Exhibit 5a, #54

HANDBOOK OF WEED MANAGEMENT SYSTEMS

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Weed Management Systems for Grain Crops

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I. CEREAL PRODUCTION PRACTICES

Weed management systems in cereals are designed to create conditions which allow cereals to reach their potential yield within limits imposed by cereal genotype and environment. Managing weeds minimizes yield losses due to weeds rather than increasing the theoretical yield potential. While entomologists and plant pathologists have developed pest management strategies for individual pests, farmers and weed scientists have been concerned with developing weed management for several grass and broadleaf weed species at a time. Current weed control measures were developed under the assumption that controlling weeds maximizes yield. However, maximizing yields may not always maximize profits because profitability of cereal production depends on fluctuating crop price, input costs, and weed density and distribution, among other factors. Currently used weed control methods may sometimes conflict with other goals, such as maximizing farmer profit, minimizing environmental degradation, or managing other crop pests. Nevertheless, some farming systems which were developed to minimize soil erosion and improve water quality, such as no-tillage, would not be feasible without herbicides for weed management.

Weed control methods used in cereals are restricted by cereal production practices. Dryland cereal production practices have been summarized (Cook and Veseth, 1991; Donald, 1990b; Dregne and Willis, 1983) and must be understood to implement weed control measures fully. Winter and spring wheat production practices, weeds, and weed control measures differ in several respects and have been reviewed for various regions in North America (Nalewaja and Arnold, 1970; Donald, 1990b). Weed management in conservation (no-till and reduced till) tillage systems also was reviewed for winter wheat (Wicks, 1985b) and spring wheat (Donald and Nalewaja, 1990).

The relative proportion of different cereals produced in the United States is presented in Figure 1. Cereals are grown in regions which are unsuitable for growing other, more profitable field crops, such as corn or soybean. Most spring-sown barley, durum wheat, and oat are produced like spring wheat in the same geographic regions (Donald, 1990b; Donald and Nalewaja, 1990) and have many common weed problems (Fay, 1990), although fewer herbicides* are registered for these crops than for spring wheat (Table 1). Production practices were reviewed for wheat (Donald, 1990b; Donald and Nalewaja, 1990), barley (Baldridge et al., 1985; Briggs, 1978), and oat (Helm and McMullen, 1989). Spring barley is grown in most of the United States, but some spring barley is sown in fall or winter in the Southwest and harvested in spring (Baldridge et al., 1976). More winter barley is grown in the South and Southeast than elsewhere.

II. WEED MANAGEMENT IN WINTER WHEAT

A. Weeds of Winter Wheat

Different weeds infest the diverse regions where winter wheat is grown, according to expert opinion (Appleby and Morrow, 1990; Banks, 1990; Mitich and Kyser, 1990a and b; Peeper and Wiese, 1990; Peters, 1990; Wicks and Smika, 1990). Weed problems differ between various cereal producing regions of North America (Fay, 1990), and many winter annual weeds infesting winter wheat are not troublesome where spring wheat, barley, and oat are grown. In the United States estimated dollar losses due to weeds in winter wheat were summarized by region on the basis of expert opinion (Bridges, 1992). Weeds of wheat that were intentionally or unintentionally introduced into North America and major routes of introduction have been summarized (Donald, 1990c). Many of the

*Since herbicide registrations and labels are constantly changing, current labels and information available through state agricultural extension service and state agricultural experiment stations should be consulted for the most recent information and recommendations.

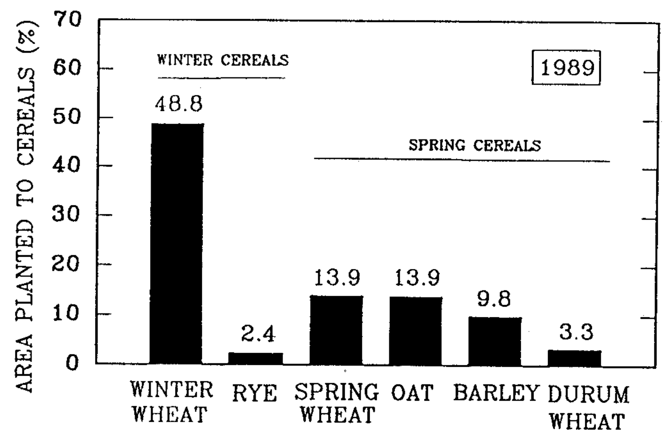

Figure 1 The relative proportion of acreage planted to small grains in the United States in 1989. (From Agricultural Statistics, 1990.)

most troublesome weeds infesting cereals in North America were intentionally introduced as herbs, as ornamentals, or for forage by settlers, whereas others were accidentally introduced in imported seed, hay, livestock, and ship ballast. The distribution and spread of downy brome (Douglas et al., 1990; Mack, 1981; Morrow and Stahlman, 1984) and jointed goatgrass (Donald and Ogg, 1991) have been reconstructed from herbaria and expert opinion. But information on the rate of spread and avenues of spread of weeds in North America is limited.

Winter annual grass weeds, such as cheat, downy brome, Italian ryegrass, jointed goatgrass, and volunteer rye, are more difficult to manage in winter wheat than are winter annual broadleaf weeds (Wiese, 1983). Fewer effective, selective herbicides are registered for grass weed management in winter wheat than for broadleaf weed management (Table 1). Most summer annual broadleaf weeds, such as kochia or Russian thistle, which emerge in spring do not concern winter wheat producers if cereal canopy closure is complete early in spring. Wild buckwheat is an exception because it emerges before winter wheat canopy closure in some parts of the Great Plains.* When disease, insects, winter kill, drought, or, less commonly, carryover herbicide residues thin winter wheat growth or stands, weeds can grow and fill in gaps. Late weed growth in gaps may not reduce yield directly but can interfere with harvesting, reduce grain quality, and result in dockage.

Summer annual weeds are best adapted to the spring wheat life cycle (Cook and Veseth, 1991; Donald and Nalewaja, 1990). Summer annual grass weeds,

*Dr. T. Peeper, 1993. Oklahoma State Univ., personal communication.

Table 1 Herbicides and Prepackaged Herbicide Mixtures Registered for Use in Small Grains by the United States Environmental Protection Agency in 1993[a]

Application time	Herbicide	Winter wheat	Winter barley	Spring wheat	Durum wheat	Spring barley	Oat	Rye	Sorghum
Early preplant	Alachlor + atrazine								X
	Atrazine + metolachlor								X
	Cyanazine + (2,4-D or paraquat; atrazine; metolachlor; alachlor)	X							X
	Glyphosate	X	X	X		X	X		X
	Glyphosate + dicamba	X	X	X		X	X		X
	Glyphosate + 2,4-D	X	X	X	X	X	X	X	X
	Metribuzin	X							
	Picloram	X	X	X	X	X	X		
Early preplant incorporated	Triallate (fall)			X	X	X			
Preplant	Alachlor + atrazine								X
	Atrazine								X
	Atrazine + cyanazine								X
	Atrazine + metolachlor								X
	Cyanazine								X
	Cyanazine + (alachlor, atrazine, metolachlor, propachlor, or propazine)								X
	Dicamba	X	X	X		X	X		X
	Glyphosate	X	X	X		X	X		X
	Metolachlor								X
	Paraquat	X	X	X		X			X

Preplant incorporated	Alachlor								X
	Alachlor + atrazine								X
	Atrazine								X
	Atrazine + metolachlor								X
	Cyanazine + (alachlor, atrazine, metolachlor, propachlor, or propazine)								X
	Diclofop	X							
	Metolachlor								X
	Triallate	X	X	X	X	X			
	Trifluralin	X				X			
	Triallate + trifluralin	X	X	X	X	X			
Postplant incorporated	Triallate	X	X	X	X	X			
	Trifluralin	X	X	X	X	X			
	Triallate + trifluralin			X	X	X			
Preemergence	Alachlor								X
	Alachlor + atrazine								X
	Alachlor + glyphosate								X
	Atrazine								X
	Atrazine + metolachlor								X
	Atrazine + propachlor								X
	Chlorsulfuron	X						X	
	Chlorsulfuron + metsulfuron	X							
	Cyanazine + (alachlor, atrazine, metolachlor, propachlor, or propazine)								X
	Dicamba	X	X	X		X	X		
	Diclofop	X							
	Diuron	X	X				X		X

(*continued*)

Table 1 Herbicides and Prepackaged Herbicide Mixtures Registered for Use in Small Grains by the United States Environmental Protection Agency in 1993[a]

Application time	Herbicide	Winter wheat	Winter barley	Spring wheat	Durum wheat	Spring barley	Oat	Rye	Sorghum
	Glyphosate	X	X	X		X	X		X
	Linuron								X
	Metolachlor								X
	Paraquat	X	X	X		X	X		X
	Propachlor								X
	Triallate	X	X	X		X			
Postemergence	Alachlor + atrazine (surface applied)								X
	Atrazine								X
	Atrazine + bentazon								X
	Atrazine + bromoxynil								X
	Atrazine + dicamba								X
	Atrazine + propachlor								X
	Bentazon								X
	Bromoxynil	X	X	X		X	X	X	X
	Bromoxynil + MCPA	X	X	X		X	X	X	
	Chlorsulfuron	X	X	X	X	X	X		
	Chlorsulfuron + metsulfuron	X	X			X	X		
	Clopyralid	X	X	X		X	X		
	Clopyralid + MCPA	X	X	X		X	X		
	Dicamba	X	X	X		X	X		X
	Diclofop	X	X	X	X	X			

	Difenzoquat	X	X	X	X	X			
	Diuron	X	X				X		X
	Fenoxaprop + MCPA		X						
	Fenoxaprop + 2,4-D + MCPA			X					
	Fenoxaprop + MCPA + Thifensulfuron + tribenuron	X		X					
	Imazamethabenz	X	X	X	X	X			
	Linuron (directed)								X
	MCPA	X	X	X	X	X	X	X	
	Metribuzin	X	X			X			
	Metsulfuron	X	X	X	X	X			
	Picloram	X	X	X		X	X		
	Propanil			X	X	X	X		
	2,4-D	X	X	X		X	X	X	X
	Triasulfuron	X	X	X	X	X			
	Tribenuron	X	X	X	X	X			
	Thifensulfuron + tribenuron	X	X	X	X	X			
Postemergence incorporated (layby treatment)	Pendimethalin								X
	Trifluralin								X
Preharvest	Diquat (dessicant)								X
	2,4-D	X	X	X		X	X	X	

[a]Other combinations of these individual herbicides or prepackaged herbicide mixtures are registered uses; consult the registration label. Registered uses may be restricted to particular states or parts of states. Consult the current registration label before use.

such as wild oat and foxtail species, concern spring wheat producers (Donald and Nalewaja, 1990; Fay, 1990; Hunter et al., 1990) more than summer annual broadleaf weeds do because there are several effective, registered postemergence herbicides for broadleaf weed management in spring wheat. Winter annual weeds are generally not a problem in spring wheat because mechanical seedbed preparation in spring usually controls small emerged winter annuals. Perennial weeds, such as Canada thistle or field bindweed, can reduce wheat yields in both spring- and fall-sown cereals but are usually localized problems (see later discussion).

B. Weed Competition, Yield Losses, and Reduced Grain Quality

Competition of weeds with winter wheat has been reviewed (Zimdahl, 1980; Zimdahl, 1990) (Table 2). In general, those broadleaf and grass weeds which have a winter annual or perennial growth habit compete more effectively with winter wheat than summer annual weeds (Peeper and Wiese, 1990; Wicks and Smika, 1990; Zimdahl, 1990). However, the extent to which weeds reduce crop yield is not well enough understood to predict crop yield loss for any small grain or sorghum accurately. Information on the extent to which weeds limit crop yield and profitability also is not "packaged" in a form that cereal farmers can use to make economic choices between alternative weed management strategies and, consequently, has had little impact on year-to-year weed management decisions of farmers.

Weeds limit cereal yield potential in arid regions partially because they increase evapotranspiration (Greb, 1983) and compete with winter wheat for limited soil moisture reserves stored in the soil profile (Cook and Veseth, 1991; Dregne and Willis, 1983). In regions where the winter wheat–fallow rotation is practiced for soil moisture conservation (Donald and Nalewaja, 1990; Dregne and Willis, 1983; Peeper and Wiese, 1990; Wicks and Smika, 1990), weeds growing in fallow can deplete soil moisture reserves before winter wheat planting and limit the potential yield of the fall-planted winter wheat crop, even if weeds are well controlled in winter wheat itself. Consequently, weeds must be controlled during the entire winter wheat–fallow rotation to minimize depletion of limited soil moisture reserves and subsequent crop yield potential. Weeds also reduce soil moisture reserves before planting dryland sorghum in spring in 2-year sorghum-fallow or 3-year winter wheat-fallow-sorghum rotations.

While weed scientists have been most concerned with relating weed density to reduced crop yield, weed dockage (i.e., chiefly green residue and weed seeds) may also limit cereal grain quality as reflected in grain grading standards. For example, U.S. Department of Agriculture grain grading standards stipu-

Table 2 Selected Studies Documenting the Impact of Density of Individual Weeds on the Yield of Small Grains, Rice, and Sorghum

Crop	Weed	Location	Reference
Winter wheat	Blue mustard	Texas	Cited by Zimdahl, 1980
	Downy brome		Cited by Zimdahl, 1980
	Fiddleneck	Oregon	Cited by Wiese, 1983
	Rigid and Italian ryegrass	Pacific Northwest	Cited by Zimdahl, 1980
	Tansymustard	Texas	Cited by Wiese, 1983
Spring wheat	Canada thistle	North Dakota	Donald and Khan, 1992
	Green foxtail		Cited by Zimdahl, 1980
	Quackgrass		Cited by Zimdahl, 1980
	Wild buckwheat	Canada	Holm and Kirkland, 1986; cited by Zimdahl, 1980
	Wild mustard	Canada	Holm and Kirkland,1986; cited by Zimdahl, 1980; Wiese, 1983
		North Dakota	Cited by Wiese, 1983
	Wild oat	North Dakota	Bell and Nalewaja, 1968 Cited by Wiese, 1983
	Yellow foxtail		Cited by Zimdahl, 1980
Spring barley	Canada thistle	Canada	O'Sullivan et al., 1982
	Common chickweed	England	Scragg and McKelvie, 1976
	Hempnettle	England	Scragg and McKelvie, 1976
	Jerusalem artichoke	Canada	Wall et al., 1986 Wall and Friesen, 1989
	Quackgrass	England	Scragg and McKelvie, 1976
	Tartary buckwheat	Canada	Remy et al., 1985
	Wild oat	North Dakota	Bell and Nalewaja, 1968
		England	Cussans and Wilson, 1975
		Canada	Dew, 1972
		England	Wilson and Peters, 1982
		Idaho	Morishita and Thill,1988a,b
		Quebec	Rioux, 1982
Grain sorghum	Common milkweed	Nebraska	Cramer and Burnside, 1982
	Smooth pigweed Palmer amaranth	Texas	Graham et al., 1988

(*continued*)

Table 2 Continued

Crop	Weed	Location	Reference
	Tall waterhemp	Kansas	Feltner et al., 1969b
	Volunteer sorghum	Kansas	Vesecky et al., 1973
	Yellow foxtail	Kansas	Feltner et al., 1969a
Rice	Barnyardgrass	Arkansas	Smith, 1974
		Arkansas	Smith, 1988
		Arkansas	Stauber et al., 1991
		Japan	Noda, 1973
		Japan	Noda et al., 1968
	Bearded	Arkansas	Smith, 1983a
	sprangletop	Arkansas	Smith, 1988
	Ducksalad	Arkansas	Smith, 1968
		Arkansas	Smith, 1988
	Eclipta	Arkansas	Smith, 1988
	Hemp sesbania	Arkansas	Smith, 1968
		Arkansas	Smith, 1988
	Junglerice	Philippines	Mercado and Talatala, 1977
	Northern	Arkansas	Smith, 1968
	jointvetch	Arkansas	Smith, 1988
	Red rice	Arkansas	Kwon et al., 1991a,b
		Louisiana	Pantone and Baker, 1991
		Arkansas	Smith, 1988
	Spreading	Arkansas	Smith, 1984
	dayflower	Arkansas	Smith, 1988

late that winter wheat should be graded as "garlicky" if it contains two bulblets of wild garlic/kg grain (Gast et al., 1990). Winter wheat is severely discounted if it is garlicky and some elevators may reject contaminated winter wheat. Wild garlic is primarily a major problem for winter wheat producers in the Corn Belt (Peters, 1990) and some southern states. Crop management practices also can influence how much weeds contribute to dockage in winter wheat. For example, dockage in winter wheat from cheat depended on crop seeding date and herbicide effectiveness in Oklahoma (Ferreira et al., 1990b). If winter wheat was seeded early in September for winter forage, dockage from cheat in winter wheat grain was greater than if winter wheat was planted later. Grain standards also limit the amount of jointed goatgrass seed permitted to contaminate winter wheat grain (Donald and Ogg, 1991).

C. Winter Wheat Grown for Both Forage and Grain

Cattle are often grazed on winter wheat fields in the Southern and Central Great Plains during winter months (Koscelny and Peeper, 1990a). Consequently, the same winter wheat crop can provide income from both forage and grain for mixed cereal-livestock farmers. However, optimal winter wheat planting dates for maximum forage production are earlier than for maximum grain production. Improperly timing winter wheat grazing can inadvertently encourage weeds, such as cheat, to build up at the expense of winter wheat grain yield and quality. For example, fall grazing in Oklahoma reduced winter wheat foliage more than cheat (52% versus 28%), leading to increased dockage in winter wheat due to cheat (9%) and reduced yield. Grazing did not influence cheat control or winter wheat yields when superimposed on metribuzin treatments (Koscelny and Peeper, 1990b). When metribuzin did not damage winter wheat itself, it reduced cheat biomass enough that winter wheat replaced cheat.

