and be prepared to respond to what has not been asked often enough. *What could go wrong? What has gone wrong? What are the appropriate responses?*

We live in a post-industrial, information-age society. No one will ever live in a post-agricultural society. Continuing to justify all agricultural activities and technology by the necessity of achieving the moral obligation and production challenge of feeding a growing world population has not been and will not be a sufficient defense for agriculture's negative environmental and human effects. We are disturbing and changing the climate and our planet's ecosystems at a pace and scope never seen in human history (Friedman, 2016).

What is the problem? Feeding the 11 billion expected to be on the planet at the end of this century is undeniably a good thing. *Is it a production problem?* Of course, it is. But enough food is produced now to feed the global population.

Nevertheless about 810+ million people still go hungry every day. After steadily declining for a decade, world hunger is on the rise, affecting 1 of 9 of the world's people. From 2019 to 2020, the number of undernourished people grew by 150 million, a crisis driven largely by conflict, climate change, and the COVID-19 pandemic.

In spite of the abundance of food, people are hungry in many countries because of inadequate food distribution, inadequate infrastructure that delays or prevents food distribution, food storage waste, waste by consumers, government policies, and poverty. *More production will not solve the hunger problem* (Sen, 1999).

It is obvious citizens of democratic societies are becoming increasingly reluctant to entrust their water, their diets, and their natural resources blindly into the hands of farmers, agribusiness firms, and agricultural scientists. Ethicists and agricultural practitioners must initiate and participate in a dialogue that leads to social consensus about the effects of agriculture's technology, its risks, and reasonable solutions. In the past, most risk was borne by users of the technology. Now there is widespread concern the risks and short- and long-term consequences of agricultural technology are borne by others.

Agriculturalists must begin to contribute the time and resources needed to listen and explain their positions and understand those of their fellow citizens. All involved in agriculture and those who enjoy abundant societies must recognize they are dealing with how we ought to live.

Agriculture practice, research, and teaching involve scientific and ethical values. Feeding the growing world population is clearly a very good thing, but it does not absolve the agricultural community from critical, ethical examination of the totality of agriculture's effects.

People throughout the world have rational concerns about the ethical dimensions of agriculture and our food system that go beyond the central need to feed humanity. Each of agriculture's multiple responsibilities includes an ethical dimension. These include:

- Achieving sustainability, resolving pollution of water and soil while assuring the availability of surface and groundwater.
- Stopping harming other species, cruelty to animals and habitat destruction.
- Stopping exploitation and inhumane treatment of farm labour, stopping the loss of small farms and rural communities.
- Considering the power of corporate farming and its lack of transparency, stopping the harmful treatment of animals.
- Addressing public concern about biotechnology and genetically modified organisms (GMOs),
- Stopping the losses of crop genetic diversity and addressing public concern about the nutritional value of foods provided by the food system.

These are not just scientific problems. We should not expect scientists alone to solve them. Leaders of the agricultural enterprise should work together with others to identify, discuss, and address them. Collective action is required to achieve morally good goals. Agriculture will gain little if it wins the production battle and loses the moral battle.

Agricultural education has given too much emphasis on what to think rather than how to think. Universities have traditionally been places where different opinions were welcomed and encouraged. The present trend toward specifying what controversial topics may or may not be welcome is disturbing. It stands in sharp contrast to the role of teaching - to lead out - to educate. Encouraging students and the general public to be aware of and discuss difficult, controversial issues is an important role of education and those who teach.

There are 1459 universities in the world with agricultural faculties. Forty US universities (Weed Science Society of America, 2023) and 78 international universities have departments of weed science (Ahmad et al., 2023). Only six US universities have a course on agricultural ethics. The worldwide agricultural curriculum lacks courses that focus on general ethical principles and their application to agricultural issues.

It is my view the lack of university courses on agricultural ethics in the USA is because the faculty who teach, plan the curriculum, and advise undergraduate and graduate students do not regard studying the ethical values of agriculture as important preparation for agricultural professionals.

When I was a student I was never advised to enrol in a class in philosophy, and I suggest my professors and their mentors were not advised. The present faculty is also not interested in or does not care to cooperate with a colleague in the Department of Philosophy to create a class on agricultural ethics and encourage students to enrol.

Such classes will be a recognition of the need to acknowledge and discuss agriculture's ethical dimensions. Agriculture has (Zimdahl and Holtzer, 2016) problems that have focused attention on production and profit, while education and practice have ignored agriculture's human and ethical dilemmas (Damasio, 1994).

