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Postemergence Quackgrass [Elytrigia repens (L.) Nevski]
Control in Corn with Sulfonylurea Herbicides

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Joseph A. Bruce

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Major professor

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POSTEMERGENCE QUACKGRASS [Elytrigia repens (L.) Nevski] CONTROL IN CORN WITH SULFONYLUREA HERBICIDES

By

Joseph A. Bruce

A DISSERTATION

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ABSTRACT

POSTEMERGENCE QUACKGRASS [Elytrigia repens (L.) Nevski] CONTROL IN CORN WITH SULFONYLUREA HERBICIDES

By

Joseph A. Bruce

Field experiments were conducted to examine the effects of herbicide rate, growth stage, cultivation, and adjuvants on quackgrass control with nicosulfuron and primisulfuron. Greenhouse experiments examined the effect of adjuvants, plant growth stage and environment on absorption, translocation, and activity of nicosulfuron in quackgrass.

Field applications of nicosulfuron controlled four-leaf quackgrass more effectively than two-leaf plants. Primisulfuron activity was similar regardless of quackgrass growth stage. Sequential applications of either herbicide provided greater full-season control than single applications to two-leaf but not four-leaf plants. Cultivation 10 days after nicosulfuron and primisulfuron applications often increased early season weed control. Nicosulfuron (35 g ai ha^{-1}) and primisulfuron (40 g ha^{-1}) applied postemergence provided quackgrass control equivalent to glyphosate (840 g ha^{-1}) applied early preplant in conventional tillage corn production.

In greenhouse studies, foliar absorption of ^{14}C-nicosulfuron and ^{14}C-primisulfuron by quackgrass was greatest with petroleum oil adjuvant (POA) plus urea-ammonium nitrate liquid fertilizer (UAN). The addition of UAN to POA provided greater nicosulfuron and primisulfuron absorption and activity in quackgrass than with POA alone. Translocation of foliar applied ^{14}C-nicosulfuron was more rapid with POA plus UAN than with UAN alone. Few differences were observed between adjuvants in the field efficacy trials. Nicosulfuron and primisulfuron activity was occasionally decreased by the addition of atrazine. Combinations with atrazine did not reduce ^{14}C-nicosulfuron or ^{14}C-primisulfuron uptake by quackgrass. Foliar absorption of ^{14}C-nicosulfuron by quackgrass was greater in one-leaf than in five-leaf plants. Total ^{14}C translocation was similar regardless of growth stage. Despite similar translocation, nicosulfuron more effectively controlled three- and five-leaf quackgrass than one-leaf plants. Absorption, translocation, and accumulation of foliar applied ^{14}C-nicosulfuron increased as air temperatures increased from 11 to 31 C. However, nicosulfuron phytotoxicity in well-watered plants was similar. Soil water potentials of -0.03 and -0.2 MPa had little or no impact on ^{14}C-nicosulfuron absorption, translocation of accumulation in quackgrass. However, as air temperatures increased, quackgrass control decreased under soil water potential of -0.2 MPa. Differences in nicosulfuron phytotoxicity due to growth stage or environmental conditions were not explained by differences in ^{14}C absorption, translocation, or accumulation.

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CHAPTER 1

REVIEW OF LITERATURE

QUACKGRASS BIOLOGY AND CONTROL IN CORN

Name. Quackgrass has been referred to by several different common and scientific names throughout the world. In 1753, Carl Linnaeus initially named quackgrass *Triticum repens* because of its resemblance to wheat (*Triticum*) and its creeping growth habit (*repens*) (44). From 1812 to 1989, the scientific name *Agropyron repens* (L.) Beauv. was used but quackgrass is currently referred to as *Elytrigia repens* (L.) Nevski in the United States. In portions of Europe the name *Elymus repens* (L.) Gould has also been used extensively (4, 30, 44, 68, 70). Quackgrass is also referred to by many different common names around the world. A sampling of theses names include couch, couchgrass, creeping couch-grass, quickgrass, quitchgrass, scutchgrass, twitchgrass, and devilsgrass (4, 30, 44).

Description. This member of the Poaceae family is described as an erect perennial which is spread by seed or rhizome. Rhizomes are round, 1.5 mm in diameter, scaly, creamy white to pale yellow in color reaching lengths in excess of one meter. Roots are fibrous arising from rhizome nodes. Culms are hollow, round, 1.5 to 3 mm diameter, erect or curved at the base, 30 to 120 cm in length, green (young) to tan (mature) in color with tips that are often very sharp. Leaves are flat, green, finely pointed, 9 mm wide, 6 to 20 cm in length, scabrous margin upper surface, smooth glabrous lower surface. Leaf sheath is pubescent on lower leaves, glabrous on upper leaves, round, split, with overlapping margins. Ligule is a small 0.5 to 1 mm obtuse membrane which is occasionally ciliate. Auricles are small and clasping at the base of leaves. Inflorescence is an erect, straight, spike, 5 to 30 cm long with rough margins, having dense or lax spikes resembling that of wheat (17, 30, 70). The unique distinguishing characteristics of quackgrass are the slender white scaly rhizomes, clasping auricles, and seed head resembling that of wheat.

Distribution and habitat. Quackgrass is a native of Europe but is now found throughout the temperate zones of the world (30). The most serious infestations occur in Europe, northern United States and southern Canada (30), however, it is also found in Australia, New Zealand, temperate regions of Asia (70) as well as New Guinea (30). The growth of quackgrass is suppressed by high temperatures and a short photoperiod. These conditions reduce the ability of quackgrass to compete in hot or tropical regions (30). Despite its intolerance of warm climates, it is still found in at least 40 countries infesting 32 different crops (30, 44).

Quackgrass was introduced to North America prior to 1751 during colonization of the eastern seaboard (56). Quackgrass seed was transported to the region in contaminated forage grass seed, animal bedding, animal feed, and animal manure (44, 70). Since its introduction to North America, quackgrass has become the most troublesome perennial grass species north of the 35th parallel (30, 74). It is closely associated with agriculture and is commonly found in orchards, lawns, waste areas, roadsides, and railroad embankments (17, 30, 70).

This cool season grass can grow on soils ranging from dry sand to wet alluvium regardless of drainage characteristics. However, it grows particularly well on fine structured soils (30, 70). Soil pH can range from 4.5 to 8, however, the optimum pH ranges from 6.5 to 8 (70). Quackgrass also has a high salt tolerance. Since quackgrass cannot tolerate contiguous tree and shrub cover it is commonly found in open areas (70). Quackgrass is typically found growing in colonies due to its' perennial nature (30). If left undisturbed, it can quickly spread to acquire more than 90% of the biomass of an abandoned field (70). Because of its ability to spread quickly and its' persistent rhizome system, quackgrass is nearly impossible to eradicate (30, 74).

Growth and development. The morphological development of quackgrass has been examined. Rhizome sections planted in the fall will typically develop aerial shoots prior to onset of freezing temperatures. Those sections without shoots remain dormant until spring. Development of aerial shoots in the spring begins between early and mid-April. Once these primary shoots reach the three- to four-leaf growth stage (mid-May), lateral shoots begin to develop from nodes closest to the soil surface. These lateral shoots develop into secondary aerial shoots or tillers (30, 56, 65). Rhizomes initiate from basal buds located on the aerial shoot below the soil surface during the same time interval (65). These rhizomes grow horizontally below the soil surface. By late May, rhizomes can have a length of 25 cm. During the first two weeks of June, rhizome growth can approach 20 to 25 cm $week^{-1}$. The initial aerial shoots elongate and produce flowering spikes. By late June or early July, rhizome apices begin to turn toward the soil surface to produce new aerial shoots. Simultaneously, a rhizome bud at the base of the aerial shoot initiates development and continues horizontal rhizome growth. This process continues until October when rhizome apices turn toward the soil surface to overwinter. Not all of the apices survive the winter. The following spring, the rhizome apices and axillary buds at the base of the overwintering aerial shoot again initiate aerial shoots for the new season (30, 54, 56).

Carbohydrate levels and transport within quackgrass plants have been examined throughout the growing season. Schirman and Buchholtz (64) found lowest carbohydrate and rhizome dry matter levels in April during early plant growth. After this period, carbohydrate levels increased slightly then remained constant throughout the remainder of the season. Holm et al. (30) reviewed the results of a similar study conducted in Sweden.

In this study, decreases in plant dry weight were also observed. However, lowest dry weights occurred once aerial shoots had developed two leaves. They determined that plants at this stage were most susceptible to extremes in environment or disturbance by man (30).

Carbohydrate translocation patterns vary greatly during the growing season. Differences in translocation may significantly impact the level of quackgrass control obtained with phloem mobile herbicides. Transport of ^{14}C-labelled carbohydrate was examined by Fiveland et al. (21). They found more carbohydrate transport to the rhizomes of three- to four-leaf quackgrass than two-leaf quackgrass. Rogan and Smith (60) examined carbohydrate export from primary shoots to developed axillary tillers and rhizomes. There was mutual translocation between primary shoots and rhizome tillers but not between primary shoots and axillary tillers. At this time, primary shoots and axillary tillers were photosynthetically independent. However, rhizome tillers were still receiving small quantities of assimilate from the primary shoot (60). If phloem herbicide transport is similar to that of assimilates, herbicide transport to rhizomes would be greater in larger quackgrass plants with developed tillers than in smaller plants.

Very little is understood about development of rhizome axillary buds. These buds can remain dormant for a long interval. However, if severed from the parent plant, the buds are generally released from inhibition and produce shoots. Similar results are observed when the rhizome apex is detached from the rhizome (65, 70). Robertson et al. (59) observed bud elongation when the scale leaf covering the bud was removed. Aqueous extracts from the scale leaves also effectively inhibited bud development. Bud elongation was greatest when the rhizome apex was removed regardless of the presence of the scale leaf (59). Growth hormones are believed to be responsible for the control of bud dormancy (40, 61, 70). Production of IAA (indole-3-acetic acid) in apical regions and transport to rhizome buds has been suggested for inhibition of bud development (70). Continuous transport of gibberellin from the parent plant may also be responsible for apical dominance in quackgrass rhizomes (61). Leakey et al. (40) suspect a combination effect of cytokinin and auxin may be responsible for bud dormancy. It is likely that multiple factors are involved in bud dormancy.

Sexual reproduction. Quackgrass is wind pollinated and generally self-sterile (30, 44, 70) however, some self-pollination has been reported (30, 54). Plants can produce from 15 to 400 seeds per stem but production of 25 to 40 seeds is typical (44, 70). Seed will remain viable after passing through the digestive system of horses, cows, and sheep but not hogs (44). Buried seed remain viable for 5 to 10 years (29, 44). Seeds do not require after-ripening prior to germination (70) but little germination occurs in the fall. Alternating temperatures from 30 to 20 C will enhance germination (30). Most seeds germinate in the top 1 to 5 cm of soil (30).

Plants produced from seed have thinner leaves and are initially weaker than plants grown from rhizomes. The onset of tiller and rhizome development occurs later with seedling plants than with plants grown from rhizomes. Regardless of the development time interval, both plants have similar development patterns. Seedlings require approximately 40 days after germination to establish a rhizome system mature enough to withstand tillage (30). Quackgrass development from seed accounts for a very small portion of the quackgrass population (56) but it is essential for continued genetic variability (70).

Asexual reproduction. Vegetative reproduction is more important for maintaining quackgrass population than reproduction by seed (70). Most rhizomes are located within the uppermost 10 to 15 cm of soil. Optimum shoot emergence occurs from rhizomes located 2.5 to 7.5 cm below the soil surface. However, shoots can emerge from greater depths if the rhizome pieces are large. Regardless of the rhizome planting depth, development of secondary rhizomes will occur within the top 5 to 10 cm of soil (30). Heavy quackgrass infestations have been estimated to produce rhizome masses in excess of 13,400 kg ha^{-1} (41) and total rhizome lengths of 80 miles $acre^{-1}$ (29). Raleigh et al. (56) planted a one node rhizome segment to examine rhizome production. By seasons end, a 3.3 m diameter colony had produced 14 rhizomes totaling 135 m in length with 206 aerial shoots. Despite this prolific rhizome growth, less than one-third of the axillary rhizome buds in a three year old sod were found to be viable (33). The below ground quackgrass components typically comprise 60 to 70% of the total plant biomass.

Economics of quackgrass. Man has used quackgrass for soil conservation, animal feed, as well as various human uses. Quackgrass has been used as a sod builder along roadsides, dikes, and in other areas where soil erosion may be a problem (44, 70). Established quackgrass in abandoned fields provides excellent cover for wildlife (70). As a forage grass, quackgrass is able to produce two cuttings of hay annually with total crude protein content comparable to that of timothy (44, 70). Dried quackgrass rhizomes have been ground for flour and utilized in bread for human consumption (18). In Michigan, quackgrass has been noted for its ability to effectively reclaim nutrients from municipal sewage effluent (44). Methanol extracts from quackgrass have been effective against mosquito larvae (*Aedes aegypti* L.) at relatively low concentrations (66).

Quackgrass is also utilized for its medicinal values. In Tanzania, the effects of arrow poison could be counteracted by chewing quackgrass and applying the macerated tissue to the wound (30). Liquid preparations from roots and rhizomes have been used for its diuretic properties. This property is believed to be due to the high glycolic acid content of quackgrass (30). Quackgrass has been used for mucilage production because of its relatively high content (11%). Rhizome extracts were used as a remedy for kidney and bladder ailments in the early 20th century (44). Despite these advantages, quackgrass is better known for its detrimental effects.

Quackgrass reduces crop growth and yield by competing for light, moisture, nutrients, and by production of allelopathic substances. Corn, soybean, oat, and canola grain yields have been reduced by the presence of quackgrass (3, 36, 50, 76, 77). Corn grain yield reductions as great as 37% (77) and 84% (3) have been reported. Delayed ear silking and delayed corn maturity was attributed to quackgrass competition (3). Bandeen and Buchholtz (3) examined nutrient uptake by quackgrass. During a single growing season, quackgrass incorporated 110, 18, and 68 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively. Between 45 and 68% of these nutrients were removed from the soil before mid-July. Corn yield reduction from this quackgrass population was not overcome by addition of soil nutrients. Since corn quickly forms a canopy over quackgrass, competition for light does not explain continued corn yield loss. They concluded that soil moisture loss or toxic inhibition by quackgrass were likely causes for the remaining corn yield reductions (3). Young et al. (77) examined the effect of soil moisture on quackgrass interference in corn. Corn yields were similar regardless of quackgrass density when soil moisture and corn nutrient levels were not limiting. With limited soil moisture, quackgrass reduced corn grain yields but irrigation improved yields of quackgrass infested corn to a level similar to irrigated corn without quackgrass (3). Based on water consumption alone, quackgrass can significantly reduce corn yields. Kommedahl et al. (37) examined the effect of quackgrass residues on corn growth in the field. When corn was grown in residue-free areas, plant heights and grain yields were greater than corn grown in areas containing quackgrass residues. This suggests that allelopathic substances released from quackgrass may also influence corn yields.

The presence of allelopathic substances in quackgrass is well documented. These substances are not exuded from living quackgrass tissue (69). Instead, the substances are released from decomposing quackgrass tissue. Extracts from decomposing tissue inhibited the growth of alfalfa, wheat, oats, peas, edible beans, corn, cucumber, barley, and flax (23, 35, 39, 71). These toxic substances reduce seedling germination, growth, and legume nitrogen fixation (23, 39, 71). The inhibitory effect of quackgrass tissue was similar regardless of growth stage but rhizome tissues have greater inhibitory effects than foliage (52). Researchers have now isolated a glycoside (23) and two flavonoids (72) from quackgrass rhizomes and foliage, respectively, which were able to inhibit growth of crop plants.

Quackgrass can reduce crop value and production in ways other than direct competition. The ability of quackgrass rhizomes to pierce and grow through potato tubers can significantly reduce tuber value (44). Quackgrass also serves as an alternate host for several insects and crop diseases. Bromegrass mosaic virus, wheat stem rust, and the wheat root rot fungi *Ophiobalus* and *Helminthosporium* are commonly associated with quackgrass (44). Cereal leaf beetle (*Oulema melanopa* (L.) and many other insects are known to feed upon quackgrass (70). By serving as an alternate host, quackgrass can harbor these diseases and insects in areas surrounding fields. Crops grown in these fields may encounter yield reductions due to infection or feeding by these crop plants.