Registration labels for certain herbicides used on cereals, including winter wheat, either forbid herbicide use where grazing is planned or impose restrictions on the interval between herbicide application and later grazing (Table 3). Such restrictions are designed to minimize the chance that herbicide residues will be present in animal products. A portion of the hectares planted to winter wheat and spring-sown cereals, such as oat, is undersown with small-seeded legumes as a method of forage legume establishment (as "companion crops"). In this way, farmers can get cash income from harvested grain and also establish a perennial forage crop at the same time. Herbicide registration labels indicate which herbicides can be safely applied to such small-seeded legume and cereal interseedings. For example, difenzoquat, imazamethabenz-methyl, MCPA, and tribenuron are registered for use on established small-seeded legumes in a winter wheat cover crop. Other herbicides, such as diuron, metribuzin, and trifluralin, can be applied to winter wheat undersown with legumes only as dormant-season treatments.

D. Nonchemical Weed Management Methods

Whether winter wheat is used for grain, silage, hay, grazing, green crop, or cover determines the profitability of the weed control measures farmers use. Management which enhances vigorous winter wheat growth suppresses weed growth both in the growing crop and after harvest (Wicks et al., 1989), minimizing the need for herbicides. Planting competitive varieties with high wheat shoot density, planting at optimum dates, fall fertilization, fallowing, and rotation with spring-sown crops, such as corn, reduce winter annual weed seed production, soil seed banks, and later infestations and enhance winter wheat

Table 3 Restrictions on Use of Herbicide-Treated Winter Wheat, Spring Wheat, or Sorghum for Livestock Following In-Crop Treatment for Weed Control According to the 1993 U.S. Environmental Protection Agency registration labels[a]

Herbicide	Restrictions on use for livestock
Alachlor	Do not graze or harvest forage for 70 days after treatment.
Alachlor + atrazine	Do not graze or harvest forage for 70 days after treatment.
Alachlor + glyphosate	Do not graze or harvest forage for 70 days after treatment.
Atrazine	Do not graze or feed forage within 21 days after treatment.
Atrazine + bentazon	Do not graze or feed treated forage for 21 days after treatment.
Atrazine + bromoxynil	Do not graze or cut for feed for 30 days after treatment.
Atrazine + dicamba	Do not graze or harvest for feed until the grain sorghum is mature.
Atrazine + metolachlor	Do not graze or feed forage for 30 days after treatment.
Atrazine + propachlor	Do not graze for 21 days after treatment. Do not graze or feed sorghum forage, silage or fodder (stubble) to dairy animals.
Bentazon	Do not graze for 12 days after treatment.
Bromoxynil	Do not graze treated small grains for 30 days after treatment. Do not cut treated sorghum for feed, fodder, or graze within 30 days after treatment.
Bromoxynil + MCPA	Do not graze or feed treated grass to livestock.
Chlorsulfuron	No registration restrictions on grazing.
Chlorsulfuron + metsulfuron	No registration restrictions on grazing.
Clopyralid	Do not graze dairy cattle for 14 days after treatment. Remove meat animals from treated areas 7 days before slaughter unless 2 or more weeks have passed since application. Do not cut treated grass for hay within 30 days after application.
Clopyralid + MCPA	Do not graze dairy animals or meat animals on forage or graze treated areas within 1 week before slaughter. Do not harvest hay from treated areas.

Table 3 Continued

Herbicide	Restrictions on use for livestock
Cyanazine	No restrictions on the registration label for grazing or feeding grain sorghum or winter wheat.
Cyanazine + metolachlor	There are no label restrictions regarding livestock use, although it is not registered for use on forage sorghum.
Dicamba	Do not graze or harvest for livestock feed before small grains or sorghum are mature. If small grains or sorghum are used for pasture or hay, remove meat animals 30 days before slaughter. There are waiting periods for lactating animals, but not for nonlactating animals. Waiting periods between treatment and grazing vary from 7 to 60 days depending upon dicamba rate. Waiting periods between treatment and hay harvest vary from 37 to 90 days depending upon dicamba rate.
Diclofop	Do not graze or harvest forage, hay or straw before grain harvest.
Difenzoquat	Do not graze or feed cut forage, hay, or silage before harvest. Wheat and barley grain and straw can be fed to livestock after harvest.
Diquat	No restrictions on the registration label regarding grazing or feeding treated crops to livestock.
Diuron	No restrictions on the registration label regarding grazing or feeding treated crops to livestock.
Fenoxyprop + MCPA	No restrictions on the registration label regarding grazing or feeding treated crops to livestock.
Fenoxyprop + 2,4-D + MCPA	No restrictions on the registration label regarding grazing or feeding treated crops to livestock.
Fenoxyprop + MCPA + thifensulfuron + tribenuron	Do not graze or feed forage or hay to livestock (harvested straw may be used as bedding).
Glyphosate	Wait 14 days before grazing or harvesting for livestock.
Glyphosate + dicamba	Do not feed or use for forage for 8 weeks after application.

(*continued*)

Table 3 Continued

Herbicide	Restrictions on use for livestock
Glyphosate + 2,4-D	Do not feed or use for forage for 8 weeks after application.
Imazamethabenz	Do not graze or cut treated forage for silage or hay (harvest wheat and barley straw may be used as bedding).
Linuron	Do not graze or feed 3 months after postemergence application to grain sorghum.
MCPA	Do not graze or forage on treated areas within 7 days of slaughter.
Metolachlor	No restrictions on the registration label regarding grazing or feeding treated crops to livestock.
Metribuzin (Lexone)	No restrictions on the registration label regarding grazing or feeding treated crops to livestock.
Metribuzin (Sencor)	Wait 14 days before grazing wheat. Wait until crop maturity to graze or harvest barley for livestock feed.
Metsulfuron	No restrictions on the registration label regarding grazing or feeding treated crops to livestock.
Paraquat	Do not graze, cut or harvest for forage or hay.
Pendimethalin	No registration label restrictions regarding grazing or feeding treated crops to livestock.
Picloram	Do not cut for feed 2 weeks after treatment. Do not graze lactating animals for 2 weeks after treatment. Meat animals should be removed from treated areas 3 days before slaughter.
Propachlor	Do not graze or feed to dairy animals.
Propachlor + atrazine	Do not graze or feed to livestock for 21 days after treatment. Do not graze or feed sorghum forage, silage or fodder (stubble) to dairy animals.
Propanil	Do not graze or cut for green chop feed.
2,4-D	Do not graze dairy cattle or meat animals being finished for slaughter for 7 to 14 days after treatment, depending upon formulation (see label). Remove meat animals from treated areas 3 to 7 days before slaughter (see label) unless 2 weeks has elapsed after treatment. Do not cut treated grass for hay within 30 days after treatment.

Table 3 Continued

Herbicide	Restrictions on use for livestock
Triallate	Do not graze livestock after treatment.
Triallate + trifluralin	No restrictions on the registration label regarding grazing or feeding treated forage to livestock.
Triasulfuron	No restrictions on the registration label regarding grazing or feeding treated forage to livestock.
Tribenuron	Do not graze or feed forage or hay to livestock. Harvested straw may be used for bedding or feed.
Thifensulfuron + tribenuron	Do not graze or feed forage or hay to livestock. Harvested straw may be used for bedding or feed.
Trifluralin	Do not graze or feed forage or hay to livestock.

Note: Herbicides and rates are based on current labels or expected labels. Before using a herbicide, refer to a current label for appropriate rates.
[a]When "grain sorghum (milo)" is specified, forage sorghum should not be treated. These restrictions minimize the chance that illegal herbicide residues will be present in meat or dairy products.

competitiveness with weeds (Wicks et al., 1989). Winter wheat is also more competitive with weeds than spring wheat, presumably because of early canopy development and closure in spring.

Some winter wheat cultivars are more competitive with weeds than others. For example, cheat competing with 'Pioneer 2157' reduced yields less than with 14 other cultivars in Oklahoma (Koscelny et al., 1990). In Nebraska, some winter wheat varieties suppressed barnyardgrass more than others both in winter wheat (Ramsel and Wicks, 1988) and after harvest (Ramsel and Wicks, 1988; Wicks et al., 1989).

Unfortunately, the basis for varietal differences in winter wheat competitiveness with weeds is too poorly understood to be routinely used as a screening criterion in winter wheat breeding programs or to be recommended by extension personnel. In one study, varietal differences in winter wheat competitiveness were unrelated to differences in interrow shading (Ramsel and Wicks, 1988). Differences in varietal competitiveness with weeds has not been extensively studied for other cereals or sorghum.

As a rule of thumb, weeds which emerge before or with the crop tend to reduce yields more than those weed cohorts which emerge progressively later after crop emergence (Zimdahl, 1980, 1990). Optimum winter wheat planting date can enhance crop competitiveness with weeds because it allows the crop to emerge and grow more quickly and uniformly before most weeds emerge. For example, in Nebraska, late fall-planted winter wheat failed to tiller sufficiently to compete with weeds as well as earlier planted wheat (Wicks et al., 1989). Both the timing of seeding and forage removal influenced wheat grain yield, cheat biomass, and herbicide efficacy for managing cheat in winter wheat in Oklahoma (Ferreira et al., 1990b). Winter wheat planted at normal seeding dates (October) yielded more than when seeded early (September) for forage production or late (November) for cheat management. Delaying seeding until November greatly reduced cheat populations. Seeding date and herbicides also influenced dockage in winter wheat due to cheat.

In Oklahoma, decreasing winter wheat row width from 23 to 8 cm increased weed-free wheat yield in two of three locations but did not increase the yield of cheat-infested winter wheat in 6 of 10 experiments (Koscleny et al., 1990). Doubling winter wheat seeding rates from 265 to 530 seed/m increased winter wheat yield in competition with cheat. However, increasing seeding rate only partially controlled cheat, although it reduced the amount of cheat seed harvested. In other research, increasing winter wheat density above the recommended density for the locale improved wild oat control, but control was still incomplete and unsatisfactory (Martin et al., 1987).

Diseases, insects, winter-kill, drought, or, occasionally, herbicide damage (whether from misapplication, drift, or carryover) may thin winter wheat stands (Cook and Verseth, 1991). When winter wheat stands are sparse or winter wheat foliage grows slowly in spring, summer annual weeds can emerge and develop more vigorously in spring than when the winter wheat canopy closes quickly and completely. When canopies are thin or not completely closed, spring herbicide treatment may be required to control weeds.

E. Herbicides for Weed Control

Herbicides registered for use on winter wheat, many of which can be combined, are summarized in Table 1. More herbicides are registered for use on winter or spring wheat than for other cereals (Table 1). Most cereal herbicides are applied postemergence and there are more herbicides for broadleaf weed management than for grass weed management. Herbicides would probably be used more if effective, selective herbicides were marketed for controlling the grass weeds cheat, downy brome, Italian ryegrass, jointed goatgrass, and volunteer rye in winter wheat.*

The winter wheat treated with herbicides and other pesticides is summarized for 1991 in Table 4. Even though there were several registered

*Dr. T. Peeper, 1993. Oklahoma State Univ., personal communication.

Table 4 Frequency and Extent of Pesticide Use in Winter Wheat in the Major Production States in 1990

Pesticide	Area treated, %	Number of applications	Rate, kg/ha	Total applied, × 1000 kg
Herbicides				
2,4-D	15.6	1.02	0.41	1090
Bromoxynil	1.6	1.00	0.21	55
Chlorsulfuron	12.6	1.00	0.01	33
Clopyralid	<1.0			
Dicamba	3.7	1.05	0.12	80
Diclofop-methyl	<1.0			
Diuron	<1.0			
Glyphosate	1.3	1.13	0.50	121
Imazamethabenz	<1.0			
MCPA	2.5	1.05	0.43	181
Metribuzin	<1.0			
Metsulfuron	<1.0			
Paraquat	<1.0			
Picloram	<1.0			
Terbutryn	<1.0			
Thifensulfuron	3.1	1.02	0.01	7
Triallate	<1.0			
Tribenuron	3.1	1.02	0.01	6
Trifluralin	<1.0			
Insecticides and Fungicides				
Benomyl	<1.0			
Chlorpyrifos	1.0	1.00	0.48	78
Dimethoate	1.2	1.08	0.28	58
Disulfoton	1.0	1.00	0.75	122
Esfenvalerate	<1.0			
Ethyl parathion	<1.0			
Malathion	<1.0			
Mancozeb	<1.0			
Methomyl	<1.0			
Methyl parathion	<1.0			
Phorate	<1.0			
Propiconazole	1.9	1.00	0.11	35
Thiophanate-methyl	<1.0			
Triadimefon	<1.0			

Source: NASS, SDA, Agricultural Chemical Usage, March, 1991

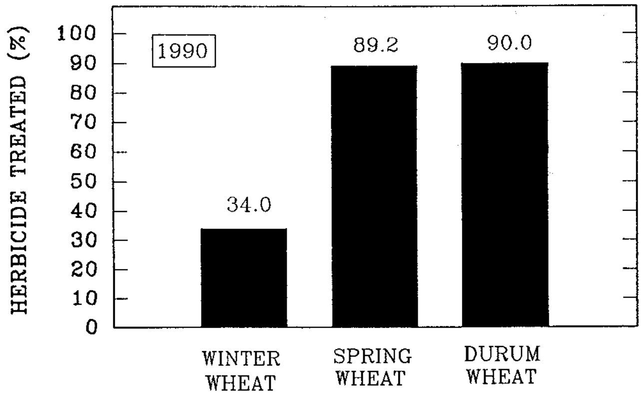

Figure 2 The relative proportion of acreage planted to winter, spring, and durum wheat that was treated with herbicide in 1990. (From Agricultural Chemical Usage, 1991.)

winter wheat herbicides, only a third of the planted winter wheat was routinely treated, compared to greater than 95% for spring wheat (USDA, 1990, 1991; Delvo, 1989) (Figures 2 and 3). In 1990, 16.2 million hectares of winter wheat were harvested, but only 34%, 4% and 3% of that was treated with herbicides, insecticides, and fungicides, respectively (USDA, 1991). Nevertheless, the total herbicide-treated winter wheat roughly equaled that of spring wheat in the United States (Figure 3), largely because so many more hectares of winter wheat than spring wheat were planted (Figure 1). The percentage of the win-

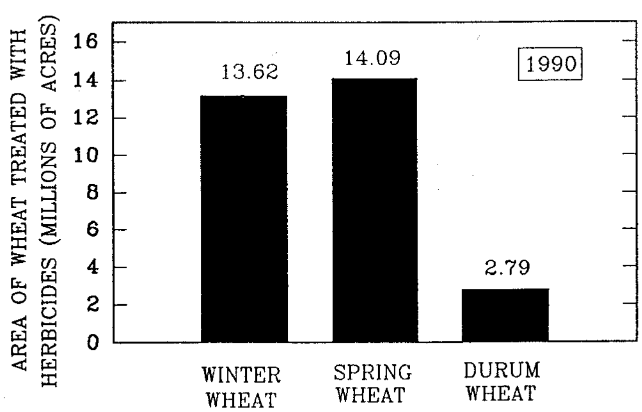

Figure 3 The acreage of winter, spring, and durum wheat treated with herbicide in 1990 (From Agricultural Chemical Usage, 1991.)

ter wheat treated ranged from 10% to 85%, depending upon the state. Consequently, some states treated no more winter wheat with herbicide than they did in the early 1950s (Osteen and Szemdra, 1989). Herbicides were used less in winter wheat than in spring-sown cereals, and nonchemical weed management measures were used more. Tables listing which weeds of winter wheat are controlled by individual herbicides have been compiled for each major wheat production region (Donald, 1990b), and current tables are available from state extension personnel.

F. Combinations of Nonchemical Management and Herbicides for Weed Control

Sometimes it is advantageous to manage weeds in winter wheat or other cereals by combining nonchemical cultural practices with application of herbicides, as has been suggested for downy brome in winter wheat (Wicks, 1984). Crop rotation for weed management often involves herbicide rotation, by default. Rotation of crops with different life cycles (fall-sown and spring-sown crops) is advantageous for preventing the buildup of certain weeds, but there are few examples supporting this assertion for crops alone without herbicide treatment (Black and Siddoway, 1976a,b). Rotation of broadleaf crops with grass or cereal crops also may be advantageous. Finally, rotation of crops with different times of planting can be used to manage weeds. Crop rotation is preferable to continuous cropping, because it limits weed shifts and reduces the likelihood that diseases and insects will increase to levels which will reduce yield.

Winter annual grasses that are especially difficult to manage in winter wheat include cheat, downy brome, Italian ryegrass, jointed goatgrass, volunteer rye, wild garlic, and wild oat (Donald, 1990b). The biology and control of certain weeds in winter wheat have been reviewed: Canada thistle (Donald, 1990a), downy brome (Morrow and Stahlman, 1984; Peeper, 1984), jointed goatgrass (Donald and Ogg, 1991), and wild oat (Jones, 1976; Smith, 1984; Smith and Hsiao, 1984). Management strategies for winter wheat weeds are discussed at greater length elsewhere (Donald, 1990b).

