Chapter I  
Introduction and review of literature

Need for new herbicides in field corn

Field corn (Zea mays L.) is grown on more hectares than any other crop in the United States. In 2000 and 2001, there were over 32 million and 31 million hectares (ha) of corn planted, respectively. Ninety-seven percent of field corn received some type of herbicide treatment (Anonymous 2001b). The herbicide applied most often to field corn (63% of acreage) is atrazine [6-chloro-N-ethyl-N’-(1-methylethyl)-1,3,5-triazine-2,4-diamine], a triazine herbicide applied preemergence (PRE) or postemergence (POST) for control of annual broadleaf weeds and some grasses (Anonymous 2001b). Two chloroacetamide herbicides, acetochlor [2-chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl)acetamide] and metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide] were applied on 41% of the corn acres for PRE control of grasses and some small-seeded broadleaf weeds. Usually atrazine is applied in combination with a chloroacetamide for broad-spectrum PRE weed control (Ahrens 1994; Anonymous 2001b).

Atrazine was developed by Geigy Laboratories in 1957 and became commercially available in 1958 (Ahrens 1994). The herbicide quickly became popular because of its excellent crop safety, sufficient residual activity, broad-spectrum weed control, flexibility in application timing and economical pricing. However, concerns about atrazine detection in surface and groundwater, carryover, poor perennial weed activity, and the spread of triazine resistant weeds have increased the need for supplements to atrazine.

There are 63 confirmed reports of weeds resistant to triazine herbicides (Heap 2001). The first report was common groundsel (Senecio vulgaris L.) in 1970 after 10 years of simazine [6-chloro-N,N’-diethyl-1,3,5-triazine-2,4-diamine] and atrazine applications in a nursery (Ryan 1970). Several triazine resistant weeds, such as, common groundsel, velvetleaf (Abutilon theophrasti Medicus), smooth pigweed (Amaranthus hydridus L.),
redroot pigweed (*Amaranthus retroflexus* L.), Palmer amaranth (*Amaranthus palmeri* (S.) Wats.), common waterhemp (*Amaranthus rudis* Sauer), common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), jimsonweed (*Datura stramonium* L.), barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), kochia (*Kochia scoparia* (L.) Schrad.), Pennsylvania smartweed (*Polygonum pensylvanicum* L.), giant foxtail (*Setaria faberi* Herrm.), and yellow foxtail (*Setaria glauca* (L.) Beauv.) can be difficult to control in corn (Heap 2001). Usually triazine resistance is conferred through a mutation of the *psbA* gene, an amino acid substitution of Ser 264 with glycine (Heap 2001). However, researchers have reported increased glutathione S-transferase activity enhancing glutathione conjugation as a mechanism for atrazine detoxification in velvetleaf (Gronwald et al. 1989; Anderson and Gronwald 1991; Gray et al. 1996).

Atrazine is a restricted use pesticide due to potential groundwater and surface water contamination (Orme and Kealey 2001). The soil half-life of atrazine varies depending on rainfall, temperature, and soil pH (Ahrens 1994). Extended soil residual activity restricts planting of many rotation crops the year following atrazine application (Hagood et al. 2001). High rainfall after atrazine applications (with low vegetation cover) causes runoff with sediment to surface water. Leaching of atrazine often occurs with lighter rain and increased soil permeability (Bacci et al. 1989). Glenn and Angle (1987) and Sauer and Daniel (1987) found that less runoff of atrazine occurred in no-till plots in comparison to conventional tillage plots. They also found the majority of atrazine runoff occurred after the first rainfall following atrazine application. Pantone et al. (1992) reported that atrazine movement was primarily due to runoff in the first month after application. They also discovered that POST applications resulted in less surface runoff than preemergence applications. They hypothesized that the higher amounts of plant material associated with no-till corn production contributed to less movement of atrazine by runoff.

Reduced tillage corn production helps prevent surface runoff of soil and pesticides. However, perennial weeds, like horsenettle (*Solanum carolinense* L.) often increase under minimum or no-till conditions (Gorell et al. 1981). PRE atrazine programs may
partially control seedling perennial weeds, but have limited activity on established weed stands (VanGessel 1999). Often PRE atrazine programs effectively eliminate competition from most annual weed species, but allow the proliferation of perennial weeds.

Atrazine has selectively controlled many annual broadleaf weeds and grasses in field corn since 1957. However, triazine resistant weeds, surface and groundwater concerns, lack of perennial weed activity, and rotation restrictions have increased the need for other herbicide chemistries.

