WEED SCIENCE AND MANAGEMENT

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Contents

Summary

The field of weed science is a relative newcomer to the agricultural arena. However, the innovations and developments that have stemmed from the research in this area have had a major impact on agricultural practices and productivity. With the introduction of the first selective herbicide onto the market, researchers ensured the continuation of the newly recognized science by demonstrating how significant herbicides could be in increasing producers' yields. Today, although chemical weed control plays a major role in weed management and remains a key element of weed science, research interests have become as diversified as any subset of sciences.

The goals of weed science remain the same, to identify and establish effective weed management strategies in order to reduce detrimental effects to agricultural crops; however, these practices now include a greater focus on sustainable agricultural and environmental conservation. Management strategies include an array of cultural practices and ideas that not only work to suppress weed populations but also help to preserve the environment.

Challenges, like herbicide resistance, force the researchers in this field to remain on the cutting edge of technology and lead to even greater developments associated with weed science. As with any science, the dynamic nature of weed science will continue to present future researchers with challenges that require innovative solutions that may once again revolutionize agriculture as it first did with the introduction of herbicides not so long ago.

1. Introduction to Weed Science and Management

1.1. What is a Weed?

Traditionally, a weed is defined as any plant growing where it is not wanted. This definition can apply to crops, native plants as well as non-native species. If it is considered to be a nuisance where it is growing, it can be termed a weed. However, weeds are not just unwanted species; they can have substantial negative impacts when they are present. Weeds can effectively compete with crop species, can lower yields, increase labor requirements and, ultimately, increase food costs for the consumer (Klingman and Ashton, 1975).

Competitive ability by weeds is determined by several plant characteristics. One of the most common traits of a weed species is its tendency to be an annual or biennial rather than a perennial; this allows the species a faster reproduction rate leading to a higher fecundity (Sutherland, 2004). Other characteristics that determine the “weediness” of a species is the ability to colonize under high sunlight and low soil moisture conditions. Plants that have capabilities of dealing with herbivory as well as plants that have allelopathic traits also tend to be better at out-competing surrounding plant species.

Some non-native species of plants are considered to be very weedy in nature. It is reported that some non-native plants can grow faster and bigger, increase reproduction rates, and can have increased survival rates when outside of their native habitat. This may be due, in part, to the loss of environmental checks that keep these plants in balance within their natural habitat. Genetic make-up also determines the ability of a plant to become weedy in nature; however, a genetic pattern has yet to be described (Ward *et al.*, 2008).

1.2. History of Weed Science

The science of weed control as we know it today is still in its infancy when compared to the other agricultural sciences. In fact, weed control received little attention or research efforts until the late 1800’s and early 1900’s even though man has been plagued by unwanted plants among cultivated fields since Biblical times. For centuries weed control has been accomplished as a byproduct of seedbed preparation. Even the modern hoe, which is synonymous with weed control, was specifically designed by Jethro Tull to break up the soil to make nutrients more readily available to the crop’s roots (Timmons, 2005).

Other early methods of weed control include labor intensive hand hoeing and hand pulling of weeds as well as cultural practices, such as crop rotation. Although hoe-hands are rare in developed countries, hand removal of weeds remains the dominant form of weed control in many undeveloped nations. Rotation practices were largely replaced by monoculture systems and chemical weed control by the 1940’s (Appleby, 2005); however, crop rotation has become an integral part of weed management in organic farming as well as integrated weed management practices in conventional farming systems. Until recently, research to understand weed populations and attempts to control weeds within a crop went largely untried and control of the weed was left in the hands of fate and some very tired farm workers.

Chemical weed control was first mentioned when describing the effects of mainly inorganic substances and their ability to offer some form of selective weed control. Some of the chemicals with herbicidal activity prior to the 1940’s were salt, iron sulfate, sulfuric acid, and copper sulfate (Klingman and Ashton, 1975). Many of these compounds were used extensively in Germany, France, and the United States within specific areas, but until the 1940’s, herbicides were not widely used as a form of weed control.

Weed science received a major boost as a valid scientific discipline with the synthesis of 2,4-D by R. Pokorny in 1941 and its subsequent commercial acceptance as an effective herbicide. Until this point, research was limited in funding as well as in interest by the scientific community; those who did dare tackle questions about weed control did so neither with the chance of recognition nor with insight from previous research. When 2,4-D appeared on the market, it offered users a cheaper option of weed control that could be applied at relatively low rates and in many agricultural settings (Ross and Lembi, 1999). The characteristics of 2,4-D offered hope that chemical weed control could revolutionize global food production, in turn, drawing a great deal of attention to weed control research.

The 1940's and 1950's saw an explosion of synthesized herbicides. By 1950, there were roughly 25 herbicides available for use (Timmons, 2005). By the late 1950's and 1960's, enough effective herbicides appeared on the market to ensure that chemical weed control was a viable replacement for hard labor mechanical weed removal. In the same manner, weed science was guaranteed a spot among respected subsets of agricultural sciences. In more recent years, weed scientists have been challenged to meet herbicide regulations to secure a safe environment for future generations. The researchers have responded with overwhelming success in the form of herbicides with low use rates, low environmental residual, and little to no non-target effects (Zimdahl, 1999). Glyphosate is an example of this technology; it was introduced during the 1970's and offered excellent weed control at these lower use rates (Ross and Lembi, 1999), and with little harm to the environment as indicated in the ranking of the World Health Organization (see also: *Land Use Management*).

In the 1980's and 1990's, herbicide introductions included new compounds at even lower rates than before, allowing for the total weight of chemicals being used to decrease even though herbicide use was on the rise. Weed science also saw the adoption of herbicide resistant crops in the 1990's. Although this technology offers an extraordinary opportunity to increase crop yield throughout the world, it has been met with scrutiny that today's weed scientists must research and overcome.

As weed science develops into a more mature science, it is assured a place among the most important areas of agriculture. However, this is the only constant within the field. Weed scientists will be faced with an ever changing landscape of problems to undertake. Today's weed researchers must be willing to explore the complex issues like herbicide resistance among weed species, effective herbicide use within conservation systems, organic herbicide use, implementation of integrated weed management and a score of other important issues within weed science. Not only must they be ready to face these issues, they must also remember that goals are of a global nature. In order to meet ever increasing food demands, weed scientists will not only have to keep an eye to the future, but also to the past since many nations still labor under these conditions.

1.3. History of Weed Management

As more and more researchers begin to explore the realm of weed science, new ideas and technologies have emerged that have drastically altered the approach to weed management. In early agricultural production, little weed control existed except through tillage and/or hand-hoeing. Agricultural mechanization efforts largely ignored weed control implements until 1914 when the rodweeder was introduced primarily for weed control (Timmons, 2005). During this time, one farmer could provide food for just six other people. As technologies improved, including weed management tactics, the number of people a single farmer could feed would see a sharp increase.

