CAWSS Oration

Weed science directions in the USA: what has been achieved and where the USA is going

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Summary

Weed science in the United States is at a critical juncture. The ranks of weed scientists are dwindling due to attrition in both the private and public sectors. Funding for weed science research in the public sector is decreasing. Yet, there is a growing demand for solutions to the environmental damage done by conventional weed management methods, to the spectre of widespread herbicide-resistant weeds, and to the spread of exotic weeds. Furthermore, the need for good public sector research to assist farmers in economically managing weeds is as great as ever. These needs are likely to remain for decades to come, insuring that weed science will continue to be a necessary discipline for insuring an adequate and economical food and fibre supply while preserving the environment.

Several new technologies promise to help weed scientists in solving the above problems. Significant reductions in herbicide use by advances in precision agriculture, integrated pest management, computer-aided decision making, utilization of high unit activity herbicides, and biocontrol can be expected. Adoption of no-till agriculture will certainly reduce the two major environmental risks of weed management, soil erosion and contamination of water by herbicides. Transgenic, herbicide-resistant crops are likely to have a net effect of improving the environmental acceptability of weed management methods while reducing farmers' costs. Even though the tools to solve existing and future weed management problems are being developed, a cadre of well-trained weed scientists will remain necessary to continue to discover, develop, and adapt new technologies to meet the continually changing challenge of managing weeds.

Introduction

This short review is intended to provide a brief history of weed science in the North America and a general picture of the current situation and prospects for the future. The status of weed science in the United States and that in Australia may differ little, because both countries are developed countries operating in the same world economy. However, it is obvious that the trends are not completely synchronized between the two countries. For example, we tend to be a little ahead of Australia in utilizing transgenic crops to control weeds, whereas a significant herbicide-resistant weed problem seems to have evolved more slowly in the United States than Australia.

Some of what I have to say here is based on my personal opinions and is speculative. I will, however, try to provide my rationale for each prediction. I hope that this essay will provoke thought about the future of the discipline of weed science worldwide.

Where we have been

During the first century and a half of its existence, the United States was largely a rural society with a large number of small subsistence farms. Weeds were largely dealt with by the toil of cheap labour and a few cultural methods.

Weed science was not a separate discipline before the advent of highly effective chemical herbicides. Managing weeds by cultural and mechanical means was simply part of established agronomic practice.

Chemical solutions

After World War II, highly effective synthetic chemical herbicides became available. They revolutionized US agriculture. The cost, in both time and money, of weed management plummeted. The significant reduction in the amount of labour required to manage weeds per unit area of farmland was one factor contributing to the steady increase in farm size during the last half of this century. The need for employment of cultural methods to manage weeds, such as crop rotation, was reduced.

New herbicides proliferated, and the number of companies involved in their discovery, development, manufacture, and sales increased. Billions of dollars were to be made. The herbicide-manufacturing companies required a range of employees involved in this new industry. Critical to their success was a good supply of scientists who understood agronomy and weed management. One could say that the burgeoning of the herbicide industry sparked the creation of weed science in the United States. A North American weed science society (the Weed Science Society of America) as well as four major regional US weed science societies, were created in the late 1940s and early 1950s, as the need for and number of weed scientists increased.

The formal training of most of these pioneer weed scientists was generally not as a weed scientist. To meet the growing demand for weed management specialists, universities responded by changing curricula to meet the need. The US Department of Agriculture and state agriculture research organizations added weed scientists to their ranks to provide the farming public with impartial evaluations and recommendations of herbicides, as well as related research information. The number of weed scientists in industry and the public sector grew steadily until the late 1970s, when the market for herbicides was near maturity.

The percentage of crop land on which herbicides are used and the amount of herbicide used per unit area of crop land both increased for several decades until the early 1980s. By this time, herbicides were used on almost all cultivated land.

The huge success of herbicides has contributed to what some call a 'pesticide paradigm' in US agriculture. For each new weed problem, the 'silver bullet' of a new herbicide as been sought. Our dependence on this paradigm is a point of great concern to some US weed scientists (e.g. Zimdahl 1991). However, this technology has served the US farmer well in the absence of economical, effective alternatives generated by public sector research.

Alternative solutions in the age of pesticides

During the past fifty years, the overwhelming majority of research expenditures for weed science have been spent on herbicide science. The solution to almost every weed problem has usually been assumed to be a herbicide. In fact, almost every weed problem in crops has been solved with synthetic chemical herbicides. The results are undeniable, and most farmers have been pleased with this approach.

Despite the success of herbicides, tillage was almost always used in combination with herbicides. This was partly because relatively little research was expended in developing no-till methods of farming, and the most effective and economical herbicides were often pre-emergence products.

