Failure to follow a pesticide label or plants experiencing drift or tank contamination can exhibit dramatic, yet characteristic plant symptoms. If the damage occurs early and is not severe, yield loss may not occur. However, if injury occurs during a critical growth stage or is severe, the damage may result in a total crop loss. The purpose of this section is to describe and illustrate typical plant symptoms due to herbicide injury and to discuss the mechanism or mode of action of commonly used herbicides. Symptoms and images of selected herbicides are provided below.

Herbicides have been characterized by the method that the herbicide controls susceptible plants. The method is the mechanism or mode of action groups. Herbicides that have a similar mechanism of action within a plant have similar symptoms or impacts on wheat. These categories are provided in Table 26.1.

A more complete discussion is provided at http://wssa.net/Weeds/Resistance/WSSA-Mechanism-of-Action.pdf. To minimize resistance, where possible, weed management strategies should integrate herbicides with different mechanisms of action.
Table 26.1. WSSA suggested group number, mechanism-of-action (MOA), and herbicide chemistry examples.

<table>
<thead>
<tr>
<th>MOA Group</th>
<th>Mechanism</th>
<th>Herbicide Chemistry Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACETYL COA CARBOXYLASE (ACCase) INHIBITORS</td>
<td>Aryloxyphenoxypropionate (FOPs) Cyclohexanecarbonitrile (DiMs) Phenylpyrazolin (DENs)</td>
</tr>
<tr>
<td>2</td>
<td>ACETOLACTATE SYNTHASE (ALS) or ACETOHYDROXY ACID SYNTHASE (AHAS) INHIBITORS</td>
<td>Imidazolinones (Imis) Pyrimidinylthiobenzoates Sulfonilaminoacetonitriletriazolinones Sulfonylureas (SU) Triazolopyrimidines</td>
</tr>
<tr>
<td>3</td>
<td>MICROTUBULE ASSEMBLY INHIBITOR</td>
<td>Benzaclidine Benzoic acid (DCPA) Dintraoaniline Phosphoramide Pyridine</td>
</tr>
<tr>
<td>15</td>
<td>VERY-LONG-CHAIN FATTY ACID INHIBITOR</td>
<td>Acetamide Chloroacetamide Oxyacetamide Tetraacetylserine herbicides</td>
</tr>
<tr>
<td>23</td>
<td>Carbetamide, chloropropanph, and propanph (Note: Group 23 types of herbicides are no longer or very rarely used in U.S. crop production.)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>SYNTHETIC AUXINS</td>
<td>Benzoic acids Phenoxyacetic acids Pyridine carboxylic acids Quinoline carboxylic acids</td>
</tr>
<tr>
<td>5</td>
<td>PHOTOSYSTEM II INHIBITORS</td>
<td>Phenylcarbamates Pyridazines Triazines Triazolines Uracils</td>
</tr>
<tr>
<td>6</td>
<td>Site B</td>
<td>Benzothiadiazinones Nitriles Phenylpyridazines</td>
</tr>
<tr>
<td>7</td>
<td>Site A but binds differently than Group 5</td>
<td>Amide Ureas</td>
</tr>
<tr>
<td>8</td>
<td>FATTY ACID AND LIPID BIOSYNTHESIS INHIBITORS</td>
<td>Phosphorodithiocates Thiocarbamates</td>
</tr>
<tr>
<td>16</td>
<td>ENOLPYRUVYL SHIKIMATE-3-PHOSPHATE (EPSP) SYNTHASE INHIBITORS</td>
<td>Glycines (glyphosate)</td>
</tr>
<tr>
<td>9</td>
<td>GLUTAMINE SYNTHETASE INHIBITORS</td>
<td>Phosphonic acids (glufosinate and bialaphos)</td>
</tr>
<tr>
<td>11</td>
<td>CAROTENOID BIOSYNTHESIS INHIBITORS (bleaching herbicides)</td>
<td>Amitrole Amides Anilidex Furanones Phenoxymethylamides Pyridazines Pyridines</td>
</tr>
<tr>
<td>12</td>
<td>Inhibits DOXP synthase</td>
<td>Clokezilone</td>
</tr>
<tr>
<td>13</td>
<td>Inhibits 4-HPPD enzyme</td>
<td>Callistemones Isoxazoles Pyrazoles Triketones</td>
</tr>
<tr>
<td>14</td>
<td>PROTOPORPHYRIN OXIDASE (PPO oxidase or Protopx) INHIBITORS</td>
<td>Diphenylethers N-phenylphthalimides Oxadiazoles Oxazolidinediones Phenylpyrazoles Pyrimidinones Thiadiazoles Triazolones</td>
</tr>
</tbody>
</table>
Wheat injury symptoms from synthetic auxins
- Rolled leaves
- Twisted, malformed heads
- Stalk bending and brittleness
- Missing kernels in spike