Professors, Department heads, and Deans of colleges of agriculture who have not chosen to address agriculture's ethical dilemmas are contributing to the problems. There is a clash between the environmental and human harm of modern agricultural production and the values held by the general society and those who practice agriculture. Ignoring value conflicts and societal concerns will lead to a loss of public support and trust in agriculture.

Our technology may outweigh our character. We hold at the level of our training - our education. We risk becoming moral people in an immoral profession (Niebuhr, 1932). "*He who knows only his side of the case knows little of that*"(Mill, 1859). We must begin to interact and listen to people who don't share our beliefs and who confront us with evidence and counter arguments (Haidt, 2022).

What we resist pursues us. What we accept transforms us. We are a mass audience consuming the same content while looking in a mirror reflecting the view we have (Haidt 2022). My experience has shown students may be more willing than the faculty to question and explore outside the agricultural curriculum

When the morally good goal of feeding a growing world population bumps up against the morally good goal of protecting the environment, one is confronted with value questions that science is not designed to answer. When the environment's natural objects are valued only in terms of their worth to humans, they can be legally destroyed or modified.

I offer a few examples of what we have and are doing. We cut down original forests, till the prairies, irrigate deserts, dam and pollute streams, overgraze hillsides, flood the valleys, and prevent forest fires. We have changed the climate and acidified the oceans. Little, if any, attention is paid to the inevitable environmental consequences: ocean hypoxic areas, soil erosion, melting ice, species extinction, and invasive species. Our predatory self-interest dominates our environmental concern.

As Kolbert (2022) correctly noted – '*It seems normal to send in the bulldozers, chainsaws, and backhoes to cut down the trees, fill the wetlands, and "develop" the land'*.

Until something or someone receives a right granted by law or public pressure, we often see the environment as something for our use. The objection that streams and forests cannot speak has been addressed. Neither corporations, States, estates, infants, incompetents, municipalities, nor universities can speak. These entities are amply represented - some might say overrepresented - in the courts.

We make decisions on behalf of and in the purported interest of others every day. The other creatures (e.g., soil microorganisms, pollinating insects), whose wants are far less verifiable, may be more important. They are more metaphysical (the fundamental nature of reality) in conception than the wants of rivers, rocks (Nash, 1977), trees (Stone, 1972) and the human benefits from and obligation to them.

Is it possible for human intelligence to increase the range of benevolent impulses and encourage us to consider the needs and rights of other humans in addition to the things to which we are bound by organic and physical relationships? Can we transcend our own interests to grant rights to the interests of our fellow humans and the creatures in the environment? If agriculture's practitioners continue to ignore agriculture's moral dilemmas because we must produce they may lose the right to determine agriculture's future and jeopardize our chances of surviving on this planet (Berry, 1977).

Suppose we fail to institutionalize the study of the ethics of agriculture. In that case, we will not learn how to ask and discuss moral questions. We should not continue to defend only the interests of agriculture when there are obviously unjust effects on the interests of the planet and our social communities. Human ingenuity has increased the treasures nature provides for the satisfaction of human needs; it will never be sufficient to satisfy all human wants.

Predictions of the future for weed science and agriculture are always tempting, often successful, and usually hazardous. If all parts of the agricultural enterprise, including professors, farmer/rancher producers, agribusiness firms, food processors, and sellers, do not begin to recognize and address agriculture's ethical dilemmas, three unwelcome outcomes may follow:

- Firstly, agriculture practitioners may find their arguments and justification for their technology and production practices ignored.
- Secondly, public unease and dissatisfaction with known and perceived effects of agricultural technology (e.g. pesticides, cruelty to animals, farm labour, and food quality) will result in increasing societal unrest and pressure for political action. Decisions on how agriculture can be practiced and how land is to be treated will be made by society and the government.
- Thirdly, The increasing concentration of food production in the hands of agribusiness companies will continue. Small farms, farmers, and rural communities will continue to gradually disappear.

Agriculture is a capital-intensive, high-tech business. Rather than wait to see if appropriate levels of sustainability and resilience can be achieved by the present capital, chemical, and energy-intensive system, agricultural people could begin to learn how to impose ethical standards on themselves. Because agriculture is a diverse, widespread enterprise, reaching an agreement will be difficult but not impossible.

