ABSTRACT

CLEMMER, KEVIN CHRISTMAN. Italian ryegrass (*Lolium multiflorum*) Control in Imidazolinone-tolerant Wheat (*Triticum aestivum*).

Italian ryegrass is the most problematic weed of small grains in North Carolina. This weed has traditionally been controlled in wheat with diclofop. However, after many years of continuous use, much of the Italian ryegrass in the state is now resistant to diclofop.

A field experiment was conducted at three locations to determine control of Italian ryegrass and response of imidazolinone-tolerant wheat to imazamox and other herbicides. Imazamox ammonium salt applied POST in the fall to 3- to 4-leaf Italian ryegrass at 35 to 53 g ae/ha controlled Italian ryegrass 90 to 100% 10 weeks after treatment. Late-season control ranged from 83 to 98% at two locations and 24 to 55% at the third location. Late-season control from spring-applied imazamox on 1- to 3-tiller ryegrass ranged from 53 to 58% at one location and 7 to 16% at the other locations. Split application of imazamox at 27 g/ha in the fall and 27 g/ha in the spring was less effective than fall-applied imazamox at 53 g/ha at two of three locations. However, split application was more effective than spring application. Fall-applied imazamox was less effective than fall-applied diclofop on diclofop-susceptible Italian ryegrass but more effective on mixed populations of diclofop-resistant and -susceptible biotypes. Pendimethalin applied PRE at 1120 g ai/ha increased late-season control 10 to 33 percentage points when used in combination with fall-applied imazamox at 35 g/ha. Imazethapyr ammonium salt at 70 g ae/ha was less effective than imazamox, while imazethapyr at 47 g/ha plus imazapyr isopropylamine salt at 16 g ae/ha and imazamox were similarly effective. Imazapic ammonium salt at 70 g ae/ha and imazamox at 53 g/ha were similarly effective at two locations, while imazapic was more effective at the third location. Imidazolinone herbicides caused only minor, temporary chlorosis on the wheat. In greenhouse experiments, a diclofop-susceptible biotype of Italian ryegrass was more sensitive to imazamox than a diclofop-resistant biotype.

Imazamox controls Italian ryegrass in imidazolinone-tolerant wheat but is only marginally effective on some broadleaf species. A fallow-area field experiment was conducted at three locations in North Carolina to determine control of Italian ryegrass by imazamox as affected by imazamox rate, weed size at application, and mixtures with the broadleaf herbicides 2,4-D, dicamba, and thifensulfuron plus tribenuron. Interactions of imazamox rate, weed size, and broadleaf herbicides were not observed. Italian ryegrass control 56 days after treatment increased as imazamox rate increased. Pooled over weed sizes at application and mixtures, imazamox at 27, 35, and 44 g/ha controlled Italian ryegrass 44, 53, and 67%, respectively, at two locations and 83, 86, and 91% at the third location. Control decreased as weed size at time of application increased. Pooled over imazamox rates and mixtures, Italian ryegrass was controlled 86, 54, and 24% at two locations when herbicides were applied to 2-leaf, 4-leaf, and 2-tiller weeds, respectively. At the third location, Italian ryegrass was controlled 95, 94, and 71% when treated at the 2-leaf, 4-leaf, and 2-tiller stages, respectively. Small increases in control were sometimes noted with mixtures of imazamox and 2,4-D dimethylamine salt at 530 g ae/ha or thifensulfuron plus tribenuron at 18 plus 9 g ai/ha, while minor decreases were sometimes noted with mixtures of imazamox and dicamba diglycolamine salt at 140 g ae/ha. In a greenhouse experiment, mixing 2,4-D with imazamox did not affect Italian ryegrass control. Dicamba reduced control, while thifensulfuron plus tribenuron increased control.

ITALIAN RYEGRASS (*Lolium multiflorum*) CONTROL IN

IMIDAZOLINONE–TOLERANT WHEAT (*Triticum aestivum*)

by

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This thesis is dedicated in honor of my Daddy and Mama

"Without their never ending love and support, none of

my accomplishments would have been possible."

Lewis Christman Clemmer Jr.