Injury cause
- Applied to rapidly growing wheat
- Applied too late

**PHENOXYCARBOXYLIC ACIDS**

Herbicide examples: 2,4-D; MCPA; Stinger®

Mechanism-of-action: Acts as a synthetic auxin, disrupting nucleic acid metabolism and protein synthesis, which ultimately leads to plant death.

Injury symptoms: Most injury occurs if applied at seedling stage or at boot stage. If applied before tillering, rolled leaves and few tillers may develop. If applied after jointing, symptoms may be twisted flag leaf, abnormal heads, and sterile spikelets (Figure 26.1). MCPA has a greater window of crop safety although high application rates or late applications may result in injury.

Figure 26.1. Head damage due to 2,4-D application. (Photo courtesy of Leon Wrage)
BENZOIC ACIDS

Herbicide example: Dicamba (Banvel®)

Mechanism-of-action: Acts as a synthetic auxin, see 2,4-D.

Injury symptoms: Symptoms are similar to 2,4-D. Sterile spikelets may occur if applied from the jointing to boot stage. Wheat varieties vary in sensitivity. Some exhibit no injury and some show extreme symptoms.

Images of dicamba injury: Symptoms of dicamba injury to wheat can be found at: http://www.kysmallgrains.org/productionmanual/weedmanagement.htm

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MOA 1 – Acetyl CoA Carboxylase (ACCase) Inhibitors
(also known as Lipid Synthesis Inhibitors)

Herbicide examples: Diclofop (Hoelon®); clodinafop (Discover®); fenoxyprop (Puma®)

Mechanism-of-action: Inhibits the formation of lipids used for membranes and stops growth of new tissue.

Injury symptoms: Can cause yellowing of wheat tips and blades soon after application (Figure 26.2). Browning and stunting of plants later. Applications after the jointing stage may result in stem breakage and lodging. Wet and cold conditions before or at the time of application can result in injury.

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Figure 26.2. ACCase inhibitor damage.
(Photo courtesy of Leon Wragge)
MOA 9 – Enolpyruvyl Shikimate-3-phosphate (EPSP) Synthase Inhibitor  
(also known as Amino Acid Derivative Herbicides)

Herbicide example: Glyphosate (Roundup®)

Mechanism-of-action: Amino acid synthesis inhibitor, stops synthesis of aromatic amino acids (those that contain a phenyl ring).

Injury symptoms: Yellowing on plant. Environmental conditions that slow growth (e.g., extreme heat, cold, or drought) reduce the effects of glyphosate. Youngest leaves near growing point yellow and die. If not too severe, heads may show malformation (Figure 26.3). Causes of injury may be drift from another field, misapplication after emergence, or tank contamination.

![Figure 26.3. Glyphosate damage to wheat.](Photo courtesy of Leon Wrage)

Wheat injury symptoms from EPSP synthase inhibitors
- Yellow then brown foliage
- Growing point dies

Injury cause
- Misapplied to wheat after emergence
- Tank contamination

MOA 10 – Glutamine Synthetase Inhibitors  
(also known as Phosphoric Acid Type Herbicides)

Herbicide example: Glufosinate (Liberty®)

Mechanism-of-action: Glufosinate stops the conversion of glutamate + ammonia to the amino acid glutamine, resulting in the accumulation of toxic levels of ammonia in leaf tissue.

Injury symptoms: Symptoms appear within 3 to 5 days after treatment. Water-soaked lesions may appear and then leaves become pale yellow (such as nitrogen deficiency) or purple (may look like phosphorus deficiency).


Wheat injury symptoms from Glutamine synthetase inhibitors
- Pale yellow or purple leaves
- Water-soaked lesions

Injury cause
- Misapplied or tank contamination
MOA 11, 12, 13, 27 – Carotenoid Biosynthesis Inhibitors
(also known as Pigment Inhibitor Herbicides)

Herbicide examples: Isoxaflutole (Balance®), tembotrione (Laudis®), clomazone (Command®), mesotrione (Callisto®)

Mechanism-of-action: There are several herbicides with different specific mechanisms of action that are included in this group of herbicides. The common strategy among these herbicides is that enzymes in the carotenoid pigment pathway are inhibited. Carotenoids are plant pigments that include chlorophyll or protect chlorophyll from destruction.