**Other Corn Herbicides**

Atrazine, simazine, and cyanazine [2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropanenitrile] are triazine herbicides primarily used for PRE control of broadleaf weeds and some grasses in field corn (Hagood et al. 2001). The EPA started a Special Review of these triazine herbicides in 1994. Consequently, E.I. duPont de Nemours and Griffin Corporation agreed to stop production of cyanazine in 1999 with total usage of the product ending on December 31, 2002 (Jones 2000). However, production and use of atrazine and simazine continues. These compounds and others disrupt photosynthesis by competitively binding to the Q_B binding area of the D1 protein within the Photosystem II (PSII) complex (Ahrens 1994). Other PSII inhibitors labeled for field corn include metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one], bromoxynil [3,5-dibromo-4-hydroxybenzonitrile], bentazon [3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one2,2-dioxide], and pyridate [O-(6-chloro-3-phenyl-4-pyridazinyl)S-octyl carbonothioate]. These PSII inhibitors control mostly broadleaf weeds but do not control a broad weed spectrum like atrazine (Hagood et al. 2001). Also, variations in corn hybrid response may occur with these herbicides (Bradshaw et al. 1994; Anonymous 2001a; Armel et al. 2001).

Chloroacetamides are usually applied PRE in combination with atrazine for broad-spectrum weed control in corn. Chloroacetamide herbicides control annual grasses and
The thiocarbamates are another group of PRE corn herbicides. The mode of action of thiocarbamates is not fully understood, but involves the inhibition of lipid biosynthesis (Heap 2002). The utility of these herbicides is limited because they must be applied with safeners (to enhance crop safety) and must be incorporated after application due to volatilization. However, they control many annual grasses, some broadleaf weeds, and suppress perennial weeds like bermudagrass (*Cynodon dactylon* (L.) Pers.), johnsongrass [*Sorghum halepense* (L.) Pers.], yellow nutsedge (*Cyperus esculentus* L.), and purple nutsedge (*Cyperus rotundis* L.) (Hagood et al. 2001; Anonymous 2001b). EPTC [S-ethyl dipropyl carbamothioate] and butylate [S-ethyl bis(2-methylpropyl)carbamothioate] are the most widely used thiocarbamates, but are only used on 1 to 2% of corn acres. (Ahrens 1994).

Synthetic auxin herbicides are effective POST on a variety of annual and perennial broadleaf weeds. The most commonly used synthetic auxin herbicides are dicamba [3,6-dichloro-2-methoxybenzoic acid], 2,4-D [(2,4-dichlorophenoxy)acetic acid], and clopyralid [3,6-dichloro-2-pyridinecarboxylic acid] (Hagood et al. 2001; Heap 2002). These compounds are thought to have a mode of action similar to endogenous auxin (IAA), thereby interfering with nucleic acid metabolism and cell wall function. This disruption leads to abnormal cell division and plant growth, with a concurrent increase in ethylene production. Symptoms include plant twisting and growth inhibition followed by necrosis and plant death (Ahrens 1994). Applications in field corn should be made early to avoid stalk brittleness, brace root formation, and other injury symptoms associated
with later applications. Volatilization of these herbicides can occur and sensitive non-target plants may be injured (Ahrens 1994; Hagood et al. 2001).

Sulfonylurea herbicides were first introduced in 1966, but it was not until 1982 that the first product was released by E.I. duPont de Nemours. This was the first group of herbicides registered that inhibited the acetolactate synthase (ALS) enzyme. This enzyme is responsible for the synthesis of the branched chain amino acids valine, leucine, and isoleucine (Beyer et al. 1988; Ahrens 1994). Various ALS inhibitors are applied PRE or POST on all major field crops and some minor crops. Nicosulfuron [2-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonfonyl]-N, N-dimethyl-3-pyridinecarboxamide], primisulfuron [2-[[[[4,6-bis(difluoromethoxy)-2-pyrimidinyl]amino]carbonyl]amino]sulfonfonyl]benzoic acid], CGA-152005 [1-(4-methoxy-6-methyl-triazin-2-yl)-3-[2-(3,3,3-trifluoropropyl)-phenylsulfonfonyl]-urea], rimsulfuron [N-[[4,6-dimethoxy-2-pyrimidinyl]amino]carbonyl]3-(ethylsulfonfonyl)-2-pyridinesulfonamide], thifensulfuron [3-[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonfonyl]-2-thiophenecarboxylic acid], halosulfuron [3-chloro-5-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid], and flumetsulam [N-(2,6-difluorophenyl)-5-methyl[1,2,4]triazolo[1,5-a]pyrimidine-2-sulfonamide] are registered for control of annual and perennial weeds in field corn. Weed control varies between herbicides as CGA-152005, thifensulfuron, halosulfuron and flumetsulam mainly control annual broadleaf weeds with some suppression of perennial broadleaf weeds. Nicosulfuron, primisulfuron, and rimsulfuron have mixed activity on annual and perennial broadleaf weeds, but control most annual and some perennial grasses (Hagood et al. 2001). Before their development, POST alternatives for grass control in corn were limited. ALS inhibitors have also helped control triazine resistant weeds in corn (Ahrens 1994; Hagood et al. 2001). However, since their introduction in 1982, 70 reported cases of weed resistance to this chemistry have been documented (Heap 2002). Now biotypes of kochia and common waterhemp are reported that exhibit cross-resistance to ALS inhibitors and triazine herbicides (Foes et al. 1998; Foes et al. 1999).
Other herbicides of limited use in corn are pendimethalin \([\text{N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine}]\) and flumiclorac \([2\text{-chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo-2H-isoindol-2yl)phenoxy}acetic \text{acid}]\). Pendimethalin is a dinitroaniline herbicide applied PRE for control of grasses, velvetleaf, and small-seeded broadleaf weeds, especially triazine resistant pigweed species and common lambsquarters. Flumiclorac is a POST protoporphyrinogen oxidase inhibitor mainly used for control of velvetleaf (Hagood et al. 2001; Heap 2002).