Winter annual bromegrasses, such as cheat and downy brome, are major problems of winter wheat in the Central and Southern Great Plains and Pacific Northwest (Wicks and Smika, 1990; Peeper and Wiese, 1990). Reduced tillage for crop residue management to reduce wind and water erosion has created a favorable environment for grass weed growth in winter wheat. In Oklahoma, cheat and downy brome densities were greater in continuous winter wheat with a stubble-mulched surface than in a nonmulched, no-till soil surface (Dao, 1987). Removing residue without tillage reduced cheat and downy brome infestations (Dao, 1987).

Massee and Higgins (1977) and Wicks (1984) suggested using a combination of cultural practices for managing downy brome. Tillage is recommended to maintain soil moisture in fallow for the later-sown winter wheat crop, but mechanical fallowing often destroys surface crop residue used for wind erosion control. Rod weeding just before planting winter wheat after mid-September was recommended to allow some downy brome to emerge before being killed by tillage. Other methods were faulted: deep moldboard plowing killed downy brome and buried seed so deeply that fewer seedlings emerged, but control was never complete; the temperatures from burning wheat residue in fall did not kill surface-lying downy brome seed but exposed the soil to erosion. Harrowing or stubble mulch tillage (i.e., undercutting with sweeps) did not completely control downy brome because its fibrous roots rerooted and plants regrew after rains. Herbicidal control of downy brome was reviewed (Peeper, 1984; Wicks, 1984), but herbicides have not been widely adopted for downy brome control because of their potential for damaging winter wheat (e.g., metribuzin) and their inconsistent weed control (Peeper and Morrow, 1990). Metribuzin is recommended for use on winter wheat fields with a history of heavy cheat infestations. According to the registration label, metribuzin should be applied to only certain winter wheat varieties and only when they have at least three to four tillers and four secondary roots greater than 5 cm long. Because herbicides for downy brome control require soil moisture for activation, they have performed erratically in arid regions with sporadic rainfall.

Wild garlic is a problem in winter wheat in the Corn Belt and some southern states because it reduces grain quality and, to a lesser extent, yield (Peters, 1990). Traditionally, postemergence 2,4-D was used to manage wild garlic (Rhodes and Shelby, 1991). Although 2,4-D did not prevent yield loss from wild garlic, it caused wild garlic scapes to grow downward so that aerial bulblets were less likely to be harvested during combining and did not contribute to dockage in winter wheat (Rhodes and Shelby, 1991). Recently, postemergence sulfonylurea herbicides, such as thifensulfuron plus tribenuron, were shown to control wild garlic effectively, increase yields, and decrease dockage in winter wheat (Gast et al., 1990). These sulfonylurea herbicides controlled offset bulbs better when applied in late March to early April than in late April (Gast et al., 1990). According to the registration label, thifensulfuron plus tribenuron should be applied when wild garlic is 2.5 to 5 cm tall but less than 30 cm tall (Rhodes and Shelby, 1991).

Phenoxy herbicides, chiefly 2,4-D and MCPA, are widely used for winter annual and summer annual broadleaf weed control in winter wheat (Table 4). Other postemergence herbicides have been marketed either as alternatives to phenoxy herbicides or as tank mixes with phenoxy herbicides to broaden the spectrum of weed control. For example, wild buckwheat is tolerant of phenoxy herbicides but can be controlled with picloram or picloram plus 2,4-D (Heering and Peeper, 1991), among other registered herbicides. Likewise, common chickweed is well controlled by mixtures of 2,4-D plus thifensulfuron, tribenuron, or thifensulfuron + tribenuron but not by 2,4-D alone (Harrison and Beuerlein, 1989). Synergistic interactions between 2,4-D and sulfonylurea herbicides were observed on common chickweed and may be exploited on other weeds for reducing application rates without sacrificing weed control. Reducing application rates of many sulfonylurea herbicides would be advantageous to reduce the chance of carryover damage to later-sown rotational crops.

Sometimes fall-applied herbicides can be used to control winter annual broadleaf weeds better and increase yields more than spring-applied herbicides in winter wheat. In Canada, fall-applied herbicides controlled field pennycress and flixweed better than spring-applied herbicides (Blackshaw, 1990). The residual herbicides chlorsulfuron, dicamba plus nonresidual 2,4-D, metribuzin, metsulfuron, and picloram applied in fall increased winter wheat yields most because they were persistent and controlled both fall- and spring-germinating flushes of field pennycress and flixweed. Bromoxynil, bromoxynil plus MCPA, MCPA, thifensulfuron, and 2,4-D applied in fall did not persist long in soil and failed to control spring flushes of either weed. Some sulfonylurea herbicides can carry over to damage rotational crops (Table 5) and registration labels caution against the increase of sulfonylurea-resistant weed populations after repeated use of sulfonylurea herbicides over several years.

More soybeans in Illinois, Indiana, Kentucky, and Ohio are being double cropped after harvesting winter wheat using no-till planting methods (Lewis, 1976). Selecting cereal and soybean varieties with short enough life cycles to match the local length of the growing season is critical for successful double cropping. Winter barley, an alternative to winter wheat, matures early, making it a good candidate double crop with soybean in some regions, such as the Carolinas (Lewis, 1976), but soybeans are most commonly double cropped into winter wheat stubble. The success of double cropping depends on available soil moisture after winter wheat harvest. Small etiolated weeds, such as clover, common ragweed, foxtails, large crabgrass, and Pennsylvania smartweed, which have not competed well with winter wheat may survive and then grow after winter wheat harvest (Triplett, 1978). It is critical to plant double cropped soybean soon after winter wheat harvest to suppress later regrowth of these previously suppressed weeds. If much time elapses between winter wheat harvest and soybean planting, these weeds grow quickly unless they are controlled with postemergence herbicides. Glyphosate or paraquat can be used to manage weeds growing after winter wheat harvest but before soybean emergence (Triplett, 1978). Winter wheat herbicides must be carefully selected to prevent herbicide carryover damage to double cropped soybean. Short residual herbicides, such as 2,4-D, dicamba, 2,4-D plus dicamba, MCPA, and bromoxynil, can be

Table 5 Restrictions on Rotational Crops That Can Be Planted in the Growing Season After Treatment or the Recropping Intervals After Treating Cereals In-Crop with Various Herbicides, According to 1993 U.S. Environmental Protection Agency Registration Labels[a]

Herbicide	Restrictions on recropping interval in the growing season after treatment
Alachlor	Corn, peanuts, peas, sorghum (milo), soybeans, or sunflower may be planted 1 year after application.
Alachlor + atrazine	Corn, peanuts, sorghum (milo), or soybean may be planted 1 year after application
Alachlor + glyphosate	Corn, cotton, dry beans, peanuts, sorghum (milo), soybeans or sunflower may be planted 1 year after application.
Atrazine	Corn or sorghum may be planted within 1 year after application. Do not plant any other crops for 1 year after application.
Atrazine on furrow irrigated bedded production	Do not replant sorghum for 8 months after application
Atrazine + bentazon	Do not plant sugar beet or sunflower in the following growing season or oat in calcareous soils
Atrazine + bromoxynil	Residual atrazine may injury crops rotated within the last year. Contact local extension agents or perform a field bioassay before planting susceptible rotational crops.
Atrazine + dicamba	If applied after June 10th, do not rotate to crops other than corn or sorghum 1 year after treatment. Plant only corn, peanuts, sorghum, or soybeans 1 year after treatment. Small grains can be planted 10 months after treatment, otherwise wait for 18 months before replanting to other crops.
Atrazine + metolachlor	Corn, cotton, peanuts, sorghum, and soybeans may be planted in the spring after application. If applied after June 10, only corn or sorghum may be planted in the following year. Do not plant spring-wheat, small grains, small seed legumes, sugar beets, tobacoo, or vegetables (including dry beans) in the year following application.
Atrazine + propachlor	Corn, sorghum, and soybeans may be grown 1 year after treatment.
Bentazon	No restrictions on the registration label.
Bromoxynil	All rotational crops can be planted one year after application.

Table 5 Continued

Herbicide	Restrictions on recropping interval in the growing season after treatment
Bromoxynil + MCPA	No restrictions on the registration label.
Chlorsulfuron	Recommended for use only where wheat or barley are grown because residues can persist for 2 to 3 years. Recropping intervals depend on crop, application rate, soil pH, cumulative precipitation, and site (see label).
Chlorsulfuron + metsulfuron	Recommended for use only where wheat or barley are grown because residues can persist for 2 to 3 years. Recropping intervals depend on crop, application rate, soil pH, cumulative precipitation, and site (see label).
Clopyralid	Barley, corn, oat, grasses, sugar beets, and wheat may be planted any time after treatment. Do no plant alfalfa, asparagus, canola, cole crops, grain sorghum, onions, popcorn, safflower, sweet corn, and strawberries for 12 months after application. Do not plant dry beans, soybeans, and sunflower for 12 to 18 months after application depending upon soil organic matter and precipitation. Other crops, including peas, lentils, potatoes, and broadleaf crops for seed, should not be planted for 18 months after treatment to avoid phytotoxicity.
Clopyralid + MCPA	Do not plant wheat, barley, oat, grasses or sugar beets for 12 months after treatment. Do not plant alfalfa, asparagus, canola, cole crops, grain sorghum, onions, popcorn, safflower, sweet corn, and strawberries for 12 months after application. Do not plant dry beans, soybeans, and sunflower for 12 to 18 months after application depending upon soil organic matter and precipitation. Peas, lentils, potatoes, and broadleaf crops for seed should not be planted for 18 months after treatment to avoid phytotoxicity.
Cyanazine	Only corn, sorghum or soybeans may be planted 1 year after treatment. If cyanazine or combinations with cyanazine are applied after June 1, only corn and sorghum can be planted 1 year after treatment. Small grains may be planted 15 months after treatment and all other crops can be planted 18 months after application.
Cyanazine + metolachlor	If the treated crop is lost, corn (field, silage, and sweet) and Concept-treated grain sorghum may be replanted immediately. Wait 4.5 months before planting barley,

(*continued*)

Table 5 Continued

Herbicide	Restrictions on recropping interval in the growing season after treatment
	oat, rye or wheat. Barley, buckwheat, cotton, oat, peanuts, pod crops, potatoes, rice, root crops, rye, safflowers, sorghum, and soybeans may be planted 9 months after treatment. Clover may be planted 18 months after treatment.
Dicamba	Corn, sorghum, soybean, and wheat may be planted in the spring following treatment with 2 lb ai/A dicamba. Check the registration label for restrictions at higher application rates. Following normal harvest of these crops or one year after treatment with dicamba at registered rates, any rotational crop may be grown.
Diclofop	There are no registration restrictions on recropping.
Difenzoquat	There are no registration restrictions on recropping.
Diquat	There are no registration restrictions on recropping.
Diuron	Wait 4 months for band application to 6 months for broadcast application to replant following grain sorghum treatment. Cotton or corn can be replanted at any time after treatment.
Fenoxyprop + MCPA	No rotational crop restrictions on registration label.
Fenoxyprop + 2,4-D + MCPA	No rotational crop restrictions on registration label.
Fenoxyprop + MCPA + thifensulfuron + tribenuron	Do not plant any crop other than wheat or barley 60 days after treatment.
Glyphosate	Do not feed or forage before 8 weeks after treatment.
Glyphosate + dicamba	Apply 15 days before planting wheat, barley, oat or sorghum. Do not plant any crop other than barley, corn, oat, sorghum, or wheat for 3 months after application or until glyphosate + dicamba disappear from the soil.
Glyphosate + 2,4-D	Do not plant crops, other than barley, corn, oat, rye, sorghum, or wheat, for 3 months after treatment.
Imazamethabenz	Barley, corn, edible bean, safflower, soybean, sunflower, and wheat may be grown in the growing season after treatment. Other crops can be planted 15 months after treatment, except sugar beets, which can be planted 20 months after treatment.
Linuron	Any crop can be planted 4 months after treatment, except for cereals. Only barley, oat, rye, and wheat can be planted 4 months after treatment.

Table 5 Continued

Herbicide	Restrictions on recropping interval in the growing season after treatment
MCPA	No rotational crop restrictions on the registration label.
Metolachlor	Barley, oat, rye or wheat may be planted within 4.5 months of application. Any crop registered for metolachlor may be planted in the following spring After 8 months any crop can be planted.
Metribuzin (Lexone)	Crops registered for the rate used may be replanted in case of crop failure, but may not be retreated within the same growing season. In the Pacific Northwest, wait 4 months after applying 0.5 lb ai/A metribuzin to plant to barley or wheat. If 2/3 lb ai/A has been applied, wait 8 months to plant barley or wheat. In areas treated with up to 1 1/3 lb ai./A, wait 10 months to plant barley or wheat.
Metribuzin (Sencor)	Wait 4 months to recrop to alfalfa, asparagus, barley, corn, forage grasses, potatoes, sainfoin, soybeans, sugarcane, tomatoes, or wheat. Wait 8 months to recrop to barley, cotton, lentils, peas, and rice. Wait 10 months to recrop to other crops except root crops. Wait 18 months to recrop to onions, sugar beets, and other root crops.
Metsulfuron	Although metsulfuron is recommended on land dedicated to wheat and barley production, other rotational crops can be grown following metsulfuron application. Detailed instructions for recropping to alfalfa, barley, Conservation Reserve Program grasses, corn, cotton, dry beans, durum wheat, flax, grain sorghum, proso millet, safflower, soybean, spring wheat, sunflower, winter wheat and other crops can be found on the registration label and depend on geographic location, soil pH, and moisture.
Paraquat	There are no registration label restrictions on recropping interval.
Pendimethalin	Winter wheat or winter barley can be planted 90 days after treatment in irrigated sorghum or 120 days after treating dryland sorghum. Any crop can be planted after 1 year.
Picloram	May be used on land to be planted to barley, grass, oat, or wheat or which will be fallowed in the year after

(*continued*)

Table 5 Continued

Herbicide	Restrictions on recropping interval in the growing season after treatment
	treatment. Do not rotate to nonregistered crops for 36 months or until a field bioassay shows that damaging residues no longer persist.
Propachlor	Corn, sorghum, and soybeans may be grown 1 year after treatment.
Propanil	No restrictions on rotational crops on the registration label.
2,4-D	Wait 3 months or until the herbicide has dissipated before planting any crop.
Triallate	Do not plant oat in the growing season after treatment.
Triallate + trifluralin	Sugar beets, red beets or spinach should not be planted for 14 months after treatment. If less than 20 inches of water are used to produce these crops, do not plant them for 20 months after treatment. Sorghum, proso millet, corn or oat should not be planted for 16 months after treatment.
Triasulfuron	Although triasulfuron is recommended on land dedicated to wheat and barley production, other rotational crops can be grown following triasulfuron application subject to a field bioassay. Detailed instructions for recropping to grain sorghum, soybean, spring wheat, winter wheat and other crops without a field bioassay can be found on the registration label and depend on geographic location, soil pH, and moisture.
Tribenuron	Wait 60 days before recropping to crops other than barley or wheat.
Thifensulfuron + tribenuron	Wait 60 days before recropping to crops other than barley or wheat.
Trifluralin	See registration label for detailed instructions on rotational intervals. 14 months before planting sorghum (milo) proso millet, corn and oat after spring application or 16 months after a fall application.

Note: Herbicides and rates are based on 1993 labels or expected labels. Before using a herbicide refer to a current label.

[a]Restrictions help avoid the chance of crop damage from phytotoxic residues and minimize the change of illegal herbicide residues in harvested nonregistered crops. Label restrictions are closely paraphrased.

applied in winter wheat, but the interval between treatment and soybean planting is critical to prevent soybean damage (Lewis, 1976).

G. Postharvest and Fallow Weed Management

Postharvest or fallow weed management is critical for soil moisture storage and successful crop production in arid regions (Wicks, 1986). Herbicides such as cyanazine, 2,4-D, glyphosate, and paraquat have been used to control weeds in fallow and reduce the number of tillage operations needed for fallow weed management (Wiese et al., 1986). When volunteer wheat or weeds were allowed to grow postharvest, they reduced soil moisture storage (Hoefer et al., 1981) and yields of later planted crops (Wicks, 1986). In the Southern Great Plains, weeds should not be allowed to grow for more than 17 days to prevent reducing yields of later-planted crops (Unger, 1983).

Tillage (mechanical fallow) or herbicides (chemical fallow) can be used to limit soil moisture depletion by postharvest volunteer cereal (Table 6) and weed growth. Fallowing by undercutting weeds with sweep-type implements limits evapotranspiration yet keeps plant residues on the soil surface, limiting wind and water erosion (Willis et al., 1983). Chemical fallow with herbicides limits erosion by keeping the soil surface covered with residue. The timing of herbicide application after harvest is critical for successful chemical fallow. In Nebraska, atrazine applied postemergence to winter wheat stubble for weed management after mid-July was more heavily infested with weeds 9 months later than residue sprayed earlier with atrazine (Wicks et al., 1989).

Weeds in fallow also can be suppressed by postharvest winter wheat residue itself if the residue is dense and cut tall (Wicks et al., 1989). When wheat was harvested in Nebraska in mid-July, weeds were controlled 56% by wheat residue 7 weeks after harvest (Hoefer et al., 1981). In Minnesota, winter wheat and winter rye residue provided residual weed control of common lambsquarters and redroot pigweed and fair control of green and yellow foxtail in later-sown soybean (Robinson and Dunham, 1954). Winter rye was more effective than winter wheat for weed management in soybeans sown into the residue. Soybean yields were not reduced by the cereals, and rye and wheat died in August. This interseeding may be less successful in drier regions because early spring regrowth of winter cereals limits soil moisture reserves and, consequently,reduces soybean germination. Winter wheat has advantages as a soil cover for no-till crop production (Moschler et al., 1967). However, the order of preference was rye > wheat = oat > barley because of winter hardiness and susceptibility to being killed by atrazine and paraquat (Moschler et al., 1967).