Quackgrass control in corn. Effective quackgrass control programs are essential to prevent crop yield reductions due to quackgrass interference. Through the integration of sound cultural practices and herbicides, quackgrass populations can be reduced to acceptable levels (65). Providing optimum conditions for crop growth will enhance its ability to outcompete quackgrass. The optimum use of soil fertility, crop planting date, crop populations, and crop row widths in combination with good seedbed preparation will help improve crop competition with quackgrass. It is also important to plant a crop which is most competitive with quackgrass (65). Doll and Kutil (15) conducted a four-year study to observe the effect of corn and soybean crop rotations on quackgrass control. They found greatest quackgrass biomass in continuous soybeans, intermediate with corn/soybean crop rotation, and least biomass in continuous corn. The quackgrass biomass in continuous corn was one-half of that observed in continuous soybeans (15).

The use of soil tillage is also important for obtaining adequate quackgrass control. Prior to the development of herbicides, tillage was the primary means of quackgrass control. Repeated soil cultivations at 7 to 21 day intervals during hot dry weather effectively reduced quackgrass infestations (14, 16, 29, 30, 42). This method will effectively control dormant rhizome buds. Repeated tillage reduced rhizome lengths (29) and enhanced quackgrass growth by release of dormant rhizome buds from apical suppression (70). Continued cultivation prevented foliage growth which is necessary for production of carbohydrates. The combination of little carbohydrate production and continued use of carbohydrates during shoot regrowth after tillage leads to depletion of carbohydrate reserves and death of the rhizome (16, 29). Tillage will also move rhizomes to the soil surface where they are most susceptible to desiccation (14, 16, 29, 30, 74). Soil cultivation in the fall also exposes rhizomes to freezing temperatures which will also lead to death by desiccation (14, 16, 30, 70, 74). To utilize tillage for quackgrass control, a producer would have to either summer fallow the land or initiate tillage after summer harvest of a cereal grain crop. For many producers, this approach does not fit into their crop rotation plans or does not represent a profitable option.

Quackgrass control is often greater when herbicides are used in combination with tillage (70, 65, 74). The use of either atrazine (6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine) or glyphosate (*N*-(phosphonomethyl)glycine) in conventional tillage corn production provided greater quackgrass control than the same herbicide treatments utilized in no-tillage corn production (26). Cultivation of quackgrass infested soybeans 7 days after postemergence applications of haloxyfop [2-[4-[[3-chloro-5-(trifluoromethyl)-2-

pyridinyl]oxy]phenoxy]propanoic acid] (32) and sethoxydim [2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one] (67) significantly improved quackgrass control. Cultivation is often substituted for a second application of herbicide in quackgrass control programs utilizing sequential applications of herbicide (14). Soil tillage is an important tool in the efforts to control quackgrass with or without the use of herbicides.

Quackgrass suppression or control can be obtained with applications of glyphosate, EPTC [*S*-ethyl dipropyl carbamothioate], atrazine, nicosulfuron [2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N*,*N*-dimethyl-3-pyridinecarboxamide], and primisulfuron [2-[[[[[4,6-bis(difluoromethoxy)-2-pyrimidinyl]amino]carbonyl]amino] sulfonyl]benzoic acid]. Due to the nonselective nature of glyphosate, it must be applied prior to crop emergence. Late fall or pre-plow spring applications to actively growing quackgrass foliage at least 20-cm in height will provide effective control without soil activity (14, 31, 74). Fall glyphosate applications often provide greater quackgrass control than the same herbicide rate applied in the spring (31). However, many producers find it difficult to make timely fall applications due to inclement weather or delayed harvests. Spring applications may delay corn planting beyond optimum dates while waiting for quackgrass to reach the desired application stage (74). Following glyphosate applications, producers must delay soil tillage at least three days (14, 74). This interval is necessary to allow adequate herbicide translocation for effective control of rhizome bud tissue (74). Glyphosate generally provides a level of quackgrass control which is persistent for several years (14, 17).

Preplant incorporated applications of EPTC at 6.6 kg ai ha^{-1} will provide some degree of quackgrass suppression. Efficacy is dependent upon thorough herbicide incorporation (two passes) to depths of 5 to 8 cm (14, 17, 74). Greatest suppression is obtained when tillage operations cut quackgrass rhizomes into small segments (14, 17, 74). Control of quackgrass with EPTC is increased if atrazine (2.2 kg ha^{-1}) plus crop oil concentrate is applied either pre-plow or postemergence (14, 17). However, due to the relative cost of EPTC treatments and the level of quackgrass control, EPTC is not widely utilized for quackgrass control in corn.

Selective postemergence quackgrass control in corn can be achieved from applications of atrazine. Optimum control is provided from a pre-plow application of 2.2 kg ha^{-1} when followed with an additional preemergence or postemergence application of 2.2 kg ha^{-1} (11, 14, 17). In some instances, the second application of atrazine in this sequential treatment may be substituted with cultivation without reducing control (14). The pre-plow application of atrazine is important for obtaining optimum quackgrass control. When applied pre-plow, more herbicide comes in contact with quackgrass rhizomes allowing greater herbicide uptake and control (11, 14). Quackgrass control is less consistent with single applications of atrazine (74). Application rates less than 2.2 kg ha^{-1} do not provide adequate control (11). Despite the benefit of postemergence selectivity in corn, atrazine treatments have some shortcomings. Soil persistence from this treatment will restrict crop rotation to atrazine tolerant crops the following year (11, 14, 17). These restrictions combined with recent changes in the registration status in the United States have reduced the utility of atrazine for quackgrass control in corn.

Nicosulfuron and primisulfuron are newly available sulfonylurea herbicides which control many grass and broadleaf weed species when applied postemergence in corn. These herbicides provide new alternatives for control of troublesome weed species such as johnsongrass [*Sorghum halepense* (L.) Pers.], shattercane [*Sorghum bicolor* (L.) Moench], and quackgrass. Both herbicides have high specific activity, requiring only 20 to 70 g ai ha^{-1} to provide effective weed control. These herbicides must be applied with an adjuvant to obtain maximum efficacy. In soils with a pH of 6.8 or less, these herbicides have a relatively short soil half-life so crop rotation is generally not a problem (1, 2).

These sulfonylurea herbicides inhibit acetolactate synthase (ALS) to effectively block synthesis of the branched-chain amino acids valine, leucine, and isoleucine (1, 49). Previous research concluded that herbicide phytotoxicity was a result of amino acid starvation (6). Researchers now believe that accumulation of the toxic metabolite, α-amino butyric acid is responsible for the phytotoxicity induced by an ALS inhibitor (38, 58). The basis of herbicide selectivity is by rapid metabolism of the herbicide in tolerant plant species (22, 49, 51). In primisulfuron tolerant barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], primisulfuron is rapidly inactivated (within 2 hours) by cytochrome P450-catalyzed hydoxylation of the pyrimidine ring followed by glycosylation (49, 22). The author is not aware of documentation regarding the metabolic pathway of nicosulfuron in tolerant species.

Nicosulfuron and primisulfuron have exhibited good activity on quackgrass. Quackgrass control in excess of 80% has been reported with both herbicides in conventional tillage corn production (9, 10, 47, 57). However, less than acceptable control has also been observed (10, 75). Quackgrass control with nicosulfuron was influenced by application rate. Bhowmik et al. (9) observed quackgrass control increase as nicosulfuron application rate increased from 17.5 g to 35 g ha^{-1}. Nicosulfuron rates greater than 35 g ha^{-1} provided quackgrass control similar to the 35 g ha^{-1} rate (9). Similar results were observed by Yenish and Doll (75). Quackgrass control was not influenced as primisulfuron rates increased from 20 to 40 g ha^{-1} (7, 47, 75).

The effect of nicosulfuron and primisulfuron application timing on quackgrass efficacy has been examined. Quackgrass control was greater when the application of either herbicide was delayed (75). Bhowmik et al. (9) observed greater nicosulfuron control of four- to six-leaf quackgrass than application on one- to three-leaf or seven- to 10-leaf plants. However, Reinhart et al. (57) observed similar nicosulfuron control of three- to four-leaf and five- to six-leaf quackgrass. Quackgrass regrowth following an early postemergence application of primisulfuron (20 g ha^{-1}) was effectively controlled with a post-directed application of primisulfuron (24). Optimum quackgrass control from postemergence nicosulfuron and primisulfuron applications may be influenced by quackgrass stage of growth.

Little research has been conducted to examined the effect of tillage on nicosulfuron and primisulfuron activity. Hand cultivation of quackgrass 4-weeks after nicosulfuron application did not influence quackgrass control (8). However, cultivation after postemergence application of nicosulfuron increased johnsongrass control (73). In no-tillage corn production, primisulfuron did not provide acceptable quackgrass control (26). In the same study, nicosulfuron provided unacceptable early season quackgrass control, however, late season control was at least 85% (26). Multiple applications of nicosulfuron and primisulfuron were necessary to provide acceptable johnsongrass control in no-tillage corn production (63).

Primisulfuron efficacy is influenced by quackgrass biotype. Gillespie et al. (25) observed similar initial control of 15 different biotypes following a postemergence application of primisulfuron at 20 g ha^{-1}. However, late season regrowth was observed with some of the biotypes. All biotypes tested had similar ^{14}C-primisulfuron absorption and translocation patterns. However, significant differences in spray retention were observed between the biotypes. They attributed the primisulfuron biotype response to differences in spray retention and total amount of primisulfuron absorbed (25).

Foliar absorption of nicosulfuron and primisulfuron by target weed species is often quite low. Johnsongrass absorption of nicosulfuron and primisulfuron plus NIS was only 12% and 3%, respectively (12). In field and greenhouse research, nicosulfuron activity on green foxtail [*Setaria viridis* (L.) Beauv.] was dependant upon adjuvant (48). In this research, methylated seed oil provided greater nicosulfuron activity than petroleum oil adjuvant or nonionic surfactant (48). Various adjuvants have enhanced the activity of other sulfonylurea herbicides. Velvetleaf (*Abutilon theophrasti* Medicus) foliar absorption of thifensulfuron [3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid] plus NIS was 15%, 24 hours after application (5). The addition of 28% urea-ammonium nitrate liquid fertilizer (UAN) to this treatment not only increased absorption to 38% but also improved velvetleaf control. Fielding and Stoller (19) observed 21% chlorimuron [2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl] benzoic acid] uptake in velvetleaf with NIS and 32% with NIS plus UAN 84 hours after treatment. In field studies, chlorimuron plus NIS and UAN provided greater velvetleaf control than chlorimuron plus NIS. However, the effectiveness of an adjuvant can be very specific. Several researchers have found that adjuvant efficacy is dependant upon the herbicide being applied and the characteristics of the target weed species (20, 43, 62). The identification of efficacious adjuvants for nicosulfuron and primisulfuron may further improve quackgrass efficacy.

The weed spectrum controlled by nicosulfuron and primisulfuron can be broadened through the use of tank-mix combinations with other herbicides. These combinations are of particular interest to achieve single application, total postemergence weed control. Our preliminary quackgrass control research examined the combinations of atrazine with nicosulfuron and primisulfuron (10). The addition of atrazine to nicosulfuron and primisulfuron treatments provided similar or greater quackgrass control than identical treatments without atrazine (10). Other researchers have observed reduced weed control from these tank-mix combinations. Nicosulfuron control of velvetleaf (13) and giant foxtail (*Setaria faberi* Herrm) (45, 46, 55) decreased when applied as a tank-mix combination with atrazine. Similar results were observed on giant foxtail (13, 27, 34), shattercane (28), and velvetleaf (27) with primisulfuron. Nicosulfuron and primisulfuron combinations with atrazine would be useful for total postemergence weed control in corn. However, research is needed to identify possible tank-mix interactions which may potentially reduce quackgrass control.

Environmental factors affecting nicosulfuron and primisulfuron activity have been examined. Nalewaja et al. (48) observed less effective green foxtail control when 2 mm of simulated rainfall fell within 24 h after nicosulfuron application. Greatest control reductions occurred when simulated rain fell within 1.5 hours after application (48). Air temperature at the time of nicosulfuron application also influences weed control. Nalewaja et al. (48) observed greater redroot pigweed (*Amaranthus retroflexus* L.) control as temperature increased from 10 to 30 C. Control of green foxtail was greatest at 20 C, intermediate at 30 C, least at 10 C. With both species, nicosulfuron efficacy was greater at 96 to 100% relative humidity than at 40 to 50% (48). Oyarzabal and Owen (53) examined soil moisture effects on shattercane and woolly cupgrass [*Eriochloa villosa* (Thunb.) Kunth] control with nicosulfuron and primisulfuron. Herbicide activity was greatest on well watered plants. Absorption of ^{14}C-labelled herbicide in shattercane was similar regardless of soil water potential. In stressed woolly cupgrass, less ^{14}C-herbicide was absorbed and translocated than well watered plants. At present, the effects of air temperature and soil moisture on absorption, translocation, and activity of nicosulfuron and primisulfuron in quackgrass have not been examined.

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CHAPTER 2

QUACKGRASS [*Elytrigia repens* (L.) Nevski] CONTROL IN CONVENTIONAL AND NO-TILLAGE CORN PRODUCTION WITH GLYPHOSATE, NICOSULFURON, AND PRIMISULFURON

ABSTRACT

Field experiments were conducted in 1990 and 1991 to examine the effect of herbicide rate, application timing, quackgrass growth stage, and cultivation on quackgrass control with nicosulfuron and primisulfuron in corn. In conventional tillage, quackgrass control with nicosulfuron was greater when application was made to four-leaf quackgrass than two-leaf quackgrass. Primisulfuron provided similar control regardless of quackgrass growth stage. Sequential applications of nicosulfuron and primisulfuron provided greater season-long control than single applications of the same rate on two-leaf but not four-leaf quackgrass. Cultivation 10 days after nicosulfuron or primisulfuron application often increased early season control, but by October few differences were observed. Postemergence applications of nicosulfuron (35 g ha^{-1}) and primisulfuron (40 g ha^{-1}) provided control equivalent to or greater than an early preplant application of glyphosate (840 g ha^{-1}). Corn yields were similar regardless of the quackgrass control program. In no-tillage corn production, glyphosate (840 g ha^{-1}) applied early preplant consistently provided at least 94% late season control which was equivalent to or greater than postemergence applied nicosulfuron (35 g ha^{-1}) or primisulfuron (40 g ha^{-1}). Early preplant applications of nicosulfuron or primisulfuron generally provided inadequate control. However, when applied as a sequential treatment with a postemergence application of atrazine, control

increased significantly. **Nomenclature:** Atrazine, 6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine; Glyphosate, *N*-(phosphonomethyl)glycine; Nicosulfuron, 2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N*,*N*-dimethyl-3-pyridinecarboxamide; Primisulfuron, 2-[[[[[4,6-bis(difluoromethoxy)-2-pyrimidinyl]amino]carbonyl]amino] sulfonyl]benzoic acid; quackgrass, *Elytrigia repens* (L.) Nevski #[1] AGRRE; corn, *Zea mays* L.

Additional index words. AGRRE, application timing, atrazine, CGA-136872, cultivation, DPX-V9360, growth stage, sequential application.

Introduction

Quackgrass is a serious weed problem in northern United States and southern Canada (13). Its ability to propagate from seed and underground rhizomes make it nearly impossible to eradicate (9, 13, 18). Severe quackgrass infestations have been reported to reduce corn grain yields by as much as 58% (20). The competitive nature of this perennial weed emphasizes the importance of an effective control program for successful corn production in these regions.

The most effective quackgrass control programs available for corn production utilize applications of glyphosate or atrazine. Due to the nonselective nature of glyphosate, it must be applied prior to crop emergence. Late fall or early spring pre-plow applications will effectively control actively growing quackgrass which is at least 20-cm in height without soil activity (8, 9, 12). Many producers have difficulty making timely fall applications due to inclement weather or delayed harvests. Spring applications may delay corn planting beyond

[1]Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds. Revised 1989. Available from WSSA, 309 West Clark Street, Champaign, IL 61820.

optimum dates while waiting for quackgrass to reach the desired application stage (18).

Selective quackgrass control in corn can be achieved from applications of atrazine. Optimum control is provided from a pre-plow application of 2.2 kg ai ha^{-1} when followed with an additional preemergence or postemergence application of 2.2 kg ha^{-1} (7, 8, 9). Despite the benefit of postemergence selectivity in corn, atrazine treatments have some shortcomings. Soil persistence from this treatment will restrict crop rotation to atrazine tolerant crops the following year (8, 9). These restrictions and recent changes in the registration status in the United States have reduced the use of atrazine for quackgrass control in corn.

Nicosulfuron and primisulfuron are sulfonylurea herbicides which provide control of many grass and broadleaf weed species when applied postemergence in corn. These herbicides provide new alternatives for control of troublesome weed species such as johnsongrass [*Sorghum halepense* (L.) Pers.], shattercane [*Sorghum bicolor* (L.) Moench], and quackgrass. In soils with a pH of 6.8 or less, these herbicides have a relatively short half-life and crop rotation is generally not a problem (1, 2).

