

Turfgrass Herbicide Mode -of-Action and Environmental Fate

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INTRODUCTION

Weeds interfere with human activities. Weeds decrease crop yields, lower the aesthetic value of turf and ornamental areas, inhibit the use of lake reservoirs and ponds, and can have harmful effects on humans and animals.

Weed control is an integrated system that utilizes preventive, cultural, mechanical, and chemical control methods. The contribution of preventive, cultural, and mechanical methods of weed control are an important part of weed control systems. Chemical control methods, or the use of herbicides, are valuable, if not irreplaceable, components of modern weed control systems. Understanding the behavior of herbicides in crop plants, weeds, and soils is paramount to their safe and effective use.

Herbicides are developed and marketed by large chemical companies. Prior to being used as a herbicide, a chemical undergoes thorough investigation by the chemical company, land grant universities, and various state and federal agencies. The herbicide must be proven to control weeds, be safe to non-target plants, humans and animals, and have no deleterious effect on the environment. Final approval for use as a herbicide is under the direct control of the United States Environmental Protection Agency.

Chemicals have been used to control weeds in noncropland for several hundred years. However, use of chemicals to selectively control weeds in crops dates from only a few years before the turn of the 20th Century. Following is a brief outline of some important milestones in the development of chemical weed control:

1880 - Charles Darwin, better known for his book "Origin of the Species", suggested that growth substances regulate plant growth. This prompted much research to isolate and identify these substances.

1897-1908 - Copper sulfate, ferric sulfate and sodium arsenite were found to selectively control broadleaf weeds in cereal crops.

1934 - German chemists reported indole-3-acetic acid (IAA) to be a growth-regulating chemical.

1935 - (France) - Dinitrophenols patented for selective weed control in cereal crops. These were the first organic herbicides.

1939-1940 - (England) - Due to German blockade, intensive research was conducted with synthetic growth regulators to increase food production. 2,4-D found to kill plants when applied at high rates. (Not reported until after World War II).

1944 - (USA) - 2,4-D and 2,4,5-T reported to selectively kill broadleaf weeds in cereal crops and Kentucky Bluegrass.

1946 - (England) - 2,4-D was demonstrated to be an effective preemergence herbicide. This firmly established the preemergence principle of selective weed control.

1950-present - Since the introduction of 2,4-D-type herbicides, chemical weed control has gained wide acceptance. Herbicides now account for about 60 percent of the total pesticide use in the United States. Currently, over 180 different chemicals are registered for use as herbicides.

HERBICIDE NOMENCLATURE

The herbicide label contains three types of names. The herbicide sold as Surflan has the trade name of Surflan, the common name oryzalin, and the chemical name of 4-(dipropylamino)-3,5-dinitrobenzenesulfonamide. The trade name is used by the chemical company to promote the sale of a specific product and is often the most recognizable name of a herbicide. The common name is a generic name that is given to a specific chemical name. Only one common name exists for each herbicide. The chemical name describes the chemistry of the herbicide compound.

Chemical companies obtain a product patent prior to the release of the herbicide in the marketplace. A company retains exclusive or proprietary rights for that herbicide for 17 years after the product patent has been issued. After the patent has expired, other chemical companies are free to market the herbicide; however, a different trade name must be used.

Often a herbicide is sold under different trade names by the same or different chemical companies. For example, halosulfuron is marketed by Monsanto for corn use as Permit and for turfgrass use as Manage.

HERBICIDE MODE OF ACTION

Herbicides are used to kill or severely inhibit the growth of non-desirable plants. The way a herbicide kills or severely inhibits plant growth is called its mode of action. Mode of action refers to the entire sequence of events that happen in the plant from the time the herbicide is absorbed to the eventual plant response (usually death). Therefore, the term mode of action includes absorption, translocation to an active site at which the herbicide inhibits a specific biochemical reaction, the degradation or breakdown of the herbicide in the plant, and the effect of the herbicide on plant growth and structure. During recent years, our understanding of the mode of action of many herbicides has drastically increased. However, there are many other herbicides whose mode of action is not completely known.

Normal growth and development is the result of many complex biochemical reactions within the plant. Herbicides adversely affect these biochemical reactions; however, not all reactions in the plant are affected by the herbicide. Physiologists that study herbicide mode of action strive to identify the specific biochemical reaction in the plant which is inhibited by the herbicide and that results in the death of the plant. The term herbicide mechanism of action refers to the primary biochemical site of action within the plant that leads to the plant response. Identifying the single biochemical reaction that is affected by the herbicide and that leads to the plant response can be difficult. Often a herbicide has been shown to have multiple modes of action. For example, 2,4-D, which was discovered during World War II, has been shown to inhibit or promote protein and nucleic acid synthesis, increase or decrease cell division, stimulate ethylene production, and increase cell enlargement. However, the exact mechanism of action for this herbicide is not known.

HERBICIDE EFFECTS ON PLANTS

The majority of herbicides can be placed into seven general mode of action categories based on their effects on or in plants.

Photosynthesis. In the presence of light, green plants produce sugar ($C_6H_{12}O_6$) from carbon dioxide (CO_2) and water (H_2O) in a process called photosynthesis. Photosynthesis is a two-phase process that occurs in the leaf chloroplasts. During the light-dependent phase of photosynthesis, light energy from the sun is transformed into biological energy in the form of ATP (adenosine triphosphate) and $NADPH_2$ (nicotinamide adenine dinucleotide phosphate). In the light-independent phase of photosynthesis, ATP and $NADPH_2$ are used to supply energy for the conversion of CO_2 into sugars. Sugars are subsequently converted into carbohydrates which represent the major stored portion of biological energy in the plant. During respiration, carbohydrates are utilized to form ATP and other types of readily usable biological energy. This energy is used to fuel or drive metabolic reactions that are necessary for plant growth and development.

Herbicides that inhibit photosynthesis interfere or block electron transport during the light-dependent phase of photosynthesis. Inhibiting photosynthesis leads to decreased sugar or food formation; however, the visual injury symptoms (chlorosis, desiccation or browning of plant tissue) occur too rapidly to be caused by starvation of the plant for food materials. Chlorosis of leaf tissue may be due to the photodestruction (damage from excessive amounts of light) of chlorophyll and other plant pigments. Also, a phytotoxic compound that destroys cell membranes may be formed when electron transport is blocked during the photosynthesis process. Cell membrane destruction would cause leakage of the cellular contents and result in the desiccation of plant tissue.

Turfgrass herbicides known to inhibit photosynthesis are the triazines, bentazon and oxadiazon. Additionally, the mode of action of the bipyridilliums, and bromoxynil have been shown to be related to the photosynthetic process.