Herbicides with various modes of action are available for corn weed management. However, weed resistance, crop rotation restrictions, application timing, and environmental and non-target plant safety, limit herbicide effectiveness. New chemistries are needed to control weeds for which control strategies are not available. Researchers recognize the need for additional herbicides for weed control in corn. Genetically modifying corn hybrids with tolerance to herbicides that control a broad-spectrum of weeds permits the utilization of additional chemistries.

**Transgenic Corn Hybrids**

Currently there are four types of herbicide resistant corn: glufosinate-resistant (Liberty Link® corn), glyphosate-resistant (Roundup Ready® corn), imidazolinone-resistant (Clearfield® corn), and sethoxydim-resistant (Poast Protected® corn). These hybrids allow the use of herbicides with different modes of action. Herbicide resistant crops may also allow the application of herbicides with a better environmental or toxicological profile (Goldburg 1992; Knake 1992). However, use of transgenic corn hybrids should be part of a herbicide rotation program and not used to intensify usage of one herbicide (Knake 1992).

Glufosinate \([2\text{-amino-4-(hydroxymethylphosphinyl)butanoic \text{acid}]\) is categorized as a non-selective herbicide used to eliminate existing vegetation prior to crop planting (Wilson et al. 1985). Glufosinate inhibits the enzyme glutamine synthetase leading to an increase in plant ammonia, causing photosynthetic interference and cell destruction.
Herbicide resistance is conferred through enhanced glufosinate metabolism in genetically altered crops (Tsaftaris 1996). Glufosinate generally controls most annual broadleaf weeds, but control of some grasses is inconsistent (Wychen et al. 1999; Hagood et al. 2001; Hamill et al. 2000). Delayed POST applications, multiple applications, additions of PRE residual herbicides, cultivation, and POST tank mixtures or sequential applications of residual herbicides has increased weed control and corn yields in glufosinate resistant corn (File et al. 1998; Tharp and Kells 1999; Krausz et al. 1999; Bradley et al. 2000b; Hamill et al. 2000; Jones et al. 2001; Ritter and Menbere 2001). However, glufosinate tank mixtures with the ALS inhibitors imazethapyr [2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-] and chlorimuron [2-[[4-chloro-6-methoxy-2-pyrimidinyl]amino]carbonyl]amino]sulfonyl]benzoic acid] decreased ALS inhibitor translocation and weed control (Starke and Oliver 1998). Ammonium sulfate (AMS) has improved the uptake and translocation of glufosinate in some broadleaf weeds and grasses (Maschhoff et al. 2000; Pline et al. 1999). Glyphosate [N-(phosphonomethyl)glycine] is a non-selective herbicide that inhibits the enzyme 5-enolpyruvytshikimate-3-phosphate synthase (EPSP). This enzyme facilitates production of the aromatic amino acids tyrosine, phenylalanine, and tryptophan (Ahrens 1994). Glyphosate resistance is conferred through insertion of a mutant EPSPS gene derived from Agrobacterium sp. strain CP4 (Harrison et al. 1996; Hetherington et al. 1999). Glyphosate controls many annual and perennial weeds. However, like glufosinate, it may require a residual herbicide or sequential applications for consistent control (Etheridge and Mueller 1998; Sparks et al. 1999; Tharp and Kells 1999; Hagood et al. 2001; Johnson et al. 2000). Tank mixtures of chlorimuron or imazethapyr with glyphosate can antagonize weed control similar to combinations with glufosinate (Lich et al. 1997; File et al. 1998; Starke and Oliver 1998).

Imidazolinone-resistant corn was created through conventional breeding methods. The ALS enzyme in imidazolinone-resistant corn is less sensitive than the enzyme in standard corn hybrids explaining its selectivity (Newhouse et al. 1991; Currie et al. 1995). Imazethapyr and imazethapyr plus imazapyr [(±)-2-[4,5-dihydro-4-methyl-4-(1-
methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid] are currently the only imidazolinone herbicides registered for weed control in imidazolinone-resistant corn. Imazethapyr is registered for weed control in alfalfa, peanuts, and soybeans, while imazapyr is registered for broadleaf weed and grass control in non-crop areas (Ahrens 1994; Hagood et al. 2001). Carryover of imidazolinone herbicides can affect corn the following year. Imidazolinone-resistant corn or a significant delay in planting date should safely allow planting of corn following imidazolinone applications the previous year (Renner et al. 1988; Hagood et al. 2001). Imazethapyr or imazethapyr plus imazapyr control most annual weeds following a residual PRE herbicide or in POST tank mixes with other herbicides such as atrazine or dicamba (Monks et al. 1996; File et al. 1998; Hooks et al. 1998; Askew et al. 1999; Walker et al. 1999).