Cultural methods of the past, such as crop rotation, cover crops, more competitive crops, planting density and row spacing, have continued to be used, but relatively little research has been conducted on these low-input solutions. In some cases, government policies have discouraged the use of crop rotation.

Relatively little research funds were available for understanding weed biology, weed ecology, biocontrol of weeds or other alternative weed management technology. This could be attributed to several factors, including: the outstanding success of the chemical approach to weed management; the relative paucity of economical solutions to weed management problems from non-chemical approaches; and the lack of clout of the weed science community in convincing policy makers of the need for such funding. My views on this have been published in more detail previously (Duke 1992, 1996b).

In contrast, for many years, public sector funding for non-chemical alternatives for management of both plant pathogens and insects has been maintained at a much higher level than that for weed management in the United States. No reliable data are available comparing the relative economic impact of weeds, insects, and plant pathogens. However, in the United States, the cost of weed management and the losses due to weeds each amount to many billions of dollars per year (Bridges 1992, Duke 1994). Furthermore, the proportion of pesticides sold in the United States that are herbicides is greater than all other pesticides combined, and the herbicide proportion continues to grow (Table 1). Without economical alternatives to herbicides provided by public sector research, US agriculture will continue to rely on herbicides well into the next century. Nevertheless, there are driving forces that will influence how herbicides are used and what alternative weed management technology will be used to complement and eventually supplant some herbicide use.

Current and future driving forces and problems

There are a myriad of economic, political, biological, and technological forces that will determine the future of weed management in the United States. In this short review, I will discuss only those that I think will have significant impacts. Predicting how these forces will interact in the future is complex.

Table 1. Pesticide production in the United States.

Pesticide type	1983	1993
Herbicides	64%	68%
Insecticides	23%	18%
Fungicides	5%	7%
Nematicides	8%	7%

Source: *Chemical Engineering News* June 26, 1995, 73 (24), 44.

Herbicides in a mature market

The herbicide market in the United States matured sometime in the 1970s. That is, the percentage of farmed acres treated with herbicides was at or near its maximum, and most market niches for herbicides were filled. Even though billions of dollars have been made and will continue to be made in this business, we have experienced about 50% attrition among US herbicide manufacturers involved in product discovery since the mid-1970s. There are now only about six US-based companies involved in herbicide discovery research, and many in this industry think that another 50% attrition will occur within the next decade. There has also been an approximate 25% reduction in the number of European herbicide discovery companies that sell directly in the US market. Japanese companies in this business have increased from zero to one company selling directly in the United States. This general attrition, even when accompanied by mergers, has resulted in fewer jobs for weed scientists, and ultimately may result in fewer products from which to choose for the farmer.

The causes of the losses in corporate players in this business are many. However, the difficulty and cost of discovering a new, successful product in a very mature, replacement market has probably been a major factor. Increased regulatory requirements have also increased costs. Furthermore, diminishing returns with traditional herbicide discovery methods have forced companies to turn to more expensive strategies, such as biorational design, natural products as leads, computational chemistry, and combinatorial chemistry. Whatever the causes, the result of continued attrition will ultimately influence weed science as a discipline in the United States and other countries.

Herbicide resistance

After a relatively long delay, compared to insecticide and fungicide resistance, cases of herbicide resistance in the United States are growing at an alarming rate. We may be somewhat behind Australia in the severity of the problem; however, our problem may be under reported compared to the Australian situation. Schemes for avoiding the evolution of resistance, as well as methods of dealing with it when it occurs, are growing topics of research. However, much more effort seems to be expended on the latter than the former.

With our current methods of using herbicides in the United States, there is little reason to expect that the rate of evolution of herbicide resistance will soon abate. In some crops, herbicide resistant weeds already cost farmers millions of dollars per year. The current situation is probably a minor problem compared to what I expect within a decade.

New weed problems

As in Australia, there is a growing awareness of and concern with exotic, invasive weeds. These species often become serious weed problems in crops, as well as rangelands and natural areas. Most of the seriously troublesome weeds in crops in the United States are introduced. There is no hope of eradication of these weeds, once they become widely spread. New weedy plant species continue to be introduced and to spread rapidly. An example is tropical soda apple (*Solanum viarum* Dunal), a native of Argentina and Brazil, that arrived in Florida in 1981 or 1982 (Mullahey *et al.* 1993) and is now found in almost every state in the southeast.

Public concern with these unwanted immigrants is beginning to influence public policy makers regarding allocation of public sector research funding. Classical biocontrol seems to be the method of choice in dealing with the problem. The problem is likely to continue for many years.