Amino Acid and Protein Synthesis. Proteins are used by plants in functional, storage, or structural roles. Functional proteins are called enzymes. Enzymes catalyze or mediate the thousands of chemical reactions that are necessary for plant growth and development. Storage proteins are commonly found in seeds. For example, soybean seed has an average protein content of 44%. Protein seed reserves are used to supply essential amino acids to young, developing seedlings until the initiation of amino acid synthesis. Both enzymes and seed proteins are composed of long chains of interconnected amino acids. Commonly, 17 to 20 different types of amino acids are found in plants; however, the amino acid composition will vary greatly between different plant proteins.

In the absence of amino acid and protein synthesis, a plant is incapable of completing the chemical reactions that are necessary for growth. Imidazolinones, sulfonylureas, and glyphosate have been shown to inhibit the synthesis of specific amino acids. Without these amino acids, protein synthesis is decreased, certain metabolic reactions cease, and the plant gradually dies over a period of one to several weeks.

Protein synthesis is under the direct control of the nucleic acid compounds DNA (deoxyribose nucleic acid) and RNA (ribonucleic acid). DNA is located in the nucleus and chloroplasts of plant cells and contains the genetic information that determines the sequence of amino acids in the various plant proteins. RNA (messenger RNA) transports the genetic information that is contained in DNA, and is involved in the assembly (transfer RNA) of amino acids into proteins.

The substituted amide herbicides interfere with nucleic acid synthesis, which in turn decreases protein synthesis. The phenoxy, triazine, and organic arsenical herbicides have also been shown to inhibit protein synthesis.

Cell Division. Potential plant growth is due in large part to the process of cell division. During cell division, a mother cell divides into two daughter cells. Each daughter cell is an exact duplicate of the mother cell. Cell division is initiated and is regulated by the nucleus of the cell. The division of the nucleus itself is called mitosis; however, mitosis is also widely used to refer to the entire act of cell division.

Herbicides that interfere with cell division are called "mitotic poisons". By blocking cell division, new cell production is decreased and eventually growth stops. Herbicides that inhibit cell division are the dinitroanilines, pronamide, dithiopyr, and bensulide.

Cell Wall Biosynthesis. Cell wall biosynthesis begins during the process of cell division and continues during the growth of the cell. The primary purpose of the cell wall is to impart rigidity and structure to the plant. Isoxaben (Gallery) inhibits cell wall biosynthesis.

Cell Membranes. A plant cell is enclosed by a cell membrane (plasma membrane) and a cell wall. Contact herbicides have been shown to cause breakdown of the cell membrane. Leakage of the cellular contents occurs, and the plant undergoes rapid wilting and desiccation often within hours of herbicide application. Plant tissues appear to be burned; however, the mode of action of most contact herbicides is not due to a simple burning or caustic action of the herbicide on the cell membrane. Specific physiological processes are known to be affected by contact herbicides. For example, the bipyridillium herbicides intercept electrons during the light-dependent phase of photosynthesis and become free radicals. The bipyridillium radical passes electrons to other compounds which results in the formation of superoxide radicals and hydrogen peroxide which are toxic and breakdown the cell membrane.

Fatty acids are primary components of cell membranes. If fatty acid synthesis is blocked or inhibited plants are unable to form cell membranes required for normal growth. The postemergence grass herbicides, sethoxydim (Vantage), fluazifop (Fusilade II), fenoxaprop (Acclaim Extra) and clethodim (Envoy) inhibit fatty acid synthesis in susceptible grass weeds.

Pigment Synthesis. Carotenoids (yellow in color) and chlorophyll (green in color) are plant pigments that are located in the chloroplasts of leaf cells. Both carotenoids and chlorophyll absorb light during photosynthesis. An additional function of carotenoids is that they protect chlorophyll molecules from photooxidation (damage from excessive light). Norflurazon (not used for weed control in turfgrasses) inhibits carotenoid synthesis. In the absence of the protective carotenoids, chlorophyll is broken down by sunlight and susceptible plants become bleached or white in color. Plant death occurs slowly due to the eventual depletion of stored food reserves and the inability of the plant to manufacture new sugars.

Growth Regulation. Auxins are naturally produced plant hormones that are involved in the regulation of plant growth. At low concentrations, auxins promote normal growth and development. At abnormally high concentrations, auxins inhibit plant growth. Auxin levels in the plant are under direct metabolic control. Applications of "auxin-type" herbicides are not under metabolic control and result in abnormal plant growth.

The exact mode of action of "auxin-type" herbicides is not known. The first symptom that is observed following "auxin-type" herbicide application is a downward twisting or curvature of the leaves and stems of susceptible plants. This can occur within hours of application. Although other

symptoms are slower to develop, plants also undergo rapid uncontrolled cell division and enlargement. Vascular tissues that are responsible for the transport of food materials and water become plugged or broken, and the plant slowly dies over a 2 to 4-week period after herbicide application. Recent evidence indicates that "auxin-type" herbicides stimulate the production of excessive amounts of ribonucleic acids (DNA and RNA). This induces uncontrolled cell enlargement and division and results in the abnormal growth of susceptible plants.

Herbicides that have "auxin-type" activity include the phenoxy, benzoic acids, and picolinic acids.

Growth Inhibition. Although all herbicides inhibit the growth of plants, the specific mechanism of action of many herbicides is unknown. The substituted amides and bensulide have been placed in the category of growth inhibition.

Bensulide has been shown to be a potent inhibitor of root growth in susceptible plants. The mode of action of this herbicide is believed to be the disruption of cell division or cell enlargement. Substituted amide herbicides inhibit seedling growth. Shoot or root growth or both may be inhibited by this group of herbicides. Reduced cell division and cell enlargement has been reported to occur in the presence of these herbicides. Nucleic acid and protein synthesis is also adversely affected by most substituted amide herbicides.

Nitrogen Metabolism. Glufosinate (Finale) has been shown to inhibit a key enzyme involved in nitrogen metabolism. This enzyme is involved in the conversion of inorganic nitrogen, in the form of ammonia, into amino acids. Glufosinate interferes with the activity of this enzyme which causes toxic levels of ammonia to accumulate in plant cells which directly inhibits photosynthesis. The end result is rapid necrosis and death of plants.

ENVIRONMENTAL FATE OF HERBICIDES

The ideal herbicide is one that controls weeds for a desired period of time and then rapidly degrades or breaks down in the soil to non-phytotoxic levels. Understanding the residual life or soil persistence of a herbicide is extremely important. It not only determines the length of weed control that may be expected but also influences the length of time that must pass before turfgrasses may be seeded or vegetative ly established on herbicide-treated sites.