Recognizing the possible undesirable outcomes and choosing to act wisely will help maintain the essential industry. I challenge you to consider some hard questions that will affect your future: *What does it mean to live well? What matters? What needs and values do you live by?. What needs and values ought you live by?*

The Future of Weed Science

Now, I turn to comments on the future of weed science. It is not another challenge, but I hope my comments make you think. Weed science, although young among the agricultural sciences, has an enviable, rich, productive history and will continue to contribute to agriculture, other disciplines, and food production. Weed control was a necessity recognized by farmers who had been controlling weeds long before herbicides were invented.

Herbicides changed the way control was done, but not its fundamental purpose —to improve the yield of desirable species. The chemical energy of herbicides replaced human, animal, and mechanical energy. No other method of weed control was as efficient at reducing the need for labour or as selective. People with hoes could distinguish weeds from crops and weed selectively.

Mechanical and cultural methods, while effective, were not selective enough. Herbicides enabled prevention, reduced weed populations, and selectively removed weeds from crops. Weed control in the world's developed countries now depends on herbicides. This situation will prevail well into the 21st century.

A Problems

Seven important problems (below) have and may continue to hinder the progress of weed science.

1. The assumption that anyone can control weeds is made by those who do not understand the complexity of agriculture or weed management. Marshall (2010) reinforced this assumption with the misconception that weed science is easy and, more importantly, has all the answers to weed problems, which it does not. Environmental and production demands will require significant adjustments in weed management and agricultural practice.
2. Although weeds have been and will continue to be components of agriculture and the environment, they lack the attention, appeal, and urgency of sudden infestations of other pests.
3. Weed science lacks foundational hypotheses "linked to established bodies of ecological and evolutionary theory to provide deeper theoretical justification, a broader vision, and increased collaboration across diverse disciplines" (Ward et al., 2014).
4. There is a lack of people and research funds (Davis et al., 2009). Research on weed biology, ecology, seed dormancy, and other problems leading to basic understanding rather than immediate control is done by too few scientists. Publicly funded interdisciplinary agricultural research has lacked adequate funding and, it seems, will remain so for decades.
5. Underlying all agricultural issues, there is always an unexamined ethical position (Zimdahl, 2022). Thompson (1995) pointed out there is only one imperative to produce as much as possible, regardless of the environmental/ecological costs and perhaps even if it is not profitable. Agricultural people cannot escape responsibility for societal views of its effect on the environment, other species, and themselves. Agriculture's views on ethical issues have not been and should be examined.
6. All in agriculture know farming is crucial to all economies (Economist, 2022) and important to the welfare of all. The public in most societies is certain food is important but is abysmally unaware of the complex processes and people who provide their food.
7. Climate change and lack of appropriate weed control practices will affect farmer's ability to produce. Modern agricultural technology developed country farmers rely on is beyond the reach of poor farmers in the developing world. More than 90% of farmland in Africa has no irrigation, 1/3 of the world's people, and 60% of Africans do not receive warnings of impending natural disasters or routine weather forecasts. Agriculture's admirable goal of feeding an expanding world population in a warmer, dryer climate would benefit from expanding its horizons beyond developed country farmers.

A few conflicting claims illustrate some future challenges for weed science.

1. Moss (2008) charged the overall direction of weed research was wrong. There was too much emphasis on scientific effect at the expense of practical application. Moss argued weed science was weed technology. He suggested his colleagues lacked an awareness of the complexities and resources needed to translate research results into actions for farmers.
2. Ward et al. (2014) claimed two broad aims have been driving weed science research: improved weed management and improved understanding of weed biology and ecology. Research has developed a very high level of repetitiveness, a preponderance of purely descriptive studies, and has failed to clearly articulate novel hypotheses linked to established bodies of ecological and evolutionary theory. Although Ward et al. (2014) noted studies of weed management remain important, they urged weed scientists to recognize the benefits of deeper theoretical justification, a broader vision, and increased collaboration across diverse disciplines (especially ecology). One might conclude weed science research has not been as good (weeds, like the poor, are still with us) as many colleagues think it has been.
3. Swanton (2022) accused weed science of being primarily reactive. Scientists responded to current needs and worked to solve on-farm problems. He recommended that the discipline make long-term thinking automatic and common instead of rare. Long-term thinking is required because weed science, a sub-discipline of agriculture, must begin to answer complex questions regarding cropping systems and environmental challenges.
4. The Editor-in-Chief of Weed Research (Marshall, 2019) introduced "the post-herbicide era of weed science". He argued this was "increasingly prescient as herbicides continue to face the ever-increasing legislative restrictions and the challenge of evolved resistance. They are key influences on the practice of intensive agriculture, whose success is intimately linked to the heart of the planetary crises: climate

change, global warming, loss of biodiversity, environmental harm, etc.