Several researchers have examined postemergence activity of nicosulfuron and primisulfuron on quackgrass. Quackgrass control in excess of 80% has been reported with both herbicides in conventional tillage corn production (3, 6, 14, 15). However, less than acceptable control has also been observed (6, 19). Quackgrass control was similar regardless of herbicide rate (4, 19), application timing (4, 5, 15), or use of cultivation (5). However other researchers found control influenced by rate (4) and application timing (10, 19). Little research has examined the efficacy of either herbicide in no-tillage corn production. Primisulfuron did not provide acceptable quackgrass control in no-tillage corn production (11). In the same study, nicosulfuron provided unacceptable early season quackgrass control, but late season control was at least 85%. Multiple applications of nicosulfuron and primisulfuron were required to provide acceptable johnsongrass control in no-till (16).

The objectives of this research are to; a) observe the effect of nicosulfuron and primisulfuron application rate, application timing, and cultivation on postemergence quackgrass control in corn and, b) compare quackgrass control from nicosulfuron, primisulfuron, and glyphosate in conventional and no-tillage corn production.

Materials and Methods

Research was conducted in mid-Michigan during 1990 and 1991 to examine quackgrass control in corn. The sites selected had a natural dense quackgrass infestation. All herbicide applications were applied with a tractor mounted compressed air sprayer. Glyphosate treatments included nonionic surfactant[2] (0.5% v/v) and were applied prior to spring tillage in 70 L water ha^{-1} at 234 kPa utilizing 8001[3] nozzle tips. Nicosulfuron and primisulfuron applications included petroleum oil adjuvant[4] (1% v/v) and were applied in 206 L water ha^{-1} at 234 kPa using 8003[5] nozzle tips. All treatments were applied to plots at least 3-m wide (4 rows) by 10-m in length. Quackgrass control and corn injury were visually evaluated with 0 representing no visible injury and 100 representing complete plant death. Evaluations were taken in mid July, August, and October.

Effect of application timing. Field trials were conducted in 1990 and 1991 to examine the effect of application timing and herbicide rate on quackgrass control with nicosulfuron and

[2]X-77 nonionic surfactant is a mixture of alkylarylpolyoxyethylene glycols, free fatty acids, and isopropanol marketed by Valent U.S.A. Corp., 1333 N California Blvd., Walnut Creek, CA 94596.

[3]Teejet flat fan tips. Spraying Systems Co., North Avenue and Schmale Road, Wheaton IL 60188.

[4]Herbimax, 83% petroleum oil, 17% adjuvant, a product of Loveland Industries, Inc. PO Box 1289, Greeley, CO 80632.

primisulfuron in conventional tillage corn production. The soil type at the 1990 site was a Marlette fine sandy loam (fine-loamy, mixed, mesic Glossoboric Hapludalfs) with 2.0% organic matter and 4.4 pH. Seedbed preparation consisted of spring chisel plow, disked twice, then planted with corn variety 'Maumee Valley 6278' on May 25. Fertility program consisted of anhydrous ammonia applied (134 kg N ha^{-1}) pre-plow. Starter fertilizer (168 kg ha^{-1}, 8% N, 26% P_2O_5, 26% K_2O) was applied in a band below the soil surface at planting. Fonofos [O-ethyl-S-phenylethylphosphonodithioate] (1.8 kg ha) was applied as a T-band at planting. Annual weed species were controlled with a preemergence application ofmetolachlor[2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] at 2.2 kg ai ha^{-1} plus cyanazine (2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropanenitrile) at 2.2 kg ha^{-1}.

Soil at the 1991 research site consisted of a Colwood-Brookston loam complex (Colwood, fine-loamy, mixed, mesic Typic Haplaquolls; Brookston, fine-loamy, mixed, mesic Typic Argiaquolls) with 2.9% organic matter and 6.2 pH. The soil was disked twice prior to planting corn variety 'Pioneer 3718' on May 23. Nitrogen at 128 kg N ha^{-1} was applied as 28% liquid urea-ammonium nitrate fertilizer solution (159 L ha^{-1}) prior to corn emergence. Annual weed species were controlled with a broadcast preemergence application of metolachlor at 2.2 kg ha^{-1} plus atrazine at 1.8 kg ha^{-1}.

Nicosulfuron and primisulfuron treatments were arranged as a factorial with three herbicide rates and three application timings; early, late, and sequential. Early and late postemergence applications were timed such that quackgrass shoots averaged two and four true leaves, respectively. The shoot height and leaf stage for corn and quackgrass at the time of application is shown in Table 1. Sequential applications consisted of one-half of the

Table 1. Plant height and leaf stage (true leaves) for quackgrass and corn prior to herbicide application in conventional tillage production. The data indicate the range and average (in parenthesis) for each species.

	Application		Quackgrass			Corn	
Year	Timing	Date	Height	Leaf stage	Density	Height	Leaf stage
			cm	no. of leaves	Shoots m^{-2}	cm	no. of leaves
Application timing study							
1990	Early post	June 16	4-25 (18)	emerge-4 (2)	112	10-19 (15)	2-3 (3)
	Late post	June 25	8-31 (25)	3-4 (4)	128	28-38 (31)	3-5 (4)
1991	Early post	June 14	8-33 (18)	emerge-4 (2)	245	13-41 (31)	4-8 (7)
	Late post	June 24	6-46 (28)	emerge-5 (4)	201	46-81 (76)	7-11 (10)
Cultural practices study							
1990	EPP	April 23	15-20 (19)	2-3 (3)	800	--	--
	Post	June 11	25-31 (28)	2-4 (2)	241	20-31 (25)	4-5 (4)
	Sequ/Cult	June 21	5-23 (18)	1-4 (3)	271	25-64 (53)	5-6 (5)
1991	EPP	May 3	4-48 (38)	emerge-4 (3)	742	--	--
	Post	June 6	3-28 (18)	emerge-3 (2)	333	19-38 (31)	5-8 (7)
	Sequ/Cult	June 17	5-28 (19)	emerge-3 (2)	398	43-81 (64)	8-11 (10)

total herbicide rate applied early postemergence (EP)[5] and the remaining herbicide applied late postemergence (LP). The interval separating the sequential applications was 9 and 10 days in 1990 and 1991, respectively.

Effect of cultivation. Field experiments were conducted in 1990 and 1991 to examine the effect of herbicide rate, application timing, and the use of cultivation in combination with herbicide treatments for quackgrass control. The research sites were adjacent to each other on a Sisson fine sandy loam (fine-loamy, mixed, mesic Typic Hapludalfs) with 2.9% organic matter and 6.9 pH in 1990 and 3.1% organic matter and 6.6 pH in 1991. Primary tillage consisted of spring moldboard plow and chisel plow in 1990 and 1991, respectively. Final seedbed preparation was accomplished by two passes with a disk. Nitrogen (134 kg ha^{-1}) was applied as urea and incorporated with the final tillage operation. Starter fertilizer (336 kg ha^{-1}, 6% N, 24% P_2O_5, 24% K_2O) was band applied at planting. Corn variety 'Pioneer 3751' was planted in 76-cm row spacings on May 15, 1990 and May 16, 1991. The entire research area received a preemergence application of metolachlor at 2.2 kg ha^{-1} and cyanazine at 2.2 kg ha^{-1} for control of annual weed species.

Nicosulfuron and primisulfuron treatments were arranged in a factorial with three herbicide rates and three cultivation systems. These systems consisted of the full herbicide rate applied EP to two-leaf quackgrass with and without cultivation and a sequential postemergence application where one-half of full rate was applied to two-leaf quackgrass and the remaining herbicide was applied approximately 10 days later. Cultivation was accomplished with a tractor mounted 4-row cultivator[6] equipped with 18-cm wide sweep shovels operated at a depth of 8 cm. Early preplant (EPP) applications of glyphosate were

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[5]Abbreviations: EP, early postemergence; LP, late postemergence; EPP, early preplant.

[6]John Deere Model 875, min-till cultivator with C-shanks. Deere and Company, Moline IL, 61265-1304

included with and without cultivation for comparative purposes. The plant heights and leaf stages for each of these applications are shown in Table 1.

Quackgrass control in no-tillage. Quackgrass control from glyphosate, nicosulfuron, and primisulfuron was examined in no-tillage corn production. Research in 1990 was conducted on a Marlette sandy loam soil with 1.8% organic matter and 4.6 pH. Corn variety 'Pioneer 3573' was planted without tillage on May 8 into an area which was previously set-aside. Starter fertilizer was applied at 224 kg ha^{-1} (4.5% N, 26% P_2O_5, 23% K_2O) below the soil surface during planting. The 1991 research was conducted on a Spinks loamy sand (sandy, mixed, mesic Psammentic Hapludalfs) with 2.1% organic matter and 5.2 pH. Corn variety 'Pioneer 3718' was planted without tillage on May 25 into corn residue. In both years, existing vegetation and annual weeds were controlled with a preemergence application of metolachlor at 2.2 kg ha^{-1} plus cyanazine at 2.2 kg ha^{-1} plus nonionic surfactant at 0.25% v/v. This treatment was applied utilizing 28% urea-ammonium nitrate liquid fertilizer (393 L ha^{-1}) as a carrier.

Nicosulfuron and primisulfuron treatments were arranged in a factorial with two herbicide rates and four application timings. These methods included early preplant, early preplant followed with postemergence applied atrazine (1.7 kg ha^{-1}) plus petroleum oil adjuvant (1% v/v), early preplant (one-half the total rate) followed with the remaining herbicide applied postemergence, and postemergence. All postemergence treatments were applied when quackgrass regrowth had reached 2 fully developed leaves. The study included a standard quackgrass treatment consisting of glyphosate (840 g ha^{-1}) applied early preplant. The weed and crop stages at the time of application are shown in Table 2.

Data analysis. All studies were conducted as randomized complete block designs repeated over time. Treatments were replicated four times in all studies except the cultivation study which had three replications. Arcsine transformation of all data was conducted prior to

Table 2. **Plant height and leaf stage (true leaves) for quackgrass and corn prior to herbicide application in no-tillage production. The data indicate the range and average (in parenthesis) for each species.**

	Application		Quackgrass			Corn	
Year	Timing	Date	Height	Leaf stage	Density	Height	Leaf stage
			cm	no. of leaves	Shoots m^{-2}	cm	no. of leaves
1990	EPP	April 27	20-23 (22)	2-3 (3)	591	--	--
	PRE	May 15	15-28 (20)	2-4 (3)	533	--	--
	Sulfonylurea post	June 1	8-43 (33)	1-5 (2)	291	5-10 (8)	2-3 (2)
	Atrazine post	June 19	8-23 (15)	1-5 (2)		15-25 (23)	3-5 (4)
1991	EPP	May 3	3-31 (23)	emerge-4 (3)	708	--	--
	PRE	May 27	10-71 (53)	1-5 (4)	741	--	--
	Post	June 16	8-79 (56)	emerge-3 (2)	630	15-25 (20)	3-4 (4)

analysis of variance. Analysis of variance of combined data indicated significant year by factor interactions in all studies, therefore treatment means for each year are presented separately. Nicosulfuron and primisulfuron treatment means were separated utilizing Fishers' Protected Least Significant Difference at the 5% level of significance. In studies containing glyphosate as a standard for comparison, Dunnett's test (P=.05) was used for comparison of the standard to nicosulfuron and primisulfuron treatments.

Results and Discussion

Effect of application timing. Effective postemergence quackgrass control (>75%) was observed at all herbicide rates and application timings. Nicosulfuron (35 g ha^{-1}) and primisulfuron (40 g ha^{-1}) generally provided similar quackgrass control within a given application timing (Table 3). The only observed difference in control was in October, 1990 when nicosulfuron provided greater control of four-leaf quackgrass than primisulfuron.

The level of quackgrass control from either herbicide was dependant upon herbicide rate. Control increased as nicosulfuron rate increased from 35 g to 70 g ha^{-1}, but this effect was observed only from EP applications evaluated in August 1990 and 1991 as well as October 1991. Quackgrass control increased as primisulfuron rate increased from 20 g to 40 g ha^{-1} in the 1990 growing season. As with nicosulfuron, control differences due to primisulfuron rate were observed only at the EP application timing. In 1991, no quackgrass control rate response was observed with primisulfuron. Previous research did not show differential quackgrass response to nicosulfuron rates from 52 g to 104 g ha^{-1} (19) or from 35 g to 140 g ha^{-1} when applied to four- to six-leaf quackgrass (3). With primisulfuron, control of four- to six-leaf quackgrass has been reported to increase as application rates increased from 10 to 30 g ha^{-1} (3).

Differences in quackgrass control due to postemergence application timing were

Table 3. Postemergence quackgrass control with nicosulfuron and primisulfuron as affected by herbicide rate and application timing in conventional tillage corn production.

		Quackgrass control[c]											
		1990 applications[b]						1991 applications[b]					
		August 15			October 15			August 15			October 15		
Herbicide[a]	Rate	EP	LP	EP/LP	EP	LP	EP/LP	EP	LP	EP/LP	EP	LP	EP/LP
	g ai ha^{-1}	%											
Nicosulfuron	35	83 fg	98 a	96 a-d	90 ef	99 a	96 b-e	76 ef	89 b-e	90 a-c	84 f-h	96 a-f	97 ab
	56	89 ef	99 a	96 a-d	95 b-e	99 a	99 ab	84 d-f	93 a-c	92 ab	94 c-g	98 a-d	96 a-e
	70	94 c-e	98 a-c	99 ab	96 de	99 a-c	98 a-d	88 a-d	92 a-d	92 a	98 a-c	99 a-e	98 a
Primisulfuron	20	77 g	90 d-f	92 d-f	84 f	91 e	96 c-e	80 ef	85 b-e	86 c-f	93 e-g	97 a-d	96 b-g
	30	86 fg	96 a-d	94 b-e	93 e	93 e	99 a-c	77 f	83 c-f	90 a-d	78 h	86 gh	96 a-g
	40	90 d-f	98 a-c	94 c-e	94 e	93 e	96 b-e	81 d-f	83 d-f	92 a-d	91 d-g	94 d-g	98 a-g

[a]Treatments include petroleum oil adjuvant at 1% v/v.
[b]EP, applied early postemergence to quackgrass averaging 2-true leaves; LP, applied late postemergence to 4-true leaf quackgrass; EP/LP, applied sequentially with 50% of the rate indicated applied EP and the remaining 50% applied LP.
[c]Treatment means with the same letter do not differ according to Fisher's protected LSD at the 5% level of significance. Comparisons valid between rows and columns of the same

apparent in 1990 and 1991. Nicosulfuron provided greater control of four-leaf quackgrass (LP) than two-leaf quackgrass (EP) in 1990. This trend was observed at the 35 and 56 g ha^{-1} application rates in August and with all rates in October. Throughout most of the 1991 study, EP and LP application of nicosulfuron provided similar control. Nicosulfuron (35 g ha^{-1}) applied sequentially in 1991 provided greater quackgrass control throughout the growing season than the same rate applied EP. In general, quackgrass control was similar whether nicosulfuron was applied as a single LP application or as a sequential application in 1990 and 1991. The only exception was observed in October 1990 when 35 g ha^{-1} applied LP provided greater control than the same rate applied sequentially.

Application timing had a significant impact on quackgrass control with primisulfuron. By the end of the 1990 and 1991 season, primisulfuron (20 g ha^{-1}) provided greater control of four-leaf quackgrass than two-leaf quackgrass. At higher application rates, control was similar regardless of leaf stage. Sequentially applied primisulfuron provided greater late season control than the same rate applied EP in 1990 (20 g or 30 g ha^{-1}) and 1991 (30 g ha^{-1}). Regardless of application timing, primisulfuron at 40 g ha^{-1} provided similar late season control. In most instances, primisulfuron applied sequentially gave control similar to a single application to four-leaf quackgrass.

Nicosulfuron and primisulfuron provided similar quackgrass control whether applied with single or sequential applications (5). Conflicting results have been reported regarding the effect of quackgrass growth stage on control. Late applications of nicosulfuron and primisulfuron have provided greater control than early applications (19). Despite early season differences, control of three- to five-leaf or five- to seven-leaf quackgrass was similar 9 weeks after treatment with primisulfuron (5). Similarly, nicosulfuron provided similar control of one- to three-leaf, four- to six-leaf, and seven- to 10-leaf quackgrass (5).

Quackgrass control was least effective when nicosulfuron and primisulfuron were applied EP at the lowest rates tested. By applying these rates at the LP timing, one could expect quackgrass control equivalent to higher rates applied EP. This approach could be used to reduce the amount of herbicide used, thus reducing weed control costs.