Every corn weed management program has its advantages and disadvantages. Genetically altered crops add another option in corn weed management. Further, there are definite advantages to mixing herbicides with different modes of action to manage weed resistance and weed species shifts. Researchers are currently investigating herbicide families that are effective in plant systems without detriment to the environment or humans. Plant systems such as photosynthesis and chlorophyll and carotenoid production offer areas for inhibition of plant development with limited risk to animals.

**Carotenoid Biosynthesis Inhibitors**

Carotenoids are pigments found in all photosynthesizing organisms. Carotenoids absorb light at the 400-500 nm range, effectively broadening chlorophyll light absorption capacity. Absorbed light is then transferred from carotenoids to chlorophyll through a resonance energy transfer. However, another important function of carotenoids is protecting plants from photo-degradation (Britton et al. 1989; Young 1991; Cunningham and Gantt 1998).
During photosynthesis, chlorophyll usually receives more light than it can successfully dissipate. Excess energy is transferred to chlorophyll, exciting the molecules to a triplet state (\(^3\text{Chl}\)). These excited molecules can interact with oxygen forming highly reactive singlet oxygen species. Singlet oxygen species are effective in the peroxidation of lipids and degradation of membranes. This peroxidation occurs through extraction of a hydrogen molecule from unsaturated lipids, creating lipid radicals. These reactions ultimately lead to cell destruction and plant death. Carotenoids prevent this chain of events by successfully quenching \(^3\text{Chl}\) before it can excite oxygen species. Carotenoids also protect chloroplasts by collecting toxic oxygen species and quenching their excess energy before membrane damage can occur (Britton et al. 1989; Young 1991; Ahrens 1994; Phillip et al. 1996; Mortenson and Skibsted 1997). Current theories suggest plants produce different carotenoids in response to various environmental stresses (Young 1991; Haldimann et al. 1995; Haldimann 1996).

Carotenoids and other isoprenoid compounds are formed from a central molecule of isopentenyl pyrophosphate (IPP). This 5-carbon molecule forms larger skeletal structures in multiples of 5 carbons, such as the 20-carbon molecule geranylgeranyl pyrophosphate (GGPP) that is a precursor to formation of other molecules in the isoprenoid pathway. Two molecules of GGPP form the basic structure of plant carotenoids (Cunningham and Gantt 1998). Many enzymes and cofactors are responsible for carotenoid production, allowing for multiple approaches for herbicide inhibition of these processes (Britton et al. 1989).

**Carotenoid biosynthesis inhibitors**

Bleaching herbicides are defined as chemicals that produce chlorotic or white foliage through inhibition of plant physiological processes that produce chloroplast pigments (Britton et al. 1989). These herbicides are divided into three main categories based on mode of action. Some inhibit the enzyme phytoene desaturase that converts phytoene to phytofluene. The herbicides norflurazon [4-chloro-5-(methy lamino)-2-(3-( trifluoromethyl)phenyl)-3(2H)-pyridazinone], fluorochloridone [3-chloro-4-
Norflurazon is registered for PRE control of grasses and some broadleaf weeds in cotton, peanuts, fruits, ornamentals, and various vine crops (Bartels and Watson 1978; Ahrens 1994; Heap 2002). Fluorochloridone was investigated for control of triazine resistant weeds in field corn, however crop safety appears to be marginal (Buhler 1988). Fluridone is registered for the control of aquatic weeds (Ahrens 1994).

Some carotenoid biosynthesis inhibitors are classified together because their modes of action are not well understood. Clomazone [2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone] is believed to inhibit enzymes in the isoprenoid pathway following the production of farnesyl pyrophosphate (Ahrens 1994). Clomazone is currently registered for weed control in cotton, soybeans, peas, snapbeans, peppers, and some vine crops (Ahrens 1994). Amitrole [1H-1,2,4-triazol-3-amine] causes accumulation of various carotenoid precursors in susceptible plants, therefore it could inhibit enzymes in carotenoid, histidine, or chlorophyll synthesis. Amitrole is registered for weed control in non-crop areas and certain trees (Burns et al. 1971; Ahrens 1994).

The newest class of carotenoid inhibitors function through inhibition of the enzyme p-hydroxyphenylpyruvate dioxygenase (HPPD). HPPD facilitates the conversion of 4-hydroxyphenylpyruvic acid to homogentisic acid (Norris et al. 1998; Pallet et al. 1998; Viviani et al. 1998). This enzyme is part of the pathway that converts the amino acid tyrosine to plastoquinone. Plastoquinone is a cofactor for the enzyme phytoene desaturase, a key enzyme in the production of carotenoids. In the absence of carotenoids, plants are unable to protect themselves from photooxidation (Norris et al. 1998). Plastoquinone also serves as an electron carrier between the Qb site of Photosystem II and Cyt b6/f and functions in shuttling electrons in other photosynthetic processes (Ort 1986; Wise and Cook 1998). Plastoquinone is also thought to have a role in scavenging for reactive oxygen species generated within the chloroplast (Wise and Cook 1998). Inhibition of HPPD also blocks production of α-tocopherol (vitamin E), an antioxidant.
compound that is believed to strengthen membrane structures and scavenge for free radicals within chloroplast membranes (Hess 1993; Pallet et al. 1998).