Environmental concerns

The two most commonly used technologies for weed management, tillage and herbicides, can both be damaging to the environment.

Loss of top soil from tillage continues to be a major environmental concern. Despite strong efforts to reduce soil erosion, moderate to severe erosion continues on more than 50% of US farmland (Anon. 1996).

Contamination of food, soil, water, and air by pesticides has become a major concern of much of the US public. Politicians and other policy makers are demanding that the risks associated with pesticide use be reduced. Since most of the agricultural pesticides used in the United States are herbicides, it is not surprising that they are often found in ground and surface waters.

Thus, possibly the two biggest threats to the environment of agriculture in the United States are caused by our two major methods of controlling weeds. Still, policy makers in the United States do not appear to have made a connection between the difficulty in reducing soil erosion and pesticide use with the lack of commitment in finding economical weed management alternatives. I hope that eventually this connection will become more clear, resulting in increased funding for basic and applied non-chemical weed management research.

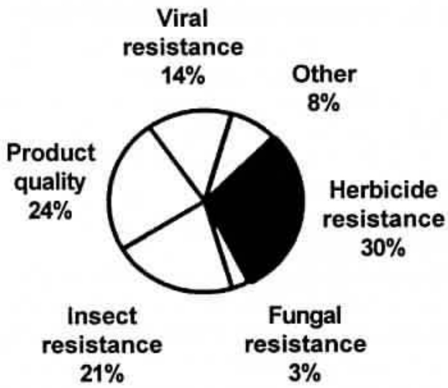

Figure 1. Permits for transgenic crops in the United States from 1987 to 1994 (Source: *Science* (1994) 266, 1472).

Transgenic crops
After a decade or more of anticipation, transgenic, herbicide-resistant crops (HRCs) are now available in the United States. The use of transgenes to create HRCs has been the most commonly created type of transgenic plant for commercial use (Figure 1). There are two reasons for this. The lure of increased herbicide sales spurred the pesticide industry to invest heavily in this technology. Furthermore, the simplicity of the one gene nature of most herbicide resistance made it an attractive object for research.

Bromoxynil-resistant cotton became available for the 1995 growing season, and glyphosate-resistant soybean was introduced in time for planting this year. Other crops resistant to these herbicides and crops resistant to other herbicides are being developed for commercialization in the near future (Dekker and Duke 1995).

How these new products will affect weed management is still speculative. My view and that of many others has been that these products will be useful new tools for farmers, but that they will not change the fundamental method by which farmers manage weeds (Duke 1995, Duke 1996a, Wilcut *et al.* 1996). Others believe that these transgenic crops will provide a radical new tool in crop production (Conner and Field 1995). Most agree that those HRCs that will probably be most successful are those that have been genetically engineered to be resistant to non-selective herbicides such as glyphosate or glufosinate (Duke *et al.* 1991, Dyer *et al.* 1993).

A major concern of some people is that HRCs will be so successful that they will disrupt the herbicide market and make farmers dependent on only a few non-selective herbicides. Another concern is that they will be so successful that public sector research for alternatives to herbicides will be limited, prolonging the pesticide paradigm (Goldburg *et al.* 1990). There is still a great deal of uncertainty about how successful this technology will be and what problems it might cause.

Weed management and human population
As an integral part of the global economy and production of the world's food supply, the United States will be profoundly affected by the still rapidly growing human population. I do not subscribe to the view of some agriculturists that technology will cope with the crisis (e.g. Waggoner 1994). As world population continues to increase exponentially, a number of other related and unrelated processes threaten to limit gains in world food production.

These include desertification, continued loss of soil fertility, salinization, evolution of pesticide resistance, loss of prime farmland to urbanization, and increased demand for meat among emerging nations. Furthermore, the incremental increases in plant productivity that we have expected from breeding programs during this century cannot be expected to continue unabated. I question whether we will have sufficient knowledge of multigenic traits to make required improvements in yields by transgenic means to meet the population crisis.

Solutions
Many promising solutions are being developed for the problems mentioned the previous section. With adequate support, most of these approaches will make major contributions to weed management problems in the future. Almost all of these technologies promise to reduce herbicide use and risk. Support of research to reduce herbicide use will do more to reduce pesticide use than any other pest management research (Table 1).

New herbicide technology
Herbicides will continue to be an integral part of North American weed management into the foreseeable future (Duke *et al.*, 1993). However, as discussed above, the point of diminishing returns has been reached in improvements in weed management with herbicides. We are likely to experience only incremental improvements in herbicides themselves. New herbicides resulting from natural products may be more environmentally acceptable than some presently used herbicides (Duke *et al.* 1996). Herbicides from biorational design might be less toxicologically suspect.