Effect of cultivation. Postemergence application of nicosulfuron (35 g ha^{-1}) and primisulfuron (40 g ha^{-1}) provided mid-season quackgrass control equivalent to or greater than that provided by early preplant glyphosate (840 g ha^{-1}) applications (Table 4). Cultivation of these treatments provided similar or greater quackgrass control than the same treatments without cultivation. At harvest, nicosulfuron and primisulfuron treated plots with or without cultivation had quackgrass control and corn yields similar to glyphosate treated plots with or without cultivation.

Postemergence quackgrass control was at least 88% with nicosulfuron in both 1990 and 1991 (Table 4). No differences in quackgrass control or corn yield were observed as nicosulfuron rates increased from 35 g to 70 g ha^{-1} regardless of cultivation. With primisulfuron, control ranged from 77% to 98% depending upon herbicide rate and cultivation. Mid-season quackgrass control increased as primisulfuron rate increased from 20 g to 40 g $^{-1}$ in 1990 cultivated treatments and both with and without cultivation in 1991. No differences were observed in late season control or corn yield due to primisulfuron rate.

Sequential applications of nicosulfuron or primisulfuron provided equivalent or greater midseason control than the same rate applied EP with or without cultivation. The use of cultivation 10 days after nicosulfuron or primisulfuron application resulted in similar or greater control than the same treatment without cultivation. With the exception of primisulfuron in 1991, all treatments, regardless of cultivation resulted in similar late season quackgrass control and corn yields. In 1991, primisulfuron applications combined with cultivation provided greater quackgrass control at harvest than the same treatment without cultivation. Corn yield in plots receiving primisulfuron (20 g ha^{-1}) and cultivation was

Table 4. The effect of herbicide rate, application timing, and cultivation on quackgrass control in conventional tillage corn.

		Quackgrass control[c]						Corn grain yield		
		July 15			October 15					
		Cultivation			Cultivation			Cultivation		
		Single application		Sequential application[b]	Single application		Sequential application[b]	Single application		Sequential application[b]
Herbicide[a]	Rate	-	+	-	-	+	-	-	+	-
	g ai ha^{-1}	%						kg ha^{-1}		
					1990					
Nicosulfuron	35	88 i	94 c-g*	94 c-g	88 ab	92 ab	94 ab	11380 a	11310 a	10640 ab
	56	89 hi	91 g-i	96 a-e	91 ab	94 ab	95 a	11020 ab	11020 ab	10770 ab
	70	90 g-i	95 b-f*	97 a-c	94 ab	96 a	94 ab	11970 a	11401 a	11700 a
Primisulfuron	20	91 f-i	94 c-g*	96 a-e	82 b	94 ab	87 ab	10850 ab	11290 a	10670 ab
	30	93 e-i*	98 ab*	97 a-d	89 ab	96 a	96 a	10830 ab	11080 a	10090 ab
	40	94 d-h*	98 a*	97 a-d	91 ab	95 a	92 ab	11180 a	10830 ab	9040 b
Glyphosate	840	66	72		84	85		11210	11100	
					1991					
Nicosulfuron	35	94 b-d	94 b-e	99 a	96 a	93 ab	96 a	18100 a-c	16820 bc	19010 ab
	56	90 c-f	96 a-c	95 ab	93 a-c	89 a-d	98 a	17840 a-c	17580 a-c	18970 ab
	70	95 a-d	98 ab	98 ab	96 a	97 a	98 a	19500 a	18510 ab	19400 a
Primisulfuron	20	80 g	94 b-d	87 e-g	77 de+	94 a-c	76 e	16760 bc	18760 ab	16030 c
	30	85 fg	96 a-c	98 ab	82 b-e	93 a	80 de	17450 a-c	18510 ab	17470 a-c
	40	90 d-f	98 a	99 a	82 b-e	98 a	82 c-e	17960 a-c	17810 a-c	17840 a-c
Glyphosate	840	86	99		88	98		17050	17630	

[a]Nicosulfuron and primisulfuron treatments include petroleum oil adjuvant at 1% v/v. Glyphosate treatment includes nonionic surfactant at 0.5% v/v.
[b]Fifty percent of the indicated rate applied at the single application timing with the remaining 50% applied 10 days later.
[c]Treatment means with the same letter do not differ according to Fisher's protected LSD at the 5% level of significance. Comparisons valid between columns and rows of a given evaluation time. Treatment means denoted with (*) are different from glyphosate within the same column as determined by Dunnett's test at the 0.05 level.

greater than the yield from sequential application of the same herbicide rate.

The utility of cultivation in combination with postemergence nicosulfuron and primisulfuron applications has been previously examined. Quackgrass control was not increased by hand cultivation 4 weeks after primisulfuron application (5). However, cultivation following nicosulfuron application increased johnsongrass control compared to treatments not receiving cultivation (17). These results concur with our findings. Generally quackgrass control was similar or greater with cultivation in early season evaluations, however, late season control was generally similar regardless of cultivation.

Quackgrass control in no-tillage. Nicosulfuron and primisulfuron applications provided quackgrass control ranging from 15% to 98% depending upon application timing (Table 5). Increasing the application rate of either herbicide generally did not improve quackgrass control from either sequential or single postemergence applications. However, increasing herbicide rate in single early preplant (EPP) applications generally increased quackgrass control.

Application timing influenced nicosulfuron and primisulfuron efficacy. With the exception of nicosulfuron in 1990, single EPP applications of either herbicide generally resulted in less quackgrass control than other application timings. Control from EPP treatments generally increased when followed with a postemergence application of atrazine (1.7 kg ha^{-1}) or a postemergence application of additional nicosulfuron or primisulfuron. Primisulfuron (40 g ha^{-1}) applied EPP gave less than 45% control in both years (Table 5). By following this EPP treatment with a postemergence application of atrazine to two-leaf regrowth, full season quackgrass control was increased to at least 85%. Sequential application (EPP followed by POST) of primisulfuron (40 g ha^{-1}) provided greater full season quackgrass control ($\geq$71%) than the same primisulfuron rate applied early preplant (<45%). Similar results were observed with sequential nicosulfuron applications and EPP

Table 5. Quackgrass control as affected by herbicide rate and application timing in no-tillage corn production.

Herbicides[a]	Rate	Quackgrass control[c]							
		July 20				October 15			
		Application timing[b]				Application timing[b]			
		EPP	EPP/POST	POST	EPP/ATR	EPP	EPP/POST	POST	EPP/ATR
	g ai ha^{-1}	%							
1990									
Nicosulfuron	35	91 b-d	97 a	95 a-c	94 a-c	82 b-d	86 a-c	82 cd*	87 a-c
	70	97 ab	98 a	98 a	98 a	93 ab	93 a-c	88 a-c	94 a
Primisulfuron	20	41 g*	85 de*	83 e*	90 c-e	15 f*	60 e*	60 e*	86 a-c
	40	56 f*	98 a	90 c-e	94 a-c	20 f*	71 de*	62 e*	87 a-d
Glyphosate	840	98				97			
1991									
Nicosulfuron	35	60 fg*	79 c-e*	93 ab	81 c-e*	23 g*	76 a-d	87 ab	85 ab
	70	80 c-e*	82 b-e*	97 a	86 b-d	62 c-e*	80 a-c	90 a	84 ab
Primisulfuron	20	30 h*	73 d-f*	91 a-c	84 b-d	20 g*	38 fg*	74 b-d	82 ab
	40	45 gh*	86 b-d	93 ab	86 b-d	44 e-g*	85 ab	78 a-d	85 ab
Glyphosate	840	97				94			

[a]Nicosulfuron and primisulfuron treatments include petroleum oil adjuvant at 1% v/v. Glyphosate treatment includes nonionic surfactant at 0.5% v/v.
[b]EPP and POST, single applications applied early preplant and postemergence, respectively; EPP/POST, applied sequentially 50% rate indicated applied early preplant followed by remaining herbicide applied postemergence; EPP/ATR, rate indicated applied EPP followed with atrazine (1.7 kg ha^{-1}) plus petroleum oil adjuvant (1% v/v) applied postemergence.
[c]Treatment means with the same letter do not differ according to Fisher's protected LSD at the 5% level of significance. Comparisons valid between columns and rows of a given evaluation time. Treatment means denoted with (*) are different from glyphosate within the same column as determined by Dunnett's test at the 0.05 level.

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followed by postemergence applied atrazine combinations in 1991. Single postemergence applications provided late season control ranging from 82 to 90% for nicosulfuron and 60 to 78% for primisulfuron. Control from these postemergence applications was equivalent to or greater than combination treatments applied early preplant and postemergence.

Early preplant application of glyphosate (840 g ha^{-1}) consistently provided at least 94% quackgrass control in no-tillage corn production (Table 5). This level of control was superior to early preplant applications of nicosulfuron (1991) and primisulfuron (1990 and 1991). The rate of glyphosate activity was much greater than either of the sulfonylurea herbicides. By three weeks after treatment, quackgrass treated with glyphosate was completely necrotic. During the same interval, quackgrass treated with nicosulfuron or primisulfuron ceased growing but had not developed necrotic symptoms.

Midseason quackgrass control from nicosulfuron (35 g ha^{-1}) and primisulfuron (40 g ha^{-1}) applied postemergence was comparable to that obtained with glyphosate. Late season control from the postemergence applied sulfonylureas was less than glyphosate in 1990 and equivalent to glyphosate in 1991. Glyphosate consistently gave excellent full season control of quackgrass sod in no-tillage corn production. Postemergence applications of nicosulfuron and primisulfuron also provided control of quackgrass, however their performance was not consistently as effective as glyphosate.

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CHAPTER 3

ADJUVANT EFFECT ON ABSORPTION AND ACTIVITY OF NICOSULFURON AND PRIMISULFURON IN QUACKGRASS [Elytrigia repens (L.) Nevski]

ABSTRACT

Greenhouse and field experiments were conducted to determine foliar absorption and activity of nicosulfuron and primisulfuron by quackgrass with various adjuvants. Foliar absorption of ^{14}C-nicosulfuron and ^{14}C-primisulfuron plus petroleum oil adjuvant (POA) was completed by 4 hours after application. Absorption of nicosulfuron and primisulfuron plus POA increased from 11 and 2% of applied, respectively, to 51 and 12% with the addition of 28% urea-ammonium nitrate liquid fertilizer (UAN) at 4% v/v. At least 83% of the absorbed ^{14}C from either herbicide penetrated the leaf epicuticular waxes. Absorption of ^{14}C-labeled herbicides was greatest with the following adjuvants: POA + UAN > nonionic surfactant (NIS) at 0.25% v/v + UAN = methylated seed oil at 0.75% v/v. The addition of UAN to either NIS or POA significantly increased ^{14}C-herbicide uptake. In greenhouse studies, nicosulfuron (35 g ai ha^{-1}) and primisulfuron (20 g ha^{-1}) applied with POA plus UAN provided greater quackgrass control than with POA alone. Despite the differences in foliar uptake in the greenhouse, few differences were observed between these adjuvants in 1989 or 1990 field efficacy trials. Quackgrass control was reduced by the addition of atrazine (1120 g ha^{-1}) to nicosulfuron plus POA in 1989 and to primisulfuron plus POA in 1990. Combinations with atrazine did not reduce ^{14}C-nicosulfuron or ^{14}C-primisulfuron uptake by quackgrass. **Nomenclature:** Atrazine, 6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine; Nicosulfuron, 2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]

sulfonyl]-*N,N*-dimethyl-3-pyridinecarboxamide; Primisulfuron, 2-[[[[[4,6-bis(difluoromethoxy)-2-pyrimidinyl]amino]carbonyl]amino] sulfonyl]benzoic acid; quackgrass, *Elytrigia repens* (L.) Nevski #[1] AGRRE.

Additional index words. AGRRE, antagonism, CGA-136872, DPX-V9360.

INTRODUCTION

Effective adjuvants enhance foliar penetration, increase foliar retention of spray solution, and improve spray delivery (20). Not all adjuvants improve herbicide efficacy and some can even reduce efficacy (25). The effectiveness of an adjuvant can be very specific. Several researchers have observed that adjuvant efficacy is dependant upon the herbicide being applied and the characteristics of the target weed species (9, 14, 23).

Nicosulfuron and primisulfuron are new sulfonylurea herbicides which control many grass and broadleaf weed species when applied postemergence in corn (*Zea mays* L.) (1, 2). These herbicides provide alternatives for control of troublesome weed species such as Johnsongrass [*Sorghum halepense* (L.) Pers.], shattercane [*Sorghum bicolor* (L.) Moench], and quackgrass. The use of nonionic surfactant (NIS)[2] or petroleum oil adjuvant (POA) is recommended to improve nicosulfuron and primisulfuron efficacy (1, 2).

Quackgrass is a serious weed problem in northern United States and southern Canada (15). Quackgrass with its underground rhizomes is a perennial that is nearly impossible to eradicate (26). Despite these traits, several researchers have reported acceptable (≥80%) quackgrass control from postemergence applications of nicosulfuron or

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[1]Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds. Revised 1989. Available from WSSA, 309 West Clark Street, Champaign, IL 61820.

[2]Abbreviations: NIS, nonionic surfactant; POA, petroleum oil adjuvant; UAN, 28% urea-ammonium nitrate liquid fertilizer; MSO, methylated seed oil.

primisulfuron (4, 6, 18, 22). However, less than acceptable control has also been observed (5, 27). It may be possible to increase quackgrass control through the use of adjuvants which increase nicosulfuron and primisulfuron absorption.

Foliar absorption of sulfonylurea herbicides by target weed species is often quite low. Absorption of thifensulfuron (3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] amino]sulfonyl]-2-thiophenecarboxylic acid) plus NIS in velvetleaf (*Abutilon theophrasti* Medicus) was 15%, 24 hours after application (3). The addition of 28% urea-ammonium nitrate liquid fertilizer (UAN) to this treatment not only increased absorption to 38% but also improved velvetleaf control. Fielding and Stoller (10) observed 21% chlorimuron (2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoic acid) uptake in velvetleaf with NIS and 32% with NIS plus UAN 84 hours after treatment. In field studies, chlorimuron plus NIS and UAN provided greater velvetleaf control than chlorimuron plus NIS. Absorption of nicosulfuron and primisulfuron was only 12% and 3%, respectively, when applied with NIS (7). In field and greenhouse research, nicosulfuron activity on green foxtail [*Setaria viridis* (L.) Beauv.] was dependant upon adjuvant (19). The identification of efficacious adjuvants for use with nicosulfuron and primisulfuron may increase quackgrass efficacy and consistency.

The weed spectrum controlled by nicosulfuron and primisulfuron can be broadened through tank-mix combinations with other herbicides. These combinations are of particular interest to achieve single application, total postemergence weed control. Preliminary research on nicosulfuron and primisulfuron combinations with atrazine provided equivalent or greater quackgrass control than similar treatments without atrazine (5). However, activity on velvetleaf (8) and giant foxtail (16, 17, 21) was reduced when applied in tank-mix combinations with atrazine. Similar results were observed with giant foxtail (8, 12, 13), shattercane (11), and velvetleaf (12) control with primisulfuron. Nicosulfuron and primisulfuron combinations with atrazine would be useful for total postemergence weed control in corn; however, research is needed to identify possible tank-mix interactions which may potentially reduce quackgrass control.

Our objectives were: a) to examine foliar absorption of nicosulfuron and primisulfuron in quackgrass, b) to quantify foliar absorption as influenced by adjuvants, and c) to examine nicosulfuron and primisulfuron efficacy on quackgrass as affected by adjuvants.

MATERIALS AND METHODS

Greenhouse research. Greenhouse studies were conducted to examine the effect of adjuvants on foliar herbicide absorption and quackgrass control. Environmental conditions were maintained at 25 C ± 4 C, and plants were grown in a 16-h photoperiod of natural and supplemental metal halide lighting with a midday photosynthetic photon flux density of 1000 $\mu E\ m^{-2}\ s^{-1}$. A rhizome from a slightly pubescent quackgrass biotype was selected from a field in Williamston, MI. This biotype was then used as a propagation source to maintain genetic uniformity among plants. All quackgrass plants were raised from single unbranched three-node rhizome segments placed at a 2-cm depth in 1-L plastic pots containing potting medium[3]. Plants were watered as needed and fertilized weekly with 50-ml of water soluble fertilizer solution (400 ppm N, 400 ppm P_2O_5, 400 ppm K_2O). Once plant growth averaged five-true leaves, the plants were clipped back to the soil surface. Herbicide treatments were applied to quackgrass regrowth averaging three-true leaves. Powdery mildew and aphid infestations were controlled with foliar applications of triadimefon [1-(4-chlorophenoxy)-3,3-dimethyl-1-(1*H*-1,2,4-triazol-1-yl)-2-butanone] and acephate (0,5-dimethyl

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[3]Baccto Professional Planting Mix. Michigan Peat Company, P O Box 980129, Houston, TX 77098.

acetylphosphoramidothionate), respectively.