Until the 1940's, chemical weed control was practiced mainly in agricultural and non-crop situations in Europe. Some of these inorganic compounds, including: salt, sodium arsenate, carbon bi-sulfide, and petroleum oils, offered weed control but not at highly effective rates. This less than superior control, coupled with the large acreage available at the time in the United States, limited the American farmer's adoption of the slightly yield-increasing inorganic herbicides (Zimdahl, 1999). By the 1940's, however, much of the United States frontier had been settled and the population was ever increasing. These factors made the timing of Pokorny's synthesis of 2,4-D in

1941 a major herbicide discovery rather than a passing novelty among heretofore uninterested farmers. The commercialization of the compound in 1945, which was relatively inexpensive, could be applied at low rates, had a broad area of uses, and was relatively well received by farmers, spawned an influx of interested developers into the herbicide arena.

By the 1960's, over 120 herbicides were available for weed management. At this time, however, public concern over health and safety issues with herbicides and herbicide residues led to growing pressure on chemical companies to develop herbicides with increased efficacy at lower rates, less residual, and less toxicological effects on non-target species. In 1974, when Monsanto introduced glyphosate to the market, the type of herbicide desired by government agencies and portions of the public had been achieved. Because of its non-selective nature, glyphosate was used mainly in non-crop situations or prior to crop planting in conservation tillage practices.

By the mid 1990's, weed control would once again receive a boost on par with that of the 2,4-D discovery when glyphosate-resistant soybeans were introduced in 1996 (Green *et al.*, 2008). This technology allowed for the use of a non-selective herbicide within a row crop setting without injury to the resistant crop. Introduction of other resistant crops on a large scale, as well as the sole dependence of some farmers on this herbicide, has inevitably produced glyphosate resistant weed biotypes. This development has required the swift adaptation of weed management research and protocol. Most recently, chemical companies have worked to design an herbicide resistant crop that contains resistance to multiple non-selective herbicides. This feat would allow farmers greater flexibility in herbicide choice, reduce dependency on a single herbicide, and reduce selection pressure toward glyphosate-resistant weed species.

At a time when farmers face the potential loss of certain herbicides due to resistant issues, adoption of alternative weed control tactics has been touted by weed researchers as a means to control weed communities as well as to prolong the field life of certain herbicides. These alternative measures can include: biological agents, mulches, use of allelopathy, cover crops, crop rotation, and soil fertility manipulation. The combination of these weed control tools along with conventional chemical control might provide effective weed management while preserving important herbicide formulations for future generations.

Much advancement has been achieved in weed control since research began in earnest. These achievements have not come without complications and defeat, however, advancements have still been made and improved weed control methods have allowed farmers to witness dramatic increases in yield. As the world's population continues to increase and agricultural land diminishes, it is imperative that the research in weed management progress with the changing agricultural needs to guarantee adequate food for ourselves and posterity.

2. Weed Biology

2.1. Characteristics of Weedy Plants

Many definitions have been proposed in an attempt to categorize weed species separately from other plant species. In general, weeds are just plants growing in unwanted areas that can often cause a negative impact on surrounding vegetation and/or the users of the land. Research into successful weeds has revealed a great distinction between weedy and non-weedy species. In most instances, weedy plants possess certain characteristics or properties that allow them to thrive and multiply in many different locations (Table 1).

Table 1. General Characteristics of Weedy Species
(adapted from Baker, 1974).

A characteristic most often noted by all who study weeds is an ability of weed species to succeed in disturbed areas (Baker, 1974). These areas, which make desirable weed habitats, must also be used to sustain human food production and livelihoods. This age old battle between man and weeds is the crux of why we seek to understand the traits that give a weed a foothold in our lives.

Weeds, like all plants, require sunlight, nutrients, and water for life. In agricultural systems, desirable crops face competition by these weedy species for a limited quantity of these resources. In undisturbed systems, native weeds could not usually outcompete the whole of the natural vegetation; however, in cropping systems, disturbance and replacement of natural vegetation with predominantly one species allows a weed a chance to employ its “weedy” traits.

In contrast to many row crops, weeds are capable of rapid development from the seedling stage to the flowering stage. Not only do weeds produce seeds in a relatively short period of time, they can also produce large quantities of seeds within this brief period of time. In addition to seed production, weedy species are often capable of vegetative reproduction which allows continuation of the species even without seed dispersal.

Other traits that define species as successful weeds include highly effective seed dispersal mechanisms and long-lived viable seeds within the seed bank. This gives weeds the ability to infiltrate undisturbed regions and proliferate if the site becomes disrupted in the future.

Weed species not only have certain characteristics (allelopathy, e.g.) that allow them to compete other species, but they may also possess certain traits to dissuade damaging herbivory. Weeds have even adopted traits to defend themselves against the ever threatening human. Weed species have the ability to adapt, rather quickly, at a genetic level to environmental factors in order to achieve species continuation. This characteristic permits weeds to continue the battle against humankind by challenging our much relied upon herbicide arsenal.

When attempting to define what makes a weed successful, there will always be a core list of traits available; however, as time passes, we can only expect this list to expand. As our understanding about and control mechanisms of weeds grow and change, so too will the traits and abilities of weedy species develop. In this manner, both weeds and humans will continue their quest of domination over the other.

2.2. Weed Life Cycles

2.2.1. Life Cycle Stages and Life History

Control of major agronomic weed species requires an understanding of the weed’s growth habits, its susceptible growth stages, and its reproductive abilities. Understanding a weed’s life cycle provides the foundation of knowledge necessary to limit the impact of weeds in the agricultural arena.

The life cycle of a weed refers to the general growth, flowering, seed production, and eventual death of a plant. Categorization of all plants falls into one of three broad classes, or life histories: annual, biennial, or perennial. This classification is determined by the length of a plant’s life cycle. Annual plants will germinate, grow, reproduce, and die within a year’s time; biennials will take two years to complete their life cycles. The life cycle of a perennial will last three or more years.

Determining the life history of a weed establishes the weed control tactics used on a particular weed because its growth and reproduction will vary based upon its specific life cycle. Certain stages throughout the life cycle of a weed provide more advantageous times for successful control than others. Many agricultural weedy species have a propensity for being annuals; annual plants generally thrive on disturbed areas like cropping areas and have rapid vegetative, hence more competitive, growth from seed. With this in mind, understanding the strengths and weaknesses of the annual life cycle has been essential in establishing effective weed control strategies.

2.2.2. Soil Seedbank

Before a weed can germinate and grow, its seed must successfully reach and remain viable in the soil seed bank of a specific area. The soil seed bank contains seeds from previous weed generations within the region and, to a lesser extent, seeds that have been disseminated into the area. Time within the soil seed bank can present a relatively vulnerable stage in the life cycle of a weed. At this point, a seed is faced with predation and decomposition or conditions unfavorable for germination. If the seed remains viable until conditions improve, it may have a chance for germination or it may remain dormant within the seed bank for many seasons. It is at this point that farmers have historically used tillage as well as herbicides to reduce the number of weed seeds in the upper soil layer and to inhibit the growth of newly germinated seeds.