Injury symptoms: White areas on plants or albino plants appear during emergence. Command® carryover may be seen early in the season; plants may recover from early season injury (Figure 26.4).

Wheat injury symptoms from Carotenoid biosynthesis inhibitors
- White tissue
- Poor emergence
- Stunted plants
- Growing point dies

Injury cause
- Applied on cool, wet, or sandy soils
- Carryover problem

Figure 26.4. Command® injury.
(Photo courtesy of Leon Wragge)

MOA 2 – Sulfonylurea (SU) Herbicides and Imidazolinone (Imi) Herbicides

Herbicide examples: Tribenuron (Express®), thifensulfuron (Harmony®), metsulfuron (Ally XP®)

Mechanism-of-action: Both SU and Imi type chemistries of herbicides inhibit the formation of branched chain amino acids.

Injury symptoms: Injury symptoms are slow to develop with first appearance 7 to 10 days after exposure. Sensitive plants generally show overall yellowing (chlorosis) and stunting. If applied at the correct rate, injury symptoms are often temporary. For grasses, the growing point yellows and plant slowly dies. A reduction in tiller number or spike number may occur. Symptoms may be noticed even if applied according to the label rates and timings, although plants often recover with no yield loss. SU and Imi herbicides typically are applied at low rates (ounces of active ingredient per acre) and tank contamination may be a problem. In high pH soils, carryover of the SU chemistry types may be problematic, whereas carryover of Imi chemistry type herbicides is more likely in low pH soils.

Images of ALS injury: Images of symptoms to wheat can be found at: http://www.extension.umn.edu/distribution/cropsystems/components/6967_01l.html
MOA 14 – Protoporphyrinogen Oxidase (PPG oxidase or PROTOX) Inhibitors

Herbicide example: Carfentrazone (Aim®)

Mechanism-of-action: Inhibits protoporphyrinogen oxidase causing a cascade of events, which eventually result in cell membrane destruction and death of the plant.

Injury symptoms: Appearance of necrotic (dead tissue) speckling on leaves within a few days after exposure. Symptoms are most often observed in seedlings shortly after emergence.

Images of carfentrazone injury: Symptoms of carfentrazone injury to crops can be found at: http://weedscience.missouri.edu/herbinjsymptoms/cellmem.html

Wheat injury symptoms from PROTOX inhibitors
- Yellowing or reddening of new leaves
- Speckling of the older, exposed leaves
- Stunting of plant
- Death of tissue and browning
- Growing point dies

Injury cause
- Misapplication
- Tank contamination

MOA 22 – Photosystem I inhibitors

Herbicide example: Paraquat (Gramoxone®)

Mechanism-of-action: Herbicide accepts electrons from photosystem I and forms a herbicide radical. This radical reduces molecular oxygen to form superoxide radicals. The radicals are extremely reactive and destroy membrane fatty acids, which lead to the destruction of cell membranes and cell death.

Injury symptoms: Symptoms are often observed within within hours, especially in sunny days. Leaves develop water soaked lesions and speckling.

Images of paraquat injury: Symptoms of paraquat injury to crops can be found in University of Missouri Weed Science publication at: http://weedscience.missouri.edu/herbinjsymptoms/cellmem.html

Wheat injury symptoms from Photosystem I inhibitors
- Limp leaves
- Water soaked appearance (looks like frost damage)
- Brown tissue in water soaked areas

Injury cause
- Drift
- Tank contamination
Herbicide example: Atrazine (Aatrex®)

Mechanism-of-action: Stops electron flow from $Q_a$ to $Q_b$ in photosystem II, which stops CO$_2$ fixation and production of ATP and NADPH$_2$, which are needed for plant growth. These herbicides bind at site A. Other effects include lipid and protein oxidation, which leads to leaky cell membranes and plant death.

Injury symptoms: Atrazine is not labeled on wheat, but injury may occur if there is soil carryover from the previous year (Figure 26.5 and 26.6). In addition, tank contamination from previous applications may occur. Triazine injury symptoms start as yellowing of the seedling and then death of the oldest leaves. Roots are malformed. If severe, plants will not survive.