Foliar absorption of ^{14}C-nicosulfuron and ^{14}C-primisulfuron was measured over a 24-h period. Herbicide treatments were prepared utilizing 2-pyrimidine ^{14}C-nicosulfuron (2.3 MBq mg^{-1} specific activity, 98.8% purity) and phenyl labeled ^{14}C-primisulfuron (1.9 Mbq mg^{-1} specific activity, and 97.2% purity). Purity for both herbicides was determined by high-performance liquid chromatography.

Radiolabeled nicosulfuron was dissolved in tetrahydrofuran. Herbicide stock solution was placed in a vial to prepare a 185 Bq μl^{-1} treatment solution. Tetrahydrofuran was evaporated from the nicosulfuron treatment solution using a nitrogen stream and then replaced with deionized water. The treatment solution was supplemented with deionized water, formulated nicosulfuron product,[4] formulation blank, and POA[5] at 1% v/v. Final treatment concentrations were 415 µmol nicosulfuron plus 57 mg L^{-1} formulation blank. These treatment concentrations correspond to a field application of 35 g ai ha^{-1} applied at 206 L ha^{-1}.

Radiolabeled primisulfuron was dissolved in methanol and utilized to prepare a 185 Bq μl^{-1} treatment solution. This solution was supplemented with deionized water, formulated primisulfuron product,[6] formulation blank, and POA at 1% v/v. This treatment contained 207 µmol primisulfuron and 32 mg L^{-1} formulation blank and less than 10% v/v methanol. The primisulfuron concentration corresponds to a field application of 20 g ai ha^{-1} applied in a 206 L ha^{-1} carrier volume. Quackgrass plants with three fully developed leaves

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[4]Accent 75 WDG herbicide. E.I. DuPont deNemours and Co., Wilmington, DE 19898.

[5]Herbimax, 83% petroleum oil, 17% adjuvant, a product of Loveland Industries, Inc. PO Box 1289, Greeley, CO 80632.

[6]Beacon 75 WDG herbicide. CIBA-GEIGY Corp., Agricultural Division, Greensboro, NC 27419.

per culm were selected to receive ^{14}C-labeled treatments. A single 2-μl droplet of treatment solution containing 370 Bq was placed on the adaxial surface of the youngest fully developed leaf with a microsyringe. The droplet was placed laterally between the leaf margin and midrib, midway between the base and tip. Herbicide absorption was quantified at 0, 2, 4, 8, 12, and 24 h after herbicide application. At the appropriate harvest interval, the treated leaf was excised and rinsed in 3 ml methanol for 45 s to remove unabsorbed ^{14}C. The methanol wash vials received 15-ml scintillation cocktail and were quantified by liquid scintillation spectrometry correcting for quench.

Herbicide distribution in leaf components. Labeled nicosulfuron and primisulfuron treatment solutions were prepared with the adjuvants POA (1% v/v) or POA plus UAN (4% v/v), and quackgrass plants were treated as previously described. Six hours after application, the treated leaf was excised and washed 45 s in 3 ml methanol to remove unabsorbed ^{14}C. The leaf was then immersed in 3 ml chloroform for 10 s to remove epicuticular waxes in the treated region. The treated leaf was then frozen. The chloroform wash was reduced to near dryness with a stream of nitrogen. Each methanol and chloroform leaf wash vial received 15 ml scintillation cocktail. Frozen treated leaves were combusted in a biological sample oxidizer using a mixture of carbon dioxide absorbent and scintillation fluid (1:2 ratio) to trap evolved $^{14}CO_2$. All samples were then quantified by liquid scintillation spectroscopy.

Effect of adjuvants on absorption. Labeled nicosulfuron and primisulfuron solutions were prepared with each of the following adjuvant combinations; none, NIS[7] at 0.2% v/v, POA at 1% v/v, UAN at 4% v/v, NIS plus UAN, POA plus UAN, methylated seed oil[8] (MSO)

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[7]X-77 nonionic surfactant is a mixture of alkylarylpolyoxyethylene glycols, free fatty acids, and isopropanol marketed by Valent U.S.A. Corp., 1333 N California Blvd., Walnut Creek, CA 94596.

[8]Scoil, a methylated seed oil product of AGSCO, Inc. Box 458 Grand Forks, ND 58206.

at 0.7% v/v, and atrazine[9] plus POA (1120 g ha^{-1} + 1% v/v). Treatments were applied to quackgrass leaves as previously described. Upon drying, calipers were used to measure droplet spread on the leaf surface. At 1 and 6 hours after treatment, treated leaves were excised and washed in methanol as previously described to remove unabsorbed ^{14}C. Samples were then quantified with liquid scintillation spectroscopy as previously described. Foliar absorption was calculated as the difference between total ^{14}C applied and the ^{14}C recovered in the methanol wash quantity divided by total applied. Absorption data for both herbicides were analyzed by nonlinear regression to generate response curves.

Herbicide efficacy. Nicosulfuron (35 g ha^{-1}) and primisulfuron (20 g ha^{-1}) were applied with the adjuvants POA (1% v/v) and POA plus UAN (1% + 4% v/v). Treatments were applied to quackgrass regrowth averaging three-leaf and 15 cm utilizing a single 8001E[10] flat fan nozzle on a continuous link-belt sprayer delivering 206 L ha^{-1} at 138 kPa. Control was visually evaluated 30 days after treatment.

Field research. Quackgrass control from postemergence applications of nicosulfuron and primisulfuron as affected by adjuvants was examined in central Michigan during 1989 and 1990. The selected research sites were infested with a dense quackgrass sod. The 1989 research site had a Parkhill loam (Fine-loamy, mixed, nonacid, mesic Mollic Haplaquepts) soil containing 3.2% organic matter and a pH of 6.2. In 1990, the soil type was a Sims silty clay loam (Fine, mixed, nonacid, frigid Mollic Haplaquepts) with 2.3% organic matter and a pH of 5.6. Spring tillage consisted of moldboard plow, followed by one disking in both years. Corn (*Zea mays* L.) varieties 'Golden Harvest 2300' and 'Great Lakes 579' were planted on May 23, 1989 and May 30, 1990, respectively. Corn was planted at a population

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[9]Aatrex 4L, CIBA-GEIGY Corp., Agricultural division, Greensboro, NC 27419.

[10]Teejet flat fan tips. Spraying Systems Co., North Avenue and Schmale Road, Wheaton IL 60188.

of 54,000 seeds ha^{-1} in rows spaced 97 cm apart in both years. Herbicides were applied to plots four rows wide by at least 7.6 m long with a tractor-mounted compressed air sprayer calibrated to deliver 206 L ha^{-1} at 207 kPa using 8003[13] flat fan nozzles. Annual weeds were controlled with a preemergence application of metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] at 2.2 kg ha^{-1} plus cyanazine [2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropanenitrile] at 2.2 kg ha^{-1}. Postemergence herbicides were applied to quackgrass averaging four visible leaves (three-true leaves) and 19 cm in height on June 18, 1989 and 23 cm in height on June 25, 1990. Quackgrass density averaged 323 and 237 shoots m^{-2} in 1989 and 1990, respectively. Quackgrass control and corn injury were evaluated visually with 0 representing no visible injury and 100 representing complete plant death. Evaluations were made 30 and 60 days after treatment, mid-October, and 1 year after treatment.

Data analysis. Each greenhouse and field study was conducted as a randomized complete block design repeated over time. Treatments in all studies were replicated four times with the exception of the 1990 field study which contained three replicates. Analysis of variance indicated no significant repeat by factor interactions in greenhouse studies, therefore means presented are a combined average of the repeats. Field results are presented separately for each year due to year by factor interactions. Mean separations were determined utilizing Fishers's Protected Least Significant Difference at the 5% level of significance.

RESULTS AND DISCUSSION

Herbicide absorption. Foliar absorption of ^{14}C-nicosulfuron and ^{14}C-primisulfuron with POA over a 24-hour period is shown in Figure 1. Nicosulfuron and primisulfuron absorption was characterized by the equations $Y = -23.26\ e^{-0.76X} + 23.33$ ($R^2=0.85$) and $Y = -30.24\ e^{-0.88X} + 30.25$ ($R^2=0.82$), respectively. The rate of absorption was greatest during

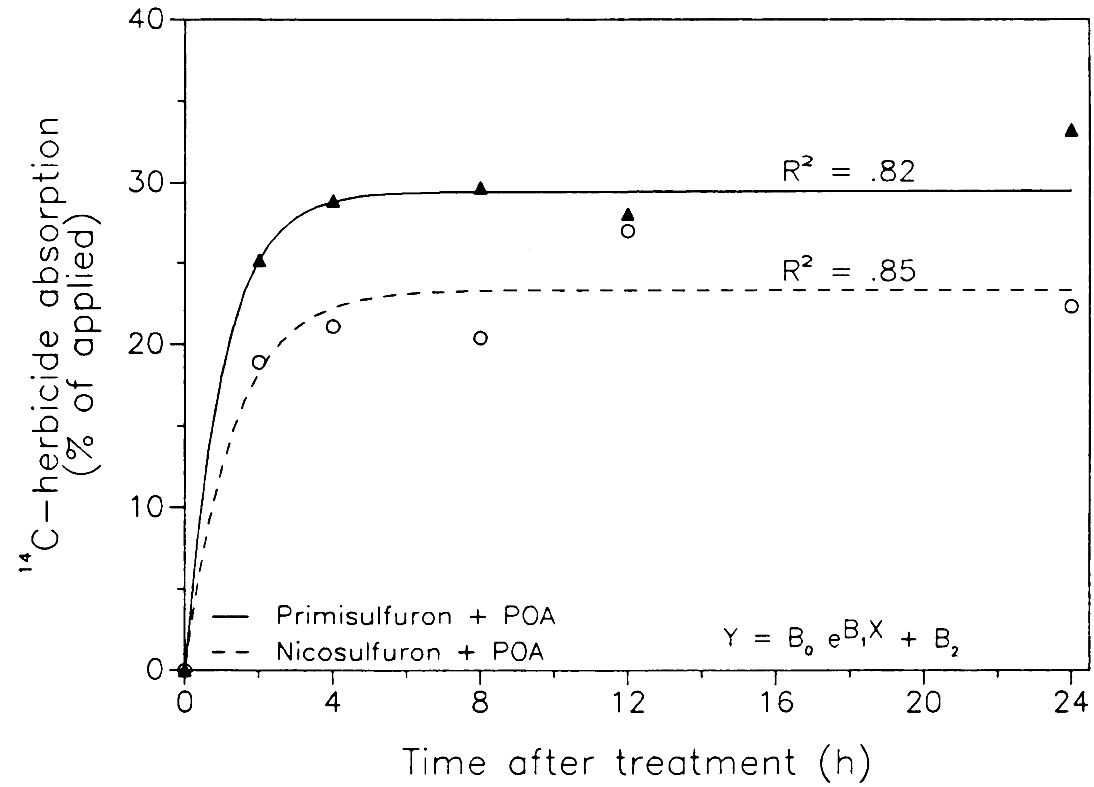

Figure 1. **Foliar absorption of ^{14}C-nicosulfuron and ^{14}C-primisulfuron by quackgrass. Treatments included ^{14}C-nicosulfuron and ^{14}C-primisulfuron plus petroleum oil adjuvant (POA) at 1 % v/v.**

the first 2 hours after application. Nicosulfuron and primisulfuron foliar absorption approached 23 and 29% of applied, respectively, within 4 hours after application. Foliar absorption at later intervals was not significantly greater than at 4 hours after application. These results indicate that the first 4 hours after application are critical for the absorption process of nicosulfuron and primisulfuron in quackgrass. Nalewaja et al. (19) examined simulated rainfall effects on nicosulfuron control of green foxtail. They observed significant reduction in control from rainfall within 1.5 hours after nicosulfuron application. After 3 hours, only slight reduction in control was observed. These results closely parallel ^{14}C-nicosulfuron absorption patterns in this study where foliar absorption was nearly completed 4 hours after application. This would indicate that a 4 hour rain-free interval after application would be critical for optimum quackgrass control.

Since foliar herbicide absorption approaches a maximum within 4 hours after treatment, all other absorption studies were quantified 6 hours after application to approximate maximum foliar uptake.

Herbicide distribution in leaf components. Following application of ^{14}C-herbicide, unabsorbed ^{14}C was quantified using a methanol leaf wash. This process removed herbicide remaining unabsorbed on the leaf surface. The use of a methanol leaf wash does not remove ^{14}C-herbicide which may be retained within the epicuticular waxes of the leaf. A 5- to 10-s chloroform wash has been utilized to dissolve epicuticular waxes and to remove herbicides retained in this region (3). A preliminary study with quackgrass indicated that a 10-s wash interval was appropriate for removing the epicuticular waxes (data not reported). This interval did not extract chlorophyll from the leaf proper since no green pigments were detected in the solution. Combustion of the leaf in a biological oxidizer represented the amount of ^{14}C which passed through the cuticle.

The amount of unabsorbed herbicide recovered (methanol wash) was greatest when either herbicide was applied with POA (Table 1). The unabsorbed ^{14}C in the nicosulfuron plus POA treatment was 89% compared to only 49% when UAN was added to the treatment. With primisulfuron plus POA, 98% of the applied ^{14}C remained on the leaf surface compared to 88% when POA plus UAN was used. Enhanced herbicide absorption was previously reported from the addition of UAN to NIS with thifensulfuron on velvetleaf (3, 9).

Small quantities of ^{14}C-nicosulfuron or ^{14}C-primisulfuron were measured in the chloroform leaf wash component (Table 1). Radioactivity recovered in the chloroform wash was greatest with treatments containing UAN plus POA. The majority of the leaf absorbed ^{14}C moved through the epicuticular waxes removed by the chloroform wash, regardless of adjuvant used. Greater than 83% of the absorbed herbicide was recovered in the leaf combustion fraction. These results indicate that quackgrass leaf epicuticular waxes do not represent an impermeable barrier to nicosulfuron or primisulfuron absorption into the leaf. It also confirms that methanol leaf wash techniques provide a good measure of foliar herbicide absorption.

Total ^{14}C recovery in this study was consistently greater with herbicide treatments containing POA than treatments containing POA plus UAN. Reduced ^{14}C recovery with the use of POA plus UAN may be due to greater herbicide translocation from the treated leaf than with POA alone. Fielding and Stoller (9) observed greater absorption and translocation of thifensulfuron with NIS plus UAN than with NIS alone.

Effect of adjuvants on absorption. Nicosulfuron and primisulfuron absorption results were very inconsistent when applied without an adjuvant or with UAN alone (Table 2). These inconsistencies were due to solution surface tension properties and the application technique utilized. The epicuticular waxes on quackgrass foliage make the leaf very difficult to wet (24). These characteristics made the application of ^{14}C-solutions containing UAN or no

Table 1. Recovery of ^{14}C-nicosulfuron and ^{14}C-primisulfuron from quackgrass leaf components and herbicide efficacy in the greenhouse as affected by adjuvants.

Treatments[a]	Rate	^{14}C recovery - 6 hours after application				Quackgrass control
		Methanol wash	Chloroform wash	Leaf combustion	Total	
	% v/v	------ % of applied ------				%
Nicosulfuron (35 g ai ha^{-1})						
POA	1.0	89	1.2	6	96	76
POA + UAN	1.0 + 4.0	49	3.0	38	90	89
	$LSD_{.05}$[c] =	8	1.0	6		7
Primisulfuron (20 g ai ha^{-1})						
POA	1.0	98	0.3	2	100	37
POA + UAN	1.0 + 4.0	88	1.0	8	97	58
	$LSD_{.05}$[c] =	5	0.4	4		4

[a] POA = petroleum oil adjuvant, UAN = 28% urea-ammonium nitrate liquid fertilizer.
[b] Evaluated 30 days after treatment.
[c] Comparisons valid within columns of the same herbicide.

Table 2. Foliar absorption of ^{14}C-nicosulfuron by quackgrass in the greenhouse and field efficacy of nicosulfuron as affected by spray solution adjuvants.

Adjuvants[a]	Rate	Foliar ^{14}C uptake[b]		Droplet diameter	Quackgrass control[c]	
		1 hour	6 hours		1989	1990
	% v/v	--------- % --------		mm	----------- % -----------	
Nicosulfuron (35 g ai ha^{-1})						
None	--	12	1	3.5	88	80
NIS	0.2	12	19	12.8	94	83
POA	1.0	6	10	14.5	94	81
UAN	4.0	0	0	4.2	--	76
NIS + UAN	0.2 + 4.0	24	30	13.2	92	82
POA + UAN	1.0 + 4.0	33	40	11.3	97	79
MSO	0.7	14	27	14.3	--	86
ATR + POA	1120 g ha^{-1} + 1.0	9	15	14.2	89	80
	$LSD_{(.05)}$[d] =	7	9	1.8	5	N.S.