There are seven major processes that greatly affect herbicide persistence. They are:

Volatility. This is the process by which a herbicide changes from the liquid or solid state to the gaseous or vapor state. Once in the vapor state the herbicide is rapidly lost from the intended area of application and poor weed control or injury to nontarget plants can occur. Chemical characteristics, soil moisture, temperature and adsorption of the herbicide to soil colloids all affect herbicide volatility. For example, under hot, dry conditions pronamide (Kerb) volatility is high. The dinitroaniline herbicides (oryzalin, trifluralin, prodiamine, benefin, pendimethalin) vary in their volatility characteristics. Oryzalin (Surflan) and prodiamine (Barricade) are considered the least volatile, followed by pendimethalin, benefin (Balan) and trifluralin (Treflan). Mechanical incorporation or a rainfall or irrigation event within 1 to 2 days of application will prevent or dramatically reduce the volatility losses of dinitroaniline herbicides. In the case of many phenoxy-type herbicides, the type of formulation influences volatility. Ester formulations of 2,4-D or MCPA, especially short-chain esters, are extremely volatile under warm, humid conditions while amine formulations are much less volatile. Only amine formulations should be used during the warm months of the year.

Leaching. The movement of herbicides in soils by water is called leaching. Leaching of herbicides can occur in any direction in the soil, but the most common direction is downward. The amount of herbicide lost to leaching is affected by soil texture, adsorption of the herbicide to soil colloids, the water solubility of the herbicide and the amount of water movement through the soil. Herbicides such as the salt forms of 2,4-D have a low tendency to be adsorbed by soil colloids and readily leach in fine sand or silt loam soils. In contrast, the dinitroaniline herbicides and most other preemergence herbicides are readily adsorbed to soil colloids and resist leaching. As a general rule, herbicides leach more in sandy soils that are low in organic matter than in soils high in clay and/or organic matter.

Leaching is sometimes correlated with the water solubility of the herbicide. Although water solubility determines the amount of herbicide that can be dissolved in water, it is not the sole factor involved in the leaching characteristics of a particular herbicide. For example, diquat is highly water soluble, but undergoes almost immediate, and non-reversible binding to clay organic matter. Because of this strong chemical attraction diquat does not leach and is non-biologically active after binding to the colloidal components of soils.

Soil erosion. The physical movement of soil particles by wind or water can result in the loss of a herbicide from the original area of application. Established turfgrasses are superb plants in reducing soil erosion. However, during establishment, or "grow-in", soil erosion can occur. Cultural practices such as the use of mulches when seeding turfgrasses is an excellent method to reduce soil erosion and enhance establishment. Certain herbicides can be used at the time of or during establishing turfgrasses. However, if physical movement of soil particles occurs during establishment there is a chance that herbicides bound to the soil particles will be moved as well.

Adsorption. Adsorption is the attraction of ions or molecules to the surface of a solid. After application many herbicides adsorb to the clay and organic-matter fractions of soils. However, herbicides adsorb poorly to sand and silt fractions of soils. The extent of herbicide adsorption increases as the percentage of organic matter and/or clay content increases. Adsorption reduces the amount of herbicide available for plant uptake, slows leaching and usually retards microbial breakdown.

The dinitroaniline herbicides, dithiopyr (Dimension) and oxadiazon (Ronstar), and most other preemergence herbicides are readily adsorbed to soils.

Photodecomposition. Herbicides broke down or degraded by sunlight. Specifically, the ultraviolet (UV) portion of sunlight is responsible for losses of herbicides due to photodecomposition. Several herbicides, such as most dinitroanilines herbicides are photodegraded and must be incorporated into soils with rainfall or irrigation to retain herbicidal activity

Chemical Processes. A herbicide can undergo chemical decomposition in the environment. Herbicides may react with chemicals as result of oxidation-reduction, hydrolysis, formation of water-insoluble salt, and formation of chemical complexes reactions. However, the primary means of herbicide degradation in the soil is microbial in nature.

Microbial processes. Microbial decomposition is one of the most important processes by which herbicides are broken down in the soil. Many organic herbicides are used by microorganisms as a food source. Soil temperature, aeration, pH, organic matter, and moisture levels that are favorable for microbial growth promote rapid herbicide breakdown.

In most cases microbial decomposition is favorable, i.e., degrading the herbicide in the environment. However, with some herbicides, microbial decomposition can occur so rapidly residual weed control can be significantly shortened. Because of enhanced microbial degradation, herbicides that belong to the thiocarbamate herbicide family (EPTC, butylate) are often formulated with an "extender" that slows microbial breakdown and extends the residual activity of the herbicide in soil. Turfgrass herbicides known to be decomposed by microbial processes include the dinitroanilines, metolachlor (Pennant), napropamide (Devrinol), pronamide (Kerb), bentazon (Basagran T/O), dithiopyr (Dimension), glufosinate (Finale), glyphosate (Roundup Pro) and isoxaben (Gallery).

Herbicide half-life. A commonly used term used to describe the persistence of herbicides is called the T_{1/2} or half-life. T_{1/2} indicates the average length of time (days, weeks, months) it takes a herbicide to reach one-half of the originally applied dosage. Preemergence herbicides usually have a longer T_{1/2} in the soil than postemergence herbicides. Long half-lives are desirable in terms of residual weed control, but can be a problem if renovation or new plantings are scheduled for a site previously treated with a preemergence herbicide.

TURFGRASS HERBICIDE FAMILIES

Herbicides may be grouped together or classified into families on the basis of similarity in chemical structure. Generally, the response of crop plants and weeds and the behavior in or on soils is similar for herbicides in the same family. The chemical structures of the various herbicides are not present in this handout. Herbicide chemical structures may be found in various Weed Science textbooks or in the Herbicide Handbook of the Weed Science Society of America.

Arsenicals

General Characteristics and Uses. The arsenical herbicides are classified either as inorganic or organic chemicals. Inorganic arsenicals such as sodium arsenite are very toxic to humans and animals and are not widely used at the present time. In contrast, the organic arsenicals are essentially nontoxic to mammals and are extensively used in a wide variety of weed control situations.

The organic arsenicals are sold under a variety of formulations and trade names (Table 1). MSMA and DSMA are the most commonly used members of this group. MSMA and DSMA are labeled for the control of annual and perennial grasses in cotton, certain turfgrass species, and noncropland areas. Broadleaf weeds are less susceptible than grasses; however, cocklebur and ragweed can be controlled with MSMA or DSMA. AMA and CMA are used primarily to control grass weeds in selected turfgrass species. Cacodylic acid differs from other members of this family in that it is nonselective. The major use for cacodylic acid is general vegetation control in noncropland areas. The organic arsenicals have no soil activity and are applied as postemergence treatments.