Because the soil seedbank experiences so many variables that affect the aboveground weed composition, a producer’s understanding of weed seed characteristics and requirements for germination in his particular region and/or crop system remains essential in developing effective, sustainable weed control strategies. For example, a lot of species germinate quickly under conditions of light or distinct day/night temperature alternations after a period of winter cold. These seeds will germinate massively in early spring without or after a superficial tillage, but they can stay dormant one year more after a deep autumn tillage, and germinate a year later after a second deep tillage.

Other weed species may have viable weed seed remaining in the seedbank for 40 or more years after deep tillage (Ross and Lembi, 1999). Cultural practices, like tillage and crop rotation, and environmental factors, like light and cold requirements, can be manipulated or monitored in order to determine what weed species will emerge at a given time and location. Producers can use this knowledge of the seedbank to develop weed control plans for short-term as well as long-term strategies.

2.2.3. Plant Growth and Reproduction

The germination and seedling stages of a weed’s life are often susceptible periods that can be targeted for weed control. At this point, seedlings require adequate nutrients, water, and light for survival; the weed seedlings must also compete with surrounding plants for these required resources. Weed control through chemical or biological means can be very effective during this time when seedlings may be at risk due to limited resource availability. However, lack of effective control at this time can result in the greatest yield loss potential for the crop.

Weed species that have become adapted to specific cropping systems will successfully outcompete the row crop by either germinating earlier than the crop while resources are greater or through rapid growth when germinating simultaneously. Weed species that emerge after crop germination usually pose less of a threat to crop yield because of limited resources. For example, redroot pigweed (*Amaranthus retroflexus* L.) poses a much greater yield risk to corn and soybean crops when emergence is concurrent with crop germination (Swanton *et al.*,2008). Determining greatest weed threats within a system and their germination patterns can help develop accurate timing of herbicide applications in conjunction with crop planting date.

Once a weed reaches the seedling stage, provided adequate resource availability, its vegetative growth up to the flowering stage is quite rapid. Moreover, the onset of flowering may be earlier and last longer than the agricultural crop in which it is growing. This adaptation by weed species allows them to be successful in particular crop settings and more susceptible to suppression under crop rotation. The extended period of flowering leads to a high number of weed seeds being produced and released into the environment. Prior to flowering, systemic herbicides can be used with the greatest effectiveness; however, once a weed reaches the flowering stage, it has reached its most resilient stage in life.

Seed production by a weed ensures the survival of the species in the future. For a viable seed to be produced, a plant requires pollination. Weedy species have developed with mechanisms to increase pollination probabilities. By being self-compatible (able to pollinate itself with its own pollen) and wind pollinated, rather than requiring specialized pollinators, weeds can guarantee improved pollination and successful seed production (Sutherland, 2004).

Not only do weed species have to produce seed to ensure survival, they must also possess a means of seed dispersal to secure a foothold into surrounding land and reduce intra-specific competition for the subsequent generations. Dissemination of weed seed can be achieved through environmental factors like wind and water, through animals and machinery, as well as through contaminated crop seed.

2.2.4. Perennial Plant Reproduction and Control

With improving technology into sustainable agriculture, conservation tillage has become widely practiced. The adoption of this farming practice has required the farming community to become knowledgeable not only in annual weed life cycles but also in the life cycles of perennial weeds. Recent research suggests a shift from annual to perennial weed dominance within conservation tillage systems, in part, due to less soil disturbance which is favorable to perennial species (Ross and Lembi, 1999). If perennials germinate from seeds, annual weed control methods may be effective for newly emerged weeds. However, if a perennial grows from a vegetative structure, new management tactics must be employed.

Perennials that can reproduce vegetative structures can be larger and faster growing than seedlings. Reproductive structures are usually high in stored food and can survive under adverse conditions. Many perennials also have the means to reproduce by seed as well as vegetatively. The combination of these factors can make perennial weed control a difficult process especially since reproductive structures can be produced any time a plant reaches maturity.

Control of perennials is usually achieved through multiple management tactics and at different times than annuals. Perennial weed control is most effective during active growth of the plant, except during early development, or as the plant enters the flowering stage. Repeated control tactics, rather than one method, applied during these susceptible periods of a perennial’s life cycle can achieve control to lessen crop damage by the weed.

Whether fighting a seasonal battle with annual weeds or a more prolonged war with perennials, understanding the weed’s life cycle is the most fundamental information necessary in order to begin implementing control strategies. Knowledge about growth stages and their procession from beginning to end helps determine the most effective plan of action. Knowing the most susceptible of the stages allows the agricultural community to obtain some control, although not complete, over one of the most persistent and costliest problems within agricultural production.

2.3. Weed Population Dynamics

The weed community within an agricultural area faces continual change from year to year as species composition is modified and shifts. The dynamic population of a weed system is influenced by natural factors, agricultural practices and their interactions. Understanding how these factors affect weed community structure, especially human interaction, can better determine how future weed populations will be managed.

2.3.1. Seed Pool Composition

The most influential element in determining above-ground weed population make-up is the composition of the soil seed bank, or the seed pool (Norris, 2007). The seed bank, or the soil's accumulation of weed seed within a specific site, is formed by seed rain within the region from previous weed species that survived to produce seed as well as from seeds dispersed into the region. It is from this reserve of seeds that the next generation of the weed community will be produced. The seed bank remains the crux of weed population dynamics; modifications to the existing seed pool, both natural and manmade, will directly affect subsequent weed communities.

In natural systems, weed seed within the seed bank must overcome several obstacles in order to remain viable for the next suitable growing season. Components of the seed pool face mortality in a number of ways, including: consumption by organisms, aging of seed, or germination and subsequent death in an unsuitable environment (Westerman *et al.,* 2005). Further persistence within the seed bank depends upon genetic components of the seed as well as the conditions of the surrounding soil. Weed species that succeed at maintaining sufficient quantities of seed within the seed bank will, most likely, be one of the dominant species within the system and continue to contribute seed rain to the seed pool in future years.

2.3.2. Cultural and Chemical Practices that Affect Weed Populations

In agricultural cropping systems, herbicides have historically been the predominant control mechanism to keep weed populations in check. However, recent research has explored the concept of manipulating the natural population dynamics of weed species with agronomic practices and found these practices to be viable weed control tactics (Westerman *et al.*, 2005). Human influence over the varying numbers of weed species is limited by what determining aspects that control weed populations can be modified. The factors that can be controlled or altered by human interaction focus on increasing weed seed mortality and decreasing the number of established weeds that can add further seed to the seed pool.

Tillage of agricultural land targets the weed seed bank, and often reduces weed seedling emergence due to seed burial or early germination in adverse conditions. In more recent years, however, the adoption of conservation tillage has reduced the dependency on tillage. In these reduced tillage systems, increased weed seed mortality may also be achieved by allowing weed seed to remain exposed and vulnerable to greater predation. In either instance, the agricultural practice effectively modifies characteristics of weed population dynamics in order to reduce the weed population within a region.