[a]Adjuvants: NIS = nonionic surfactant, POA = petroleum oil adjuvant, UAN = 28% urea-ammonium nitrate liquid fertilizer, MSO = methylated seed oil, ATR = atrazine.

[b]Uptake calculated as 100 * ((total ^{14}C applied - methanol wash ^{14}C) (total ^{14}C applied)$^{-1}$).

[c]Evaluated 30 days after treatment.

[d]Comparisons valid within columns.

adjuvant very difficult. Once droplets were applied to the leaf surface, they were very easily displaced. All other adjuvants modified droplet surface tension properties sufficiently to improve leaf retention, thus improving consistency of treatment results.

Foliar absorption of ^{14}C-nicosulfuron and ^{14}C-primisulfuron was measured at 1 and 6 hours after application with eight different adjuvant combinations. Nicosulfuron absorption in quackgrass ranged from 0 to 40% of the total ^{14}C applied (Table 2). At 1 hours after application, nicosulfuron absorption was greatest with POA plus UAN (33%) followed by NIS plus UAN (24%). At 6 hours after application, absorption with POA plus UAN increased to 40%, greater than either NIS plus POA (30%) or methylated seed oil (MSO) (27%).

Foliar absorption of primisulfuron in quackgrass ranged from 8 to 28% (Table 3). Greatest primisulfuron absorption occurred with the use of POA plus UAN. At 1 and 6 hours after application, absorption was 21 and 28%, respectively, with POA plus UAN. Absorption with MSO and NIS plus UAN was 22% and 20%, respectively, 6 hours after application. Herbicide absorption was similar when either NIS or POA was used.

Foliar absorption of nicosulfuron and primisulfuron improved from the addition of UAN to either NIS or POA as compared to either component applied alone at both 1 and 6 hour harvest intervals. Similar results were reported for thifensulfuron and chlorimuron combined with NIS plus UAN or NIS alone in velvetleaf (3, 9, 10).

Foliar absorption of nicosulfuron was similar when POA was applied with or without atrazine (Table 2). Absorption of primisulfuron was greater 6 hours after application with atrazine plus POA than when POA was the only adjuvant (Table 3). Previous research has indicated possible reductions in nicosulfuron or primisulfuron efficacy when tank-mixed with atrazine (8, 11, 12, 21). Based on our observations in quackgrass, antagonism with nicosulfuron or primisulfuron combinations with atrazine was not due to reduced

Table 3. Foliar absorption of ^{14}C-primisulfuron by quackgrass in the greenhouse and field efficacy of primisulfuron as affected by spray solution adjuvants.

Adjuvants[a]	Rate	Foliar ^{14}C uptake[b] 1 hour	Foliar ^{14}C uptake[b] 6 hours	Droplet diameter	Quackgrass control[c] 1989	Quackgrass control[c] 1990
	% v/v	---------- %	--------	mm	---------- %	----------
Primisulfuron (20 g ai ha^{-1})						
None	--	2	11	3.5	90	84
NIS	0.2	11	8	13.8	94	86
POA	1.0	9	9	18.2	93	91
UAN	4.0	8	13	5.8	--	70
NIS + UAN	0.2 + 4.0	12	20	14.3	97	87
POA + UAN	1.0 + 4.0	21	28	9.5	94	92
MSO	0.7	13	22	12.7	--	89
ATR + POA	1120 g ha^{-1} + 1.0	6	14	12.0	97	76
	$LSD_{(.05)}$[d] =	3	5	2.3	4	11

[a]Adjuvants: NIS = nonionic surfactant, POA = petroleum oil adjuvant, UAN = 28% urea-ammonium nitrate liquid fertilizer, MSO = methylated seed oil, ATR = atrazine.
[b]Uptake calculated as 100 * ((total ^{14}C applied - methanol wash ^{14}C) (total ^{14}C applied)$^{-1}$).
[c]Evaluated 30 days after treatment.
[d]Comparisons valid within columns.

nicosulfuron or primisulfuron foliar absorption.

Measurements of spray droplet diameter on the leaf surface at dryness were taken prior to harvest. The least amount of spread was observed in treatments containing either no adjuvant or UAN. All other adjuvants sufficiently modified droplet surface properties to increase droplet diameters (Tables 2, 3). Comparisons of droplet diameter to herbicide absorption appear unrelated since adjuvants with similar absorption had large differences in droplet diameter. Based on this observation, the degree of droplet dispersal on a leaf is not a good indicator of the potential for an adjuvant to modify herbicide absorption. Similar findings were reported by Wanamarta et. al (25) for sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) use on quackgrass.

Herbicide efficacy. Control of three-leaf quackgrass with nicosulfuron and primisulfuron in the greenhouse was dependant upon adjuvant selection. The addition of UAN to POA significantly increased quackgrass control with nicosulfuron (35 g ha^{-1}) from 76% to 89% 30 days after treatment (Table 1). Similar results were observed with primisulfuron. Since nicosulfuron and primisulfuron absorption was greater with POA plus UAN than POA alone, differences in control appear related to foliar herbicide absorption. Similar results have been reported with thifensulfuron and chlorimuron absorption and control of velvetleaf (3, 9, 10).

Similar growing seasons were observed in field studies in 1989 and 1990. In both seasons, rainfall was adequate to above normal with normal temperatures. In general, quackgrass control in 1989 was greater and more consistent than that observed in 1990 (Tables 2, 3). Quackgrass emergence from the soil and shoot height at the time of postemergence application was more uniform in 1989 than in 1990. Uniformity differences can be attributed to differences in primary tillage depth and resulting quackgrass rhizome distribution. The moldboard plow depth was greater in 1990 than in 1989, probably resulting in greater vertical rhizome distribution through the plow layer in 1990. As a result, quackgrass shoot emergence occurred over a greater time interval. This lead to a wide range of quackgrass heights at the time of application in 1990 and more shoot emergence after application than in 1989. This would account for greater variability observed in 1990 quackgrass control results.

Quackgrass control within treatments was similar throughout the growing season (Tables 2, 3). Early season control ratings are presented since control was similar throughout the growing season. All herbicide treatments experienced some degree of new shoot emergence after treatment. Typically new shoots were not observed until 60 days after treatment, however, new shoots were observed as early as 30 days after treatment in 1990.

Postemergence applications of nicosulfuron (35 g ha^{-1}) without an adjuvant provided 88% and 80% quackgrass control 30 days after treatment in 1989 and 1990, respectively (Table 2). In 1989, the use of NIS, POA, NIS plus UAN, and POA plus UAN with nicosulfuron significantly increased control compared to no adjuvant. Nicosulfuron applied with NIS, POA or POA plus UAN gave similar quackgrass control (≥94%). In 1990, no significant differences in control were observed 30 days after treatment regardless of the adjuvant used. The lack of differences were due in part to the emergence of new quackgrass shoots following the postemergence herbicide application (data not presented). Examination of these late emerging shoots indicated that they originated form greater soil depths than nearby treated shoots which had emerged prior to herbicide application.

Quackgrass control with primisulfuron was at least 90% in 1989 (Table 3). Compared to primisulfuron alone, the addition of NIS, NIS plus UAN, POA plus UAN, and atrazine plus POA significantly increased quackgrass control. In 1990, none of the adjuvants applied with primisulfuron provided greater control than primisulfuron applied alone.

The addition of UAN to either NIS or POA did not increase nicosulfuron (Table 2) activity on quackgrass compared to NIS or POA without UAN. Similar results were observed with primisulfuron in both years (Table 3). Greenhouse studies with both herbicides revealed greater foliar absorption and activity from the addition of UAN to either POA or NIS. These conflicting results may be due to differences in quackgrass epicuticular wax composition due to the different environments in which the plants were grown.

The addition of atrazine to nicosulfuron plus POA reduced quackgrass control from 94% to 89% in 1989 but not in 1990 (Table 2). Primisulfuron efficacy was not affected by atrazine in 1989 (Table 3). However, in 1990, primisulfuron plus POA efficacy declined from 91% to 76% when atrazine was added to the treatment solution. Foliar absorption studies indicated that atrazine did not affect the absorption of ^{14}C-nicosulfuron or ^{14}C-primisulfuron in quackgrass (Tables 2, 3). Hart and Penner (12) observed reduced control of giant foxtail and velvetleaf when primisulfuron was applied with atrazine. They reported no effect on primisulfuron absorption; however, primisulfuron translocation to meristematic regions declined in the presence of atrazine. A similar response may occur in quackgrass.

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CHAPTER 4

EFFECT OF GROWTH STAGE AND ENVIRONMENT ON FOLIAR ABSORPTION, TRANSLOCATION, AND ACTIVITY OF NICOSULFURON IN QUACKGRASS [Elytrigia repens (L.) Nevski]

ABSTRACT

Experiments were conducted to examine the influence of adjuvant, growth stage, air temperature, and soil moisture on nicosulfuron activity, absorption, and distribution in quackgrass. The addition of 28% urea-ammonium nitrate liquid fertilizer (UAN) to ^{14}C-nicosulfuron plus petroleum oil adjuvant (POA) provided greater ^{14}C absorption than POA alone. Translocation of ^{14}C with POA alone at 168 h after treatment (HAT) was similar to POA plus UAN at 24 HAT. Total translocation was similar at 168 HAT, regardless of adjuvant. Foliar absorption of ^{14}C-nicosulfuron by quackgrass was greater in one-leaf than five-leaf plants. Total translocation of ^{14}C-nicosulfuron was similar regardless of growth stage. However, nicosulfuron was more phytotoxic to three- and five-leaf than one-leaf quackgrass. ^{14}C-Nicosulfuron absorption, translocation, and accumulation increased with increasing temperatures independent of soil moisture. Under adequate soil moisture conditions (-0.03 MPa) nicosulfuron activity was not influenced by temperature. Nicosulfuron efficacy was not influenced by soil moisture at a cool (11/6 C) temperature. As plant moisture stress increased, due to low soil moisture and increasing air temperature, nicosulfuron efficacy declined. Differences in nicosulfuron efficacy due to growth stage or environmental conditions could not be explained by differential ^{14}C recovery, absorption, translocation, or accumulation. **Nomenclature:** Nicosulfuron, 2-[[[[(4,6-dimethoxy-2-

pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N*,*N*-dimethyl-3-pyridinecarboxamide; quackgrass, *Elytrigia repens* (L.) Nevski #[1] AGRRE.

Additional index words. AGRRE, application timing, control, DPX-V9360, moisture stress, soil moisture, temperature, urea-ammonium nitrate.

Introduction

Nicosulfuron is a postemergence herbicide which provides selective grass and broadleaf weed control in corn (1). This sulfonylurea herbicide inhibits acetolactate synthase (ALS)[2] to effectively block synthesis of the branched-chain amino acids valine, leucine, and isoleucine (1). Previous research concluded that herbicide phytotoxicity resulted from amino acid starvation, however, researchers now believe that accumulation of the toxic metabolite, α-amino butyric acid is responsible for the phytotoxicity induced by an ALS inhibitor (12, 17).

In field studies, nicosulfuron has provided effective control of quackgrass. Shoot regrowth from vegetative reproductive tissues has been observed in some instances (Chapter 2). Quackgrass control was enhanced by the addition of 28% urea-ammonium nitrate liquid fertilizer (UAN)[4] to nicosulfuron plus petroleum oil adjuvant (POA)[4]. Nicosulfuron absorption was greater in the presence of POA plus UAN than with UAN alone. Total recovery of ^{14}C was lower with POA plus UAN treatments, possibly due to greater translocation from the treated leaf (Chapter 2).

Control of quackgrass and johnsongrass [*Sorghum halepense* (L.) Pers.] with

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[1]Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds. Revised 1989. Available from WSSA, 309 West Clark Street, Champaign, IL 61820.

[2]Abbreviations: ALS, acetolactate synthase; UAN, 28% urea-ammonium nitrate liquid fertilizer; POA, petroleum oil adjuvant; HAT, hours after treatment.

nicosulfuron is influenced by growth stage. Phytotoxicity improved when nicosulfuron was applied to larger quackgrass (Chapter 2) and johnsongrass (4, 15) rather than smaller plants. Control differences could not be attributed to differential absorption, translocation, or accumulation of nicosulfuron in johnsongrass (15).

Soil moisture content and air temperature has previously influenced sulfonylurea efficacy. Oyarzabal and Owen (16) observed greatest nicosulfuron activity on well watered woolly cupgrass [*Eriochloa villosa* (Thunb.) Kunth] and shattercane [*Sorghum bicolor* (L.) Moench]. Kochia [*Kochia scoparia* (L.) Schrad.] control with thifensulfuron (3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid) (13) and chlorsulfuron (2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide) (14) was also better at field capacity than when plants were drought stressed. However, velvetleaf (*Abutilon theophrasti* Medicus) control was similar with thifensulfuron regardless of soil moisture (20). Greater herbicide efficacy was observed with lower air temperatures with chlorsulfuron (14), chlorimuron (2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoic acid) (7), and thifensulfuron (20). However, Nalewaja and Adamczewski (13) reported greater kochia control with thifensulfuron when day/night temperatures were increased from 10/8 to 30/24 C. Quackgrass growth is generally suppressed by increasing temperatures (10) which may adversely influence nicosulfuron phytotoxicity.

Quackgrass research was initiated to examine: a) the effect of UAN on the absorption and distribution of nicosulfuron, b) the influence of growth stage on nicosulfuron absorption, distribution, and activity, and c) soil moisture and air temperature effects on nicosulfuron absorption, distribution, and activity in quackgrass.

Materials and Methods

General experimental procedures. Greenhouse experiments were conducted to examine foliar absorption and translocation of ^{14}C-nicosulfuron over time as affected by UAN. Treatments were arranged as a factorial with two herbicide treatments and three harvest timings; 24, 72, and 168 h after application (HAT)[4]. Plants were treated with a foliar application of nicosulfuron (35 g ha^{-1}) plus petroleum oil adjuvant (POA)[4] with and without UAN.

Greenhouse conditions were maintained at 25 C $\pm$ 4 C with a 16-h photoperiod of natural and supplemental metal halide lighting with a midday photosynthetic photon flux density of 1000 $\mu E\ m^{-2}\ s^{-1}$. A rhizome from a slightly pubescent quackgrass biotype was selected from a field in Williamston, MI. This biotype served as a propagation source for all plants to maintain genetic uniformity within studies. Quackgrass plants were raised from single unbranched three-node rhizome segment placed at a 2-cm depth in 1-L plastic pots containing potting medium[3]. Plants were watered as needed and fertilized weekly with 50-ml of water soluble fertilizer solution (400 ppm N, 400 ppm P_2O_5, 400 ppm K_2O). Aphid infestations were controlled with foliar applications of acephate (O,S-dimethyl acetylphosphoramidothioate).

Radiolabeled herbicide solutions were prepared in the laboratory, utilizing 2-pyrimidine ^{14}C-nicosulfuron with a specific activity of 2.3 MBq mg^{-1} and 98.8% purity as determined by high-performance liquid chromatography. Labeled nicosulfuron was dissolved in tetrahydrofuran and then utilized to prepare a 390 Bq μl^{-1} treatment solution. Tetrahydrofuran was then evaporated in a nitrogen stream and replaced with deionized water. The labeled herbicide solution was supplemented with deionized water, formulated

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[3]Baccto Professional Planting Mix. Michigan Peat Company, P O Box 980129, Houston, TX 77098.

nicosulfuron product[4] and formulation blank. Two separate treatment solutions were prepared to include POA[5] at 1% v/v and POA plus UAN at 4% v/v. Final treatment concentrations were 415 μmol nicosulfuron plus 57 mg L^{-1} formulation blank. These concentrations correspond to a broadcast application of nicosulfuron at 35 g ha^{-1} delivered in 206 L water ha^{-1}.

Effect of UAN. Quackgrass plants selected for treatment had two culms each originating from adjacent buds on the parent rhizome. One of these culms had three fully developed leaves while the other culm had not yet developed a true leaf. These three-leaf plants ranged from 20 to 33 cm averaging 25-cm in height. These plants represent the typical quackgrass size and stage observed at the time of field nicosulfuron applications. Prior to herbicide application, the uppermost fully developed leaf (third leaf) was covered with plastic wrap. The plants then received a broadcast foliar application of nicosulfuron (35 g ai ha^{-1}) plus either POA (1% v/v) or POA plus UAN (1% plus 4% v/v). This application was made with a continuous link-belt single nozzle sprayer equipped with a 8001E[6] tip calibrated to deliver 206 L ha^{-1}. Upon drying, the plastic wrap was removed from the third leaf to allow for application of ^{14}C-nicosulfuron. A total of 5480 Bq were delivered from a microsyringe to the third leaf as seven 2-μl droplets of treatment solution.