Currently there are three herbicide families that inhibit HPPD: 1) benzoyl isoxazoles 2) pyrazoles and 3) triketones. There is, however, little information on the efficacy of pyrazoles which are registered for broadleaf weed control in rice (*Oryza sativa* L.) (Hall 2001). The triketones and benzoyl isoxazoles have 3 herbicides registered for weed management in field corn and will be discussed in detail.

**RPA 201772 (or EXP 31130A)**

RPA 201772 [5-cyclopropyl-4-(2-methylsulfonyl)-4-trifluoromethylbenzoyl] isoxazoles] (proposed common name isoxaflutole) is a preemergence herbicide for control of annual broadleaf weeds and some grasses in field corn (Luscombe et al. 1994). This herbicide is classified in the benzoyl isoxazole family, a herbicide family discovered by Rhone-Poulenc Agriculture Company in 1989. The herbicidal properties of benzoyl isoxazoles were discovered serendipitously as Rhone-Poulenc pharmaceutical researchers screened these compounds as potential hydroxymethylglutaryl coenzymeA (HMGCoA) reductase inhibitors. RPA 201772 was discovered in 1990, and its herbicidal activity identified the following year (Pallet et al. 2001). RPA 201772 is registered under the trade name Balance® (Anonymous 2001c).

Preemergence applications of RPA 201772 produce bleaching symptoms in meristematic tissue with a concurrent reduction in plant growth, differing from phytoene desaturase inhibitors. This reduction in plant growth may occur from accumulations of tyrosine and/or simultaneous reductions in α-tochopherol (Pallet et al. 1998). The mode of action of RPA 201772 is inhibition of the enzyme HPPD (Norris et al. 1998; Pallet et al. 1998; Viviani et al. 1998).

RPA 201772 is not the true inhibitor of HPPD, but becomes herbicidally active through opening of the molecule’s isoxazole ring, thus becoming a diketonitrile derivative
HPPD is titrated by DKN, suggesting it is an irreversible inhibitor of the enzyme. DKN does not alter itself in binding to HPPD, but binds tightly to the enzyme and disassociates slowly from the enzyme inhibitor complex. DKN is further transformed to a herbicidal inactive benzoic acid derivative (Viviani et al. 1998).

RPA 201772 conversion to its metabolites occurs in soil, water, and plant tissue, leading to variations in herbicidal activity. Opening of the isoxazole ring can occur spontaneously under high pH environments (pH > 9.0), rapidly converting RPA 201772 to DKN (Pallet et al. 2001). RPA 201772 is more stable in acid solutions (pH 5.2) where after 2 wk 70% of the parent material remains. After 2 wk under basic conditions less than 10% of the parent molecule remains. Under acidic conditions temperature is the only factor that affects RPA 201772 hydrolysis, whereas under basic conditions temperature has very little effect on hydrolysis. The bacteria *Pseudomonas* sp. also affects the rate of RPA 201772 hydrolysis (Sprague et al. 1999d; Beltran et al. 2000).

RPA 201772 has residual soil activity of about 6 wk in the field (Luscombe et al. 1994). The half-life of RPA 201772 does not appear to vary between clay loam and sandy loam soils. RPA 201772 usually has a half-life of just 12 hr to 3 d and its metabolism is affected by pH, moisture, temperature, and soil type. RPA 201772 half-life was significantly greater at 2% moisture than at 30% moisture; and half-life was much lower at 10C than at 30C (Pallet et al. 2001). Mitra et al. (1999) found that soil half-life of RPA 201772 may be light dependent. Under no-sunlight conditions soil half-life was 23 hr, while in the light soil half-life was 20 hr. Rouchard et al. (1998a) reported that RPA 201772 dissipation in the soil increased at pH 7.2 in comparison to pH 5.5.

DKN, the herbicidal active metabolite, has a soil half-life of 20-30 d and is more soil mobile than RPA 201772 (Pallet et al. 2001). DKN sorption to soil increases with an increase in soil organic matter. RPA 201772 also binds strongly to high organic matter soils, but binds to all soil types more than DKN, possibly due to its lower water solubility. DKN sorption is not influenced by clay particles, however an increase in Ca$^{2+}$ concentration increases DKN soil sorption possibly due to an increase in cationic bridges.
DKN sorption decreased when soil pH was increased from 4.5 to 8.5. Due to the low pH of the isoxazole ring, protons can readily attach to DKN at low soil pH thus increasing sorption of DKN to the cation exchange (Mitra and Bhowmik 2001).