A growing proportion of research effort among herbicide manufacturers appears to be going into extending the lifetime of older herbicides by improving formulations and matching them with complementary herbicides.

Precision weed management
Microelectronics offer to do more to reduce herbicide use in the near term than any other technology. This technology can be used to support two precision herbicide application approaches.

The first of these is the application of herbicides, through the use of satellite-based global positioning systems (GPS). GPS mapping of field for soil type and other factors that might influence needed herbicide rates has the potential to precisely tailor herbicide applications. This technology will be best used in application of pre-emergence or soil-incorporated herbicides.

Herbicide spray systems that detect weeds in real time, directing herbicide only to weeds detected are already on the market in the United States on a small scale (Houtsma 1994). Prototypes of more advanced models of these systems can now move across a field as fast as 20 km h^{-1}, detecting weeds as small as 2 cm in diameter, and accurately targeting them with a herbicide spray. Large, multi-row systems are being developed by a major agricultural implement company. Such systems, in concert with GPS, would have the capability of mapping the weed population in a field, allowing for comparison at different times during the same growing season or from year to year.

At this time, these systems cannot distinguish between crops and weeds, but research is being conducted to use image analysis to identify more than one weed species in order to direct the proper selective herbicide to the proper species. With advances in computer capabilities and miniaturization of video cameras, this goal should be achievable within the next decade, provided adequate research funding is available.

Real time, weed-detecting spray systems will be especially useful in no-till agriculture, as the farmer can wait for weeds to develop before making the economic commitment to controlling them. In conventional tillage, there might be concern about getting into wet fields at the proper time for adequate results with post-emergence herbicides. However, this is less of a problem in zero tillage fields.

Reduced tillage agriculture
In the United States, tillage probably still does more long-term environmental harm than any other agricultural practice. In addition to the loss of top soil, reduced tillage often impedes mobility and enhances degradation of pesticides (e.g. Gish *et al.* 1995, Locke *et al.* 1996). Even though no-tillage agriculture can make farmers more dependent on herbicides for weed management, the adverse environmental effects of herbicides in no-tillage farming are generally reduced for the reasons stated in the previous section.

Cover crops, especially allelopathic cover crops, can reduce the need for post-emergence herbicides in non-tilled fields. For example, Smeda (1993) has found that soybeans planted directly into sorghum-Sudangrass (*Sorghum bicolor* × *Sorghum sundanense*) killed by glyphosate requires minimal additional herbicide treatment for adequate weed control.

The potential success of no-tillage agriculture has been improved by the option of using non-selective herbicides such as glyphosate and glufosinate with HRCs. These products will accelerate the adoption of reduced and no-tillage agriculture.

Integrated pest management (IPM)

In this United States, integrated pest management has often really meant integrated management of insects and plant pathogens. Weed science has often been left out or under-emphasized in IPM strategies. For example, no-tillage agriculture has been opposed by some entomologists and plant pathologists because of the increased potential for insects and plant pathogens with increases ground cover. Conversely, weed scientists almost always consider only integrated weed management (IWM) in their strategies. Our knowledge of the influences of management of different pest types on each other is still very limited, and, when known, often ignored. For example, pesticides can have profound secondary effects on crops, influencing their resistance, both negatively and positively, to other pests that are not targets of the pesticide (Lydon and Duke 1993).

Integrating all of the available weed management tools into an economical and sustainable weed management scheme is a daunting but highly desirable endeavour (Coble 1996, Swanton and Murphy 1996). A great deal of information from the realm of weed biology will be required to achieve a truly comprehensive approach to IWM and IPM. To evaluate the myriad of inputs that will be required for this, computer-aided decision making will be necessary. This will be the other important impact of microelectronics on weed management (see *Precision weed management* section above).

Decision aids for weed management

Computer-assisted decision aids offer the possibility of making true IPM possible. Such decision aids exist for providing advice on whether to apply herbicides and, if so, which herbicide, when, and how much should be applied (e.g. Wilkerson *et al.* 1991).

However, financial support in the United States for this needed area of research is woefully lacking. Even if adequate research funds were available, bringing together the proper mix of pest management scientists, ecologists, economists, and simulation experts to generate a balanced and useable IPM decision aid program would be difficult. In the near term, I expect to see refinement and proliferation of programs that handle components of IPM separately.