Plants were harvested at 24, 72, and 168 h after herbicide treatment. At harvest time, the treated leaf was excised and rinsed for 45 s in a scintillation vial containing 3 ml methanol to remove unabsorbed ^{14}C. Leaf washes conducted immediately after ^{14}C

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[4]Accent 75 WDG herbicide. E. I. duPont deNemours and Co., Wilmington, DE 19898.

[5]Herbimax, 83% petroleum oil, 17% adjuvant, a product of Loveland Industries, Inc. PO Box 1289, Greeley, CO 80632.

[6]Teejet flat fan tips. Spraying Systems Co., North Avenue and Schmale Road, Wheaton IL 60188.

application effectively removed at least 98% of the unabsorbed ^{14}C. Plants were uprooted and gently washed in water to remove soil from the roots. Plants were then sectioned into the following seven parts: treated leaf, above treated leaf, below treated leaf (to soil surface), crown, parent rhizome and associated roots, new culms, and new rhizomes. Since few plants had new rhizomes, the data for these parts were pooled with the new culms. All plant parts were frozen and later lyophilized. Dry weights of each part were recorded prior to combustion in a biological sample oxidizer. A mixture of carbon dioxide absorbent and scintillation fluid (1:2 ratio) was used to trap evolved $^{14}CO_2$. Each methanol leaf wash vial received 15-ml scintillation fluid. All samples were then quantified by liquid scintillation spectrometry correcting for quench.

Effect of growth stage. Experiments were conducted to examine the effect of growth stage on nicosulfuron activity, absorption, and distribution in quackgrass. Quackgrass plants were established in the greenhouse as previously described. Plantings were delayed in order to simultaneously obtain plants at one-, three-, and five-leaf growth stages. Quackgrass plant heights averaged 14, 24, and 32-cm for one-, three-, and five-leaf plants, respectively, at the time of herbicide application. At this time, separate control and ^{14}C translocation studies were initiated. To examine quackgrass control, nicosulfuron was applied at 0, 8, 16, and 32 g ha^{-1} with POA at 1% v/v to one-, three-, and five-leaf quackgrass. Treatments were applied to plants as previously described. Quackgrass control was visually evaluated 30 days after treatment.

Radiolabeled nicosulfuron solution was prepared as previously described to contain POA at 1% v/v. The uppermost fully developed quackgrass leaf was covered with plastic wrap. Nicosulfuron (35 g ha^{-1}) plus POA (1% v/v) was applied to the plants as previously described. After removal of the plastic wrap, the leaf was treated with ^{14}C-nicosulfuron solution as previously described. Plants were harvested at 168 HAT and ^{14}C quantified.

Plants were sectioned as previously described except that tillers from the treated culm were treated as an additional section.

Effect of air temperature and soil moisture. Studies were initiated to examine the effect of air temperature and soil moisture on nicosulfuron activity, absorption, and distribution in quackgrass. Treatments were arranged as a factorial with two soil water potentials, -0.03 and -0.2 MPa, and three day/night air temperatures of 11/6, 21/16, and 31/26 C.

Plants were initiated in the greenhouse at 26 $\pm$ 3 C with a 16-h photoperiod of natural and supplemental high-pressure sodium lighting with a midday photosynthetic photon flux density of 1000 $\mu E\ m^{-2}\ s^{-1}$. Three node rhizome segments were planted in 0.5-L pots containing sandy clay loam soil (54% sand, 26% silt, 20% clay) with 2.3% organic matter and pH of 6.7. Plants were maintained as previously described.

Through previous research, a moisture retention curve was developed for this particular soil[7]. From this curve, the soil water content (g/g) could be determined for a specific soil water potential (MPa). At planting, the initial soil moisture content was determined for the soil. This moisture level and the amount of soil (g) in each pot was utilized to establish a specific soil water potential for each pot.

Three days prior to herbicide application, quackgrass plants were selected for uniformity and transferred into growth chambers with day/night temperatures of 11/6, 21/16, and 31/26 C. Chambers were maintained at 60% relative humidity with a 16-h photoperiod from fluorescent and incandescent lighting with a photosynthetic photon flux density of 750 $\mu E\ m^{-2}$ s-1. Each growth chamber contained two groups of plants, well-watered and water-stressed. Plants were watered twice daily to 18 and 9.5% (wt/wt) soil moisture which correspond to water potentials of -0.03 and -0.2 MPa, respectively. These

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[7]Zollinger, Richard K. 1989. Perennial sowthistle (*Sonchus arvensis* L.) distribution, biology and control in Michigan. Ph. D. Dissertation, Michigan State University.

values were established from the soil moisture curve described above.

Separate studies were initiated to examine nicosulfuron activity and ^{14}C distribution. Quackgrass plants for the efficacy study were removed from the growth chamber and treated with nicosulfuron at rates of 0, 8, 16, and 32 g ha^{-1} plus POA (1% v/v) as previously described and then returned to the growth chamber once leaves were dry. Seven days after treatment, all plants were returned to the greenhouse and watered as needed. Thirty days after treatment, all plants were visually evaluated for control.

Plants utilized in the ^{14}C-nicosulfuron absorption and translocation study were pre-sprayed and then treated with ^{14}C-nicosulfuron plus POA as previously described. At the time of application, all plants had three fully developed leaves and averaged 18-cm in height. Within 60 minutes after treatments, plants were returned to the growth chambers and maintained until harvest 168 h later. New culms and new rhizomes were not consistently present on all plants. As a result, ^{14}C accumulation in these parts are not presented, but their contribution to ^{14}C recovery and translocation is included.

Data analysis. Treatments in all studies were arranged as a factorial in a randomized complete block design with four replications repeated over time. All data were subjected to analysis of variance. Significant repeat main effects were observed in some translocation studies, but no repeat by factor interactions were observed. As a result, treatment means presented are the result of the combined analysis. Treatment mean separations were made utilizing Fisher's protected least significant difference at the 5% confidence level. Data representing distribution of nicosulfuron were expressed as a percentage of total radioactivity applied to the plant.

Results and Discussion

Effect of UAN. Recovery of ^{14}C from quackgrass 168 HAT was at least 80% of that applied (Table 1). Recovery decreased as harvest was delayed. The addition of UAN to nicosulfuron plus POA generally resulted in less ^{14}C recovery compared to nicosulfuron plus POA alone. These losses may be attributed to root exudation of ^{14}C (5), metabolism and subsequent release of carbon dioxide (6), or loss of ^{14}C containing roots during plant harvest. Reduced recovery at 168 HAT is presumed to be attributed to a combination of these factors, but research was not conducted to identify the source of these losses. Camacho et al. (3) obtained 88% recovery of applied ^{14}C-nicosulfuron in johnsongrass at 24 HAT.

Foliar absorption of ^{14}C-nicosulfuron when applied with POA increased from 18% to 42% as harvests were delayed from 24 to 168 HAT (Figure 1). These results are contrary to those obtained in Chapter 3 where ^{14}C-nicosulfuron plus POA absorption reached a plateau within the first four hours of a 24 h study. These differences between studies may be due to differences in leaf cuticular wax composition or environmental conditions at the time of application. In addition, the rate of increase in absorption may have been so slow that the increase was not obvious in the 24 h experiment in Chapter 3.

The addition of UAN to ^{14}C-nicosulfuron plus POA provided significantly greater ^{14}C absorption at all harvest times than without UAN. These results concur with those found in Chapter 3 where the addition of 28% UAN to POA increased nicosulfuron absorption in quackgrass. The addition of UAN to nonionic surfactant has also improved thifensulfuron and chlorimuron absorption in velvetleaf (2, 8, 9). Similar absorption of ^{14}C-nicosulfuron was observed with the adjuvants POA plus UAN regardless of harvest time.

Radioactivity in the treated leaf increased from 15 to 30% of applied from 24 to 168 HAT, respectively with POA (Figure 2). With POA plus UAN, 41% of the applied ^{14}C was

Table 1. ^{14}C recovered from quackgrass at 24, 72, and 168 h after application of ^{14}C-nicosulfuron as affected by UAN.

	^{14}C Recovery after application		
Adjuvant[a]	24	72	168 h
	---------- % of applied ----------		
POA	94	92	87
POA + UAN	88	90	80
$LSD_{.05}$[b]	---------- 5 ----------		

[a]Treatment include petroleum oil adjuvant (POA) at 1% v/v with and without 28% urea-ammonium nitrate liquid fertilizer (UAN) at 4% v/v.
[b]Mean comparisons valid within or between columns.

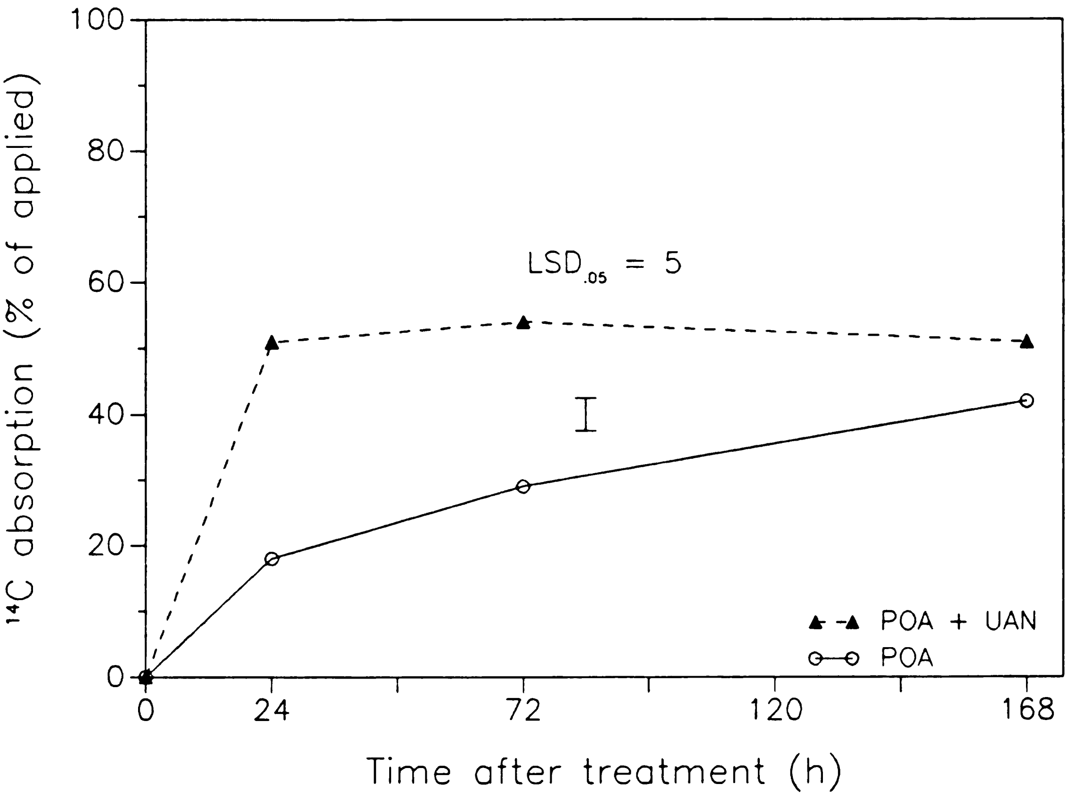

Figure 1. **Foliar absorption of ^{14}C-nicosulfuron in quackgrass as affected by UAN. Treatments included petroleum oil adjuvant (POA) at 1% v/v with and without 28% urea-ammonium nitrate liquid fertilizer (UAN) at 4% v/v.**

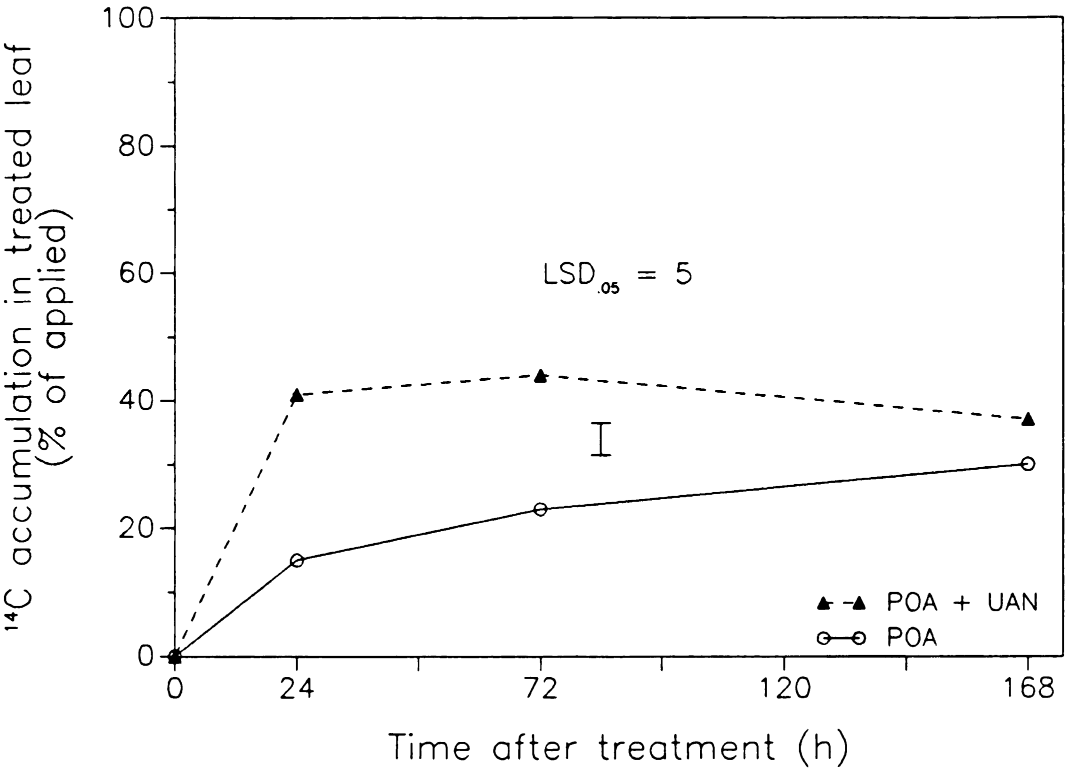

Figure 2. **Accumulation of ^{14}C in the treated leaf of quackgrass as affected by UAN. Treatments included ^{14}C-nicosulfuron plus petroleum oil adjuvant (POA) at 1% v/v with and without 28% urea-ammonium nitrate liquid fertilizer (UAN) at 4% v/v.**

recovered from the treated leaf at 24 HAT. Similar ^{14}C accumulation was observed at 168 HAT. Accumulation of ^{14}C in the treated leaf was greater with POA plus UAN than with POA alone at all harvest times.

Translocation of ^{14}C from the treated leaf during the first 24 HAT progressed more rapidly when the treatment included POA plus UAN compared with POA alone (Figure 3). For treatment with POA alone, 168 HAT were needed to obtain ^{14}C translocation equivalent to that obtained with POA plus UAN at 24 HAT. The accumulation of ^{14}C in the treated leaf and translocation from the treated leaf followed a similar pattern (Figures 2 and 3). This suggests that the amount of ^{14}C translocated from the treated leaf increased as a result of increased ^{14}C concentrations in the treated leaf.