Mode of Action. The organic arsenicals are readily absorbed by leaves and have been shown to translocate throughout the plant. With the exception of cacodylic acid, susceptible plants are slowly killed by these herbicides. Injury symptoms are initially leaf chlorosis and a cessation of growth that is followed by desiccation and eventual death of the plant. Cacodylic acid is a contact type of herbicide and kills plants more quickly than other members of this family. Organic arsenical herbicides have been shown to interfere with ATP production and the activity of certain enzymes.

Soil Characteristics. Upon contact with soil colloids, the organic arsenicals are tightly bound and are very resistant to leaching. The elemental arsenic that is present in these herbicides does not breakdown in the soil and concern has existed over the possible buildup of toxic levels of arsenic. At standard use rates, the organic arsenicals have not been shown to contribute significant amounts of arsenic to the soil system.

Table 1. Members of the organic arsenical herbicide family used in turfgrasses.

Common Name	Trade Name
Cacodylic acid	Bolls-Eye, Phytar 560, Others
CMA	Super-Crab-E-Rad-Calar, Others
DSMA	DSMA Liquid, Ansar 8100, Others
MSMA	Bueno 6, Mesamate, Weed-Hoe, 912, MSMA 6.6, MSMA Turf

Aryl-Oxy-Phenoxy

General Characteristics and Uses. This family is a relatively new and unique class of herbicides. Members of this family have activity only on grass weeds and do not control broadleaf weeds, sedges, or rushes (Table 2).

These herbicides have both soil and foliar activity. Extremely short soil persistence (1 to 4 weeks) and the necessity of high rates for soil application relative to foliar application rates have limited the use of these herbicides to foliar applications. However, preemergence control of annual grasses for a short time period has been observed following application. Diclofop (Illoxan) is labeled for the control of goosegrass on golf course bermudagrass turf. Fluazifop-P (Fusilade II) is labeled for the postemergence control of annual and perennial grasses in tall fescue and zoysiagrass. Applications to annual grasses 2 to 6 inches in height provide better control than later applications. Perennial grass control also varies according to growth stage and multiple applications are necessary for effective control. Fenoxaprop (Acclaim Extra) is sold for use in for use in cool-season turfgrasses and zoysiagrass.

Mode of Action. These herbicides are rapidly absorbed by leaves and are translocated to the actively growing points (near the nodes, buds on stolons and rhizomes, etc.) of grass weeds, where they inhibit meristematic activity. Death occurs slowly over a 1 to 3-week period. Treated foliage will redden and may become chlorotic. Nodes blacken and die and leaves will easily break or pull from the nodal region.

Soil Characteristics. These herbicides are essentially nonmobile and average only 1 to 4 weeks in soil persistence.

Table 2. Members of the aryl-oxy-phenoxy herbicide family used in turfgrasses.

Common Name	Trade Name
diclofop	Illoxan
fenoxaprop	Acclaim Extra
fluazifop-P	Fusilade II

Benzoic Acids

General Characteristics and Uses. Dicamba (Vanquish, Banvel) is a member of this family. Dicamba is used primarily as a postemergence treatment for the control of broadleaf weeds in turfgrass species. It is a common active ingredient in various 2-way or 3-way herbicide mixtures that contain herbicides such as 2,4-D, MCPA and 2,4-DP (Table 4).

Mode of Action. Dicamba is absorbed by leaves and roots and is extensively translocated. The mode of action of the benzoic acid herbicides is believed to be interference with nucleic acid (DNA and RNA) and protein synthesis that leads to rapid, uncontrolled abnormal growth. Visual injury symptoms for broadleaf plants are: a) stems curve downward and become twisted or crooked, and b) leaves become puckered and may curve down or up. Dicamba drift on soybeans results in an upward cupping of the leaves. On grasses, the benzoic acid herbicides can cause leaves to be tightly rolled in an onion-like fashion, interfere with brace root formation in corn, and may cause temporary brittleness of stems. Note. Many of the visual injury symptoms are similar for the benzoic acid, phenoxy, and picolinic acid herbicide families. Separation of differences can be difficult under field conditions.

Soil Characteristics. Dicamba readily leaches, particularly in sandy soils under conditions of high rainfall. Due to its mobility in the soil, dicamba should not be applied over the root zone of ornamental shrubs and trees. Soil microorganisms are responsible for the breakdown of dicamba. Under temperature and moisture conditions favorable for microbial activity, the persistence of dicamba is 1 to 6 weeks. Longer levels of persistence may be expected under cool temperature and low soil moisture conditions.

BENZONITRILES

General Characteristics and Uses. Members of this herbicide family include bromoxynil (Buctril). Bromoxynil has no soil activity and is used as a folia ge-applied herbicide in turfgrasses for the control of seedling broadleaf weeds.

Mode of Action. Bromoxynil is a contact herbicide that undergoes little if any translocation. The mode of action of bromoxynil is the inhibition of electron transport in respiration and photosynthesis.

Soil Characteristics. Bromoxynil is not strongly adsorbed to soils and has an average half-life of seven days.

Bipyridylliums

General Characteristics and Uses. This herbicide family is composed of diquat (Reward) and paraquat (Gramoxone Extra). Paraquat is not labeled for use in turfgrasses. Diquat is nonselective, contact in action, foliage applied, and has no soil activity. Diquat is used for the control of emerged weeds in dormant bermudagrass.

Mode of Action. Diquat is rapidly absorbed by leaves and green stem tissue and undergoes limited or no translocation in plants. Treated plants rapidly wilt and become desiccated within a few hours of application. Diquat requires light for maximum herbicide activity, and inhibits photosynthetic electron transport. Due to the inhibition of electron transport, phytotoxic free radicals are formed and cause extensive damage to cell membranes.

Soil Characteristics. Diquat carries two positive charges (cationic). Clay minerals and certain fractions of soil organic matter are negatively charged. Upon contact with negatively charged soil particles, diquat is rapidly bound. Diquat persists for long periods of time in soils, but are biologically inactive due to an almost irreversible binding to the negatively charged soil colloids.

Cyclohexandiones

General Characteristics and Uses. Sethoxydim (Vantage) and clethodim (Envoy) are postemergence herbicides similar to the aryl-oxy-phenoxy herbicide family in that they have activity only on annual and perennial grasses. Broadleaf weeds and nutsedge(s) are not controlled by sethoxydim or clethodim. Both herbicides have only limited soil activity and are used exclusively as a postemergence treatment. Sethoxydim is registered for centipedegrass and fine fescues (not tall or turf-type fescues). Additionally, sethoxydim is used to suppress tall fescue seedhead development on roadsides. Clethodim is registered for the control of annual bluegrass in dormant bermudagrass and for the suppression of bermudagrass in centipedegrass (sod farms only).