5. Buhler (2006; 2017) argued weed scientists must develop integrated cropping systems and weed control strategies in a comprehensive, environmentally and economically viable system. This approach would "help reduce economic effects and improve weed control practices." Herbicides will continue to be an essential part of integrated cropping systems.
6. Westwood et al. (2018) claimed weed science was at a "critical juncture" because decades of chemical control have dramatically increased herbicide-resistant weed populations. The problems were critical because there were few new herbicides, new modes of action, and no economically acceptable alternative to herbicides in large acreage crops. They suggested new modes of action could be discovered using genetic engineering, computing power, automation, employment of artificial intelligence and machine vision to improve weed management.
7. Gould (2002) portrayed the situation well by contrasting "immediate and practical" with "distant and deep" issues. Immediate and practical issues are about potent and unanticipated effects (e.g. herbicide resistance). Distant and deep issues include legislative, ethical, aesthetic and practical consequences of altering agriculture's fundamental geometry and permitting scientists in the developed world to change the way agriculture is and ought to be practised. He advocated proper development and use while giving adequate, proper consideration to human and environmental health, agricultural progress, and sustainability.

In this review, I deal with thoughts about the future weed science research, but not in terms of what will be accomplished. It is conjecture, not prophecy. It might be best conceived as a proposal of what ought to be done. It may not be what will be done because research does not always follow a straight path, and other developments may change what is desirable and possible. For example, environmental legislation mandating reduced herbicide use could rapidly change the way agriculture is practised.

A description of research needs is a safer prophetic stance. It describes what could be done rather than describing what the situation will be several years hence. This approach, of course, reduces the possibility the prophet may be wrong.

B Research Needs

Dependence on herbicides for weed control is equivalent to treating the symptoms of a disease without actually curing the disease. Agriculture would be far better served if weed scientists learned how to control weed seed dormancy and seed germination so weeds could be prevented rather than controlled after they appear. No one knows enough about weed seed dormancy, and much research remains to be done to reach the prevention goal.

Throughout this essay, the emphasis will be on the two major goals put forth by Ward et al. (2014):

1. Discussion and debate of appropriate goals and the pathways necessary to achieve the goals;
2. Rediscovery of the ability to pose critical research questions designed to advance the theoretical underpinnings of weed science.

Weed science began when herbicides (e.g., 2,4-D) made control possible without studying much about weeds. Those who controlled had to know what weeds were to be controlled and where they were growing. That is, control was not blind. There are objects to be controlled, and they are known. But, with herbicides, it has not been necessary to know much more about weeds.

In general, herbicide development has neither exploited weak points in a plant's life cycle nor used specific physiological knowledge for control purposes. The safest approach has been to aim for complete control of weeds in a crop. As knowledge grows, scientists find some plants may be beneficial and should not be controlled (Chandrasena, 2023).

A series of projects could be developed to study the regulation of seed and bud dormancy of perennial weeds and the development and life of reproductive propagules (Wyse, 1992). Population genetics and modelling of crop-weed systems will contribute to improved weed management.

C Weed Ecology

Important insights on the future role of weed ecology are found in two recent papers - Neve et al. (2018; 35 authors) and MacLaren et al. (2020; six authors). Both papers support the increasingly dominant claim that the present weed management system is unsustainable because of its many negative effects and dependence on chemical, capital, and petroleum energy.

Both papers strongly advocate combining multiple known weed management techniques in a new integrated weed management system. The creation of an integrated system based on agro-ecological approaches will require multi-disciplinary - trans-disciplinary participation. A host of other authors (Buhler, 2006; 2017; Young, 2012; 2020; Jordan et al., 2016; Young et al., 2017; Swanton and Valente, 2018; MacLaren et al., 2020) have also advocated strongly for the incorporation of weed ecology into integrated weed management systems.

MacLaren et al. (2020) argue that "new herbicides, gene editing, and seed destructors do not address needed systemic challenges and are unlikely to provide sustainable solutions".

Neve et al. (2018) advocate a better understanding of weed evolution, climate change, weed invasiveness" and, perhaps the greatest challenge, "*disciplinary challenges for weed science*". Neve et al. (2018) advocate as a solution, the "*integration of agro-ecological weed management with socio-economic and technological approaches*".