The amount of radioactivity translocated from the treated leaf accounted for less than 15% of that applied (Table 2). Of the total ^{14}C translocated, at least 85% moved to plant parts below the treated leaf and 29% accumulated in below-ground parts and developing shoots. The proportion and direction of ^{14}C translocated indicate that nicosulfuron is phloem mobile in quackgrass. Similar accumulation patterns were observed with nicosulfuron in johnsongrass (3, 15). These studies also reported greater accumulation of ^{14}C in shoot tissue immediately below the treated leaf than in rhizome tissues. Less than 2.5% of the applied ^{14}C accumulated in the crown or parent rhizomes of quackgrass. In johnsongrass, less than 5% of the absorbed ^{14}C was translocated to rhizome tissues (3, 15). Accumulation of ^{14}C in plant parts generally increased over time when POA was used as the adjuvant, but this was not observed with POA plus UAN. These trends were not as evident with ^{14}C concentration. This may be due to the increased variability associated with this type of concentration measurement. The use of POA plus UAN with nicosulfuron provided greater absorption and more rapid translocation than POA alone. Greater nicosulfuron phytotoxicity was observed in Chapter 3 with POA plus UAN than with POA alone. This

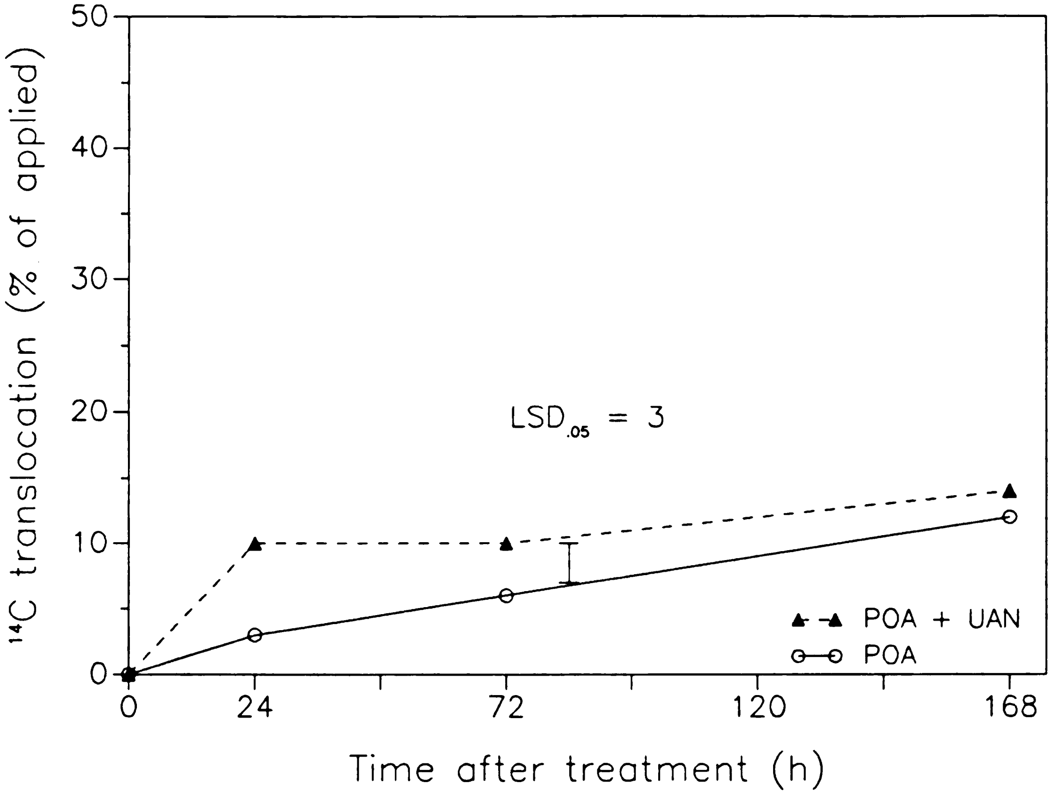

Figure 3. **Translocation of ^{14}C from the treated leaf of quackgrass as affected by UAN. Treatments included ^{14}C-nicosulfuron plus petroleum oil adjuvant (POA) at 1% v/v with and without 28% urea-ammonium nitrate liquid fertilizer (UAN) at 4% v/v.**

Table 2. Accumulation of ^{14}C translocated from the treated leaf at 24, 72, and 168 h after application.

		Accumulation of ^{14}C translocated from the treated leaf							
		Amount				Concentration			
Adjuvant[a]	Plant part	24	72	168 h	$LSD_{.05}$[b]	24	72	168 h	$LSD_{.05}$[b]
		------ % of applied ------				---------- dpm mg^{-1} ---------			
POA	Above treated leaf	0.2	0.8	1.8	0.7	77	96	157	NS
	Below treated leaf	1.2	2.9	6.8	2.7	92	214	560	240
	Crown	0.2	0.5	0.7	0.1	179	410	564	NS
	Parent rhizome	0.5	1.1	1.6	0.7	10	30	40	14
	New shoots	0.4	0.9	1.3	NS	80	128	188	NS
POA + UAN	Above treated leaf	0.9	1.3	2.2	0.6	163	351	347	NS
	Below treated leaf	5.5	5.4	7.1	NS	761	539	472	NS
	Crown	0.7	0.5	0.9	NS	404	357	593	NS
	Parent rhizome	1.4	1.1	2.4	NS	26	54	52	NS
	New shoots	1.1	1.3	1.8	NS	239	311	372	NS

[a]Treatment solutions include ^{14}C-nicosulfuron plus petroleum oil adjuvant (POA) at 1% (v/v) with and without 28% urea-ammonium nitrate liquid fertilizer (UAN) at 4% (v/v).
[b]Mean comparisons valid within rows.

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difference may be explained by greater nicosulfuron absorption and more rapid translocation with POA plus UAN than with POA alone.

Effect of growth stage. Absorption and translocation of ^{14}C-nicosulfuron plus POA was examined in one-, three-, and five-leaf quackgrass to explain differences in quackgrass control. Total recovery of ^{14}C was greater from three- and five-leaf quackgrass than one-leaf plants at 168 HAT (Table 3). These results are possibly due to differences in ^{14}C lost during soil removal from plant roots. The ^{14}C concentration was greater in one-leaf plant roots than either three- or five-leaf plants (data not presented). This concentration difference would result in greater ^{14}C losses for one-leaf than three- or five-leaf plants assuming similar quantities of roots were lost during the harvesting process.

The amount of ^{14}C absorbed and remaining in the treated leaf was greater in one-leaf than in five-leaf quackgrass plants (Table 3). Despite the differences in absorption, the amount of ^{14}C translocated from the treated leaf was similar among all growth stages.

The crown and parent rhizome of one-leaf plants accumulated more ^{14}C than three- or five-leaf plants (Table 4). Translocation of ^{14}C to other plant parts was similar regardless of plant growth stage.

Quackgrass control with nicosulfuron was greater when plants were treated at the three- or five-leaf stage than at the one-leaf stage (Table 5). This effect was observed with application rates of 16 and 32 g ha^{-1} applied with POA alone. In previous field research, four-leaf quackgrass plants were controlled more effectively with nicosulfuron than two-leaf plants (Chapter 2). Other researchers have reported that nicosulfuron efficacy was greater when applied to larger johnsongrass (>five-leaf) rather than smaller plants (4, 15, 19).

Since nicosulfuron absorption and accumulation in vegetative reproductive tissues was greater in one-leaf quackgrass than three- or five-leaf quackgrass, control of one-leaf quackgrass might be expected to be greater than three- or five-leaf quackgrass. However,

Table 3. The effect of quackgrass growth stage on ^{14}C recovery, absorption, and distribution in quackgrass 168 h after ^{14}C-nicosulfuron application[a].

	^{14}C recovered			
	1-leaf	3-leaf	5-leaf	$LSD_{.05}$[b]
	---------------------- % of applied ----------------------			
Total recovery	84	89	90	4
Absorption	34	32	27	6
Treated leaf	26	22	17	6
Translocated[c]	8	10	10	NS

[a]Treatments included petroleum oil adjuvant at 1% v/v.
[b]Mean comparisons valid within rows.
[c]Translocated from the treated leaf.

Table 4. Accumulation of ^{14}C in quackgrass plant parts 168 h after application of ^{14}C-nicosulfuron as affected by growth stage[a].

	Accumulation of ^{14}C translocated from the treated leaf			
Plant part	1-leaf	3-leaf	5-leaf	$LSD_{.05}$[b]
	--------------- % of applied ---------------			
Above treated leaf	1.2	1.3	0.9	NS
Below treated leaf	3.5	6.2	7.0	NS
Tillers	--	1.1	0.5	NS
Crown	1.7	0.5	0.1	0.6
Parent rhizome	1.0	0.6	0.4	0.4
New shoots	0.3	0.2	0.2	NS
New rhizomes	--	0.3	0.9	NS

[a]All treatments included petroleum oil adjuvant at 1% v/v.
[b]Mean comparisons valid within rows.

Table 5. Quackgrass control in the greenhouse with nicosulfuron as affected by quackgrass growth stage.

Nicosulfuron rate[a]	Quackgrass control[b]		
	1-leaf	3-leaf	5-leaf
g ai ha^{-1}	---------- % ----------		
0	0	0	0
8	2	10	10
16	10	41	50
32	51	73	83
$LSD_{.05}$[c]	---------- 14 ----------		

[a]All treatments included petroleum oil adjuvant at 1% v/v.
[b]Evaluated visually 30 days after treatment
[c]Mean comparisons valid within and between columns.

the opposite control results were observed in greenhouse efficacy trials and field experiments (Chapter 2).

Obrigawitch et al. (15) and Camacho et al. (3) observed greater control of johnsongrass with nicosulfuron as plant size increased to 8 leaves. Control differences could not be attributed to differences in translocation, accumulation, or foliar absorption (3, 15). Obrigawitch et al. (15) reasoned that rhizome carbohydrate reserves were at a minimum in the larger growth stages which made plants more susceptible to nicosulfuron applications at this time. This may not be the true for quackgrass. In their review of quackgrass, Holm et al. (10) reported minimum carbohydrate reserves in rhizomes when plants were showing two developed leaves. At this stage, plants are most susceptible to environmental stress or disturbance by man. In our greenhouse and field research, plants with more than two leaves were controlled more effectively with nicosulfuron than plants with two leaves or less.

It is likely that the effect of growth stage on quackgrass control with nicosulfuron is due to differences in spray retention. Since one-leaf plants have less leaf area than three- or five-leaf plants, less spray solution will be intercepted by the one-leaf plants. This reduction in amount of herbicide available for absorption may be responsible for less complete control of one-leaf plants compared to three- or five-leaf plants.

Effect of air temperature and soil moisture. Quackgrass plants exposed to a day/night temperature of 21/16 C with -0.2 MPa soil water potential and 31/26 C with 0.03 and 0.2 MPa were visibly stressed. Symptoms included rolled leaves, growth cessation, and purple discoloration of plant tissue. Approximately three days after treatment, growth of untreated plants resumed for all plants except those at 31/26 C and -0.2 MPa. Plants exposed to 11/6 C did not appear stressed regardless of soil moisture.

The effect of air temperature and soil moisture on translocation of foliar applied ^{14}C-nicosulfuron was examined. At least 86% of applied radioactivity was recovered from plants harvested at 168 HAT (Table 6). Total ^{14}C recovery was not affected by soil moisture, but increasing temperature from 21 C to 31 C reduced recovery. This difference may be attributed to increased metabolism of herbicide to carbon dioxide in plants with increasing temperature. Coupland (6) observed greater ^{14}C-glyphosate metabolism to $^{14}CO_2$ in quackgrass at 26 C than at 10 C.

Absorption and translocation of ^{14}C increased as soil moisture increased within the 21/16 C environment, but no significant differences were observed at 11/6 and 31/26 C (Table 6). Despite differences in translocation at 21/16 C, soil moisture generally did not influence ^{14}C accumulation in individual plant parts (Table 7). Although nicosulfuron phytotoxicity decreased with decreasing soil moisture at 21/16 and 31/26, this response was not explained by differences in nicosulfuron absorption, translocation, or accumulation in vegetative reproductive tissue.

Air temperature had a significant impact on nicosulfuron distribution in quackgrass. Within a soil moisture level, increasing air temperature significantly increased absorbed ^{14}C, ^{14}C in the treated leaf, and ^{14}C translocated from the treated leaf (Table 6). An approximate two-fold increase in nicosulfuron absorption and 4-fold increase in translocation was observed as temperature increased from 11/6 C to 31/26 C. As a result, more radioactivity was recovered in all plant parts as temperature increased (Table 7). Radioactivity concentration (DPM mg^{-1}) also increased with increasing air temperature. Greater ^{14}C accumulation in vegetative reproductive tissues (crown and parent rhizome) with increased temperature, would be expected to result in greater nicosulfuron efficacy, but this was not observed (Table 8).

Nicosulfuron activity from 16 and 32 g ha^{-1} applied to quackgrass was not influenced by temperature when plants were grown with adequate (-0.03 MPa) soil moisture (Table 8). However, quackgrass control decreased as temperature increased from 11/6 to 21/16 C at

Table 6. The effect of day/night air temperature and soil water potential on ^{14}C recovery, absorption, and distribution in quackgrass 168 h after application of ^{14}C-nicosulfuron[a].

	^{14}C recovered						
	-0.03 MPa			-0.2 MPa			
	11/6 C	21/16 C	31/26 C	11/6 C	21/16 C	31/26 C	$LSD_{.05}$[a]
	% of applied						
Recovery	94	94	88	95	93	86	3
Absorbed	13	19	24	10	15	24	4
Treated leaf	12	16	19	9	13	19	3
Translocated[c]	1	3	5	1	2	5	1

[a]All treatments included petroleum oil adjuvant at 1% v/v.
[b]Mean comparisons valid within rows.
[c]^{14}C translocated from the treated leaf.

Table 7. The effect of day/night air temperature and soil water potential on distribution of ^{14}C translocated from the treated leaf 168 h after ^{14}C-nicosulfuron application[a].

	Accumulation of ^{14}C translocated from the treated leaf						
	-0.03 MPa			-0.2 MPa			
Plant part	11/6 C	21/16 C	31/26 C	11/6 C	21/16 C	31/26 C	$LSD_{.05}$[b]
	% of applied						
Above treated leaf	0.1	0.2	0.6	0.1	0.2	0.5	0.1
Below treated leaf	0.4	1.8	2.5	0.4	1.0	2.7	0.7
Crown	0.2	0.4	0.7	0.2	0.3	0.5	0.1
Parent rhizome	0.3	0.5	0.6	0.2	0.4	0.5	0.2
	DPM mg^{-1}						
Above treated leaf	10	21	97	17	15	60	56
Below treated leaf	16	47	54	17	34	78	24
Crown	30	36	71	27	22	69	30
Parent rhizome	10	15	15	8	8	12	6

[a]All treatments included petroleum oil adjuvant at 1% v/v.
[b]Mean comparisons valid within rows.

Table 8. Quackgrass control with nicosulfuron as affected by day/night air temperature, soil water potential, and herbicide rate[a].

Nicosulfuron rate	Quackgrass control[b]					
	-0.03 MPa			-0.2 MPa		
	11/6 C	21/16 C	31/26 C	11/6 C	21/16 C	31/26 C
g ai ha^{-1}	%					
0	0	0	0	0	0	0
8	49	41	52	56	29	27
16	67	66	75	76	51	51
32	88	88	82	90	77	77
$LSD_{.05}$[c]	10					

[a]All treatments include petroleum oil adjuvant at 1% v/v.
[b]Control was evaluated visually 30 days after treatment.
[c]Mean comparisons valid within or between columns.

low soil moisture levels (-0.2 MPa), regardless of nicosulfuron application rate. Research with chlorsulfuron (14), chlorimuron (7), and thifensulfuron (20) has shown greater herbicidal activity at lower temperatures. However, Nalewaja and Adamczewski (13) reported greater kochia control by thifensulfuron when day/night temperatures were increased from 10/8 to 30/24 C.

Soil moisture did not influence the control of plants grown at 11/6 C (Table 8). However at 21/16 and 31/26 C, quackgrass control generally decreased as soil water potential decreased from -0.03 to -0.2 MPa. Oyarzabal and Owen (16) also observed greatest nicosulfuron activity on well watered woolly cupgrass and shattercane. Kochia control with thifensulfuron (13) and chlorsulfuron (14) was better at field capacity than when drought stressed. However, velvetleaf control was similar with thifensulfuron regardless of soil moisture (20).

Differences in nicosulfuron activity not explained by herbicide absorption, translocation, or accumulation may be related to herbicide retention and differential plant metabolism. Less herbicide may have been intercepted and retained by stressed plants. These stressed plants likely had smaller leaf area for spray interception, due to leaf rolling. Rossi and Neal (18) examined fenoxaprop [(±)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid] retention on moisture stressed smooth crabgrass (*Digitaria ischaemum*). They observed a 20% reduction in fenoxaprop retention as soil moisture stress increased to -0.8 MPa. It is likely that decreased nicosulfuron retention is contributing to decreased efficacy of moisture stressed quackgrass.

The effect of moisture stress on plant metabolism rate may also influence nicosulfuron activity. Moisture stressed plants typically accumulate increased levels of amino acids since slower growth rates result in decreased protein synthesis (11). As the demand for amino acids declines in stressed plants, ALS inhibition may have a less pronounced effect than in nonstressed plants where amino acid demand is high. As a result, there may be greater accumulation of α-amino butyric acid in nonstressed plants than stressed plants resulting in greater herbicide phytotoxicity of nonstressed plants (12,17). Future research is needed to determine if plant moisture stress indeed influences the accumulation of α-amino butyric acid in plants treated with an ALS inhibitor.

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