Table 6 Registered Herbicides for Control of Volunteer Wheat in Field Crops and Fallow According to the 1993 U.S. Environmental Protection Agency Labels

Herbicide	Corn	Cotton	Chemical fallow	No-till before corn, grain sorghum, soybean emergence	Grain sorghum	Soybean
Atrazine	X		X		X	
Clethodim		X				X
Clomazone			X			X
Cyanazine	X	X	X		X	
EPTC	X					
Fluazifop		X				X
Fluazifop + fenoxyaprop						X
Fluazifop + fomesafen						X
Glyphosate			X	X		
Glyphosate + 2,4-D			X			
Metribuzin						X
Paraquat			X	X		
Pronamide			X			
Quizalofop						X
Sethoxydim		X				X

III. WEED MANAGEMENT IN SPRING WHEAT

A. Competition and Yield Loss Assessment

The surveyed distribution of weeds of spring wheat has been summarized for the Northern Great Plains (Dexter et al., 1981; Fay, 1990) and the neighboring Prairie Provinces of Canada (Hunter et al., 1990) (Table 7). Competition and yield loss assessment for weeds of spring wheat are summarized in Table 2 (Zimdahl, 1990). Estimated dollar losses in the United States due to weeds in spring wheat were summarized by region, based on expert opinion (Bridges, 1992). Secondary effects of weeds on spring wheat, such as decreased grain quality, have not been extensively studied. Wild oat, a major weed of spring wheat in the Northern Great Plains, reduced yield, but not percentage grain protein or seed size, important grain quality factors (Bell and Nalewaja, 1968). In fact, spring wheat percentage protein increased as yield was reduced by increasing wild oat densities, probably a stress effect. Tartary buckwheat reportedly darkened spring wheat flour and reduced its value (Remy et al., 1985).

B. Nonchemical Weed Management Methods

Nonchemical methods for weed management in spring wheat were recently reviewed (Donald and Nalewaja, 1990), including control of wild oat (Hunter, 1983) and Canada thistle (Donald, 1990a). Measures to prevent weed seed from being spread between fields include planting weed-free crop seed and cleaning grain drills, harvesting equipment, and combines between fields (Donald and Nalewaja, 1990).

Weed control is a major justification for crop rotation (Kirby, 1980). More research is needed to characterize better the relative competitiveness of spring wheat with weeds versus other spring-sown cereals or row crops. For example, spring-sown barley was more competitive with wild oat than spring wheat in North Dakota, as determined by smaller yield reductions at comparable wild oat densities (Bell and Nalewaja, 1968). Forages, barley, and fall rye were more competitive with weeds than spring wheat (Holm and Kirkland, 1986).

Spring wheat competitiveness with weeds can be enhanced by changing planting practices (i.e., early spring planting, decreasing row spacing, or increasing plant populations). For example, increasing wheat population increased wheat yields in competition with wild mustard (Holm and Kirkland, 1986). Some extension agents suggest that farmers grow competitive spring wheat cultivars as a weed management measure; however, they would be hard-pressed to name particular varieties or growth characteristics that make some varieties of spring wheat more competitive than others. More research is needed on this possibility for managing weeds in all cereals.

The timing of primary tillage can be used to manage weeds in spring wheat. Fall tillage or summer fallow controls winter annual weeds (Holm and

Table 7 Comparison of the Frequency of the Most Common Weeds of Spring Wheat[a]

	Spring wheat		Barley		Oat	
Weed	1978	1979	1978	1979	1978	1979
Green foxtail	94	95	98	99	89	95
Wild oat	67	67	63	68	73	45
Wild buckwheat	54	66	53	86	65	77
Redroot pigweed	52	67	33	56	34	61
Yellow foxtail	17	27	–	25	15	31
Kochia	26	27	28	30	16	42
Russian thistle	22	33	16	–	25	57
Common lambsquarters	20	40	37	35	36	73
Canada thistle	11	17	15	32	7	15
Field bindweed	9	19	9	10	12	24
Wild mustard	12	39	13	32	19	54
Night-flowering catchfly	8	8	8	20	–	–
Volunteer sunflower	10	15	16	11	13	–
Perennial sowthistle	8	–	21	9	14	14
Prostrate pigweed	6	15	4	–	–	19
Russian thistle	–	–	16	16	26	54
Quackgrass	–	–	4	8	–	15
Wild rose	3	11	–	–	5	–

Source: Dexter et al. (1981).

[a](*N* = 859 in 1978 and *N* = 89 in 1979), barley (*N* = 303 in 1978 and *N* = 100 in 1979), and oat (*N* = 176 in 1978 and *N* = 74 in 1979) in North Dakota.

Kirkland, 1986), as does preplant primary tillage (i.e., chisel plowing) and secondary tillage for seedbed preparation (i.e., field cultivation-harrowing) in spring (Cook and Veseth, 1991). Although cultivation is not usually suggested for solid-seeded spring cereals or spring wheat, postseeding harrowing until spring wheat is 12.5 to 15 cm tall has successfully controlled summer annual broadleaf weeds, such as mustards, stinkweed, and Russian thistle, in Canada (Holm and Kirkland, 1986).

C. Herbicides for Weed Control

The major herbicides registered for use in spring wheat are summarized in Table 1; many of them can be applied as mixtures. Of the 6.4 million hectares planted to spring wheat in 1991, 89% and 7% were treated with herbicides and insecticides, respectively (USDA, 1991). The percentages of planted hectares treated with particular herbicides in spring wheat and durum wheat are summarized in Tables 8 and 9. In 1989, herbicide-treated spring wheat varied from a low of 71% in Montana to a high of 97% in Minnesota (Delvo, 1989). Ninety percent of the durum wheat was treated with herbicides (125,550 hectares, chiefly in North Dakota). Except for soil-applied triallate and trifluralin for grass control, most herbicides are applied postemergence to spring wheat and other spring-sown cereals (Table 1). Consequently, they are well adapted to no-till production practices. A history of the early introduction of phenoxy herbicides (Kirby, 1980) and wild oat herbicides (Banting, 1984) and a summary of herbicide use for wild oat control in Canada (Smith and Hsiao, 1984) have been published. While spring wheat is not generally grazed or harvested for forage in the Northern Great Plains (Donald and Nalewaja, 1990), farmers who graze spring cereals should be aware of restrictions on the interval between herbicide application and grazing or cutting (Table 3). Tables that indicate which weeds of spring wheat are controlled by individual herbicides have been constructed for each major wheat production region (Donald, 1990b), and current summaries are available from state extension agents.

Cereal yields are reduced less if summer annual weeds, such as wild oat, emerge progressively later after spring wheat or barley emergence (Donald and Nalewaja, 1990). Consequently, timely planting according to regional seeding recommendations minimizes spring cereal yield losses due to weeds. Early, timely application of postemergence herbicides is critical to kill weeds when they are young and prevent yield losses in spring wheat. "Time-of-removal" experiments in spring wheat show that weeds must be removed within 2 to 4 weeks of crop emergence to prevent initial yield loss (Zimdahl, 1980). Unlike hand hoeing or cultivation of row crops, there is a lag between herbicide application and later weed death during which weeds can continue to compete with cereals (Gillespie and Nalewaja, 1988).

Table 8 Frequency and Extent of Pesticide Use in Spring Wheat in the Major Production States in 1990

Pecticide	Area treated, %	Number of applications	Rate, kg/ha	Total applied, × 1000 kg
Herbicides				
2,4-D	53.4	1.03	0.38	1359
Bromoxynil	8.6	1.03	0.31	181
Chlorsulfuron	3.3	1.14	0.02	3
Clopyralid	2.0	1.00	0.11	15
Dicamba	21.3	1.00	0.09	125
Diclofop	3.6	1.00	0.92	212
Difenzoquat	2.9	1.00	0.68	127
Fenoxyprop	3.3	1.00	0.09	18
Glyphosate	<1.0			
Imazamethabenz	2.4	1.00	0.39	61
MCPA	32.4	1.06	0.34	755
Metsulfuron	<1.0			
Picloram	<1.0			
Thifensulfuron	5.3	1.00	0.01	4
Triallate	4.3	1.00	1.13	312
Tribenuron	10.2	1.00	0.01	7
Trifluralin	5.4	1.00	0.56	193
Insecticides and Fungicides				
Carbaryl	1.6	1.15	0.92	108
Carbofuran	1.0	1.00	0.26	16
Ethyl parathion	<1.0			
Malathion	<1.0			
Mancozeb	<1.0			
Methyl parathion	3.1	1.00	0.44	86
Propiconazole	1.7	1.00	0.15	16

Source: NASS, SDA, Agricultural Chemical Usage, March 1991.

Properly timed postemergence herbicide application influenced the profitability of herbicide use in spring wheat in North Dakota (Gillespie and Nalewaja, 1988). Control of wild oat and wild mustard and profitability were greatest when diclofop plus bromoxynil was applied at the two-leaf stage compared with the three- to five-leaf stage or boot stage of spring wheat. Delaying herbicide treatment reduced economic returns, and controlling wild oat without controlling wild mustard was less profitable than controlling both weeds.

Table 9 Frequency and Extent of Pesticide Use in Durum Wheat in the Major Production States in 1990

Pesticide	Area treated, %	Number of applications	Rate, kg/ha	Total applied, × 1000 kg
Herbicides				
2,4-D	50.0	1.00	0.46	289
Bromoxynil	<1.0			
Chlorsulfuron	<1.0			
Dicamba	24.6	1.00	0.09	28
Diclofop	5.2	1.00	0.81	53
Difenzoquat	<1.0			
Glyphosate	<1.0			
Imazamethabenz	<1.0			
MCPA	34.3	1.04	0.40	177
Methsulfuron	<1.0			
Thifensulfuron	<1.0			
Triallate	13.4	1.00	1.03	174
Tribenuron	10.4	1.07	0.01	1
Trifluralin	30.6	1.00	0.45	175
Insecticides and Fungicides				
Carbaryl	<1.0			
Carbofuran	<1.0			
Malathion	<1.0			
Methyl parathion	<1.0			

Note: Herbicides and rates are based on current labels or expected labels. Before using an herbicide refer to a current label for appropriate rates.
Source: NASS, SDA, Agricultural Chemical Usage, March 1991.

Combining crop management practices which suppress weeds with use of herbicides helped improve weed management in spring wheat. For example, N-fertilizer placement, spring wheat row spacing, and wild oat herbicides in no-till spring wheat all influenced wild oat control (Reinertsen et al., 1984). Fewer wild oat plants emerged when ammonium nitrate was band applied below the spring wheat seed than when it was surface-applied. Narrow row spacing (20 cm) increased wheat yields and shoot dry weight more than wider spacings (40 cm) in competition with wild oat. Wild oat densities increased from 68 to 95 plants/m as crop spacing was increased from 20 to 40 cm. Triallate reduced wild oat populations more than difenzoquat or no herbicide but did not reduce wild oat shoot dry weight any more than difenzoquat.

Most herbicides used for grass or broadleaf control in spring wheat are applied postemergence and, consequently, are well suited for use in reduced- or no-tillage farming systems (Table 1). Herbicide formulation may influence the efficacy of soil-applied herbicides, such as triallate, in reduced or no-till crop production (Carlson and Morrow, 1986). Granular triallate before or at planting without incorporation adequately controlled wild oat in no-till spring wheat in Washington. The emulsifiable formulation of triallate was not as effective as the granular formulation. Preplant incorporation of both triallate formulations controlled wild oat better than surface-applied treatments, but surface treatment with both formulations still controlled wild oat well.

Weed management strategies for specific weeds of spring wheat are discussed at greater length elsewhere (Donald and Nalewaja, 1990). Even though most spring wheat herbicides are applied postemergence, some postemergence herbicides have residual soil activity. For example, chlorsulfuron, metsulfuron, and triasulfuron plus surfactant applied at planting controlled annual broadleaf weeds (kochia and wild mustard) for the entire growing season in North Dakota in place of glyphosate, if applied when spring wheat was no-till planted (Donald and Prato, 1991). Residual suppression of kochia and wild mustard was observed in the following growing season. However, repeated use of residual sulfonylurea herbicides may lead to development of herbicide-resistant weeds and persistent phytotoxic residues may limit rotational crop options.

IV. WEED MANAGEMENT IN BARLEY

A. Weed Competition

Barley is grown for different purposes in different regions in North America. It is marketed as a feed grain in Canada (Baldridge et al., 1985), but it is sold chiefly for malting in the Northern Great Plains. Barley is also used for forage or grazing, but farmers must observe grazing or feeding restrictions on herbicide registration labels, as noted for winter and spring wheat (Table 3). How barley will be used and grain grading standards influence the profitability of weed management strategies for barley.

The major weeds of barley in the Northern Great Plains have been surveyed (Table 7), but weed competition and the impact of weeds on barley yield and grain quality have not been studied as much as for wheat (Zimdahl, 1980, 1990) (Table 2). Estimated dollar losses in the United States due to weeds in barley, based on expert opinion, were summarized by region (Bridges, 1992). Little has been published on the impact of weeds on barley grain quality although weeds can reduce quality. For example, Tartary buckwheat reportedly decreased barley malting quality (Remy et al., 1985).

B. Nonchemical Weed Management Methods

Crop rotations are not as rigid for spring-sown barley (Baldridge et al., 1985) as they are for winter wheat. Typical rotations include alternate barley/fallow, row crop/barley, and continuous barley. Barley can be rotated with winter- and spring-sown crops to prevent the buildup of weeds and other pests. In the Northwestern Great Plains, a 3-year winter wheat or spring wheat–barley–fallow rotation is often used (Baldridge et al., 1985). Other typical rotations include 4-year winter wheat–oilseed (generally sunflower or safflower)–barley–fallow, safflower–barley–winter wheat rotation, and winter wheat–barley (winter wheat planted no-till into barley residue). Herbicide treatment in one crop may provide residual control in later crops. For example, trifluralin applied in sunflower in the Northern Great Plains controlled foxtails in spring barley and spring wheat in the following growing season (Black and Siddoway, 1976a,b). The mechanism of residual control with trifluralin was not determined, although it probably included both crop life cycle rotation and herbicide rotation.

Selection of competitive crops is often suggested as a weed management strategy. However, there are few reports comparing barley competitiveness with weeds to competitiveness of other crops in the absence of herbicides. In Canada, barley was more competitive with green foxtail than flax (Rahman and Ashford, 1972) and more competitive with wild oat than either canola or spring wheat (O'Donovan, 1988). Barley is reportedly more competitive than spring wheat with the following weeds: quackgrass (Williams, 1977), Tartary buckwheat (Remy et al., 1985), wild buckwheat (Pavlychenko, 1940), wild mustard (Pavlychenko, 1940), and wild oat (Bell and Nalewaja, 1968; Pavlychenko, 1940). Continuous monoculture is discouraged for producing all field crops because of the potential for buildup of weed, insect, and disease problems. An irrigated barley weed management system including herbicides allowed fewer barnyardgrass and redroot pigweed plants to survive than in corn, pinto bean, or sugar beet in Colorado (Schweizer et al., 1988). The reasons barley was more competitive with particular weeds than other cereals are not known and deserve further research.

Crop management practices, such as planting date, can drastically influence barley yields in competition with weeds, as observed for spring wheat. The interval between barley and weed emergence can impact the magnitude of barley yield losses due to weeds. In fall-tilled and no-tilled barley in Quebec, delaying spring seeding past the local optimum dates (May 15 to June 22) decreased yields, in part, because annual weeds increased (Barnett et al., 1984). As planting was delayed on a fall-prepared seedbed, subsequent barley yield decreased unless the seedbed was harrowed to control weeds immediately before late planting.

The effectiveness of planting date as a weed management strategy depended on weed and crop emergence relative to one another. In Alberta, when barley emerged 1 week before wild oat, barley yields were greater than when wild oat emerged 1 week before barley (McBeath et al., 1970). The later wild oat emerged after spring wheat or barley emergence, the less yield was reduced in Canada. In England, quackgrass and hempnettle did not reduce the yield of early-planted barley, but hempnettle reduced yield if barley planting was delayed (Scragg and McKelvie, 1976).

The presence of weeds, their density, and their emergence behavior must be known when considering planting date as a weed management strategy for any cereal. For example, delayed seeding for wild oat control may favor the buildup of later emerging species, such as green and yellow foxtails, in the Northern Great Plains. Also, weed-free barley yields will be reduced if planting is delayed past the optimum local planting date.

Past research on increased barley seeding rate to suppress weeds in cereals was briefly reviewed (Zimdahl, 1980) and has been known since the 1930s (Pavlychenko, 1940). In England, seeding spring barley at 180 kg/ha reduced wild oat and quackgrass competition more than seeding at 90 kg/ha at two row widths (10 and 20 cm) (Cussans and Wilson, 1975). Barley seeding rate decreased wild oat growth more than row width.

The influence of fertilization on weed competition with barley and spring wheat was reviewed (Zimdahl, 1980). Early research showed that fertilizer improved yields only when weeds (e.g., wild oat) were controlled. Spring barley or wheat yields were not increased by broadcast fertilization with N-P in competition with wild oat in North Dakota. Wild oat took advantage of surface-applied fertilizer better than cereal crops.