Other agronomic practices that have been shown to help control weed populations are crop rotation and the timing of the planting date. By rotating crops, farmers can control seed production and/or plant establishment. Continuation of a monoculture system selects for weed species adapted to those particular management practices; rotation of crop choice allows for a diversification of herbicide modes of action to be incorporated into a system and disrupts the favorable environment of the predominant weed species in the system. Early planting dates of crops not only offer the possibility of increased yield, but also allow the crop valuable growing time without competition from weed seedlings. When weed seeds begin to emerge, crops have already become well established and are less affected by seedling competition; weed seedlings remain at a disadvantage due to limited resources and may not survive to produce seed. Late planting of crops also offers a benefit by allowing weed seed to germinate and be destroyed prior to crop planting. Both rotation and planting date achieve some manner of control over weed population size in an agricultural area.

2.3.4. Weed Population Changes due to Soil Property Modification

Many opportunities exist to alter weed communities through agricultural practices by modifying the properties of the surrounding soil. Presently, there are numerous ways documented as to how soil characteristics can be altered to favor crop seed rather than weed seed. Some alterations include: mulching, use of legume residues in lieu of synthetic fertilizers, use of cover crops, and directed placement of soil amendments.

Mulching, plastic covers, and cover crop incorporation can lend to suppression of weed seedling emergence by reducing light penetration to the soil surface thus inhibiting seedling growth. Mulches and plastic coverings are usually limited to gardens and high value systems like plant propagation and tomatoes. For large agricultural productions, cover crops remain the most widely used form of ground cover. The use of cover crops has also been reported to reduce weed seedling growth through allelopathy, or chemical inhibition (Westerman *et al.*, 2005). Both practices make use of altering the growing conditions within or on the soil surface in order to increase weed seedling mortality and reduce competitive pressure on the crop.

Agricultural procedures that change the type and/or placement of nutrients and resources have also been noted as effective control strategies against weed populations. The use of legume-based green manures instead of synthetic fertilizers have shown the ability to provide adequate nutrients for large seeded crops while the delayed nutrient release has been growth inhibiting to small seeded weed species (Liebman, 2000). Not only do these green manures release nutrients essential for the crop, they also release potentially phytotoxic chemical that can be harmful to germinating weed seed. If nutrients and resources like water can be of limited availability to weed seed, then germinating weed seed will be reduced. This limitation can be achieved by directing water and fertilizer placement into close proximity with the crop and less available to surrounding weed seed. These alterations to soil amendments can modify soil properties to an extent that lessens the impact of the weed community on agricultural settings.

Weed populations are ever changing and it is difficult to predict their future shifting patterns. Species composition within a region is determined not only by the genetics of certain weed seeds, it is also dependent upon external factors and stresses like weather conditions and presence or lack of seed predators. When agricultural production is factored into the equation, there are many interactions that can redefine the weed population composition within a region. It is these interactions and their results that we must focus on better understanding in order to manipulate weed population dynamics in our favor. Once we more fully understand our role in the subtleties of weed population establishment, we can better employ multi-faceted control measures that rely less and less on one dominant management system and more on an integrated, sustainable weed management system.

3. Chemical Weed Control

The discovery and introduction of the phenoxyacetic herbicides in the early 1940’s spawned a new era in agricultural weed control. Prior to the development of the organic herbicides, like 2,4-D, chemical weed control relied mainly on large quantities of inorganic compounds that proved to be rather inefficient at weed control as well as potentially hazardous to non-plant organisms. Farmers’ willingness to embrace chemical weed control tactics were based on factors such as reduced costs in comparison to mechanical weed removal, loss of willing field hands to perform these tasks, as well as increased yield associated with herbicide incorporation into a farming system. Many of the properties that led to the widespread adoption by farmers of the phenoxy herbicides would continue to be sought after by chemical developers; for an herbicide to become a mainstay on the market, it needed to be effective at low rates, control a broad range of weed species, and be relatively inexpensive. By the 1990's, there were over 180 compounds being used in many different formulations as herbicides (Zimdahl, 1999; Timmons, 2005).

Increased pesticide regulatory pressure in many developed countries has become the driving force behind the search for herbicides with a new set of properties much more stringent than the properties that made adoption of early herbicides a successful enterprise. Present day developers search for chemical formulations that offer the same, or greater level of activity as older formulations, in smaller quantities, that can potentially be used in several crop settings; in addition to these requirements, researchers look for compounds that have a flexible application period, are cost effective for farmers, and meet environmental standards set by regulatory boards (Rüegg *et al.*, 2007).

Because of the extreme cost in developing new herbicidal compounds coupled with tougher regulation requirements, companies are specifically seeking out new modes of action for herbicides in the safest possible formulations. The prolonged and costly transition from laboratory to market place has severely reduced research and development within the herbicide sector. This reduction in development, along with the loss of registration of many older herbicide compounds, could have a detrimental impact on agricultural production in the very near future. With the world's population continually increasing and demanding even more output by our agricultural systems, reduced crop yield due to the loss of effective herbicides could be devastating to the world food markets.

While integrated weed management practices are being developed and practiced which will eventually offer effective weed control through chemical as well as physical, biological and cultural methods, weed population dynamics are so complex and not readily understood as of yet that effective and complete adoption of these practices may be slow to materialize. Until the time that alternative weed control tactics are viable and effective options, in addition to herbicides, chemical weed control as a primary weed control practice will be necessary in order to sustain global food requirements and maintain successful, profitable agricultural systems.

Below are discussed the common chemical weed control practices in a variety of cropping systems: conventional tillage, conservation agricultural systems, conventional and herbicide-tolerant cropping patterns.

3.1. Conventional-Tillage Systems

Row crop systems have historically been planted into cultivated areas for a variety of reasons including: increased aeration of soil, increased absorption of precipitation, and to disturb the surface crust (Klingman and Ashton, 1975). In earlier agricultural days, weed control through tillage was just a byproduct of cultivation for the purpose of preparing the seedbed and the benefits listed previously. In more recent decades, tillage has been lauded as an effective means of weed control for small seeded annuals. Tillage of agricultural areas leads to the burial of weed seed and reduces their exposure to necessary stimuli for germination.

When herbicides became a mainstay in agriculture beginning in the 1960's, tillage, along with chemical applications, allowed for efficacious control of not only annuals, but many perennials as well. Incorporation of a chemical agent into a tillage treatment could offer control of plants that could not easily be destroyed by tillage alone.

Not only does the use of herbicides in a tilled system broaden the scope of weed control to include perennials as well as annuals, it also offers effective weed control at different times throughout the growing season. Tillage only offers good weed control when planting begins; however, weed seed or seedlings that escape tillage can survive to compete with the crop. Cultivation later in the season for extended weed control may be detrimental to the crop itself. Inclusion of chemical weed control measures allows for applications to be made before and after crop emergence without the crop sustaining permanent injury.

Other chemical applications require tillage to obtain maximum effectiveness. Some herbicides, like the dinitroaniline and trifluralin, are soil-active herbicides that are incorporated through tillage into the soil for weed control (Klingman and Ashton, 1975). In this way, tillage reduces germination of weed seed and the herbicide controls germinating seeds before they can compete for resources needed by the emerging crop.