Wheat injury symptoms from triazine herbicides
Yellow and brown leaves

Injury cause
Cool wet conditions slowing wheat growth
Crop oil synergy if applied as a post emergence
MOA 6 – Photosystem II Inhibitor - Benzonitriles

Herbicide example: Bromoxynil (Buctril®, Bronate®)

Mechanism-of-action: Stops electron flow in photosynthesis in photosystem II, but unlike atrazine, binding of the herbicide occurs at site B. The final effects are similar to atrazine.

Injury symptoms: Symptoms appear as leaf tip chlorosis, general wilting, speckling and necrotic lesions to tissue where application has occurred. Young tissue that emerges after application generally is unaffected. Wheat is typically tolerant to bromoxynil (unlike atrazine), but injury may occur if cool or very high temperatures occur. Recovery is generally rapid.


Wheat injury symptoms from benzonitrile herbicides
  Yellow and brown leaves
  Injury cause
  Crop oil with the post-emergence application

MOA 3 – Mitosis Inhibitor - Microtubule Assembly - Dinitroanalines

Herbicide examples: Trifluralin (Treflan®), pendimethalin (Prowl®)

Mechanism-of-action: Inhibit the growth of roots or shoots of seedlings by binding to tubulin, which leads to loss of microtubules assembly, structure, and function. This in turn leads to stoppage of cell division and cell wall formation.

Injury symptoms: Symptoms are apparent during or soon after plant emergence (Figure 26.7). Shortened, swollen root types (root clubbing), shoots are thick, short, and may be purple in color. Injury occurs if DNA herbicide is incorporated too deeply into the seeding zone. Contributing factors to increased plant injury include wet, cool soils or other stress factors such as soil compaction or drought. Carryover from a previous year’s application can occur if applied late and cool conditions have occurred.

Wheat injury symptoms from dinitroanalines
  Stunted plants
  Roots short and thick
  Injury cause
  Carryover
  Misapplication
  Over-application

Figure 26.7. Dinitroanaline injury.
(Photo courtesy of Leon Wrage)
MOA 8 and 16 – Fatty Acid and Lipid Biosynthesis Inhibitor

Herbicide example: Triallate (Far-go®)

Mechanism-of-action: Inhibit biosynthesis of fatty acid and lipids (not through ACCase); biosynthesis of proteins; and inhibits gibberellin synthesis.

Injury symptoms: Appear during or soon after plant emergence. Reduction in cuticular wax deposition that may lead to increased disease or other stress severity. Injured seedlings may show reduced coleoptile length, stunting, or delayed emergence. Shoot tips may also fail to unroll from the coleoptiles giving the plant a buggy-whip appearance.

Images of thiocarbamate injury: Images of thiocarbamate injury on wheat can be found in the online publication, “Herbicide and Nonherbicide Injury Symptoms on Spring Wheat and Barley,” University of Minnesota Extension at: http://www.extension.umn.edu/distribution/cropsystems/components/6967_01l.html

<table>
<thead>
<tr>
<th>Wheat injury symptoms from triallate</th>
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<tbody>
<tr>
<td>Buggy whipping (leaf entrapment)</td>
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<tr>
<td>Stunted plants</td>
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<tr>
<td>Leaves emerge from the side of the coleoptile</td>
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<table>
<thead>
<tr>
<th>Injury cause</th>
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</thead>
<tbody>
<tr>
<td>Over-application</td>
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<tr>
<td>Incorporated too deeply into germinating zone of wheat</td>
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<tr>
<td>Cool, wet soils</td>
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</table>

MOA 15 – Mitosis Inhibitor - Very-long chain Fatty Acid Inhibitor - Acetanilides

Herbicide examples: Metolachlor (Dual®), acetochlor (Harness®)

Mechanism-of-action: Growth inhibitor that stops the formation of very long fatty acids. This stoppage has effects on the formation of all cell membranes. Seedling roots and shoots of susceptible plants stop growing.

Injury symptoms: Death of the plant occurs soon after emergence or no plants emerge in the area.

<table>
<thead>
<tr>
<th>Wheat injury symptoms from acetanilides</th>
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</thead>
<tbody>
<tr>
<td>Poor emergence</td>
</tr>
<tr>
<td>Stunted plants</td>
</tr>
<tr>
<td>Leaf out before emergence</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Injury cause</th>
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<tbody>
<tr>
<td>Over-application</td>
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<tr>
<td>Cool, wet soils</td>
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</table>

Wheat injury symptoms from triallate

Buggy whipping (leaf entrapment)
Stunted plants
Leaves emerge from the side of the coleoptile

Injury cause
Over-application
Incorporated too deeply into germinating zone of wheat
Cool, wet soils
Additional information and references


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