C. Herbicides for Weed Control

Currently registered barley herbicides and herbicide combinations are summarized in Table 1. There are few soil-applied herbicides for use in barley, as was noted for spring wheat. Herbicide efficacy for weed management can be improved by barley competitiveness. For example, barley competition enhanced trifluralin control of green foxtail compared with control by trifluralin alone in Canada (Rahman and Ashford, 1972). Weed management with herbicides is similar in barley, durum wheat, oat, and spring wheat.

V. WEED MANAGEMENT IN OAT

The major weeds of oat in the Northern Great Plains have been surveyed (Table 7). Estimated dollar losses in the United States due to weeds in oat were summarized by region, based on expert opinion (Bridges, 1992). Because there were fewer effective registered herbicides and herbicide combinations for oat than for other cereals (Table 1), oat should not be planted on weedy fields. Fields with wild oat should be avoided since wild oat cannot be selectively controlled in oat with herbicides (Helm and McMullen, 1989) and nonchemical weed management is ineffective. The best management strategy for wild oat control is to rotate to crops on which registered wild oat-control herbicides can be safely used, rather than to plant oat.

Good weed management in preceding crops is important for subsequent oat production. Fallowing in the growing season before planting oat can be used for reducing weed infestations in oat in the Northern Great Plains and elsewhere (Mitich and George, 1981). In nonirrigated oat, fallow tillage should be delayed until fall rains stimulate weed germination, before controlling weeds with tillage (Mitich and George, 1981). In irrigated oat, irrigation can be used to stimulate weed germination before starting tillage (Mitich and George, 1981). The "antidote" or "safener" strategy has been tried on oat for wild oat control with wild oat herbicides that would normally damage oat but has not been successful enough for commercial use (Chang et al., 1974).

VI. WEED MANAGEMENT IN SORGHUM

Sorghum production practices have been summarized (Bennett et al., 1990; McKinney, 1992) and weed management practices were briefly reviewed for conventional tillage (Phillips, 1970; Wiese, 1983) and conservation tillage (no-till and reduced-till) production systems (Wiese et al., 1985). Weed problems in sorghum differ between production regions. Estimated dollar losses in the United States due to weeds in sorghum were summarized by region on the basis of expert opinion (Bridges, 1992).

A. Weed Competition

Most research on sorghum competition with weeds was conducted in the Central Great Plains with irrigated and nonirrigated sorghum populations of 250,000 plants/ha and 75,000 to 100,000 plants/ha, respectively (Table 2). Damage thresholds from weeds for sorghum were briefly reviewed (Swann, 1980), but this competition information is not used by farmers in making weed control decisions, as noted for other cereals. There is essentially no published information on how weeds impact sorghum grain quality. In the only published study on the impact of weeds on sorghum harvesting efficiency, mixed weed populations which were killed and desiccated by freezing did not influence harvesting efficiency (Burnside et al., 1969). However, combining had to be delayed to allow weeds to dry.

"Time of removal" experiments for different weeds were used to estimate the interval from sorghum emergence to control of weeds before yields were reduced. These studies demonstrated that weeds emerging within the first few weeks after crop emergence reduced yields more than later emerging weeds (Burnside and Wicks, 1967), as observed for small grains. When sorghum was grown in 40-cm rows and kept weed-free for only 1 to 3 weeks after planting, it yielded as much as sorghum kept weed-free for the entire growing season in Nebraska. If sorghum infested with smooth pigweed, foxtail, and crabgrass was kept free of weeds for 4 weeks after planting, later emerging weeds did not reduce yields. Sorghum yields were progressively reduced as the period between planting and weeding increased from 4 to 8 weeks. In later research in Nebraska, sorghum yields were reduced 4%, 12%, and 18% when mixed populations of weeds were removed 3, 4, and 5 weeks after sorghum emergence (Burnside and Wicks. 1969). If weeds were allowed to grow for 2 weeks before being controlled, yields were not reduced. This information is valuable in planning weed management measures with either cultivation or herbicides.

B. Nonchemical Weed Management Methods

The profitability of the best weed management methods depends on yield potential, the weeds that are present, and weed density (Greer, 1990). Herbicides are best used to supplement traditional nonchemical weed management measures, not to substitute for them. Nonchemical methods, such as cultivation, may be sufficient for controlling light weed infestations (Bauman and Weaver, 1991).

Crop rotation has been suggested as a way to manage weeds in sorghum, but the efficacy of particular rotations on individual weeds has not been well documented (Bauman and Weaver, 1991). Good weed management in the previous rotational crop has been demonstrated to improve weed control in sorghum in Georgia (Diawara and Banks, 1990). Combining crop rotation with herbicide rotation may control weeds in late-planted sorghum better than crop rotation alone.

Weed shifts were observed in a cultivated soybean-sorghum rotation in Nebraska (Burnside, 1978). Green foxtail, large crabgrass, and tall waterhemp decreased as problems in atrazine-treated sorghum over time, but velvetleaf and Pennsylvania smartweed increased. Rotation to winter wheat or soybean treated with trifluralin was used to manage shattercane in sorghum planted in the subsequent growing season (Wiese et al., 1977). Common milkweed has been managed by rotating to alfalfa for several years before planting sorghum (Wiese et al., 1977). Both alfalfa's perennial life cycle and repeated mowing management probably reduced common milkweed populations in later-planted sorghum. Field sandbur has been managed in sorghum by rotation to winter wheat (Wiese et al., 1977).

Row spacing influenced grain sorghum competitiveness with weeds in Oklahoma (Smith et al., 1990) and Nebraska (Burnside and Wicks, 1969). Sorghum planted in narrow rows (61 cm) was more competitive with barnyardgrass, large crabgrass, and Texas panicum than sorghum in wide rows (91 cm) (Smith et al., 1990). In Nebraska, the yield of narrow row (50 cm) sorghum competing with mixed weed populations also was greater than that of wide row (100 cm) sorghum (Burnside and Wicks, 1969), but row spacing did not influence yield when kept weed-free by hand weeding. Narrow row spacing in nonirrigated, nontilled sorghum yielded well in competition with weeds (green foxtail, tall waterhemp, and large crabgrass) (Burnside, 1977). Postemergence atrazine reduced mixed weeds more than increasing plant population did, but sorghum population was correlated with observed weed control.

C. Weed Management in Various Sorghum Cropping Systems

Herbicides registered for use on sorghum are summarized in Table 1, although many more mixtures of these herbicides are registered. Young, volunteer sorghum can be controlled with postemergence paraquat or glyphosate before emergence of rotational crops (Wiese and Chenault, 1987).

Weed Management in Conventional Sorghum

Combinations of management practices, such as crop rotation, tillage, and herbicide application, offer the most potential for weed management in conventional sorghum. Wiese et al. (1977) suggested that total reliance on herbicides in sorghum has caused weed shifts and encouraged the buildup of certain weed species on farms. In Kansas and Nebraska, pigweeds present in the 1950s were controlled by 2,4-D and propazine, leading to increases of annual grass weeds, such as fall panicum, witchgrass, field sandbur, and green foxtail (Houston and Kimbrough, 1991; Swann, 1980; Wiese et al., 1977), which were not controlled by these broadleaf herbicides. In continuous sorghum, low rates of atrazine alone encouraged the buildup of severe infestations of stinkgrass (Chamberlain et al., 1970). Many, but not all, grasses can be suppressed in sorghum with atrazine, cyanazine, propachlor, and linuron (Wiese et al., 1977), although these are generally considered to be broadleaf herbicides. Control of broadleaf weeds probably allowed field sandbur to increase in Kansas sorghum fields (Wiese, 1983), and Texas panicum has increased elsewhere, in part because it is resistant to atrazine and alachlor (Swann, 1980).

Grass Weed Management

Annual grass weeds can be controlled before sorghum planting by mechanical seedbed preparation. If preemergence herbicides, such as alachlor or metolachlor, are not applied at planting for controlling grasses, grass weeds emerging after sorghum can be controlled by cultivation, or by pendimethalin or trifluralin applied as a postemergence-incorporated lay-by treatment (Table 1). These dinitroaniline herbicides have been used successfully on weeds, such as Texas panicum, but should be applied only after sorghum brace roots are well developed (Swann, 1980). Linuron plus surfactant as a postdirected application is used for controlling both grasses and broadleaf weeds.

Weedy sorghum and other grasses are major problems for sorghum producers, especially if crop rotation is not practiced. There are five types of weedy sorghums: tall mutants, off-types, silage types, rhizomatous grassy types, and nonrhizomatous grassy types. Tall mutants are 30 to 60 cm taller than grain sorghum hybrids but appear normal otherwise. The presence of numerous tall mutants in sorghum fields suggests that foundation seed was impure. Off-type sorghum or off-color heads do not look like the planted hybrid and off-type sorghum suggests that pollen from some other sorghum interfered with normal pollination. Silage-type sorghum is tall and thick stemmed. Because silage-type sorghum matures after grain sorghum, yield losses are likely in infested fields. Rhizomatous grassy-type sorghum is tall, tillers excessively, and produces sterile seedheads that look like johnsongrass. Rhizomes of this sorghum type are not as large or well established as johnsongrass and tend to winter-kill. Nonrhizomatous grassy types (shattercane) are tall and also tiller excessively. Their loose open heads produce viable seed which shatter and are very persistent in the soil seed bank (Burnside et al., 1977). Many of these weedy sorghums were introduced as contaminants in sorghum seed.

Hand roguing or spot herbicide treatment (e.g., glyphosate or paraquat) of small infestations of both rhizomatous and nonrhizomatous grassy sorghum is recommended to limit the buildup of weed populations. Because shattercane is difficult to control in sorghum, it is preferable to manage it by crop rotation and use of effective herbicides in rotational crops (Wiese et al., 1977; Wiese, 1983), in addition to cultivation. In dryland areas, shattercane can be managed by rotating to winter wheat or alfalfa for 3 years or more (Wiese, 1983). Shattercane also can be controlled in soybean with dinitroaniline herbicides, such as trifluralin. Rotation to corn allows the use of herbicides on shattercane that would normally damage sorghum. Farm machinery should be cleaned before moving between fields to prevent infesting of new fields (transferring seed from field to field). Limiting grazing on infested fields will also minimize the spread of weed-type sorghums from one field to another in manure.

Johnsongrass, a perennial rhizomatous sorghum species, is difficult to control selectively in sorghum (Greer, 1990). Fall plowing is recommended to bring rhizomes up to the soil surface, where they will dry and freeze over winter. Multiple cultivations during winter expose rhizomes to killing low temperatures and desiccation, but cultivation alone is not completely effective on johnsongrass (Obrigawitch et al., 1990). Cultivation after johnsongrass emerges in spring can stimulate uniform emergence under favorable environmental conditions in the Southern Great Plains (Greer, 1990). Short residual, nonselective, postemergence herbicides applied in fall also controlled johnsongrass if there was sufficient fall foliage growth to treat. Glyphosate is recommended in both fall and spring before planting sorghum, usually when johnsongrass is at least 30 cm tall (Greer, 1990). Glyphosate applied in mid-June, late July, or mid-September 1 year before planting sorghum totally controlled weeds in no-till sorghum in Texas (Brown et al., 1988). Glyphosate applied in mid-June controlled weeds better than at other times. In other research, fall-applied glyphosate controlled johnsongrass better than preemergence metolachlor or pendimethalin applied in sorghum. Fall plowing or spring disking more than 7 days after glyphosate treatment provided enough time for the herbicide to translocate to roots and also to prepare a seedbed. Preemergence metolachlor or alachlor controlled seedling johnsongrass in spring in sorghum (Greer, 1990), whereas atrazine was ineffective (Houston and Kimbrough, 1991).

Perennial Broadleaf Weed Management

Postemergence herbicides for annual broadleaf control in sorghum (Table 1) failed to control perennial weeds adequately. For example, 2,4-D did not adequately control common milkweed in sorghum (Wiese et al., 1977). If one does not wish to rotate to a perennial crop, such as intensively managed alfalfa, for controlling common milkweed (Wiese et al., 1977), fall-applied glyphosate at ≥ 1.1 kg/ha can be used before harvest to control common milkweed in the following year (Gigax and Burnside, 1976). However, this may require preharvest spot treatment of common milkweed patches growing in late-harvested row crops.

Nonselective translocated herbicides have been studied as fall-applied treatments for controlling honeyvine milkweed in sorghum planted 1 year after treatment (Claassen and Moshier, 1989). The following herbicide treatments suppressed this perennial for 9 months and increased the yield of sorghum planted in the following growing season: glyphosate at 3.4 kg/ha, glyphosate plus dicamba at 1.7 plus 0.6 kg/ha, glyphosate plus 2,4-D at 1.7 plus 1.1 kg/ha, picloram at 0.28 kg/ha, and all combinations of picloram at 0.14 and 0.28 kg/ha plus 2,4-D at 0.06 to 1.1 kg/ha. However, honeyvine milkweed had regrown enough that these fall-applied herbicides did not prevent yield losses of winter wheat planted 13 months after treatment. Honeyvine milkweed had regrown enough after 24 months to require retreatment.

Field bindweed is a continuing problem in sorghum and cereals in the Great Plains. Dicamba at ≥ 4.5 kg/ha applied 1 year before planting controlled field bindweed in sorghum in Colorado (Schweizer and Swink, 1971). However, dicamba residues were too persistent and phytotoxic to most other irrigated crops to allow their recommendation. Unfortunately, dicamba at lower rates and mixes of 2,4-D and dicamba were less effective for managing field bindweed than dicamba at higher rates. Combinations of herbicide, cultivation, and crop rotation were much more effective than reliance on dicamba or 2,4-D alone for field bindweed control. Glyphosate applied after the previous crop harvest or before planting can also be used to manage field bindweed.

Weed Management in No-Till Sorghum

Data from early research indicated that no-till sorghum in the Great Plains had several limitations: inconsistent weed control (Phillips, 1969), herbicide carry-over damage to succeeding crops (Phillips, 1969), and lack of profitability. However, recent research on no-till sorghum weed control has been more successful. In a winter wheat–fallow–sorghum rotation in Nebraska, atrazine applied alone after winter wheat harvest did not adequately control volunteer wheat, downy brome, or barnyardgrass, which depleted soil moisture reserves (Wicks et al., 1988). However, atrazine plus paraquat controlled weeds better and reduced weed biomass while maintaining greater crop residues for erosion control. This combination treatment increased soil moisture conservation and subsequent no-till sorghum yields compared with conventional seedbed preparation.

Preplant or planting-time "burndown" herbicides are often mixed with soil-residual herbicides for season-long weed control in no-till sorghum (Lewis et al., 1988). Either paraquat or glyphosate can be combined with residual herbicides, such as atrazine or a mixture of atrazine plus metolachlor, for longer broadleaf weed control or broadleaf plus grass control, respectively. As expected, paraquat alone did not control weeds for the entire growing season because it has only postemergence contact activity (Wicks and Grabouski, 1986). Disking for seedbed preparation and 2,4-D application before cultivation controlled broadleaf weeds, but not grasses, although Russian thistle escaped, presumably because it is a summer annual that emerges over an extended period later in the growing season.

Early preplant herbicides play an important role in no-till sorghum production by maintaining good weed control, reducing the chance of herbicide damage to sorghum, and increasing sorghum yields. Fall-applied herbicides, such as atrazine or cyanazine, controlled emerged winter annual weeds, such as henbit in Texas (Baumann and Weaver, 1991). Cyanazine may also be applied in late fall and up to 30 days before sorghum planting. In Nebraska, triazine herbicides were applied 41 and 25 days before no-till sorghum planting in standing wheat stubble (Wicks, 1985a). Cyanazine applied 41 days before planting did not damage sorghum but caused 18% injury when applied at planting (Wicks, 1985a). Metolachlor plus 2,4-D applied before planting was superior to alachlor plus 2,4-D for grass control. In Nebraska, no-till sorghum treated with paraquat, atrazine, and terbutryn yield 33% more than sorghum produced on a tilled seedbed (Wicks and Grabouski, 1986). Herbicides applied 14 days before planting gave more consistent control than when applied at planting.

Preemergence herbicides applied after sorghum planting are restricted for use to certain states (Table 1). Sorghum seed must be treated with safeners if either alachlor and metolachlor is used (Greer, 1990). Although these herbicides controlled small-seeded annual grasses well, Texas panicum and seedling Johnsongrass escaped control (Greer, 1990). Propachlor was not as effective for grass control as alachlor or metolachlor in Oklahoma (Greer, 1990). If these preemergence herbicides are not activated by rainfall within several days of planting, light cultivation may be needed to control emerging weeds (Greer, 1990).

Some selective postemergence herbicides can be applied until sorghum is 10 to 15 cm tall. Postemergence herbicides are useful for weed management if preemergence herbicides fail or are not applied (Greer, 1990). Postemergence atrazine must be applied to grass seedlings when they are small, 1 cm tall or less, and control is inferior to that achieved on broadleaf weeds. Addition of appropriate surfactants, crop oil concentrates, and crop oils made grass control more consistent with atrazine, but only for small grasses less than 5 cm tall (Swann, 1980). Atrazine is safest on sorghum when it is treated after the three-leaf stage (Swann, 1980).

If only broadleaf weeds are present, postemergence 2,4-D or dicamba can be applied. Postemergence 2,4-D can be applied later than some other herbicides (Wiese, 1983). Weeds in sorghum can be treated only after sorghum is 10 cm tall (measured at the point of emergence of leaves from the whorl) but before it is 38 cm tall (seedhead formation). High clearance drop nozzles should be used to apply 2,4-D after sorghum is 25 cm or more tall.