RPA 201772 generally remains on the soil surface due to its strong affinity for soil particles and its low water solubility. In contrast, DKN is more water soluble than RPA 201772 and has a greater tendency to leach in the soil. Therefore, RPA 201772 is most likely absorbed by weed seeds emerging near the surface while DKN is most likely absorbed by roots penetrating deeper in the soil. However, even though RPA 201772 has low water solubility, it is very lipophillic and is taken up by plants and seeds 5 to 6 times more than DKN. Once inside the plant, DKN is more mobile due its higher water solubility. Rapid conversion of RPA 201772 to DKN occurs within plants, thereby reducing the internal concentration of RPA 201772. This reduction in internal RPA 201772 concentration creates a passive uptake gradient due to higher RPA 201772 levels in the soil compared to the plant. DKN is transported in both mature and young leaves through symplastic and apoplastic movement, however movement from young to mature leaves appears symoplastically driven. Therefore, both RPA 201772 and its DKN derivative are important in plant uptake, herbicidal movement and activity (Pallet et al. 1998; Sprague et al. 1999d; Pallet et al. 2001).

One concern with RPA 201772 is variations in corn response. Significant injury, especially in course textured soils or after heavy rainfall can occur with RPA 201772 applications. Increased injury has been observed when RPA 201772 is tank mixed with BAYFOE 5043 plus metribuzin (Axiom) or acetochlor. However, injury is mostly transient and yields are not usually affected (Obermeier et al. 1995; Bhowmik and Prostak 1996; Curvey and Kapusta 1996; Wilson and Hines 1996; Geier and Stahlman 1997; Knezevic et al 1998; Sprague et al. 1999a; Sprague et al. 1999c,). Crop response varies between hybrids due to variations in their ability to rapidly convert RPA 201772 to its inactive benzoic acid derivative. It also appears that RPA 201772 uptake may play a role in the tolerance of some corn hybrids to RPA 201772 (Sprague et al. 1999a). Generally, conversion of DKN in field corn occurs within 6 hr after treatment, explaining
its margin of selectivity in the crop (Pallet et al. 2001). There also appears to be no difference between uptake and translocation of RPA 201772 and its metabolites in corn versus sensitive weed species, further supporting the role of metabolism in selectivity (Pallet et al. 1998).

Sprague et al. (1999b) evaluated several corn safeners for their ability to reduce initial crop response from RPA 201772 applications. The highest level of crop protection was from the antidotes MON-13900 and R-29148. However, R-29148 was the most consistent, offering protection for all corn hybrids screened by efficiently enhancing metabolism of RPA 201772 and its diketonitrile metabolite. Because of increased crop response in the presence of PBO (a mixed function oxidase inhibitor) and increased corn tolerance in the presence of antidotes, Sprague et al. (1999b) concluded that RPA 201772 is metabolized by cytochrome P-450 monooxygenases.

Preemergence applications of RPA 201772 control redroot pigweed, velvetleaf, common sunflower (*Helianthus annuus* L.), kochia, Pennsylvania smartweed, palmer amaranth, prairie cupgrass (*Eriochloa contracts* Hitchc.), fall panicum (*Panicum dichotomiflorum* Michx.), wild proso millet (*Panicum miliaceum* L.), broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash], wild mustard [*Brassica kaber* (DC.) L.C. Wheeler], Venice mallow (*Hibiscus trionum* L.), woolly cupgrass [*Erichloa villosa* (Thunb.) Kunth], eastern black nightshade (*Solanum ptycanthum* Dun.), corn speedwell (*Veronica arvensis* L.), horseweed [*Conyza canadensis* (L.) Cronq.], and barnyardgrass (*Digitaria sanguinalis* (L.) Scop.) (Luscombe et al. 1994; Bhowmik and Prostak 1996; Mosier et al. 1995; Obermeier et al. 1995; Simkins et al. 1995; Striegel et al. 1995; Curvev and Kapusta 1996; Obermeier et al. 1996; Geier and Stahlman 1997; Knezevic et al. 1998; Sprague et al. 1999c, Young et al. 1999). Control of common ragweed, common cocklebur (*Xanthium strumarium* L.), common waterhemp, giant foxtail, green foxtail [*Setaria viridis* (L.) Beauv.], yellow foxtail, longspine sandbur [*Cenchrus longispinus* (Hack.) Fern.], wild buckwheat (*Polygonum convolvulus* L.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], common lambsquarters, smooth pigweed and morningglory species (*Ipomoea sp.*) was inconsistent with RPA 201772 at varying rates and under different field conditions. Preemergence
tank mixtures of atrazine and/or a chloroacetamide may increase the control of these species (Luscombe et al. 1994; Bhowmik and Prostak 1995; Obermeier et al. 1995; Simkins et al. 1995; Curvey and Kapusta 1996; Obermeier et al. 1996; Geier et al. 1997; Knezevic et al. 1998; Sprague et al. 1999c; Young et al. 1999).