The scientific system that helped create these problems accepts credit but resists accepting blame for negative effects, therein is part of the tragedy. It is an example of the agricultural mindset and justifies Mayer and Mayer's (1974) conclusion – "the system is unsustainable". Their second claim - the integration and isolation of the system have led to what they call – "*The Island Empire*". Agriculture is a vast, wealthy, powerful intellectual and institutional island. The Land-Grant system created Colleges of agriculture and allowed agriculture's isolation within the university and from mainstream American life.

Mayer and Mayer (1974) accused agricultural colleges of being separated from the university, mainstream scientific thought, and national discussions about social policy. Agriculture does not ask for and only reluctantly receives outside criticism. They said: "Those who practice agriculture must move off their 'island".

Much of the basic information required to develop computer-based models of weed-crop systems and available control techniques has come and will continue to be derived from weed biology and ecology research. What plants compete for and when competition is most severe between crops and weeds is known in sufficient detail to be useful in the development of weed-management systems.

The still-used (Dawson, 1965) period threshold concept of weed competition affirms that weed competition is nearly always time-dependent. Seedling weeds at crop emergence are less detrimental than those emerging later. This principle led to the timely use of herbicides and other techniques for weed management. Some crop cultivars are more competitive and this needs to be considered in developing integrated weed management systems. It is a basis for cooperative work with plant breeders.

Weed populations change with time, and reasons are beginning to be understood. A major challenge presently dominating weed research is the appearance of herbicide resistance, often after only a few years of use in one field. Active research is coupled with the development of techniques to combat it. When resistance occurs, it does not lead to totally unmanageable weed populations because other weed-control techniques (e.g., cultivation, crop rotation) and other herbicides are available.

Understanding why populations change, and management of population shifts is important to the development of successful, sustainable weed management. However, as Harker et al. (2012) note, the best way to reduce selection pressure for herbicide resistance is to reduce herbicide use, although the dominant weed-management programs continue to advocate herbicide use.

Even casual observers of the world of weeds will recognize weed problems have changed (see Van Wychen, 2016; 2020; 2022; Fernandez-Quintanilla et al., 2007). Some of the most difficult weeds in most crops today were not important 10 or 20 years ago. This is evidence weed scientists have developed successful solutions to some weed problems. It is also true that many common weeds (e.g., pigweeds, lambsquarters, velvetleaf, Canada thistle, cheatgrass) have been targets of control programs for many years. Thus, we have simultaneous evidence of success and continuing problems.

It is also evidence that nature abhors empty niches. When successful control efforts have reduced the population of a species, they inevitably leave space unoccupied and resources unused. Other species move into empty niches created by successful weed control.

Solutions to this dilemma take two forms. The first solution is to reduce the attractiveness of the niche. Farmers typically overprovide for crops. Fertilizer placement and precise rate recommendations have reduced surplus nutrients, but nitrogen runoff due to excessive application is a significant problem with notable externalities. Whole fields are irrigated, and light cannot be controlled. If water could be placed (e.g., drip irrigation) as precisely as fertilizer and only as much was provided, the attractiveness of the niche and the success of potential invaders could be reduced = preventive weed management.

The second approach has elements of prevention. Some of the important problem weeds of the next decade are already in fields or lurking on the edges. If they were identified and their weedy potential determined, weed scientists, cooperating with ecologists (see MacLaren et al., 2020), could try to predict those most likely to be successful invaders. They could be managed before the invasion. Invasive plant management is now a major area of weed science research, as indicated by the 2008 launch of the Weed Science Society of America's journal *Invasive Plant Science and Management*.

Basic biological-ecological knowledge is essential to either approach. Without it, weed scientists may be doomed to endure the Red Queen effect (a character in Lewis Carroll's classic book *Through the Looking Glass* - 1871). The Red Queen tells Alice, "In this place, it takes all the running you can do to keep in the same place". Weeds and their control, especially with herbicides, seem to be evolving at about the same rate. In trying, and often succeeding, to eliminate weeds from fields, weed scientists have created, in a sense, better, more ecologically successful weeds while accepting herbicide's negative environmental effects.

A difficult and central issue for weed science is understanding the nature of weeds: What makes a weed a weed? How can weeds consistently come out ahead when matched up against the finest commercial varieties plant breeders have developed? Weeds persist, they spread, and they out-compete crop plants, reducing yields when left uncontrolled. Weeds are not conscious, but they seem to be clever. The nature of the competitive ability weeds possess seems an interesting target for research and an appropriate target for analysis through the generation of mutants.