Weed Management in Double Cropping

The short growing season in the northern United States limits double cropping for grain, but double cropped forage sorghum can be grown after cereals (Okoli et al., 1984). In Wisconsin, conventionally planted spring oat can be followed by no-till corn, soybean, and grain sorghum for forage. However, corn had several advantages over sorghum in this climate. Canning peas are harvested early and can also be followed by minimum-till sorghum (Ndon et al., 1982). However, phytotoxic carryover residues of trifluralin applied to peas reduced sorghum stands 44% and yield 17% (Ndon et al., 1982). Herbicides in the preceding double crop must be chosen to minimize the chance of carryover damage to sorghum. Either atrazine plus paraquat or paraquat plus 2,4-D in reduced-till sorghum controlled green foxtail and common lambsquarters very well.

Rescue Herbicide Treatments and Sorghum Desiccation

"Salvage" or "rescue" herbicide treatments can be applied late in sorghum development to control large weed escapes that might interfere with harvest. Such treatments aid in harvest, but generally do not improve sorghum yields. Nonselective herbicides, such as paraquat and glyphosate, have been applied to tall-growing weeds in sorghum with a recirculating sprayer (Carlson and Burnside, 1981) or rope-wick applicator (Rhodes and Shelby, 1991). Spray drift and splash caused unacceptable grain sorghum injury with the recirculating sprayer (Carlson and Burnside, 1981).

Interest in preharvest desiccation of sorghum dates back to the 1950s (Bovey, 1969). Desiccants are applied at physiological maturity (i.e., black layer formation). At this time, grain moisture content is 30% to 40%, whereas sorghum can be safely stored only below 14%. Properly timed preharvest desiccation is advantageous because it aids in harvesting by drying green sorghum leaves and weeds without hastening sorghum maturity. Paraquat and diquat were shown to be effective desiccants in the late 1960s (Bovey, 1969; Gigax and Burnside, 1976). Sodium chlorate also can be used at moisture contents below 25% (Houston and Kimbrough, 1991). Preharvest glyphosate hastened seed drying without affecting sorghum seed germination or sorghum lodging (Gigax and Burnside, 1976). Preharvest glyphosate was superior to paraquat or sodium chlorate because these latter two treatments did not adequately kill the lower sorghum leaves (Bovey et al., 1975a). There were added weed control benefits of preharvest desiccation with glyphosate, especially for perennial weeds. Common milkweed regrowth was reduced in the growing season after applying fall-applied glyphosate to sorghum (Gigax and Burnside, 1976). Emerged johnsongrass, cogongrass, and browntop panicum present at harvest were killed by glyphosate (Bovey et al., 1975a).

Weed Management in Ratoon Cropping

Ratoon cropping of sorghum is not widely practiced in the United States because the growing season is usually too short. Ratoon sorghum can be grown when the growing season exceeds 225 days, but grain sorghum varieties with good regrowth after first harvest must be selected (Banks and Duncan, 1983). Successful weed control in first crop sorghum improved weed control in ratoon (second crop) in Georgia. Soil disturbance by hoeing after the first crop was harvested stimulated volunteer sorghum and annual grass weed growth. The method of stalk removal also influenced sorghum seed shattering and the incidence of volunteer sorghum in the ratoon crop. After the first harvest, nonselective herbicides controlled weeds for the subsequent ratoon sorghum crop. However, glyphosate applied to the stalks of the first crop caused some chlorosis and stunting of the subsequent ratoon crop. Metolachlor plus propazine controlled volunteer sorghum and grass weeds in ratoon crop sorghum when applied preemergence at planting and followed at harvest by metolachlor, cyanazine, or pendimethalin.

VII. WEED MANAGEMENT IN RICE

Rice is a major food crop in the world, grown under a wide range of cultural and environmental conditions; however, all of the rice grown in the United States is flooded, with many variations on when and how flooding is applied. Weed management in rice has been extensively reviewed (Chisaka, 1977; Eastin, 1983; Eastin, 1991; Moody, 1991; Smith et al., 1977). Weed management in rice consists of a combination of chemical, cultural, and preventative measures designed to reduce their occurrence and/or competitiveness. In the United States herbicides play a major role in weed management. Without herbicides, direct and indirect effect of weeds would account for a 70% reduction in rice yield (Abernathy, 1981). Even with present weed management, including use of herbicides, weeds account for an average 17% yield reduction in United States rice (Chandler, 1981). Estimated dollar losses in the United States due to weeds in rice has been summarized on the basis of expert opinion (Bridges, 1992).

A. Weed Competition

Weed competition with rice has been documented to reduce yields not only in the United States (Smith, 1968; Smith, 1970; Smith 1983b; Smith, 1988; Smith et al., 1977; Zimdahl, 1980) but elsewhere in the world (Zimdahl, 1980; Chisaka, 1977) (Table 1). Weeds typically compete with rice for light, nutrients, space, and water. However, competition for water is not as critical as with most nonirrigated crops since all United States rice is flooded for at least part of the growing season.

In addition to reducing yield, weeds can increase rice lodging, which interferes with harvesting operations and further reduces grain quality and yield. Seed from weeds such as dayflower, hemp sesbania, morningglory, and red rice are also very difficult to separate from the rice grain, thereby decreasing quality. Many weeds harbor disease organisms and insects which can attack rice (Eastin, 1983).

Integrated weed management systems depend on the weeds present or expected to be present. Weed histories of individual fields are very helpful in developing weed management systems to address particular problems. An integrated weed management system depends on the interaction of several types of weed control measures and requires a higher level of weed management than the use of herbicides alone. Various components of a weed management system are discussed in the sections that follow.

B. Nonchemical Weed Management Methods

Crop Rotation

Continuous rice culture tends to increase infestations of difficult-to-control weed species and soil-borne disease problems which may be present. In much of the southern United States, a rotation involving 1 year in rice and 2 years in other crops is normal. This rotation can be rice/soybean/soybean, rice/sorghum/soybean, rice/cotton/soybean, or a number of other crop options. There have been cases in Texas of effectively managing johnsongrass in sorghum by growing rice in the preceding 2 years, offsetting levees the second year in order to control johnsongrass, which is killed by flooding. Weed management techniques are available in several other crops which can be rotated with rice, such as cotton, sorghum, and soybeans, to control many problem weeds in rice, thereby helping to deplete the weed seed reserve. Many weeds which are difficult to control in rice, such as alligatorweed, red rice, and sprangletop, can be effectively controlled in soybeans or other broadleaf crops. Aquatic alligatorweed is partially controlled by lack of adequate moisture in rotational crops, while many grasses and broadleaf weeds are controlled by cultivation and/or herbicides used in the rotational crop.

The potential carryover of herbicides from one crop to others, such as atrazine from sorghum to rice, should be considered in planning crop rotations. Very few, if any, rice herbicides pose any significant carryover hazards to rotational crops. Many weeds can be controlled with crop rotations combined with other good weed management practices that otherwise would not be controlled in a continuous monoculture.

Prevention

If a weed species is not present in a field, the best management technique is to prevent its introduction. This requires good sanitation, particularly in using clean equipment. Equipment coming from a weedy field must be cleaned before entering a clean field; otherwise mud and debris on equipment can carry weed seed into clean fields.

The use of weed-free seed for planting cannot be overemphasized. In most states, even certified rice seed can contain some red rice seed; therefore, not only should the seed be certified but its source should be known in order to determine whether the seed producer had any red rice. Other weed seed can also be present with rice seed. The main consideration in preventative weed management is to do the necessary things to prevent introducing new weed seed. For a detailed discussion of preventative weed management refer to Chapter 3.

Cultural Practices

Many cultural practices used in rice production influence weeds and their management. Most cultural practices have been developed to optimize rice production; however, some have evolved specificially as weed management practices.

Precision grading of rice fields allows better water management by allowing shallower flooding and use of smaller levees, allowing a larger percentage of field area to be used to grow rice. In level fields with many high and low spots water is too deep for rice in low spots and too shallow for weed control in high spots. Precision grading improves weed management through better control of water depth. It also allows water to be applied quickly and more uniformly.

The method of seedbed preparation is determined by the anticipated seeding method. Rice can be 1) water seeded, using presprouted rice; 2) water seeded, using dry rice seed; 3) dry seeded, broadcast on the soil surface; or 4) drilled with a grain drill. Seeding method often determines the type of weeds present in rice. If rice is seeded on dry ground followed by flushing for emergence and moisture until flooding, terrestrial weeds predominate early in the growing season. Aquatic weeds predominate when rice is water seeded, particularly when the water is never completely drained. Each of these situations requires a different weed management strategy.

A dense rice stand can outcompete some weed species. Seeding rates resulting in rice stands of 160 to 200 healthy plants per square meter (15–20 per square foot) are optimum for both yield and competition with weeds. Current, widely grown semidwarf rice cultivars are less competitive with weeds than traditional cultivars; therefore, early season weed management is more critical for semidwarf cultivars than for conventional cultivars.

Planting date influences the type of weeds and difficulty of control. If rice is planted too early, it does not compete well with weeds because of slow crop growth in cool weather. Early planting also favors weeds such as barnyardgrass, while late planting encourages dayflower more than early planting. Planting date must be chosen for its effect on not only weeds and their management, but also yield potential. Planting too late or too early decreased yield even if rice was weed-free.

Fertilizer can significantly affect weeds and their control. Very early phosphorus application generally stimulates weed seed germination and growth while phosphorus applied into flooded fields stimulates growth of algae and other aquatic weeds. To reduce this weed stimulation, phosphorus is usually applied to rotational crops 1 year before planting rice. If this was not done, only enough phosphorus is used for the desired yield goal, since excess phosphorus not only stimulates weeds but reduces rice yields. Nitrogen timing can influence weed growth. Nitrogen is generally split between two or three applications; this practice not only is better for rice but eliminates excess nitrogen available to stimulate early weed growth. By timing fertilizer applications to time of flooding and herbicide applications, fertilizer and herbicide use is more efficient and effective.

Water management, a major cultural practice for rice, can also be used for weed management. Not only the timing of flooding is important; the depth of flooding is also critical in weed control. However, in practice there must be a compromise between the use of shallow water for rice growth and deep water for weed control. While shallow flooding is better for rice growth and yield, deep flooding (10–20 centimeters) controls many terrestrial weeds, such as young barnyardgrass. However, if applied early in the growing season, flooding may cause rice internodes to elongate, resulting in a weakened plant with a tendency to lodge before harvest. Early flooding also stimulates growth of aquatic weeds such as algae, alligatorweed, and ducksalad, and waterprimrose, which may necessitate draining fields and allowing the soil to dry. This stresses rice and allows terrestrial weeds, such as barnyardgrass, to germinate. While water management cannot be used as the only early season weed management practice, understanding its effect allows it to be used in a total weed management program. Because older rice tolerates deeper flooding than many weeds, deeper flooding can be used to reduce or prevent terrestrial weed germination.

Mechanical cultivation is not feasible in United States rice production. Hand weeding, or roguing, of specific weeds, such as red rice, in seed rice fields is practiced on limited hectares; however, this is not economically feasible in production fields.

Biological Weed Management

A biological control for northern jointvetch using the fungus *Colletotrichum gloeosporioides* species Asaeschynomene has been developed. This fungus is specific for northern jointvetch. Moreover, there are regions where United States rice is grown where it is feasible to use this biological control late in the growing season even after the time when most herbicides normally would be applied.

C. Herbicides for Weed Management

Even with available nonchemical weed management practices, herbicides are considered the backbone of any rice weed management program in the United States (Table 10). Rice herbicides, like all pesticides, must be properly used to prevent lack of weed control, crop injury, and/or damage to the environment. Since herbicide registrations and labels are constantly changing, current labels and information available through state agricultural extension services and state agricultural experiment stations should be consulted for current information and recommendations.

Essentially all United States rice is treated with at least one herbicide during the growing season. Barnyardgrass, junglerice, dayflower, sprangletop, red rice, and aquatics are the major weeds of United States rice. Aquatics include alligatorweed, waterprimroses, algae, ducksalad, and several other common weeds.

Table 10 Herbicides Registered for Use on Rice in 1992 in the United States

Time of application	Herbicide
Preplant	Molinate
	Thiobencarb
Preemergence	Quinclorac
	Thiobencarb
Early postemergence	Acifluorfen + surfactant
	Bentazon
	Propanil
	Propanil + molinate
	Propanil + pendimethalin
	Propanil + thiobencarb
	Quinclorac
Midpostemergence	Bromoxynil
	Fenoxaprop
Postflooding	Acifluorfen + surfactant
	Bensulfuron methyl
	Bentazon
	Molinate
Late postemergence	MCPA
	Triclopyr
	2,4-D

Note: Herbicides and rates are based on current labels or expected labels. Before using an herbicide refer to a current label for appropriate rate and species controlled.

Propanil has been the standard herbicide in rice for many years. It is a postemergence herbicide that, while used primarily for barnyardgrass and junglerice control, is very effective on many other common weeds in rice. Since propanil has no soil residual, weeds can reinfest rapidly after application, however. When using propanil without a residual herbicide, a second application is generally needed to control weeds until rice is flooded. While propanil controls barnyardgrass, addition of other herbicides expands the spectrum of weed control and/or provides residual activity. Addition of pendimethalin or thiobencarb to propanil not only provides residual control of barnyardgrass but increases sprangletop control. Addition of molinate to propanil, while not providing residual control, helps control emerged sprangletop and dayflower. Propanil interacts with carbamate and organophosphate insecticides and can injure rice. Therefore, these insecticides should not be applied with or within a few days of application of propanil.

Preemergence thiobencarb controls barnyardgrass well when applied to dry seeded rice; however, it does not control broadleaf signalgrass and several problem broadleaf weeds which propanil will control as a postemergence herbicide. Preemergence quinclorac controls barnyardgrass and many other grasses and broadleaf weeds well in rice, but it is ineffective on sprangletop.

Fenoxyprop-ethyl applied to four- to five-leaf rice before flooding will control many grass weeds. This herbicide controls larger barnyardgrass than propanil or quinclorac. It also controls sprangletop but does not completely control broadleaf weeds. Also, if rice is too young when treated, fenoxyprop-ethyl can injure it.

Acifluorfen or bentazon can be used postemergence to control several broadleaf weeds. Bentazon is particularly effective on dayflower and yellow nutsedge while acifluorfen controls hemp sesbania well. Just before flooding, bromoxynil can be applied to control many broadleaf weeds. Fenoxaprop can also be used at this time.

After rice is flooded, molinate granules can be used for control of barnyardgrass, dayflower, and sprangletop while bensulfuron-methyl can be used to control many aquatic broadleaf weeds. Bentazon or acifluorfen can be used either preflooding or postflooding.

After rice has started tillering but before panicle initiation, 2,4-D, MCPA, or triclopyr can be used for control of broadleaf weeds that have escaped previous herbicide applications.

Red rice is particularly difficult to manage in rice since it is the same species as the rice crop. At present no herbicides completely control red rice in rice; however, there are some management techniques that can be used to suppress it. Red rice is best controlled by rotating to a crop, such as cotton, sorghum, or soybeans, in which herbicides for red rice control are available. High rates of alachlor, metolachlor, or trifluralin in soybeans or cotton, or propazine or atrazine in sorghum, or atrazine in corn control red rice. Usually 2 years of this program will reduce red rice to a level at which a rice crop can be produced.

Several weed management practices can be combined to provide fair to good red rice suppression in rice, if red rice infestations are sparse. Cultural practices primarily involve use of continuous or pinpoint flooding combined with use of preplant-incorporated molinate or preplant, surface-applied thiobencarb before flooding. Presprouted rice is then broadcast by air into flooded fields, and flooded fields are either drained for a short time or not drained to prevent red rice from germinating. Continuous flooding inhibits germination of red rice. Table 10 lists the herbicides registered for use on rice in 1992 in the United States.

VIII. CONTROL OF VOLUNTEER CEREALS AND SORGHUM

Volunteer cereals are occasionally weeds in some rotational crops or fallow. Volunteer cereals may have to be controlled before planting no-till row crops, or if thin spring cereal stands warrant recropping to later-sown crops (Chow, 1983; Donald, 1990b; Wicks et al., 1988).

Although tillage for mechanical fallow or seedbed preparation kills seedling winter wheat and other cereals before planting other crops, large established plants are controlled better with herbicides. In no-tillage systems, herbicides are substituted for tillage for controlling volunteer cereals. In no-tillage systems, nonselective herbicides, such as glyphosate and paraquat, serve this role but must be applied before crop emergence. In fact, no-tillage farming systems would probably not be possible for erosion control without nonselective postemergence herbicides for contact weed control. Volunteer cereals can be selectively controlled in the major field crops with several postemergence grass herbicides (Table 6) (Beardmore and Linscott, 1989; Chow, 1983; Friesen and Wall, 1990; Weston, 1990).

The optimum time and rate of glyphosate or paraquat to use to control volunteer cereals have been evaluated so that only the lowest rates and least costly treatments can be used before crop emergence in no-till farming systems. Postemergence glyphosate or paraquat at 0.25 kg/ha adequately controlled winter wheat (Wiese and Chenault, 1987). Paraquat at 0.3 to 0.6 kg/ha applied postemergence reduced winter wheat biomass 84% when applied at the one- to three-leaf stage but was less effective on larger plants (Anderson and Nielsen, 1991). Glyphosate is generally more effective than paraquat for controlling large, established winter wheat and other cereals.