Mode of Action. Cyclohexandiones are rapidly absorbed by leaves and is translocated to the actively growing points (near the nodes, buds on stolons, and rhizomes, etc.) of grass plants, where meristematic activity is inhibited. These herbicides inhibit fatty acid biosynthesis. Death occurs slowly over a 1 to 3-week period. Treated foliage will redden, become chlorotic, and die in an inward direction from the leaf tip. Nodes blacken and die and leaves will easily break or pull from the nodal region.

Note. Visual injury symptoms for cyclohexandione and aryl-oxy-phenoxy herbicide family are similar. Separation of differences can be difficult under field conditions.

Soil Characteristics. The soil persistence of sethoxydim is very short and averages only 1 to 2 weeks. Clethodim half-life in the soil averages only 3 days. These herbicides do not readily leach.

Dinitroanilines

General Characteristics and Uses. The dinitroanilines are a large herbicide family and are extensively used in turfgrasses to control annual grasses and certain annual broadleaf weeds (Table 3). These herbicides have no foliar activity, and are applied prior to weed emergence.

The dinitroaniline herbicides are volatile and susceptible to photodegradation (breakdown by sunlight). If adequate water (rainfall or irrigation) is not received within 1 to 7 days of a preemergence application, approximately ½ inch of irrigation water should be applied. Oryzalin (Surflan) is the least volatile of the dinitroaniline herbicides.

Mode of Action. The dinitroaniline herbicides are readily absorbed by roots and shoots, but undergo very limited if any translocation. Dinitroanilines inhibit root and shoot growth. Depending upon the species, root growth may be inhibited more than shoot growth. The mode of action of dinitroanilines is the inhibition of cell division. Inhibition of lateral root development and short, thickened, club-like roots that appear "pruned" are symptoms of dinitroaniline injury.

Soil Characteristics. The dinitroanilines do not readily leach. Soils high in clay or organic matter content require higher rates due to the adsorption of dinitroanilines to these soil components. The dinitroanilines vary in their soil persistence, and reseeding restrictions must be followed to avoid carryover injury. The dinitroanilines are usually degraded to noninjurious levels in 4 to 6 months, unless higher than normal application rates have been used. Soil microorganisms are involved in the breakdown of the dinitroanilines.

Table 3. Members of the dinitroaniline herbicide family used in turfgrasses.

Common Name	Trade Name
benefin	Balan
oryzalin	Surflan
benefin +oryzalin	XL
benefin + trifluralin	Team
pendimethalin	Pendulum, Pre-M
prodiamine	Barricade

Imidazolinones

General Characteristics and Uses. The imidazolinone herbicide registered for use on fine turfgrasses is imazaquin (Image). Imazaquin is used for the postemergence control of nutsedge spp., wild garlic and certain broadleaf weeds in warm-season turfgrasses (except bahiagrass). Cool-season turfgrasses are not tolerant to imazaquin.

Mode of Action. Imazaquin is rapidly absorbed by the foliage and roots and is readily translocated to the meristematic regions of the plant. Similar to the sulfonyleurea herbicide family, imazaquin inhibits the synthesis of the amino acids valine, leucine, and isoleucine. A reduction in these amino acids leads to decreased protein synthesis and an impairment of plant growth. Plant death occurs slowly over a period of one to several weeks. Visual symptoms of injury are:

1. Susceptible weeds are severely stunted with shortened internodes.
2. The foliage of grass weeds may turn red to purplish in color.
3. Chlorosis and necrosis progresses from the growing tips of shoots throughout the plant.

Note. Many of the visible injury symptoms for the imidazolinone and sulfonyleurea herbicide families are similar. Separation can be difficult under field conditions.

Soil Characteristics. The binding and leaching characteristics of the imidazolinone herbicides are highly dependent upon soil pH. In general, the imidazolinones are weakly bound at pH above 6.5, but binding will increase with increasing levels of clay and organic matter, and at low (acid) soil pH levels. Imazaquin has less soil persistence in acid pH soils than in high pH soils. Imazaquin is degraded primarily by soil microorganisms. It is non-volatile and is not highly sensitive to photodegradation.

Phoxys

General Characteristics and Uses. The phoxys were developed during World War II as a part of the chemical warfare research effort. In 1944, foliar applications of 2,4-D were reported to selectively control dandelions in a Kentucky bluegrass turf. In 1946, it was reported that 2,4-D selectively controlled weeds when applied immediately after corn had been planted. These two experiments demonstrated the effectiveness of the phoxxy herbicides for broadleaf weed control in grass crops; either as a postemergence or preemergence application.

The phoxxy herbicides are extensively used for the control of broadleaf weeds in turfgrasses (Table 4). Most turfgrasses are tolerant to 2,4-D; however, St. Augustinegrass and centipedegrass can be injured by 2,4-D particularly on hot (>85°F), humid days. 2,4-D is commonly formulated with MCPP, dicamba, triclopyr or 2,4-DP for the broad spectrum control of annual and perennial broadleaf weeds. 2,4-D is formulated as a salt, ester, or oil soluble amine salt form of the parent acid (2,4-dichloro-phenoxyacetic acid). The following are general characteristics of the various forms of 2,4-D:

I. Salt Formations

- A. Amine salts are more commonly used than the ammonium, sodium, potassium, and lithium salts.
- B. Amine salts form true solutions in water.
- C. Salt forms of 2,4-D can form insoluble precipitates when mixed with hard water (water high in calcium and magnesium) or fluid fertilizers.
- D. Salt forms are not as quickly absorbed by plant foliage as ester forms. Generally, a 6 hour rain-free period is required for maximum activity.
- E. Salt forms are considered nonvolatile under normal field conditions. However, spray drift to sensitive crops (ornamentals, cotton, tobacco, grapes, others) can occur with only slight wind movement.

II. Ester Formations

- A. Esters form emulsions in water.
- B. Ester formulations are usually compatible with fluid fertilizers.
- C. Ester formulations are quickly absorbed by plant foliage and are relatively resistant to removal by rain.
- D. Esters are classified either as low volatile or high volatile formulations. Ester formulations should not be used during the warm months of the year when conditions are favorable for volatilization.

III. Oil Soluble Amine Salts

- A. These formulations form emulsions in water.
- B. These formulations are similar to esters in that they are quickly absorbed by plant foliage and are relatively resistant to removal by rain.
- C. These formulations are considered to be nonvolatile; however, spray drift may still occur.

Cotton, tobacco, vegetable crops, and desirable ornamental tree and shrubs can be injured by the spray and/or vapor drift of 2,4-D. Amine or oil soluble amine formulations should be used during the warm months of the year. Additionally, applications should not be made under windy conditions.