Goethe's "The Sorcerer's Apprentice", Mary Shelley's "Frankenstein", and, more recently, Michael Crichton's "Jurassic Park" reinforce the often inchoate fear of intelligent, rational concern about a powerful form of life manufactured with good intentions but excessive hubris, which might one day slip out of control (Specter, 2016).

The 1950s gave us catchy phrases that still resonate—*Better Living Through Chemistry and Atoms For Peace*. We don't hear similar things now. Chernobyl/Fukushima nuclear reactors, Agent Orange, space shuttle crashes, thalidomide, ozone destruction, pesticides in food, and climate change dominate the public's thoughts. Scientists clearly solve problems, yet, in the public's view, untoward problems continue to occur.

These well-known problems, combined with human drug disasters, have made people suspicious of the efficacy and trustworthiness of science and scientists (Lemonick, 2006). It is in this context public doubts about genetic modification of anything are raised and must be addressed. Weed scientists and others involved with GM technology often think they could educate/tell people about what they do (William et al., 2001).

Education is important, but careful listening followed by a conversation among equals may be better, especially at a time when science has made mistakes and is regarded with well-founded suspicion. Weed scientists should not regard themselves as the only acceptable arbiters of how developments in their science should be created and used. Because of public perceptions of greed, a bit of arrogance on the part of developers and a misunderstanding of science, many people view genetic modification as a hazard, not salvation, and reject it (Specter, 2016).

D Education

A review of some published articles on the future of weed science reveals few comments on the role of education. Research and appeals for more funding (Davis et al. 2009) dominate. There is at least one undergraduate weed science class at all US Land Grant universities and several others required of undergraduate and graduate students. The absence of discussion of what students ought to know among those who teach is disturbing.

Surely, the education of the next generation of weed scientists with "innovative and diverse teaching practices", advocated by Chauhan et al. (2017), is as important to the collective future of weed science as biotechnology, invasive species, and new herbicides. If it is, why isn't education closer to the top of the future agenda? We must integrate weed management and education.

E Other Challenges

A. Scientific

Several other research areas should be considered when planning weed science's future. They include:

- The value, advantages, and disadvantages of monoculture agriculture.
- The role of companion cropping and regular inclusion of cover crops in weed management? Can weeds be cover crops? (See Young, 2020).
- The long-term effects of soil erosion after regular ploughing and cultivation? One effect is all too apparent in the brown colour of many country rivers (Logan, 1995; Montgomery, 2007).
- The future and influence of perennial crops.

Weed scientists were not too concerned with long-term effects when the science was developing. Weeds decreased crop yield — a detrimental long-term effect. The vision did not extend much farther because solving the weed problem was a sufficient challenge. Any technology used for enough time has demonstrable environmental and social effects.

A longer-term view will help reveal these effects and compel their consideration before widespread use is achieved.

- Weed scientists must begin to work more closely with economists who ask, what does it cost and what is it worth? What is it worth to do the work to develop a more competitive cultivar, deplete the soil seed bank and achieve assurance of 80% or 100% weed control?
- What will it be worth to be able to predict weed problems? No one knows, but the answers are important to IWM systems.
- How will nanotechnology affect weed science? Nano integrates biological material with synthetic materials to build new molecular structures. Synthetic biology goes beyond moving existing genes to creating new ones programmed to perform specific tasks. It operates at the nanoscale (one billionth of a meter = 10^{-9}m) of living and non-living parts. It has enormous potential for good and harm (Shand and Wetter, 2006).

Weed scientists are aware of the scientific research opportunities and challenges. There are equally important, although less discussed, social and moral challenges. The primary goal of agricultural scientists has been to develop technologies that enable achieving the maximum yield of a few crops in the world's developed (rich) countries. It is a good goal, but one must ask if it is the right goal (Kirschenmann, 2012; Zimdahl, 2022).

Is it more important than enabling the poor of the world to feed themselves? Can the seemingly unending task of discovering new technologies to maximize yields lead to a sustainable agricultural system to feed 9 billion or more people? Is maintaining rural communities a proper goal for agricultural science, or is that someone else's task?

Should achieving maximum yield and profit always take precedence over preserving the environment? Liu et al. (2015) found cultural practices with negative effects on global food production. "It is crucial for agricultural sustainability to increase crop yields and simultaneously decrease environmental impacts of agricultural intensification".

B. Sustainability

Achieving sustainable agriculture is a goal all agricultural scientists share. Even a cursory review of current writing on agriculture reveals achieving sustainability has obtained the generally revered status of motherhood with one important difference.