Although the combination of herbicides and tillage offers cost effective, efficient means to grow and produce increased yield crops, this production system will face many challenges in the future, along with all farming systems, in order to remain a viable option for agricultural production. As herbicide resistance and environmental degradation by agriculture become more understood, conventional growing systems with tillage and chemical products, may no longer be suitable for providing a large portion of the world’s supply. For the present time, it remains a valuable production system for meeting the demands of a growing global population.

3.2. Conservation-Agriculture Systems

As the world population continues to increase, agriculturally suitable land will be required to produce more crops to sustain life on Earth. With the rapid loss of soil annually, maintaining crop land for current and future food production has become a difficult task. To aid in the control of soil erosion, several different cropping systems have been developed. Conservation tillage is the term broadly applied to these non-conventional tillage systems. Because conservation tillage refers to varying systems with different goals, a detailed definition is not totally agreed upon by the scientific community. However, a generalized, accepted definition is any tillage practice with at least thirty percent plant residue on the soil surface after planting in an attempt to reduce soil and water loss.

Conservation tillage has a wide range of other positive environmental effects. In addition to conserving soil and soil water, conservation tillage systems have been credited with reducing crop production costs, reduced labor, stabilized macro-porosity which increases water infiltration, and increased nutrient mineralization.

With these environmental benefits being realized under conservation agriculture systems, adoption rates to some form of conservation tillage are on the rise in recent years. However, there are some drawbacks to these systems that have hampered their adoption by many farmers. Most notable is the need for increased herbicide use to control early season weed infestations typically destroyed by tillage. Not only does the increased dependency on herbicides raise a farmer’s input costs, it also has the potential to introduce greater amounts of chemicals into the environment through runoff.

Herbicide use in conservation systems poses unique challenges to producers due, in part, to the weed species composition under these tillage systems in comparison to conventionally tilled production systems. It has been noted by some researchers that not only does weed populations increase under reduced tillage, but species composition also shifts to include more perennial species

(Swanton *et al.,* 2008). The shift caused by a reduction in tillage can require more herbicide applications to control hardy perennial weeds or a complete change in herbicide programs to achieve control over dominant species that were of minor concern in previously tilled fields. While searching for new effective herbicide management strategies, farmers can face rising production costs and reductions in crop yields.

Due to the need to preserve and prolong the productivity of our remaining farmland, it is assured that conservation tillage systems will become even more important as sustainability in addition to profitability continue to shape the outlook of agricultural management practices. Because chemical weed control has offered such reliable management since its widespread adoption, future research will undoubtedly ensure the inclusion of herbicides into conservation practices whatever challenges we face.

3.3. Weed Management in Conventional Crop Varieties

A large majority of today's conventional farming systems incorporate some type of chemical weed control into their weed management strategy. With herbicide tolerant crops available and widely adopted, one can easily forget the different challenges faced by those who still use conventional crop cultivars. However, a vast majority of the herbicide market is still geared toward these conventional systems.

With the boom of herbicide production in the 1950's and 1960's, effective and safe in-season weed control was achieved through the selective properties of the individual herbicide. Today's newly developed herbicides still seek this selectivity but with a broader range of weed control. Because selective compounds cannot effectively control all weed species, farmers must remain knowledgeable about currently available compounds in order to achieve adequate control with minimal input. Even so, conventional crops may still require multiple treatments of various herbicidal compounds throughout the season in order to obtain maximum yield.

Although there is a need for greater understanding of specific weed infestations to be controlled and herbicides to be used associated with the use of conventional crop cultivars in comparison to herbicide resistant crops, there are several benefits to choosing these crops instead of tolerant crops. Farmers using these cultivars have a wide array of chemical compounds at their disposal. Although development of new compounds has slowed and loss of older compounds has reduced overall selection, a large quantity of reliable chemical products remains available for use in farming operations. With the use of conventional crops, the potential for the development of herbicide resistant weed species remains lower due to a lessened chance of overdependence on one specific herbicide. With herbicide resistance threatening to cut lifespan of previously dependable herbicides, this one factor of non-tolerant crops has become a major benefit for their continued use in agriculture.

Conventional crops require great effort and time by farmers employing these varieties; however, before the advent of herbicide tolerant crops, these crop cultivars were all that was available. Farmers were able to effectively meet global demand at that time, and it is certain that conventional crop varieties, even with herbicide tolerant crops available, will continue to play a role, to some degree, in future agriculture production systems.

3.4. Weed Management in Herbicide-Tolerant Crop Varieties

A new design of chemical weed control was introduced with the development of genetically engineered glyphosate-tolerant crops in the late 1980's (Appleby, 2005). Since that time, several other non-selective herbicides, including glufosinate and bromoxynil, have been used to produce herbicide-tolerant cultivars in some of the United States' major crops. Before this time, conventional breeding techniques had been able to achieve this feat to a limited degree commercially with select herbicides and species (Green *et al.*, 2008). With the market introduction of these crops in the 1990's, considerable adoption rates, almost total conversion in some instances, have redefined weed management strategies in agricultural systems.

Movement from conventional crop cultivars to genetically modified herbicide-tolerant crops allowed farmers to achieve successful weed control with little input. Tillage practices could be reduced, soil-applied herbicide treatments could be eliminated, and farmers could forego early season post-emergence herbicide applications and still obtain sufficient weed control. The reliance on one control option substantially reduced input costs and remains a major factor behind continued adoption of this technology.

With any new technology, problems and concerns will inevitably arise. Herbicide-tolerant crops prove no exception. Implementation of this technology by farmers has lead to the repeated use of one chemical product for weed suppression. This overdependence on one herbicide formulation has been shown to increasingly select for herbicide-tolerant weed biotypes, leading to the development of herbicide-resistant weed populations that can no longer be controlled with that particular herbicide. Not only does this emergence of resistant biotypes create concerns over the field life of an herbicide, it also increases the potential for substantial increases in weed biotypes for which no effective control is available.

The future success of herbicide-tolerant crops rests equally with the agrochemical industry as well as with the farmers who use this technology. Advances have been made in which crops are stacked with genes offering tolerance to two or more herbicides with different mechanisms for weed control. However, without farmers' willingness to adopt a rotation scheme of these herbicides along with the incorporation of non-chemical weed control strategies, further use of one of the most revolutionary agricultural technologies in recent history may be in peril.

4. Cultural Weed Control

Although the majority of farming systems in the United States use some form of chemical weed control for maximum weed suppression, a small portion of the farming community has begun to focus on physical and ecological management practices that can be employed to reduce or eliminate the need for herbicide control. The basis for these management tactics is that with an understanding of how and to what extent farming practices affect weed populations, these cultural practices can be manipulated in such a way that weed species can be controlled while reducing economic loss and preserving environmental resilience (Westerman *et al.*, 2005).

Many cultural practices have been noted to affect weed populations including: tillage, crop rotation, planting date, row spacing, and cover cropping. Three of these practices, tillage, crop rotation, and cover crop residues, have repeatedly been shown to adequately maintain low levels of weed populations when used in addition to herbicides. Use of these tactics offer some preventative measure against weed establishment before planting; less emergence allows in-season weed control to be achieved through reduced herbicide applications or through other cultural control techniques.