Potential foliar weed uptake and residual soil activity has led to investigations of RPA 201772 in no-till corn burndown programs (Young and Hart 1998). RPA 201772 plus 2,4-D or glyphosate is effective in controlling many annual broadleaf and grass weeds (Striegel et al. 1995). Vrabel et al. (1996), has reported good foliar activity of RPA 201772 in no-till burndown, with the added benefit of soil residual activity. Giant foxtail plants treated with a foliar application of RPA 201772 exhibit both apoplastic and symplastic herbicide movement (Young and Hart 2000). Addition of non-ionic surfactant (NIS), crop oil concentrate (COC), and methylated seed oil (MSO) increased foliar retention of RPA 201772 on leaves of giant foxtail. MSO and COC were more effective than NIS at moving RPA 201772 through the cuticle of giant foxtail plants. MSO was more effective than COC or NIS at increasing translocation of RPA 201772 in giant foxtail (Young and Hart 1998).

The safety of RPA 201772 use in corn is in question. According to reports, RPA 201772 has low toxicity, no mutagenicity to bacteria and mammals, and has little or no residual activity on crops planted a year after application (Luscombe et al. 1994). However, RPA 201772 is listed as a restricted use pesticide due to potential drift and runoff affects on non-target plants (Anonymous 2001c). Recently, RPA 201772 was identified by the EPA as a potential carcinogen (Orme and Kegley 2001).

**SC 0051 (or ICIA 0051)**

SC 0051 [(2-(2-chloro-4-(methylsulfonyl)benzoyl)-1,3-cyclohexanedione] (proposed common name sulcotrione) is registered in field corn for PRE and POST control of broadleaf weeds and some grasses in Europe (Beraud et al. 1993). It is sold under the trade names Galleon® and Mikado®. Previous research hypothesized SC 0051 inhibited
the enzyme phytoene desaturase (Mayonado et al. 1989). However, it was later proven to be a competitive inhibitor of the enzyme HPPD (Secor 1994). SC 0051 was the first triketone produced commercially, and like RPA 201772, was created through serendipitous discovery (Anonymous not dated; Lee et al. 1997; Heap 2001).

Natural plant products initially led researchers to the first HPPD inhibitors. Hellyer (1968) discovered that in some myrtaceous Australian plants, $B$-triketone compounds were contained within steam-volatile oils. In 1977, Zeneca Ag Products scientists noticed that few weed species emerged beneath the bottlebrush plant ($Callistemon citrinus$ Stapf.). Analysis of the soil and plant excretions brought forth a herbicidal compound like Hellyer (1968) described and it was named leptospermone. This compound exhibited activity on both grasses and broadleaf weeds and was safe to corn at rates up to 1 kg/ha. This compound and other synthetically altered compounds were patented in 1980 by Zeneca Ag products (Gray et al. 1980; Lee et al. 1997; Mitchell et al. 2001).

In 1982, while attempting to produce compounds similar to sethoxydim, a cyclohexanedione graminicide that inhibits acetyl-CoA carboxylase, researchers accidentally discovered an antidote for thiocarbamate injury in soybeans. Further alterations to the molecule resulted in a compound expressing similar symptoms as seen with leptospermone (Lee et al. 1997; Mitchell et al. 2001). Hence, the first 2-benzoylecyclohexane-1,3-dione herbicides or triketones were patented in 1986 (Michaely and Kratz 1986). In 1988, an updated patent stated information on the synthesis of benzoylecyclohexane-1,3-dione herbicides, including SC 0051 (Michaely and Kratz 1988).

The longevity, movement, and activity of SC 0051 changes with soil composition, soil pH, and climatic conditions. This compound has a reported half-life of 15 to 72 days (Hatzios 1998). However, Baer and Calvet (1999) have reported a 50% reduction in applied material only 2 days after treatment (DAT). SC 0051 tends to leach in sandy loam soils at pH > 6.0 and binds tightly to soils pH < 6.0 (Mayonado 1988; Rouchaud et
al. 1998b). Rouchard et al. (1998c) also reported that SC 0051 dissipates rapidly with increasing soil pH. Conversely, Wilson and Foy (1992) found no strong relationship between clay content and soil pH in the mobility of SC 0051. They discovered SC 0051 strongly adsorbs to soils high in organic matter. This strong adsorption to organic matter limits microbial degradation and decreases the rate of herbicide dissipation (Rouchard et al. 1996). Also, SC 0051 movement in the soil is generally lower in summer corn crops, but higher in winter wheat systems, suggesting cropping systems and climate may also play a vital role in SC 0051 soil activity (Rouchaud et al. 1998b).