Mode of Action. The phenoxy herbicides are readily absorbed by foliage and roots and undergo extensive translocation in sensitive plants. These herbicides have been in existence since World War II but their exact mode of action is still under investigation. 2,4-D has been shown to interfere with nucleic acid (DNA and RNA) and protein synthesis which results in cells undergoing rapid uncontrolled cell division and elongation. Vascular tissues become plugged or broken, food and water transport is prevented, and the plant slowly dies over a 1 to 3-week period. Visual injury symptoms are:

A. Broadleaf plants - Leaves crinkled, often puckered, strap-shaped, stunted and malformed. Leaf veins appear somewhat parallel rather than netted. Stems crooked, brittle, shortened internodes, and may crack and form aerial roots.

B. Grass plants - Leaves rolled near base in an onion-like fashion. Tip of terminal leaf often free and flag-like in appearance. Stems curved or crooked, brittle, with short internodes. Brace roots on corn may be malformed.

Note. Many visual injury symptoms are similar for the phenoxy, benzoic acid, and picolinic acid herbicide families. Separation can be difficult under field conditions.

Soil Characteristics. The salt forms of 2,4-D are readily leached in sandy soils. Ester formulations are resistant to leaching. Soil persistence is very short and averages only 1 to 4 weeks under warm moist conditions. Soil microorganisms are responsible for the breakdown of

2,4-D. Other phenoxy herbicides are generally similar to 2,4-D in their soil persistence and breakdown characteristics.

Table 4. Members of the phenoxy herbicide family used in turfgrasses.

Common Name	Trade Name
2,4-D	Chaser, See 2,4-D, others
MCPA	MCPA, others
MCPP (mecoprop)	MCPP-4, Lescopex
2,4-DP (dichlorprop)	--
2,4-D+2,4-DP+MCP	Dissolve, Triamine
2,4-D+dicamba ¹	Four Power Plus
2,4-D+dicamba+MCP ²	Three-Way, Triplet, Triplet Southern, Trimec Classic, Trimec Southern
2,4-D+MCPA+MCP	Triamine II

¹ Dicamba is a benzoic acid herbicide sold in combination with phenoxy herbicides.

²The ratios of 2,4-D, MCP and dicamba in these 3-way herbicides is dependent upon the formulation sold by the manufacturer.

Picolinic Acids

General Characteristics and Uses. Members of this herbicide family used in turfgrasses include triclopyr (Turflon Ester) and clopyralid (Confront - also contains triclopyr). Triclopyr is also formulated with 2,4-D, dicamba, MCPA and sold under a numerous trade names. Triclopyr and clopyralid are used for the postemergence control of broadleaf weeds in cool-season and certain warm-season turfgrasses.

Mode of Action. These herbicides are rapidly absorbed by leaves and roots are extensively translocated in sensitive plants. Triclopyr and clopyralid are believed to kill plants in a manner similar to the benzoic acid and phenoxy herbicide families. Additionally, visual injury symptoms are similar for these three herbicide families.

Soil Characteristics. Triclopyr and clopyralid are not strongly adsorbed by soil colloids and readily leach, particularly in sandy soils that are low in organic matter. Triclopyr and clopyralid degrade rapidly in the soil with an average half-life of approximately 40 days. Soil microorganisms are involved in the breakdown of these herbicides.

Substituted Amides

General Characteristics and Uses. The substituted amide used in turfgrasses is metolachlor (Pennant). Metolachlor controls annual grasses and some broadleaf weeds, but it is primarily used for the preemergence control of yellow nutsedge and annual sedges.

Mode of Action. Metolachlor is absorbed by the shoots and roots of the germinating seedlings. Susceptible weeds do not generally emerge above the soil surface. Only limited translocation has been shown to occur. The exact mode of action is not well understood, but metolachlor is believed to interfere with nucleic acid and protein synthesis. Metolachlor has been shown to inhibit the growth of both root and shoots.

Soil Characteristics. Metolachlor does not readily leach and persists in the soil for 3 to 10 weeks and is not considered to cause problems in crop rotational sequences. Metolachlor is degraded by soil microorganisms.

Substituted Ureas

General Characteristics and Uses. The substituted urea used in cool-season turfgrasses and zoysiagrass is siduron (Tupersan). Bermudagrass is not tolerant to siduron. Siduron is used at the time of seeding and in established cool-season turfgrasses for the control of crabgrass and annual foxtails. Siduron does not control annual bluegrass, goosegrass, fall panicum and annual broadleaf weeds. Siduron is also labeled for the suppression of bermudagrass that is encroaching into creeping bentgrass putting greens. Siduron has no foliar activity and is used as a preemergence treatment.

Mode of Action. Siduron is readily absorbed by plant roots and is extensively translocated in the xylem tissues. Absorption through leaves is minimal. Unlike other members of the substituted urea family, siduron does not inhibit photosynthesis. Siduron disrupts cell division and has been shown to be a potent inhibitor of root growth in sensitive species.

Soil Characteristics. Siduron is very resistant to leaching. Siduron has an average soil half-life of 90 days. Residues have not been detected after one year following applications of higher than normal use rates. Siduron is non-volatile, moderately resistant to leaching and is degraded by soil microorganisms.

Sulfonylureas

General Characteristics and Uses. Halosulfuron (Manage) and chlorsulfuron (TFC) are currently (1999) the only sulfonylureas labeled for use on fine turfgrasses. Metsulfuron (Escort), sulfometuron (Oust), and Chlorsulfuron (Telar) are labeled for use on roadside turfgrasses and other noncropland areas. Members of this herbicide family have high levels of herbicide activity at very low application rates. For example, foliar applications of halosulfuron at rates of 2/3 to 1 1/3 ounce of formulated product per acre will control yellow and purple nutsedge in turfgrasses.

Mode of Action. The sulfonylurea herbicides are rapidly absorbed by roots and shoots of susceptible weed species and undergo extensive translocation in the plant. The sulfonylureas inhibit the synthesis of the amino acids valine, leucine, and isoleucine. This family of herbicides slowly kills plants over a period of one to four weeks. Visual symptoms of injury are:

1. Susceptible weeds are severely stunted with shortened internodes.

2. The foliage of grass weeds may turn red to purple in color.
3. Chlorosis and necrosis progresses from the growing tips of shoots throughout the plant.

Note. Many of the visible injury symptoms for the sulfonylurea and imidazolinone herbicide families are similar. Separation of differences can be difficult under field conditions.