As the agricultural community continues its attempts to reduce its dependence on chemical weed control as its sole weed management practice, it is likely that these practices will receive greater attention by researchers. With increased study and understanding, these techniques can be better adapted for implementation into row crop systems to further lessen the reliance on herbicide use.

4.1. Tillage

Tillage has been used for decades as a means to control weed species in cropping systems. Initially, weed control was a byproduct of seedbed preparation; weed management was not a primary goal of tillage practices. In more recent times, the ability of tillage to offer control over unwanted weed species has been realized and now drives the continuation of tillage practices.

Deep tillage achieves weed control through the burial of weed seed or through the destruction of weed root systems. Tillage can be employed most effectively when germination of weed seed is allowed between the initial tilling and final cultivation (Buhler, 2002). This practice reduces the number of viable weed seed available for germination in the upper portion of the soil; weed seed that escapes burial and germinates is subsequently destroyed by further cultivation. Deep tillage is primarily used in conjunction with herbicide applications in order to obtain the greatest weed suppression in a row crop setting.

The movement in the past two decades toward a more sustainable farming system that reduces the loss of soil and water relies on a reduction of tillage practices to achieve this goal. In the past, the shift to less tillage has resulted in a greater reliance on herbicides for effective weed control due to a higher number of weeds present in these reduced tillage systems (Steckel *et al.*, 2007). However, some research has suggested that initial weed densities under reduced tillage systems will be greater, but these numbers drop dramatically over time when compared to conventional tillage systems due to increased seed predation, decomposition, and germination under detrimental environmental conditions. With this advantage, reduced tillage could eventually replace conventional tillage in some instances without the need for greater herbicide inputs.

Regardless of what system is chosen, various degrees of tillage manipulation have continually been used to effectively control weed species in row crop systems. As farming systems are modified to meet greater demands worldwide, tillage practices, in some form, will remain as one of the many tools available to farmers in their fight against weeds.

4.2. Cover Crop Residues

Weed management obtained by cover crop residues is potentially achieved through several avenues. The use of cover crops helps to increase weed suppression without tillage. Cover crops can compete with winter or summer weeds for water and light availability reducing the number of weeds. The cover crop residue also acts as a mulch to impede the germination and growth of weed seeds. The allelopathic effects of some cover crop residue may also provide a measure of weed suppression in primary crop production. These weed control capabilities of cover crops and residues combined with the use of herbicides could potentially provide acceptable weed control in comparison with conventional farming systems.

Use of cover crops can be expected to remain limited if the usual cost trend shows little or no net gain in profit as reported in some instances. Fortunately, some research shows that cover crops can possibly help reduce total farm cost; some researchers believe that cover crops could potentially reduce fertilizer and herbicide costs as well as cut the need to use as much pesticide (Lindwall *et al*., 1994). If farming systems employing the use of cover crop residues could continue to be shown to offer weed control as well as potentially offer other benefits to the farmer, this cultural practice may gain a greater acceptance (see also: *Conservation Agriculture*).

4.3. Crop Rotations

Diversification of cropping systems has been explored for many years as a means of weed control. The thought behind broadening the crop species included in a crop rotation to achieve weed suppression is that multiple crop systems provide numerous different environmental stress factors which aid in controlling weed populations. By incorporating diverse crop life cycles, planting dates, harvest times, and farming practices, accumulation of weed seed from specialized weed species can be suppressed. In this manner, problematic weed species can remain in check without the need for multiple herbicide applications.

Rotation of crops allows for producers to reduce potential weed seed numbers by shifting management practices rather than relying on any single management strategy that selects for weed species tolerant to these practices. Not only does the implementation of multiple management practices reduce the selection pressure for more tolerant, less controllable weed species, it also broadens the niches available for seed predators (Westerman *et al*., 2005). With greater numbers of weed seed predators present in a cropping system, weed species that survive to produce seed should have lower populations in successive years compared to monoculture systems due to increased predation.

More diverse crop rotations have been used to reduce populations of weed species that pose the risk of infestation. With the dominant weed species controlled to lower levels, resources are available to a more diverse, yet less competitive, number of weed species. The presence of these less competitive weed species maintains adequate resources for weed seed predators in subsequent years without posing the threat of severe injury or yield loss to the crop.

Adopting successful rotation systems in order to achieve effective weed control requires skill and knowledge by the producer. A grower must understand what crops grow best in rotation as well as how management practices for one crop affect successive crops. For manipulating crop rotations for optimal weed control, a grower must also be acutely aware of problematic weed species in each crop and how the population will respond in a diversified system. However, economic benefit may reduce any hesitancy toward crop rotation adoption. Successful rotation systems can greatly reduce input costs by decreasing the amount of herbicide needed for weed control. With greater demand for alternative weed control strategies by producers, diversification of crop rotation practices will continue to be a key component of successful weed management.

5. Biological Weed Control

As a shift is made in agriculture towards more sustainable systems with less environmental impact, newer avenues of weed control are beginning to be more intensely examined. One such area receiving greater attention in recent years is that of biological weed control. Biological weed control is a strategy that relies on selective pathogens and weed seed predators to reduce weed populations to non-competitive numbers rather than seek total weed control. In this manner, producers can utilize naturally occurring entities to achieve some level of control which can be incorporated into an overall weed management strategy.

Early achievements in biological control of weeds were mainly limited to aquatic and pasture areas. Most of this control relied on particular insects that selectively preyed on unwanted vegetation. Today, however, studies have focused on more agents, including fungi, bacteria, and viruses as a means to gain weed suppression in row crop settings. The use of this form of biological weed control can be implemented through an initial introduction that becomes a self sustaining population or through repeated application of a pathogen as a bio-herbicide (Appleby, 2005).

Several aspects of biological control have restricted production and implementation on a wide scale. These limits exist for industrial producers as well as the agricultural growers wishing to employ these control mechanisms. For growers, lack of total weed control, limited species control ability, varying failure rates and high costs of the agents have stalled their willingness to practice a weed management system that incorporates a biological agent. Commercial production is hindered by soaring costs associated with research and development, regulatory requirements, and formulation concerns like shelf life. Despite these drawbacks research continues in hopes of further developing this area of weed control.

With the desire mounting by the agricultural community to develop sustainable production systems that integrate multiple weed control techniques, biological weed control has attained greater importance in recent years. Even with their limited use in the past, bio-herbicides and natural predators offer the potential for one more means to achieve sustainable, high yield production systems. As this technology moves forward, their use will become even more probable for growers searching to diversify their weed management system.

6. Integrated Weed Management

Despite years of effective weed control measures being developed and implemented into row crop systems, weeds continue to pose the greatest risk of economic loss for producers. Today's agricultural producers rely heavily on tillage and chemical methods to achieve adequate weed suppression; however, the ability of weed species to quickly adapt and shift according to management techniques has led to increased incidence of herbicide-resistant weed populations as well as weed communities that can withstand the effects of tillage. The continued reduction in efficacy of conventional control techniques, combined with environmental concerns and rising input costs, has increased the demand for alternative weed control options.