SC 0051 controls common lambsquarters, velvetleaf, jimsonweed, horseweed, common ragweed, barnyardgrass, large crabgrass, goosegrass, common cocklebur, smooth pigweed, broadleaf signalgrass, kochia, wild proso millet and yellow foxtail (Anonymous not dated; Ritter 1987; Katz et al. 1988; Mayonado 1988; Reddy and Bhowmik 1991; Wilson and Foy 1990). Activity on seedling johnsongrass, sicklepod, morningglory spp., yellow nutsedge, and purple nutsedge is moderate (Anonymous not dated; Vidrine and Kitchen 1987). Additions of atrazine or atrazine/chloroacetamide combinations may improve herbicide performance, however some reductions in control were observed with these PRE combinations (Anonymous not dated; Ritter 1987; Vidrine and Kitchen 1987; Katz et al. 1988; Mayonado 1988; Reddy and Bhowmik 1991; Wilson and Foy 1990). Some researchers reported significant corn injury from SC 0051 with yield losses at higher rates (Vidrine and Kitchen 1987; Reddy and Bhowmik 1991). SC 0051 was never registered in the United States due to its weakness on foxtail species and redroot pigweed (Hall 2001).

Other analogues of SC 0051 were examined in field corn. SC 0774 controlled most grass species, but was weak on most broadleaf weeds. Field corn exhibited significant response to SC 0774. Safeners, however significantly reduced crop response (Anonymous not dated(a); Katz et al. 1988; Mayonado 1988; Wilson and Foy 1990). SC 0735 was examined in field corn and rice. Mayonado et al. (1988) and Katz et al. (1988) found SC 0735 controlled giant foxtail, horseweed, common lambsquarters, jimsonweed,
common ragweed, and velvetleaf. However, neither compound was registered for field corn.

**Mesotrione**


Mesotrione has an excellent environmental and toxicological profile. Mesotrione and its metabolites are short-lived and residues are not detectable at corn harvest (Black et al. 1999; Drost and Simmons 2000). Like SC 0051, mesotrione movement and activity in the soil varies with soil pH and organic matter (Black et al. 1999). This compound is safe to non-target plants, mammals, birds, and water-dwelling species. Mesotrione is non-carcinogenic, is low in toxicity, and has minimal risk of groundwater contamination. The EPA, because of these qualities, considered mesotrione a reduced risk pesticide. (Black et al. 1999; Drost and Simmons 2000; Anonymous 2001d).

PRE applications will likely be made in combination with a chloroacetamide or atrazine/chloroacetamide mixture to increase weed control. PRE mesotrione/acetochlor tank mixtures control velvetleaf, pigweed spp., prickly sida, common waterhemp, common lambsquarters, hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. ex A. W. Hill] common ragweed, kochia, sicklepod, jimsonweed, nightshade spp., smartweed spp., fall panicum, green foxtail, giant foxtail, yellow foxtail, barnyardgrass, large crabgrass, and common sunflower (Lackey et al. 1999; Ohmes et al. 2000). Mesotrione also provided fair control of large crabgrass, barnyardgrass, and broadleaf signalgrass. However, activity is less on giant foxtail, shattercane, and johnsongrass (Ohmes et al. 2000).
POST mesotrione applications control many annual broadleaf weeds, large crabgrass, red rice (*Oryza sativa* L.), and barnyardgrass (Sutton et al. 1999; Beckett and Taylor 2000; Armel et al. 2001). POST mesotrione combinations with other corn herbicides may increase control of some perennial weed species (Armel et al. 2000; Armel et al. 2000a; Bradley et al. 2000a). POST applications should include an adjuvant system of 1% v/v crop oil concentrate (COC) and 2.5% v/v urea ammonium nitrate (UAN) (Wichert and Pastushok 2000). The addition of low rates of atrazine in POST applications enhances mesotrione efficacy over larger or more difficult to control weeds (Johnson and Young 1999; Armel et al. 2000; Beckett and Taylor 2000; Johnson and Young 2000a; Mueller 2000; Armel et al. 2001). However, tank mixtures with foliar organophosphate insecticides should be avoided to prevent increased crop phytotoxicity (Nichols and Clemens 2000). Temperature and relative humidity may affect the efficacy of mesotrione on some weed species (Johnson and Young 2000b).

In studies with radiolabeled herbicide, weed uptake of mesotrione occurred rapidly, where 55 to 90% uptake occurred within 24 hr (Mitchell et al. 2000). Susceptible weeds absorb mesotrione through leaves, roots, and seeds. The uptake in maize is much slower and may account for part of its selectivity. However, corn selectivity is due mostly to rapid cytochrome P450 metabolism of mesotrione. Phosphor image analysis shows excellent xylem and phloem movement of mesotrione in susceptible plants (Bartlett and Hall 2000; Mitchell et al. 2001).

**Objectives**

Limited information is available on the efficacy of mesotrione. The main objective of this research is to evaluate mesotrione in corn weed management programs on Virginia’s coastal plain soils. Secondary objectives included: 1) investigation of mesotrione in conventional tillage and no-tillage weed management programs; 2) investigation of mesotrione effectiveness on certain perennial weeds; 3) evaluation of PRE and POST mixtures of mesotrione with other herbicides; 4) evaluation of mesotrione efficacy on
weed species with biotypes resistant to other herbicide modes of action; 5) evaluation of mesotrione in herbicide-resistant corn varieties; 6) evaluation of uptake, translocation, and metabolism of mesotrione in Canada thistle [Cirsium arvense (L.) Scop].


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