There is little debate about what motherhood is or its worth and goodness. The difference is in spite of the nearly universal adulation of agricultural sustainability, *there is little agreement on its nature, what is to be sustained, or how it is to be accomplished* (Zimdahl, 2022, p. 135).

Production is and always will be important, but it is not possible to create sustainable agriculture without a sustainable culture. The reverse is also true (LeVasseur, 2010). It is impossible to have a serious, comprehensive discussion of sustainable agriculture without including community and culture (Holthaus, 2009). Within the agricultural community achieving sustainability is viewed as mainly or wholly technical in nature. It requires different farming methods and the adoption of alternative technologies (Morgan and Peters, 2006), which will be significantly aided by advances in biotechnology.

This view ignores the moral, educational, and political tasks that must be considered. In Morgan and Peters' view (2006), it requires a commitment to "philosophical principles that depart from the utilitarian premises of industrial agriculture". It is a demanding task that requires new thinking and a change in attitude toward the earth. It requires us to cease attempting to achieve dominion over the earth and achieve humility and reverence before the world (Berry, 2002).

The majority of the mainstream agricultural community does not agree with Liu et al. (2015). The dominant view has been supporting crop intensification is the best route to feed 9 billion people and protect the environment. But there is no room for complacency, especially that invoked by some biotechnology advocates (Fischer et al., 2014).

Finally, a caution. Those engaged in agriculture and its sub-discipline, weed science, possess a definite but unexamined moral confidence or certainty about the correctness of what they do. The basis of moral confidence is not obvious to those who have it or to the public. Agriculture's unexamined moral confidence is potentially harmful. It is necessary for all engaged in agriculture to analyze what it is about their science and their society that inhibits or limits their science.

All should strive to nourish and strengthen the beneficial aspects and change those that are not. To do this, agricultural people must be confident to study themselves, their science, and its institutions, and be dedicated to the task of modifying the goals of both (Zimdahl, 2022).

Agriculture's Human Dimension

Doohan et al. (2010) claim that "the human dimension of weed management is most evident when farmers make decisions contrary to science-based recommendations". Agricultural scientists and many levels of administration may be aware their recommendations are often ignored but usually do not ask why because such questions are beyond their area of expertise. Scientists do science, leading to science-based recommendations. When recommendations are ignored, the reasons could be economic (too expensive), stubbornness, lack of trust, and different perceptions of risk and benefit.

Doohan et al. (2010) argue that farmers exhibit an inverse relationship between perceived risk and benefit. If any technology is regarded as beneficial, it is automatically perceived as low risk, which, of course, is not true. Ignoring farmers' reasons is perilous for agriculture's future.

Agricultural scientists have contributed to increasing crop production over several decades. Pesticides have been the primary control technique (Fernandez-Cornejo et al., 2014). Because of their efficacy and ease of use, there has been over-reliance on them at the expense of other control methods (Blackshaw et al., 2008).

If the only or primary goal of weed science is to increase production, the quest for better herbicides must continue. If the goal is sustainable weed management in a sustainable environment and society, other control techniques must be investigated and integrated. Research on non-herbicide weed management must show low or no risk of crop failure and reduced profit. The goal should be the development of successful weed-management systems with minimal or no effect on the flora and fauna of soil, water, or air and no adverse effects on people or other creatures.

Scientists and others engaged in agriculture are not, by nature or choice, politicians. Failure or inability to consider we live in a political world and are affected by it is a prescription for disappointment or disaster. Political considerations affect our daily life. A major political accomplishment in many countries is cheap food, especially in urban areas. It affects the way we practice agriculture and manage weeds. If the government removed itself from agricultural policy-making and markets, cheap food might disappear.

Given the agricultural and environmental history, concern about environmental pollution from agriculture is a fairly recent political development. It wasn't too long ago that pesticide use in agriculture meant prosperity and progress rather than human harm, environmental pollution, and lack of corporate responsibility. For example, a study commissioned by the American Farm Bureau, an organization noted for its defense of agriculture (King, 1991), showed only 15% of the American public was in favour of abolishing pesticide use in agriculture. However, 66% of those surveyed thought pesticide use should be limited in the future, and 38% thought farmers were using more pesticides than they had in the past.

Such information and concern have political meaning and consequences. About 70% of US agricultural produce harbours some trace of pesticides (Gross, 2019). Such challenges are often dismissed by the agricultural community because they are regarded as biased, irrelevant and lacking supporting scientific evidence.