Intense research in this area has provided a number of nonchemical alternatives to aid in weed control; unfortunately, use of a single, alternative control practice does not always achieve sufficient weed suppression. When combined, however, these practices, along with conventional control methods, create a successful weed management system that reduces the risk of weed control failure while simultaneously reducing dependency on chemical control which preserves environmental integrity and field life of important herbicidal compounds. The combination of these control techniques offers a more comprehensive, integrated weed management system that relies on physical, cultural, biological, and chemical means, as well as their interactions, to suppress weed populations below their economic injury threshold (Buhler, 2002; Swanton *et al.*, 2008).

The idea of integrated pest management came into practice in agricultural systems during the 1960's, however, this concept remained largely confined to insect and disease management systems. Although integrated weed management falls under this broad field of integrated pest management (IPM) and seeks to achieve similar goals, only recently has the agricultural community pursued this comprehensive management strategy. This delay is due, in part, to the relative effectiveness of conventional weed control practices as well as the complex responses of weed species to farming practices. With concerns mounting over the fate of necessary herbicide formulations in response to increased herbicide resistance and environmental contamination, researchers have tackled the intricacies of weed responses in order to further develop integrated weed management.

The goal of integrated weed management is to develop a system of weed control that incorporates many tactics to achieve long-term suppression. There has been a long list of physical, cultural, chemical, and biological mechanisms suggested to play a role in weed management; however, a fundamental knowledge of these components as well as the weed species is crucial to implementing a successful control strategy. A grower's understanding of the important elements of weed control is of great importance when attempting to adopt an integrated control strategy.

A producer's practices before, during, and after a growing season determines the success or failure of an integrated weed management system. Prevention, as well as control, plays an integral part in managing a weed population. A grower must remain aware of practices in and around agricultural sites in order to eliminate the introduction of potentially devastating weed species. Introduction can occur through several avenues that can be prevented through diligence including contaminated crop seed and machinery.

Weed management of existing weed species within the seed bank can be affected prior to crop planting and emergence. Tillage practices, either conventional or reduced, help determine what weed species will emerge and in what quantities. Other factors that affect weed response prior to planting are use of cover crops, crop choice (both in cultivar and in rotation scheme), as well as pre-plant incorporated herbicides (Swanton *et al.*, 2008). Management of these practices affects the competitiveness of the crop and the ability of weed seedlings to germinate.

Weed management during planting and after crop emergence plays a critical role in successful weed reduction throughout the growing season and maintaining a high-yield crop. This period is limited in options for weed control, and many growers often rely on chemical means to suppress weed growth. There are, however, several other tactics that can aid in diminishing the weed population including: planting date, row spacing, seeding rate, and fertilization practices. In-season management strategies now also include biological herbicide options in addition to traditional herbicide formulations. Integrating management of these factors with components of pre-plant weed management can lessen the dependence on a single control tactic and reduce the risk of weed control failure by implementing multiple strategies of weed suppression.

Although an integrated weed management system is beneficial on many fronts, long-term, conscious efforts by farmers to adopt this type of control practice has been a slow process. Several perceived notions by the agricultural community may be to blame for the lack of enthusiasm over a comprehensive management practice. The farming community is hesitant to rely on any control measure that they feel will increase management risk without potential economic benefit. Herbicide based management strategies are driven by consistently effective weed control; alternative weed control measures are sometimes more varied in their short-term control capabilities. However, long-term weed control is the goal of these tactics. With chemical control methods as a cost-effective tool for weed management, farmers have had little economic incentive to search for more diversified management practices. As on-farm costs soar due to rising fuel prices, the need to explore alternate management tactics may advance adoption rates of integrated weed management.

Integrated weed management systems have resulted from the culmination of research efforts by weed scientists to help create more sustainable agricultural systems with reduced dependency on a single weed control method. Although this type of system remains not yet fully developed, the future of agricultural production will most certainly rely on a weed management system that utilizes every available tool against its mightiest adversary.

7. Herbicide Resistance

Since the introduction and widespread adoption of 2,4-D by farmers in the late 1940's, agricultural production has become more and more dependent upon chemical weed control to achieve adequate weed suppression and profitable crop yields. The addition of herbicides into farming systems has allowed for great improvements in crop production and cost control but with a potential risk that could threaten long-term availability of many herbicides that farmers have come to rely upon.

Repeated use of the same, or similar, herbicides within a field or region greatly increases the chance of emergence of an herbicide-resistant weed population by selecting for naturally occurring tolerant biotypes that possess a mutation that inhibits herbicide uptake. It is this repeated use of presently effective herbicides by farmers that threatens the lasting potential of these herbicides and has spurred the scientific community to greater research into herbicide resistance development. It has also spawned the development of herbicide-resistant management practices in an attempt to rescue present-day weed control chemicals at risk of being lost to resistance troubles as well as to ensure the future success of weed control with herbicides.

7.1. Resistance Development

Since the first notice of herbicide resistance among weed species, scientists have sought to understand the components behind resistance development. In most instances, resistance to an herbicide exists naturally in small numbers within a weed population as a single gene mutation (HRAC, 1998; Ross and Lembi, 1999). Many times, this mutation is associated with fitness costs to the specific biotype which keeps its quantities at low levels within the population. When a weed population becomes resistant to a certain herbicide, it is the culmination of several incidents that has allowed for the selection of this resistant biotype to become the dominant biotype within the population.

Many factors play a role in the development of a weed species’ ability to resist herbicide control under normal herbicide application rates. Most notable of these factors are cultural practices by farmers that provide selection pressure for resistant weed species like repeated use of herbicides with one mode of action either by failing to rotate herbicide products or by rotating between herbicides that work in the same manner. The primary driving force behind producers repeatedly relying on one herbicide mode of action has been the large-scale adoption of herbicide-resistant crops. This practice provides heavy selection pressure for naturally resistant weed biotypes within the system; it also poses a potential means of resistance gene flow from the resistant crop variety into related weed species in the surrounding environment.

Other factors that lend to herbicide resistance development include highly efficacious herbicides that offer complete control of susceptible biotypes (allowing for resistant biotypes to thrive freely), persistent exposure to herbicides by soil residual formulations, and monoculture settings where management systems go unaltered from one growing season to the next.

Specific plant biology also helps determine to what extent and how fast herbicide resistance will develop in a weed population. Annual weed species have been shown to develop herbicide resistance at a greater rate than perennials due to the relatively large number of seeds produced each season with the potential to secure resistant populations with the next generation (Ross and Lembi, 1999). When resistance is produced by the mutation of a single, dominant gene at a fast rate, the particular herbicide-resistant weed biotype will appear at a much quicker rate as well.

When a weed population becomes resistant to one type of herbicide, it is common to see resistance carry over to other herbicides with the same mode of action even if the weed population has never been exposed to the other herbicides in question. This cross resistance of weed biotypes to multiple herbicides adds to the urgency of devising management strategies for herbicide resistance.