Transgenic, herbicide-resistant crops

The arrival of the HRC has the potential to reduce herbicide risks, decrease the costs of weed management, and promote no-tillage agriculture (Duke 1995, 1996, Duke *et al.* 1991, Dyer *et al.* 1993). They may also be valuable tools in fighting herbicide resistance, because no resistance has yet evolved to glyphosate or glufosinate, the two herbicides more likely to gain wide acceptance with HRCs. Some in the environmentalist community have come to opposite conclusions about the impacts of HRCs (e.g. Goldburg *et al.* 1990), although the vigour of their attacks seems to have abated. Environmentalists are also concerned with the possibility of herbicide resistance-conferring transgenes being transferred to weeds related to crops. This is a legitimate concern, but perhaps not as serious a concern as the escape of insect and pathogen resistance transgenes, as these genes may be useful to weeds outside of the agro-ecosystem, potentially disrupting natural ecosystems.

I have concern that HRCs have been oversold by both their proponents and opponents. Proponents have claimed that these products will revolutionize weed management, and opponents agree. But, the revolution is not one that opponents view as environmentally desirable. I have questions about how well these products will perform. Already, in the United States, evidence that the much heralded crops containing transgenes encoding *B. thurengiensis* toxins do not always perform as expected is surfacing. There are many potential problems with transgenic crops (Dyer *et al.* 1993) that are seldom mentioned. Lower than expected yields in HRCs can be the result of factors other than suboptimal varietal germplasm. One of the wonderful things about science and nature is that it is not arbitrary. So, if there are unknown or unreported technical problems with these products, they will become evident.

Because resistance had not yet been documented to glyphosate or glufosinate, HRCs resistant to these herbicides have been offered as solutions to our herbicide-resistant weed problem. Nature abhors a vacuum, so we can expect that overuse of these herbicides with these HRCs will result in the eventual filling of the ecological niche vacated by glufosinate- and glyphosate-sensitive species and biotypes. The best case scenario is that the niches will be filled slowly by weed species with a low level of natural resistance to these herbicides, causing farmers to increase application rates incrementally until other weed management methods must be enlisted. The worst case might be evolution of highly resistant biotypes of normally sensitive weed species, as has been recently reported for glyphosate in Australia. Furthermore, movement of the herbicide-resistance transgene to weedy relatives of the HRC may occur. For example, in the United States the biggest weed problem in rice in some areas is red rice, a weedy variety of rice. The potential for use of HRC varieties of rice in the United States in red rice-infested areas (Linscombe *et al.* 1996) could be limited unless introgression barriers are devised.

One cannot generalize about all HRCs. Each product will be judged on its own merits, and the marketplace will eventually determine the winners and losers. Observing the success, or lack of it, of HRCs and other transgenic crops during the next decade should make it the most interesting and exciting times in the history of agriculture.

Biocontrol

Biocontrol of weeds in agronomic and horticultural crops must rely on inundative approaches, rather than the classical, inoculative approach. Very little research has been conducted in the United States, and only two such products have been marketed. Neither product is now on the market. One of the products (*Phytopthora palmivera*) worked too well, behaving more like a classical biocontrol agent in controlling stranglervine (*Morrenia odorata*) in citrus groves. The other, a fungal agent that controlled northern jointvetch (*Aeschynomene virginica*) in rice and soybeans, could not match the economical weed control of herbicides. Many biocontrol agents have been patented in the United States (Julien 1992, Watson 1993). A microbial biocontrol agent, *Xanthomonas campestris pv. poae*, for control of annual bluegrass (*Poa annua*) in turf will be marketed in the United States and Japan in 1997, but the prospects for the large scale marketing and adoption of biocontrol agents for weed management in crops is not good for the next decade or more.

Zorner *et al.* (1993) and I concur that the lack of success biocontrol in the United States can be partially attributed to inadequate fundamental research to overcome a number of daunting technical and biological problems. This fundamental research is most appropriately in the public sector arena, at least until commercial successes demonstrate that there is money to made using this environmentally friendly approach.

There is currently a resurgence in interest in the United States in use of the classical, inoculative approach of pitting an exotic insect or pathogen against exotic weeds. This strategy may be helpful in combating exotic, invasive weeds in non-crop settings.

Prospectus

I have discussed a range of present and future weed management problems in North America and the tools with which we can expect to solve them. The continuing erosion of support for weed science research in North America is a cause for concern that we will not adequately meet these challenges (Duke 1996b). Many of the needed solutions are most appropriately solved by public sector research, but the resources in this realm are small and are shrinking. Apparently, weed scientists have done an inadequate job of communicating this situation to the public and to policy makers. We certainly cannot be accused of exaggerating the problem. Our future now seems to be largely tied to needs as they arise, rather than to a pro-active approach to research. Whether the current research resources available will provide the information base and technology to adequately solve future weed management problems is questionable.

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