Soil Characteristics. The sulfonylurea herbicides are susceptible to limited amounts of leaching in soils. Adsorption of these herbicides to soil clays is low; however, there is a limited amount of adsorption to organic matter. Leaching is also affected by soil pH. At a soil pH of less than 6.0, chlorsulfuron was shown to leach less than at higher soil pH values. The persistence and activity of the sulfonylureas is drastically affected by soil pH. At soil pH values near or above 7.0, the persistence and activity of this herbicide family is greater than at acid soil pH values. Members of the sulfonylurea herbicide family vary in soil persistence and injury to rotational crops can occur unless rotational guidelines are followed. Chlorsulfuron can persist for 3 to 4 years in alkaline soils (pH > 7.0). Chemical hydrolysis that is followed by microbial degradation are the primary means by which the sulfonylureas are broken down in the soil.

Triazines

General Characteristics and Uses. The triazine herbicides (Table 5) are extensively used for annual bluegrass and annual broadleaf control in most warm-season turfgrasses (except bahiagrass). Cool-season turfgrasses are not tolerant to triazine herbicides. With the exception of simazine, the triazines are used as soil- and foliage-applied herbicides. Simazine has essentially no foliar activity but through root uptake will control many emerged winter annual weeds.

Mode of Action. The primary means of entry into plants for the triazines is by root uptake. However, other than simazine, the triazines are also absorbed by plant foliage. The addition of adjuvants (crop oils, surfactants) to atrazine has been shown to enhance foliar activity. The triazines are readily translocated when absorbed by roots but not when absorbed by shoots. They are potent inhibitors of electron transport in the light-dependent phase of photosynthesis. Starvation of the plant for food materials was once thought to be the primary means of death; however, membrane disruption due to the formation of toxic compounds may be involved in the death of triazine-treated plants. Since light is required for herbicide activity, weed seedlings emerge from the soil and become chlorotic prior to dying.

Visual symptoms of injury for the triazines are:

A. Leaf veins often remain green, but tissue between the veins (interveinal tissue) becomes chlorotic and eventually undergoes desiccation.

B. Leaves die in an inward direction from the leaf margins and tips.

Note. Many of the injury symptoms are similar for the triazine and substituted urea herbicide families. Separation of differences can be difficult under field conditions.

Soil Characteristics. The triazine herbicides are readily adsorbed to the clay and organic matter fractions of the soil. Leaching can occur, particularly in low organic matter sandy soils and under conditions of high rainfall. Metribuzin is the most mobile of the triazine herbicides used in warm-season turfgrasses. The average length of soil persistence varies for triazine herbicides.

Metribuzin has a half-life ranging from 14 days to 2 months. Atrazine and simazine may persist in the soil for up to 12 months; however, in the humid regions of the Southeast, residual weed control from these herbicides is approximately 2 to 4 months. Soil microorganisms are involved in the breakdown of these herbicides in the soil.

Table 5. Members of the triazine herbicide family used in turfgrasses.

Common Name	Trade Name
atrazine	Aatrex, Atrazine, Others
metribuzin	Sencor Turf
simazine	Princep, Wynstar

UNCLASSIFIED HERBICIDES

Bensulide

General Characteristics and Uses. Bensulide (Betasan, others) is used for the preemergence control of annual grass weeds in cool- and warm-season turfgrasses. Bensulide has a low solubility in water and is essentially immobile in soils. To compensate for the lack of movement in soil, bensulide should be incorporated either mechanically or by irrigation water to place the chemical in the weed seed germination zone.

Mode of Action. Bensulide is not readily absorbed by shoot or root tissue and does not translocate in the plant. This herbicide prevents seedling development shortly after germination by inhibiting cell division. Bensulide should not be applied to newly sprigged turfgrasses because root development at the stolon nodes can be inhibited for several weeks.

Soil Characteristics. Bensulide is strongly adsorbed by the clay and organic matter fractions of soils and is very resistant to leaching. It is nonvolatile but is slightly susceptible to photodecomposition. Bensulide is relatively persistent and has an average half-life of 4 to 6 months. Bensulide is slowly degraded by soil microorganisms.

Bentazon

General Characteristics and Uses. Bentazon (Basagran T/O) is a selective, foliage-applied, contact herbicide that is used for yellow nutsedge and broadleaf weed control in warm and cool-season turfgrasses. This herbicide has no soil activity on weeds when used at labeled rates.

Mode of Action. Bentazon is foliage absorbed and undergoes little if any translocation in the plant. The mode of action is the inhibition of photosynthesis. Visual injury symptoms are leaf necrosis and death of sensitive weeds within two to seven days of application.

Soil Characteristics. Bentazon is not readily adsorbed to soil particles. Rapid incorporation into soil organic matter by microorganisms prevents the leaching of bentazon below a 10 to 12 inch

soil depths. Bentazon has a very short persistence and reaches undetectable levels in the soil within six weeks.

Dithiopyr

General Characteristics and Uses. Dithiopyr (Dimension) is used for the preemergence control of annual grasses and certain annual broadleaf weeds in turfgrasses (including creeping bentgrass and bermudagrass putting greens.) Unlike other preemergence herbicides, dithiopyr has postemergence activity on seedling (before tillers develop) crabgrass. However, postemergence activity is not observed on other annual weeds, including goosegrass.

Mode of Action. Dithiopyr is readily absorbed by roots and to a lesser degree by leaves. It accumulates in the meristematic regions but does not translocate. Dithiopyr inhibits cell division. Root tips of injured plants appear club-shaped in appearance. Tolerance appears to be through differential uptake.

Soil Characteristics. Dithiopyr is strongly absorbed to soil colloids and has low tendency for leaching. The potential for movement in runoff water is also low due to the low water solubility and adsorption of dithiopyr to soil colloids and turfgrasses. Dithiopyr has a short to moderate length of persistence in the soil and is degraded primarily by soil microorganisms. Other losses can occur through volatility and to a lesser extent by photodegradation.

Ethofumesate

General Characteristics and Uses. Ethofumesate (Prograss) is a selective soil- and foliar-applied herbicide that is used for annual bluegrass control in tall fescue, bentgrass and perennial ryegrass seed crops in Washington and Oregon. In the south it is used primarily for the control of annual bluegrass in bermudagrass fairways that are overseeded with perennial ryegrass, and to control weeds in seedling or established perennial ryegrass turf.

Mode of Action. Ethofumesate is absorbed by young shoots and roots of susceptible weed species. The postemergence activity of ethofumesate is limited to very young weeds as ethofumesate is not absorbed by leaves after the plant has produced a mature cuticle. Ethofumesate is translocated within the plant following coleoptile or root absorption but is not translocated out of treated leaves. Ethofumesate is believed to inhibit photosynthesis and respiration.

Soil Characteristics. Ethofumesate has been shown not to leach in soils that have an organic matter content greater than 1%. Soil microorganisms are responsible for the degradation of ethofumesate in soils. The soil persistence of ethofumesate is affected by climate, soil type and microbial activity. Under warm, moist conditions and cold, dry conditions the half life of ethofumesate is 5 and 14 weeks, respectively.