It is clear that development of new herbicide-resistant weed biotypes is becoming more evident among growing numbers of agricultural systems worldwide. The rising number of resistant species may be attributed to greater research and documentation of existing species; however, new resistant biotypes are appearing at alarmingly high rates in many different classes of herbicides due to the on-farm mismanagement of weed control chemicals and over reliance on a single mode of action for repeated seasons. Without the addition of effective herbicide-resistant management practices to agricultural production as well as proper farmer education on management implementation, the agricultural community could very well face the impending loss of necessary herbicide products that cannot be quickly filled.

7.2. Resistance Management

With herbicide resistance becoming an area of great concern in the agricultural arena in recent decades, much research has been conducted in order to understand what mechanisms lead to the development of specific resistance incidents.

The primary factor most commonly attributed to increasing herbicide resistance development is the dependency on a single herbicide or similar herbicides for principal weed control within a farming system. Resistance management practices define a broader weed control strategy that relies on an integrated approach including cultural practices as well as chemical means to reduce selection pressure for resistant weed biotypes (HRAC, 1998). The implementation of these integrated weed management practices have proven, in some instances, to be costly and labor intensive; however, adoption of more extensive weed control methods may be the only way to guarantee long-term efficacy and availability of many of today’s herbicides.

Specific cultural practices that have been suggested as means to reduce reliance on one type of chemical control include: crop rotation between systems with different herbicide programs, returning to more intense tillage practices to reduce weed populations, and settling for less complete weed control in order to reduce the amount of herbicide being used in a field. Drawbacks to the incorporation of these practices into weed control systems could include economic loss as well as negative environmental impacts that might slow down the acceptance of alternative weed control strategies.

Management of herbicide resistance also requires a greater knowledge about herbicide modes of action and their use at the farmer level. If farmers include a rotation of different herbicide groups in their chemical weed control program, they can help reduce overexposure of a weed population to one specific herbicide, in turn reducing pressure that selects for the resistant weed biotype in a weed population (Ross and Lembi, 1999).

In an attempt to slow the development of herbicide resistance and to devise and educate farmers of resistance management practices, the agrochemical industry developed the Herbicide Resistance Action Committee (HRAC) in 1989. This organization focuses research on understanding resistance development as well as using this information to suggest practical and cost effective guidelines for on-farm management practices. The long-term goal of this organization is to ensure that herbicide resistance is kept in check so that farming systems can remain profitable and sustainable in the face of persistent weed competition.

Although herbicide resistance management guidelines and understanding begins at the level of the scientific community, ultimate management success lies in the hands of individual farmers. Mismanagement of and lack of education about proper use of available herbicide products on farms will continue the progression toward greater incidence of herbicide resistance. To slow this movement, it is necessary for industry and science to come together to develop effective management strategies and, more importantly, educate the farming community as to how important their role is in guaranteeing lasting chemical weed control options.

8. Conclusions

The dynamic nature of weed science offers a host of challenges for those who attempt to undertake any portion of this relatively new subset of science. The founding researchers in this field have accomplished astounding feats worthy of great merit not only for their scientific advancement, but also for their great improvement in agricultural productivity capabilities. In its infancy, weed science has helped bring to fruition technologies and concepts that have overwhelmingly increased productivity, profitability, and sustainability never before realized in the agricultural arena. The initial scientists devoted their careers to research and ideas not previously understood or of relative concern to many. Their effort and perseverance laid the groundwork for a field of study noteworthy of praise not only in agriculture but in the whole of the scientific community.

The legacy left by early weed scientists set a high benchmark for those who follow after them. Yet, it was these standards that catapulted this field to the important role it now plays in global agricultural production. These standards must be maintained, if not surpassed, in the future if weed science is to continue to meet and overcome the awaiting challenges certain to face the world's agricultural industry.

Related Chapters

Glossary

Allelochemicals: Chemicals produced by a plant species that, when released, can potentially affect the growth of other nearby plant species.

Allelopathy: Inhibition of a plant's growth due to the release of bio-chemicals in the environment.

Bio-herbicide: A herbicide comprised of living organisms, such as insects, fungi, and bacteria that feed upon a specific weed species.

Cover crop: A crop grown to enhance soil conditions in preparation for the planting of a primary crop.

Herbicide: A substance that can inhibit growth or cause the death of a plant when exposed to the substance.

Macro-porosity: The extent to which large macro-pores, or channels, exist within the soil. The system of macro-pores aids in the movement of water and air into the plant root zone.

Management: A producer's set of practices that is put into place in an attempt to grow a quality product and, ultimately, preserve the profitability and productivity of that specific crop land.

Mulching: The mixing of organic and soil materials in order to improve topsoil conditions, including the reduction of weeds. Mulches can be any number of natural or manmade materials.

Phenoxyacetic herbicide: A distinct group of the phenoxy herbicides which includes 2,4-D and is used to control broadleaf weed species.

Phenoxy herbicide: A large group of herbicides that inhibits normal plant growth by mimicking a plant growth hormone which induces excessive and fatal growth.

Pollination: The transfer of a flower's pollen from the anther to the stigma to facilitate the fertilization of the flower's ova, or eggs.

Sodium arsenate: An arsenic-containing herbicide that has been removed from the market due to toxicity concerns.

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Biographical Sketches

Jessica Kelton - After receiving a Bachelor's degree in Biology from Troy University, Jessica Kelton began pursuing a Master's degree in Weed Science with Auburn University's Agronomy and Soils department under the direction of Dr. Andrew Price.

Andrew Price - After receiving Bachelor's and Master's degrees in Plant and Soil Sciences from The University of Tennessee and a PhD in Crop Science from North Carolina State University, Andrew Price has worked at the USDA-Agriculture Research Service National Soil Dynamics Laboratory in Auburn, Alabama, where he has been conducting weed biology and management research in conservation agriculture systems. Dr. Price also serves as an affiliate faculty member at Auburn University. Research goals include the development of integrated farming technologies and strategies for managing weeds which increase adoption of conservation production systems that reduce economic risks and improve farm profitability; improve soil quality and productivity; reduce risks from short-term droughts; and enhance carbon storage.

Table 1. General characteristics of weedy species (adapted from Baker, 1974).

- Germination requirements fulfilled in many environments.
- Discontinuous germination (internally controlled) and great longevity of seed.
- Rapid growth through vegetative phase to flowering.
- Continuous seed production for as long as growing conditions permit.
- Self-compatible but not completely autogamous or apomictic.
- When cross-pollinated, unspecialized visitors or wind utilized.
- Very high seed output in favorable environmental circumstances.
- Produces some seed in wide range of environmental conditions; tolerant and plastic.
- Have adaptations for short- and long-distance dispersal.
- If a perennial, has vigorous vegetative reproduction or regeneration from fragments.
- If a perennial, has brittleness, so not easily drawn from ground.
- Has ability to compete inter-specifically by special means (rosette, choking growth, allelochemicals).