Postemergence atrazine plus either glyphosate or paraquat adequately controlled both established volunteer winter wheat and downy brome before planting of no-till sorghum (Wicks et al., 1988). In contrast, preemergence atrazine alone did not control these species well (Wicks et al., 1988). Combinations of atrazine with either glyphosate or paraquat can also be used for weed control in no-till corn.

Various surfactants have been added to glyphosate in an attempt to improve volunteer cereal control with lower application rates (O'Sullivan et al., 1981). Many surfactants and other additives, such as ammonium sulfate, increase glyphosate phytotoxicity to weeds and volunteer cereals (McWhorter and Derting, 1985; O'Keeffe and Makepeace, 1985; Turner, 1985). Directions for using spray tank additives with glyphosate are included in the registration label. Glyphosate applied in low spray volumes was more phytotoxic to cereals than when applied in higher volumes, allowing lower application rates to be used for controlling volunteer cereals (O'Sullivan et al., 1981).

Residues of rye, barley, and wheat killed with either paraquat or glyphosate suppressed weed growth for at least part of the growing season in no-till farming systems. For example, glyphosate-killed cereal residue prevented weed growth for 45 days after treatment in spring, but weeds escaped by 60 days after treatment in Kentucky (Weston, 1990). Herbicide-killed rye and wheat residues suppressed weeds longer than barley residues (Weston, 1990). Corn can be no-till planted into herbicide-killed barley, rye, oat, and spring wheat (Moschler et al., 1967). Paraquat plus atrazine successfully killed weeds and volunteer barley growing in barley stubble before no-till planting. Volunteer rye, oat, and spring wheat were easier to kill than barley with either atrazine or paraquat alone. Herbicide-killed cereal residues have potential for managing weeds in no-tillage farming systems in some locations, but more research is required to ensure that such systems control weeds as predictably as herbicides do now.

IX. CEREAL CROP DAMAGE FROM HERBICIDES

Yield-reducing crop damage from herbicides can occasionally limit the potential benefit of herbicides for reducing yield loss due to weed competition. Registered herbicides (Table 1) can sometimes damage cereals on particular soils, under abnormal or extreme environmental conditions, if they are improperly applied, or if the application is improperly timed relative to cereal growth stage. Common application errors include incorrect sprayer calibration and overlapping spray swaths, especially if sprayers are not turned off when turning near field borders.

A. Damage to Grain Crops from Registered Herbicides

Winter and Spring Wheat Damage

Damage to winter and spring wheat from registered herbicides has been reviewed for the following herbicides: diclofop (O'Sullivan, 1990), difenzoquat (Donald, 1990e), propanil (Eberlein, 1990), picolinic acid herbicides (Gillespie, 1990; Heering and Peeper, 1991; Martin et al., 1989; Ogg and Young, 1991), substituted ureas, triazines, and triazinones (Baker and Peeper, 1990; Ratliff et al., 1991), and sulfonylurea herbicides (Donald, 1990d; Ferreira et al., 1990a).

The damage that phenoxy herbicides can cause wheat has been studied most and early studies on these herbicides have shaped subsequent research. Several factors influenced the phytotoxicity of postemergence phenoxy herbicides to spring wheat: herbicide formulation, application rate, growth stage of cereals when treated, cereal variety, and seasonal environment (Shaw et al., 1955). Injury symptoms from 2,4-D and other phenoxy herbicides were unique and diagnostic (Olson et al., 1951; Shaw et al., 1955). Symptoms varied with the rate and date of 2,4-D application; they included leaf rolling, an erect growth habit, reduced tillering, failure of heads to emerge from the boot, emergence of heads laterally through rolled leaves, stunting, variable numbers of seed per seedhead, and delayed maturity (Shaw et al., 1955). Both phenoxy and benzoic acid herbicides injured plant parts undergoing meristematic activity at the time of treatment more than nongrowing tissue (Friesen et al., 1964; Lemerle et al., 1986). Consequently, treatment timing determined which of the injury symptoms named appeared. Yields are not always reduced even if shoots become injured by phenoxy herbicides. Yield losses were greatest if 2,4-D was applied soon after emergence (Olson et al., 1951). Yield also was reduced if phenoxy herbicides were applied between spring wheat emergence and tillering. The safest period to apply phenoxy herbicides was from the three-leaf stage until just before the boot stage (Olson et al., 1951; Shaw et al., 1955). Yield losses resulted from phenoxy injury during seedhead formation (Olson et al., 1951) or flowering (Shaw et al., 1955). Such late treatments usually are unwarranted for preventing yield loss due to weeds but may expedite harvesting.

Properly timed herbicide application to match tolerant growth stages of spring and winter wheat is critical to prevent damage or yield loss from phenoxy herbicides, such as 2,4-D and MCPA (Ivany et al., 1990; Martin et al., 1989; Schroeder and Banks, 1989); benzoic acid herbicides, such as dicamba (Martin et al., 1989); picolinic acid herbicides, such as clopyralid and picloram (Gillespie, 1990; Heering and Peeper, 1991; Martin et al., 1989; Ogg and Young, 1991); and triazinones, such as metribuzin (Blackshaw, 1990).

Commercially available cultivars of winter and spring wheat differ in their susceptibility to certain registered herbicides. Some normally tolerant varieties may be damaged if herbicide rates above the registered use rate are applied. Varietal tolerance is particularly critical for metribuzin on winter wheat (Baker and Peeper, 1990; Ratliff et al., 1991) and difenzoquat on spring wheat (Donald, 1990e). However, visible damage from herbicides may not always decrease spring wheat yield (Ivany and Nass, 1984). Current herbicide registration labels should be consulted because herbicide use may be limited to particular varieties.

Barley Damage

Both barley yields and malting quality can be reduced if phenoxy or benzoic acid herbicides are improperly timed in relation to barley growth stage or if high rates are applied (Lemerle et al., 1986; Martin et al., 1989; Olson et al., 1951; Shaw et al., 1955), as observed for spring wheat. Phenoxy and benzoic acid herbicide (Friesen et al., 1964; Lemerle et al., 1986; Briggs, 1978; Shaw et al., 1955) and picloram (Chang and Foy, 1971) injury symptoms were also similar to those in spring wheat.

Treatment timing with phenoxy and benzoic acid herbicides influenced crop yield, crop quality, and injury symptoms observed. When 2,4-D was applied to winter barley at various growth stages (Olson et al., 1951; Shaw et al., 1955), barley tolerated 2,4-D best between tillering and the two-joint stage, compared to the five-leaf stage, booting, or full bloom. As plants aged, fewer symptoms were observed on the main stem, but tillers exhibited increased injury (Friesen et al., 1964). Dicamba, applied later, injured tillers and had a greater impact on yield because seed production from tillers was more important to total yield than seed production from the main stem. Differences were observed in the response of barley varieties to herbicides, as noted for wheat (Clay et al., 1988; Hageman and Behrens, 1981; Lemerle et al., 1986; Miller et al., 1978).

Sorghum Damage

Atrazine can occasionally decrease sorghum yield by reducing stand and stunting surviving plants when applied preemergence or postemergence and burning leaves when applied postemergence (Swann, 1980). Atrazine damage to sorghum was rate dependent (Burnside and Moomaw, 1975). The registered rate range for preemergence- or postemergence-applied atrazine varies with soil texture, pH, organic matter, and location in order to minimize the risk of sorghum damage (Houston and Kimbrough, 1991). Irrigation after treatment caused more damage from atrazine, especially on sandy soils, because it leached into the root zone and sorghum roots absorbed it (Chamberlain et al., 1970). Fall plowing reduced the likelihood of atrazine injury more than spring plowing at one of two locations in Nebraska (Burnside and Moomaw, 1975), presumably by reducing root uptake of atrazine when sorghum was small.

Lower atrazine rates were registered for postemergence-applied than for preemergence-applied atrazine, decreasing the likelihood of crop damage (Houston and Kimbrough, 1991). In fact, in certain regions, atrazine can only be applied postemergence because of the potential for sorghum damage from preemergence treatment. Postemergence atrazine was less likely to damage sorghum if roots were well established when plants were treated. As sorghum developed, it became more tolerant to postemergence atrazine (Chamberlain et al., 1970; Swann, 1980).

Metolachlor or alachlor can occasionally damage sorghum; injury symptoms include reduced stand (Roeth et al., 1983; Simkins et al., 1980), stunting (Simkins et al., 1980), delayed maturity (Simkins et al., 1980), and decreased yield (Simkins et al., 1980). Like atrazine injury, metolachlor or alachlor injury depended on application rate and soil characteristics (texture, clay, organic matter, and pH) (Houston and Kimbrough, 1991), even if sorghum seed was treated with a safener to prevent damage. For example, alachlor damaged unsafened sorghum grown on coarse textured soils but did not damage sorghum when soil organic matter was more than 3% (Houston and Kimbrough, 1991).

Soil moisture also modified sorghum tolerance to alachlor and metolachlor (Ketchersid et al., 1981). Sorghum was not damaged by alachlor or metolachlor if the soil surface remained dry until sorghum emerged (Ketchersid et al., 1981), presumably reducing herbicide uptake by the emerging sorghum shoot. Alachlor or metolachlor was more likely to damage sorghum when shoots emerged under moist conditions in the field, conditions enhancing herbicide uptake. Herbicide incorporation modified sorghum tolerance. Metolachlor was less damaging applied preemergence than preplant-incorporated (Roeth et al., 1983).

Since the 1960s, seed-applied safeners have been tested on sorghum to protect it from thiocarbamate or chloroacetamide herbicides without success in reducing crop damage (Eastin, 1972). More recently introduced seed safeners make use of metolachlor and alachlor on grain sorghum commercially possible (Devlin et al., 1983; Foy and Witt, 1990; Wiese et al., 1986). Seed-applied flurazole (Screen) is used for alachlor, and cyometrinil (Concept II) is used for metolachlor (Roeth et al., 1983). Cyometrinil-treated grain and forage sorghum seed are commercially available for use with metolachlor and atrazine plus metolachlor. These safeners act by enhancing alachlor or metolachlor degradation in sorghum (Fuerst and Gronwald, 1986; Zama and Hatzios, 1986).

Sometimes sorghum has been damaged by postemergence 2,4-D (Ross, 1970), especially if sorghum was small when treated (Wiese, 1983). Injury symptoms included inhibited root development followed by later lodging, stalk brittleness, stunting, leaf curling, head sterility, and reduced yield. Registered broadcast application of 2,4-D is limited to sorghum that is less than 20 cm tall; directed or drop nozzle application is suggested thereafter so that the leaf whorl of sorghum is not treated (Houston and Kimbrough, 1991). If weeds emerge with sorghum, farmers sometimes treat sorghum when it is too young, risking damage. If sorghum emerges before weeds, herbicide application at the wrong time is less likely (Wiese, 1983). Treatment of sorghum at the boot, flowering, and early dough stages can reduce yields.

Trifluralin and pendimethalin are registered for controlling grass and small-seeded broadleaf weeds only as postemergence lay-by treatments in sorghum. Sorghum generally was not damaged by postemergence- (lay-by)-applied trifluralin incorporated with a rolling cultivator or sweep after sorghum roots were well developed (Banks et al., 1978). This herbicide-incorporating implement threw treated soil into the rows to control weeds within the row (Banks et al., 1978). The selectivity of registered lay-by treatment and unregistered preplant-incorporated trifluralin to sorghum was positional (Barrentine and Warren, 1971). Consequently, sorghum roots of very young seedlings growing into trifluralin-treated soil can be stunted, limiting later sorghum shoot growth. In fact, sorghum has been used as a bioassay specie to test for the persistence of the dinitroaniline herbicides isopropalin, nitralin, and trifluralin (Brewer et al., 1982; Hamilton, 1979; Nelson et al., 1983; Romanowski and Libik, 1978).

B. Damage to Grain Crops from Herbicide Drift and Carryover Applied to Other Crops

Winter Wheat

On occasion, winter wheat can be damaged by persistent residues of herbicides applied to previously grown rotational crops. Triazine herbicides, most commonly atrazine applied to corn or sorghum, have damaged later sown winter wheat and other cereals, especially after drought (Wiese et al., 1986). Drought also increased the chance of damage to winter wheat from atrazine applied for weed management in "chemical fallow" (14 month fallow, pH 7.4 and 1.3% organic matter) (Anderson, 1984). Atrazine used for chemical fallow may be more damaging to winter wheat planted on eroded hilltops because soil organic matter is often lower there than elsewhere and hilltops may be more arid, leading to greater atrazine persistence.

Herbicides other than atrazine reportedly can carry over to damage rotational winter wheat. Norflurazon applied to cotton damaged winter wheat planted 14 months after application (Keeling and Abernathy, 1989). Imazapyr applied in fallow for field bindweed management (not now registered for use) damaged winter wheat planted 122 days later in Texas (Schoenhals et al., 1990).

The potential for herbicide carryover damage should be considered when planning crop rotations including winter wheat and other cereals. Herbicide registration labels should be consulted for appropriate regional waiting periods for planting winter wheat after herbicide application, to prevent damaging rotational winter wheat. For example, short residual herbicides, such as cyanazine, alachlor, and metolachlor, should be substituted for atrazine in spring when planting corn or sorghum before fall-sown winter wheat (Wiese et al., 1986). Triazine herbicides persist longer when environmental conditions, such as limited soil moisture, reduce microbial degradation of triazines or alkaline soil pH limits chemical hydrolysis of triazines to nonphytotoxic degradation products.

Barley Damage

Atrazine residues have damaged barley planted a year after atrazine-treated corn (Baldridge et al., 1985; Brinkman et al., 1980a). Spring barley or spring wheat tolerated atrazine carryover better than oat in Wisconsin (Brinkman et al., 1980a). In other research, picloram carryover did not reduce barley germination, but it inhibited subsequent barley growth (Chang and Foy, 1971). Also, ethofumesate applied to sugar beet at commercial rates persisted and damaged later sown winter wheat and barley in Colorado (Schweizer, 1975). Residues of diuron, prometryn, and trifluralin applied to safflower did not persist to damage barley in Arizona (Hamilton, 1979). Barley tolerance to trifluralin is not surprising because it is registered for use on barley.

Oat Damage

Oat has been damaged by atrazine applied 1 year earlier to corn (Baldridge et al., 1985; Brinkman et al., 1980a,b). Oat grain quality (100-seed weight and groat protein percentage) were reduced when atrazine damage was severe (Brinkman et al., 1980b). Tillage system modified oat damage from persistent residues of atrazine in Nebraska (Burnside and Wicks, 1980). Oat grown in reduced tillage were less damaged than conventionally tilled oat 1 year after atrazine application. Different oat varieties were damaged to different extents by atrazine in Wisconsin (Brinkman et al., 1980b; Smith and Buchholtz, 1964). However, differential varietal tolerance was not great enough to warrant breeding for atrazine resistance (Brinkman et al., 1980b). In northern states such as Wisconsin, it is advisable to replant something other than oat if atrazine is applied 1 year earlier (Smith and Bucholtz, 1964). Granular formulations of atrazine persisted longer than other formulations (Bucholtz, 1965), and environmental conditions reducing atrazine breakdown enhanced the likelihood of residual damage to oat 1 year after atrazine application to corn (Bucholtz, 1965; Brinkman et al., 1980a,b). Consequently, atrazine carryover damage is more likely in cold or arid environments. In western Nebraska, EPTC and trifluralin also carried over to damage oat when incorporated with a rotary-hoe-like implement or disk (Robison and Fenster, 1968).

Sorghum Damage

Sorghum can be damaged by drift, especially of sulfonylurea herbicides, such as nicosulfuron or primisulfuron, applied to corn (Rhodes, 1990). Herbicides can also persist to damage rotational sorghum. In Wisconsin, the stand and yield of sorghum planted after harvesting trifluralin-treated canning peas were reduced 44% and 17%, respectively (Ndon et al., 1982). In Nebraska, sorghum planted after soybean treated with trifluralin was damaged by phytotoxic trifluralin residues (Burnside, 1978). Damage from trifluralin was less after moldboard plowing than on no-till plots. Trifluralin applied to winter-planted safflower in Arizona persisted longer in some years to damage bioassay sorghum planted in soil collected in the following spring (Hamilton, 1979).

Persistent residues of chlorsulfuron and some other sulfonylurea herbicides applied to cereals can damage sorghum (Peterson and Arnold, 1986). Typical sulfonylurea herbicide injury symptoms on sorghum include stunting, purple leaf coloration, and reduced yield. Herbicide-delayed maturity could reduce yield during years of early frost. Sorghum yield was reduced up to 60% when planted 15 months after chlorsulfuron in Colorado and Kansas; no reductions were observed after 27 months (Sutherland and Long, 1987). Similar chlorsulfuron persistence and degrees of crop damage have been observed elsewhere (Peterson and Arnold, 1986; Wiese et al., 1988). Sorghum yields were not decreased when planted 12 to 26 months after picloram application in Texas, depending upon application rate (Bovey et al., 1975b).

Sorghum is damaged by thiocarbamate herbicides, such as EPTC and butylate, which are registered for weed control in corn (Oliver et al., 1968). While residues of these herbicides usually do not persist from one year to the next at damaging concentrations, sorghum may be injured if it is planted into EPTC-treated soil soon after herbicide application. This situation might arise during replanting sorghum soon after failure of a corn crop to emerge.