An example is in the Consumer Reports article by Roberts (2024). The findings are ignored or dismissed by those who wilfully ignore the effects of criticism on political action. Political acts change many things, and agriculture has to recognize and work in a political milieu or suffer the consequences of regulation by those who do.

Conclusion

The American author and farmer Wendell Berry (1981b) has written often and eloquently about problems facing American agriculture and their solutions. He advocates solving for pattern: "To the problems of farming, then, as to other problems of our time, there appear to be three kinds of solutions."

The first solution causes a ramifying series of new problems. The only limitation of the new problems is they "arise beyond the purview of the expertise that produced the solution". Those who are burdened by the new problems are not those who devised solutions for the old problems. This kind of solution shifts the burden away from those who created the problem.

The second solution is one that immediately worsens the problem it is intended to solve. These are often quick-fix solutions that, within weed science, take the form of questions such as - what herbicide will kill the weed? Adopting this kind of problem-solving leads to the need for more quick-fix solutions. Everyone who has tried to fix something is familiar with this kind of solution. What was tried first didn't work, and some studies (perhaps, little knowledge) revealed that loosening another bolt or screw would do it. Alas, loosening that screw was the wrong thing to do because it loosened other things, and suddenly parts were everywhere and neither the source of each part nor a way to fit them back together was known.

The third, most desirable solution creates a ramifying series of solutions. These solutions make and keep things whole. For Berry (1981b), a good solution is one that acts constructively on the larger pattern of which it is a part. It is not destructive of the immediate pattern or the whole. Good solutions solve for the whole system, not for a single goal or purpose.

Those who create the next generation of integrated, sustainable agricultural production systems for simple and complex problems will do well to remember Berry's admonition as they search for solutions. One must know the whole system and devise solutions that create more solutions to maintain the pattern and improve the system. Agriculture's inevitable problems should be viewed as a good family physician views patients — in family, not just individual terms. It is the entire system, not just the current problem, that must be managed.

Contributing to the elimination of hunger in the world is a proper goal for weed science. It is a goal consistent with the Millennium Goals of the UN (Sachs, 2005, pp. 211–212). Two of the goals are relevant to agriculture and worthy of attention. These large-scale goals include:

- Eradicating extreme poverty and reducing hunger by half and
- Ensuring environmental sustainability.

Although progress has been made, neither goal has been achieved. In his Recollected Essays, Berry (1981a, p. 98) writes eloquently about a vision of the future shared by those who want to create alternative futures, including alternative, improved, sustainable agricultural systems. His words are a good place to end thoughts about the future. Readers may determine if I have reached beyond my knowledge and ability.

We have lived by the assumption that what was good for us would be good for the world. We have been wrong. We must change our lives so that it will be possible to live by the contrary assumption that what is good for the world will be good for us. And that requires that we make the effort to know the world and to learn what is good for it. We must learn to cooperate in its processes and to yield to its limits.

But even more important, we must learn to acknowledge that the creation is full of mystery; we will never clearly understand it. We must abandon arrogance and stand in awe. We must recover the sense of the majesty of the creation and the ability to be worshipful in its presence. For it is only on the condition of humility and reverence before the world that our species will be able to remain in it. Berry's challenge is clear - Change requires more than the contemplation of fixed verities. It must move beyond reproducing the qualities of the science to which we have devoted our careers.

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Table 1. Examples of Knowledge Required to Develop Improved Weed-Management Systems and Decision Aid Models. Adapted from Buhler, D. D., Hartzler, R. G., Forcella, F. (1997). Implications of weed seed bank dynamics to weed management. Weed Science, 45, 329–336.

Management Goal	Research Need
Management Decision Aid Model	• Relationship of the size of the weed seed bank to the final weed population • Emergent rate of individual species • Determination of economic optimum thresholds for control • Interaction of management practice and weed seed production • Effect of weed density on control
Prediction of seedling emergence	• Mechanism of dormancy • Determination of interactions of environmental conditions • Seed germination and dormancy
Effect of Management	• Effect of crop rotations on weed seed bank size • Effect of living and dead mulches • Rate of seed predation and decay • Rate of seed mortality • Light requirements for seed germination • Role of tillage and cultural practices
New Herbicides and Biopesticides	• Discovery of new Modes of Action (MOAs) • Genetic engineering and new options for manipulating herbicide selectivity • Creation of entirely novel approaches to weed management
Artificial Intelligence	• Computing power and automation • Use of machine vision and global positioning systems