Fenarimol

General Characteristics and Uses. Fenarimol (Rubigan) is a systemic turfgrass fungicide that is used to control annual bluegrass (*Poa annua*) in bermudagrass putting greens that are overseeded with perennial ryegrass, bentgrass or perennial bluegrass (*Poa trivialis*). Fenarimol has

preemergence activity only on annual bluegrass. The normal application sequence is to apply two to three applications of fenarimol, each at a 10 to 14 day interval, with the last application occurring at least two weeks prior to overseeding. Fenarimol will not control perennial bluegrass or established annual bluegrass.

Mode of Action. Fenarimol reduces the biosynthesis of gibberellins. Gibberellins are naturally produced plant hormones that are involved in plant cell elongation. In the absence of gibberellins, internode lengths are reduced and overall plant growth becomes severely stunted.

Glufosinate

General Characteristics and Uses. Glufosinate (Finale) is a non-selective, non-soil residual herbicide used for spot treating weeds, and preplant weed control in turfgrasses. Glufosinate does not have soil activity and controls a wide range of weeds through foliar uptake.

Mode-of Action. Glufosinate is quickly absorbed by the weed and requires only a four hour rain-free period. It undergoes only limited translocation or movement within plants. This herbicide inhibits the activity of the plant enzyme responsible for the conversion of ammonia into amino acids. When this enzyme is inhibited toxic levels of ammonia accumulate leading to cellular disruption and plant death.

Soil Characteristics. Glufosinate is only weakly bound to soil colloids and is highly mobile in the soil. However, glufosinate has half-life in the soil of only 7 days. Due to rapid degradation by soil microorganisms, glufosinate has not been detected more than 6 inches deep in the soil.

Glyphosate

General Characteristics and Uses. Glyphosate (Roundup Pro) is a non-selective systemic herbicide used as a preplant weed control prior to establishing turfgrasses, for spot treating weeds, and for the control of annual bluegrass in dormant bermudagrass. This herbicide has no soil activity, has little selectivity, and is applied directly to the foliage of weeds. Glyphosate effectively controls most annual weeds and herbaceous and wood perennial plants.

Mode of Action. Glyphosate is absorbed by leaf and green stem tissue and undergoes extensive translocation in plants. Glyphosate translocates in the photosynthate stream that moves from the leaves to underground storage organs (roots, rhizomes, tubers, etc.). Increased translocation and kill of underground storage organs of perennial plants is achieved when glyphosate is applied at or near flowering than with applications during the vegetative growth stages. The mode of action of glyphosate is the inhibition of amino acid and protein synthesis. Visual symptoms of injury slowly develop and are:

1. Wilting, chlorosis, and necrosis of young foliage which slowly spreads to older foliage.
2. The regrowth of perennial plants may be distorted with wrinkled or deformed leaves.

Soil Characteristics. Glyphosate is strongly adsorbed by soil colloids and has a low potential for leaching. This herbicide has essentially no soil activity and seed, sodding and sprigging operations can be safely conducted after application. Glyphosate is degraded by soil microorganisms and has a half-life of less than 60 days.

Isoxaben

General Characteristics and Uses. Isoxaben (Gallery) is used for the preemergence control of annual broadleaf weeds in cool- and warm-season turfgrasses. Isoxaben is not effective in controlling annual grass weeds such as crabgrass spp.; however isoxaben tank-mixes with annual grass control herbicides such as proflam, pendimethalin and oryzalin are very useful for the control of a wide range of annual grass and broadleaf weeds.

Mode of Action. Isoxaben is rapidly absorbed by plant roots and is translocated to the leaves. Only limited amounts (< 3% of that applied after 72 hours) is absorbed by leaves. Isoxaben controls susceptible weeds by inhibiting cell wall biosynthesis. Tolerance appears to be due to differential absorption. Symptoms of isoxaben injury are similar to the dinitroanilines with plant stunting, reduced root growth and root tip swelling being observed. Foliar applications to sensitive plants can cause growth inhibition, stem and petiole cracking and swelling, and malformed leaf hairs.

Soil Characteristics. Isoxaben is tightly adsorbed to soil colloids and only undergoes slight amounts of leaching. Half-lives range from 50 to 120 days with weed control commonly observed for 5 to 6 months after application. It is degraded by soil microorganisms. Isoxaben is not volatile.

Oxadiazon

General Characteristics and Uses. Oxadiazon (Ronstar) is a preemergence herbicide labeled for use in turfgrasses (except centipedegrass) and woody ornamentals. Oxadiazon controls most annual grasses and many small-seeded broadleaf weeds. Both granular (G) and wettable powder (WP) formulations of oxadiazon are available. The potential for injury limits the use of Ronstar 50WP to dormant bermudagrass, zoysiagrass and St. Augustinegrass. In contrast, Ronstar G may be safely used on dormant or actively-growing bermudagrass, bluegrass, perennial ryegrass, St. Augustinegrass, zoysiagrass and tall fescue. Oxadiazon may also be used immediately before or after sprigging, bermudagrass, zoysiagrass and seashore paspalum. Ronstar formulations are not labeled for use on putting greens. Red fescue, bentgrass and centipedegrass are only marginally tolerant to oxadiazon.

Mode of Action. Oxadiazon is classified as a contact herbicide and has postemergence activity on young seedlings. Oxadiazon is primarily used as a preemergence treatment and affects the shoot of sensitive weeds as they grow through the treated zone. Light is required for herbicidal activity.

Soil Characteristics. Oxadiazon is a moderately persistent herbicide with a half-life of three to six months. It is strongly adsorbed to soil colloids and does not readily leach. Oxadiazon is not considered to be volatile.

Quinclorac

General Characteristics and Uses. Quinclorac (Drive) is used for the postemergence control of crabgrass spp. and certain other weeds in established common and hybrid bermudagrass, Kentucky bluegrass, buffalograss, tall fescue, perennial ryegrass and zoysiagrass. This herbicide

may also be used at the time of sprigging bermudagrass and zoysiagrass. Non-tolerant turfgrasses include bahiagrass, centipedegrass and St. Augustinegrass. Quinclorac also has preemergence activity on crabgrass spp.

Mode of Action. Quinclorac is readily absorbed by emerging roots and shoots and by leaves. It is translocated within the plant to meristematic areas. The exact mechanism of action is not fully understood but appears to involve the auxin levels within the plant. In grasses, quinclorac has been reported to affect soil wall biosynthesis and cause an increase in ethylene and cyanide production.

Soil Characteristics. Quinclorac is rapidly degraded by soil microorganisms and can be moderately persistent. Soil mobility of quinclorac is highly variable and depends on soil type and organic matter.