Herbicides applied to cotton have carried over to damage sorghum under certain circumstances. In Tennessee, fluometuron damaged sorghum planted 3 to 9 weeks after treatment (Jackson et al., 1978). This situation might arise if sorghum were replanted after poor cotton emergence. Sorghum was successfully planted 3 weeks after band or broadcast application of fluometuron, but a 9 week delay was required after a broadcast application (Jackson et al., 1978). In Texas, preplant-incorporated and preemergence-applied norflurazon applied to cotton damaged sorghum planted 14 months later (Keeling et al., 1989). Preplant-incorporated norflurazon was more persistent than preemergence norflurazon, as measured by sorghum damage.

Sorghum has been injured by imidazolinone herbicides. In Texas, imazapyr in fallow controlled field bindweed (89%) for 1 year (Schoenhals et al., 1990), but sorghum planted the spring after application was injured (15%). In Virginia, imazapyr on pea and snap bean injured sorghum more than 50% when planted in the following growing season (Vencill et al., 1990). Consequently, this use is currently not registered. Imazethapyr residues can persist to damage sorghum the year after application to soybean.

C. Crop Damage to Other Crops from Herbicides Applied to Cereals

Spring Wheat Herbicides

Herbicides applied to winter or spring wheat can damage other crops, either as drift or because phytotoxic residues persist to damage later-sown rotational crops (Table 6). For example, drift from volatile phenoxy or benzoic acid herbicides (2,4-D, MCPA, dicamba, and picloram) has damaged sunflower, soybeans, and sugar beets, as well as shelterbelt trees, in the Northern Great Plains (Donald and Nalewaja, 1990). Carryover of the imidazolinone herbicide imazamethabenz injured sugar beet, lentil, and rape nearly 14 months after application in Montana (Fellows et al., 1990). Imazamethabenz persistence was greater in soils with lower pH. The sulfonylurea herbicide chlorsulfuron limited which rotational crops could be successfully grown for up to 7 years after application at two locations in Alberta (Moyer et al., 1990). Moyer et al. (1990) suggested that the need for long recropping intervals was due to Alberta's low temperature and high soil pH, which lengthened chlorsulfuron persistence. Because of the potential for carryover damage from chlorsulfuron and the development of sulfonylurea herbicide–resistant weeds, use of chlorsulfuron has been severely restricted compared to its initial registration label. Other shorter-residual sulfonylurea herbicides have replaced chlorsulfuron for use on cereals in many regions.

Sorghum Herbicides

Drift of 2,4-D applied to sorghum damaged cotton more than soybean (Houston and Kimbrough, 1991). In contrast, dicamba drift from applications to sorghum damaged soybean more than cotton. Bentazon is a useful substitute for 2,4-D or dicamba on sorghum where the chance of drift to neighboring crops poses problems of crop damage (Houston and Kimbrough, 1991).

Residual atrazine from applications to sorghum has damaged subsequently planted crops, as noted earlier for cereals (Table 6). In Nebraska, atrazine damaged rotational soybean (Burnside, 1978) and winter wheat (Burnside and Schultz, 1978). In a 6-year study, atrazine carryover was not a major problem in no-till but was a problem in conventional tillage in Nebraska, using oat as a bioassay plant in the field (Burnside and Wicks, 1980). In the Texas panhandle, alachlor and metolachlor could be used on sorghum without damaging later-sown winter wheat, but atrazine damaged rotational wheat (Wiese et al., 1986).

APPENDIX A

List of Crops and Weeds in Chapter

Common name	Scientific name	BAYER code
Crops		
Alfalfa	(*Medicago sativa* L.)	MEDSA
Barley	(*Hordeum vulgare* L.)	HORVS
Canola	(*Brassica campestris* L.)	BRSRA
Clover	(*Trifolium* sp.)	TRFXX
Corn	(*Zea mays* L.)	ZEAMX
Cotton	(*Gossypium hirsutum* L.)	GOSHI
Dry beans	(*Phaseolus vulgaris* L.)	PHSVX
Durum wheat	(*Triticum durum* Desf.)	TRZDU
Flax	(*Linum usitatissimum* L.)	LIUUT
Lentil	(*Lens culinaris* Medik.)	LENCU
Oat	(*Avena sativa* L.)	AVESA

(*continued*)

Appendix A Continued

Common name	Scientific name	BAYER code
Pea	(*Pisum sativum* L.)	PIBST
Pinto bean	(*Phaseolus vulgaris* L.)	PHSVX
Potato	(*Solanum tuberosum* L.)	SOLTU
Rape	(*Brassica napus* L.)	BRSNW
Rice	(*Oryza sativa* L.)	ORYSA
Rye	(*Secale cereale* L.)	SECCE
Safflower	(*Carthamus tinctorius* L.)	CDUCA
Sorghum	(*Sorghum bicolor* (L.) Moench.)	SORVU
Soybean	(*Glycine max* L.)	GLXMA
Sugar beet	(*Beta vulgaris* L.)	BEAVA
Sunflower	(*Helianthus annuus* L.)	HELAN
Spring wheat	(*Triticum aestivum* L.)	TRZVX
Winter wheat	(*Triticum aestivum* L.)	TRZVX
Weeds		
Alligatorweed	(*Alternanthera philoxeroides* (Mart.) Griseb.)	ALRPH
Barnyardgrass	(*Echinochloa crusgalli* (L.) Beauv.)	ECHCG
Bearded sprangletop	(*Leptochloa fascicularis* (Lam.) Gray)	LEFFA
Blue mustard	(*Chorispora tenella* (Pallas) DC.)	COBTE
Browntop panicum	(*Panicum fasciculatum* Sw.)	PANFA
Canada thistle	(*Cirsium arvense* (L.) Scop.)	CIRAR
Cheat	(*Bromus secalinus* (L.))	BROSE
Cogongrass	(*Imperata cylindrica* (L.) Beauv.)	IMPCY
Common chickweed	(*Stellaria media* (L.) Vill.)	STEME
Common hempnettle	(*Galeopsis tetrahit* L.)	GAETE
Common lambsquarters	(*Chenopodium album* L.)	CHEAL
Common milkweed	(*Asclepias syriaca* L.)	ASCSY
Common ragweed	(*Ambrosia artemisiifolia* L.)	AMBEL
Dayflower	(*Commelina* sp.)	COMXX
Downy brome	(*Bromus tectorum* L.)	BROTE
Ducksalad	(*Heteranthera limosa* (Sw.) Willd.)	HETLI
Eclipta	(*Eclipta prostrata* L.)	ECEPA
Fall panicum	(*Panicum dichotomiflorum* Michx.)	PANDI
Fiddleneck	(*Amsinckia* sp.)	AMSXX
Field bindweed	(*Convolvulus arvensis* L.)	CONAR
Field pennycress	(*Thlaspi arvensis* L.)	THLAR
Field sandbur	(*Cenchrus incertus* M.A. Curtis)	CCHIN
Flixweed	(*Descurainia sophia* (L.) Webb. ex Prantl)	DESSO
Green foxtail	(*Setaria viridis* (L.) Beauv.)	SETVI
Hemp sesbania	(*Sesbania exaltata* (Raf.) Rydb. ex A. W. Hill)	SEBEX

Appendix A Continued

Common name	Scientific name	BAYER code
Henbit	(*Lamium amplexicaule* L.)	LAMAM
Honeyvine milkweed	(*Ampelamus albidus* (Nutt.) Britt.)	AMPAL
Italian ryegrass	(*Lolium multiflorum* Lam.)	LOLMU
Jerusalem artichoke	(*Helianthus tuberosus* L.)	HELTU
Johnsongrass	(*Solanum halepense* (L.) Pers.)	SORHA
Jointed goatgrass	(*Aegilops cylindrica* Host)	AEGCY
Junglerice	(*Echinochloa colona* (L.) Link)	ECHCO
Kochia	(*Kochia scoparia* (L.) Scrad.)	ECHSC
Large crabgrass	(*Digitaria sanguinalis* (L.) Scop.)	DIGSA
Morningglory	(*Ipomoea* sp.)	IPOXX
Nightflowering catchfly	(*Silene noctiflora* L.)	MELNO
Northern jointvetch	(*Aeschynomene virginica* (L.) B.S.P.)	AESVI
Palmer amaranth	(*Amaranthus palmeri* S. Wats.)	AMAPA
Pennsylvania smartweed	(*Polygonum pensylvanicum* L.)	POLPY
Perennial sowthistle	(*Sonchus arvensis* L.)	SONAR
Quackgrass	(*Elytrigia repens* (L.) Nevski)	AGRRE
Red rice	(*Oryza sativa* L.)	ORYSA
Redroot pigweed	(*Amaranthus retroflexus* L.)	AMARE
Rigid ryegrass	(*Lolium rigidum* Gaudin)	LOLRI
Russian thistle	(*Salsola iberica* Sennen & Pau)	SASKR
Shattercane	(*Sorghum bicolor* (L.) Moench)	SORVU
Smooth pigweed	(*Amaranthus hybridus* L.)	AMACH
Sprangletop	(*Leptochloa* sp.)	LEFXX
Spreading dayflower	(*Commelina diffusa* Burm. f.)	COMDI
Stinkgrass	(*Eragrostis cilianensis* (All.) E. Mosher)	ERACN
Stinkweed	(*Pluchea camphorata* (L.) DC.)	PLUCA
Tall waterhemp	(*Amaranthus tuberculatus* (Moq.) J.D. Sauer)	AMATU
Tansymustard	(*Descurainia* sp.)	DESXX
Tartary buckwheat	(*Polygonum tartaricum* L.)	POLTA
Texas panicum	(*Panicum texanum* Buckl.)	PANTE
Velvetleaf	(*Abutilon theophrasti* Medik)	ABUTH
Waterprimrose	(*Ludwigia* sp.)	LUDXX
Wild buckwheat	(*Polygonum convolvulus* L.)	POLCO
Wild garlic	(*Allium vineale* L.)	ALLVI
Wild mustard	(*Brassica kaber* (DC.) L.C. Wheeler)	SINAR
Wild oat	(*Avena fatua* L.)	AVEFA
Wild onion	(*Allium canadense* L.)	ALLCA
Wild rose	(*Rosa* sp.)	ROSXX
Witchgrass	(*Panicum capillare* L.)	PANCA
Yellow foxtail	(*Setaria glauca* (L.) Beauv.)	SETLU
Yellow nutsedge	(*Cyperus esculentus* L.)	CYPES

APPENDIX B

List of Pesticides in Chapter

Common name	Chemical name
Herbicides	
Acetochlor	2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide
Acifluorfen	5-[2-chloro-4-(trifluoromethyl)phenoxyl]-2-nitrobenzoic acid
Alachlor	2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl)acetamide
Atrazine	6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine
Barban	4-chloro-2-butynyl-*m*-chlorocarbanilate
Bensulfuron	methyl 2-[[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-amino]sulfonyl]methyl]benzoate
Bentazon	3-(1-methylethyl)-(1*H*)-2,1,3-benzothiadiazin-3(3*H*)-one 2,2,-dioxide
Bromoxynil	3,5-dibromo-4-hydroxybenzonitrile
Butylate	*S*-ethyl bis(2-methylpropyl)carbamothioate
CGA 131036	2-(2-chloroethoxy)-*N*-[[4-methoxy-6-methyl-1,3,5-triazin-2-yl)-amino]carbonyl]benzenesulfonamide
CGA 92194	α-[(1,3-dioxolan-2-ylmethoxy)imino]benzeneacetonitrile
Chlorsulfuron	2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]-carbonyl]benzenesulfonamide
Clopyralid	3,6-dichloro-2-pyridinecarboxylic acid
Cyanazine	2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methyl-propanenitrile
Cyometrinil	(*Z*)-α[(cyanomethoxy)imino]benzeneacetonitrile
Diallate	*S*-(2,3-dichloro-2-propenyl)bis(1-methlethyl)carbamothioate
Dicamba	3,6-dichloro-2-methoxybenzoic acid
Diclofop	(±)-2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid
Difenzoquat	1,2-dimethyl-3-5-diphenyl-1*H*-pyrazolium
Dipropetryn	2-ethylthio-4,6-bis(isopropylamino)-*s*-triazine
Diquat	6,7-dihydrodipyrido[1,2-α:2′,2′,1′-*c*]pyrazinediium ion
Diuron	*N*′-(3,4-dichlorophenyl)-*N*,*N*-dimethylurea
DPX-R9674	Chlorsulfuron + metsulfuron
EPTC	*S*-ethyl dipropyl carbamothioate
Ethofumesate	(±)-2-ethoxy-2,3-dihydro-3,3-dimethyl-5-benzofuranyl methanesulfonate
Fenoxyprop	(±)-2[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid
Flamprop-methyl	methyl *N*-benzoyl-*N*-(3-chloro-4-fluorophenyl)-*D*-alaninate
Fluazifop	(*R*)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]prop-anoate acid
Fluometuron	*N*,*N*-dimethyl-*N*′-[3-(trifluoromethyl)phenyl]urea
Flurazole	phenylmethyl 2-chloro-4-(trifluoromethyl)-5-thiazolecarboxy-late
Glyphosate	*N*-(phosphonomethyl)glycine

Appendix B Continued

Common name	Chemical name
Haloxyfop	(±)-2-[4-[[3-chloro-5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid
Imazamethabenz	(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-4(and 5)-methylbenzoic acid
Imazapyr	(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylic acid
Imazethyapyr	2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid
Isopropalin	4-(1-methylethyl)-2,6-dinitro-*N*,*N*-dipropylbenzenamine
Linuron	*N*′-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea
MCPA	(4-chloro-2-methylphenoxy)acetic acid
Methazole	2-(3,4-dichlorophenyl)-4-methyl-1,2,4-oxadiazolidine-3,5-dione
Metolachlor	2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide
Metribuzin	4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one
Metsulfuron	methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]benzoate
Molinate	*S*-ethyl hexahydro-1*H*-azepine-1-carbothioate
MON-4606 (flurazole)	phenylmethyl 2-chloro-4-(trifluoromethyl)-5-thiazolecarboxylate
Naphthalic anhydride	napththalene-1,8-dicarboxylic acid anhydride
Nicosulfuron	2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N*,*N*-dimethyl-3-pyridinecarboxamide
Nitralin	4-methylsulphonyl-2,6-dinitro-*N*,*N*-dipropylaniline
Norflurazon	4-chloro-5-(methylamino)-2-(3-(trifluoromethyl)phenyl)-3-(2*H*)-pyridazinone
Oryzalin	4-(dipropylamino)-3,5-dinitrobenzenesulfonamide
Paraquat	1,1′-dimethyl-4,4′-bipyridinium ion
Pendimethalin	*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine
Picloram	4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid
Primisulfuron	methyl 2-[[[[[4,6-bis(difluoromethoxy)-2-pyrimidinyl]amino]carbonyl]amino]sulfonyl]benzoate
Prometryn	*N*,*N*′-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine
Propachlor	2-chloro-*N*-(1-methylethyl)-*N*-phenylacetamide
Propanil	*N*-(3,4-dichlorophenyl)propanamide
Propazine	2-chloro-4,6-bis(isopropylamino)-*s*-triazine
Quinchlorac	3,7-dichloro-8-quinolinecarboxylic acid

(*continued*)

Appendix B Continued

Common name	Chemical name
R-25788	2,2-dichloro-*N*,*N*-di-2-propenylacetamide
Sethoxydim	2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one
Sodium chlorate	sodium chlorate
2,4-D	(2,4-dichlorophenoxy)acetic acid
Terbutryn	2-(tert-butylamino)-4-(ethylamino)-6-(methylthio)-*s*-triazine
Thifensulfuron (Thiameturon)	methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino] carbonyl]amino]sulfonyl]-2-thiophenecarboxylate
Thiobencarb	*S*-[(4-chlorophenyl)methyl]diethylcarbamothioate
Triallate	*S*-(2,3,3-trichloro-2-propenyl)bis(1-methylethyl)carbamothioate
Triasulfuron	2-(2-chloroethoxy)-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]benzenesulfonamide
Tribenuron	methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methyl-amino]carbonyl]amino]sulfonyl]benzoate
Triclopyr	[(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid
Trifluralin	2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine
Insecticides	
Carbaryl	1-naphthyl methylcarbamate
Carbofuran	2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate
Chlorpyrifos	*O*,*O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl)phosphorothioate
Dimethoate	*O*,*O*-dimethyl *S*-methylcarbamoylmethyl phosphorodithioate
Disulfoton	*O*,*O*-diethyl *S*-[2-(ethylthio)ethyl]phosphorodithioate
Esfenvalerate	(*S*)-α-cyano-3-phenoxybenzyl (*S*)-2-(4-chlorophenyl)-3-methyl-butyrate
Ethyl parathion	*O*,*O*-diethyl *O*-(4-nitrophenyl)phosphorothioate, ethyl ester
Malathion	*O*,*O*-dimethyl phosphorodithioate of diethyl mercaptosuccinate
Methomyl	*S*-methyl *N*-[(methylcarbamoyl)oxy]thioacetimidate
Methyl parathion	*O*,*O*-diethyl *O*-(4-nitrophenyl)phosphorothioate, methyl ester
Phorate	*O*,*O*-diethyl *S*-[(ethylthio)methyl]phosphorodithioate
Fungicides	
Benomyl	methyl 1-(butylcarbamoyl)benzimidazol-2-ylcarbamate
Mancozeb	Zn, Mn ethylene bisdithiocarbamate
Propiconazole	1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1*H*-1,2,4-triazole
Thiophanate-methyl	dimethyl [(1,2-phenylene)bis-(iminocarbonothioyl)]bis [carbamate]
Triadimefon	1-(4-chlorophenoxy)-3,3-dimethyl-1-(1*H*-1,2,4-trizol-1-yl)-2-butanone

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