Joyce Sockwell Clemmer

BIOGRAPHY

Kevin C. Clemmer grew up on his family's farm near Burlington, NC. His parents, Lewis and Joyce Clemmer, are currently farming and still reside on the farm, where they received the Farm Family of the Year award (1999).

Kevin graduated from Southern Alamance High School, Graham, North Carolina in 1995. He attended East Carolina University and North Carolina A&T State University before he enrolled at North Carolina State University in 1997 and received the Bachelor of Science degree in Agronomy in 1999. Kevin was very active and involved during his undergraduate career. His university affiliations included: Agri-Life Council representative; Agronomy Club, Alpha Zeta, and Farmhouse Fraternity. While participating in these activities, Kevin received the G.C. Klingman Apprenticeship, the N. C. State Leadership Certificate, and placed third in the ASA, SSA Research Symposium Speech Contest.

When not in school, Kevin spent his time working on the family dairy farm and growing alfalfa, corn, wheat, and soybeans as well as working as an undergraduate research assistant under Dr. Alan York. Kevin graduated *Cum Laude* in December of 1999. Upon graduating, he pursued a Master of Science degree in the Crop Science Department, concentrating in weed science under the direction of Dr. Alan York. As a graduate student, he became a member of The Honor Society of Gamma Sigma Delta. Kevin was also the Crop Science Graduate Student Association Treasure and Finance Chair for the Earl A. Wernsman Seminar.

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The only way I have been able to accomplish the things in my life is through hard work and great friends to help me along the way.

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Literature Review

Italian ryegrass (*Lolium multiflorum* Lam.) is the most problematic weed of small grains in North Carolina. It is a winter annual grass weed that germinates from early fall through late winter. It is used as a forage crop but is also a major weed in small grains, turf, and nurseries. Italian ryegrass has been listed as one of the 10 most troublesome weeds of wheat in 10 of the 13 southern states (Elmore 1988).

Wheat (*Triticum aestivum*) and Italian ryegrass possess similar life forms, life histories, and physiological and phenotypical characteristics (Concannon 1987). Both species emerge at nearly the same time under favorable conditions and exert similar demands for light, water, and nutrients (Concannon 1987; Hoveland et al. 1976). Italian ryegrass is usually more erect and taller than wheat. Competition is aggravated when critical stages of growth and development of species overlap. A taller species in the mixture is expected to compete more effectively for light than a shade-intolerant species with similar relative growth rates (Liebl and Worsham 1987b; Smith and Levick 1974).

A decrease in light availability from plant establishment to spike initiation caused decreased wheat tiller production and grain yield (Wiley and Holliday 1971). Competition for light during vegetative growth reduced the number of grains per spikelet (Smith and Levick 1974). In a competition study between wheat and Italian ryegrass in Oregon, wheat was noted as the stronger competitor during the vegetative stages, but ryegrass was the stronger competitor during the reproductive stages (Hashem et al. 1998). During the reproductive stages, Italian ryegrass was taller, had more leaf area and longer duration, greater leaf:weight ratio, and greater specific leaf area:weight ratio. Wheat dominated in the top leaf canopy layer in the mixture during the vegetative stages while Italian ryegrass dominated during reproductive stages. In mixtures, the relative leaf area index (LAI) of ryegrass at the top canopy layer explained 66% of the total variance in grain yield of wheat (Hashem et al. 1998).

The presence of Italian ryegrass very early in the growing season at a "low" density (450 plants/m^2) reduced wheat growth (Smith and Levick 1974). Italian ryegrass decreased grain and straw yield of wheat (Stone et al. 1993). In a competition study conducted in Oregon, nine ryegrass plants/m^2 in mixture with 100 plants/m^2 of wheat reduced wheat grain yield by 33% (Hashem et al. 1998). In North Carolina, wheat grain yields were reduced an average of 5% for each 10 Italian ryegrass plants/m^2 (Liebl and Worsham 1987b). Wheat yield reductions increased from 10 to 30% when Italian ryegrass densities were increased from 10 to 40 plants/m^2 (Appleby et al. 1976). As a result of competition with Italian ryegrass, grain yield of winter wheat was reduced by as much as 50% (Appleby et al. 1976; Lee et al. 1999).

Rerkasem et al. (1980) found that the competitive ability of annual ryegrass was lowest when it germinated after wheat and highest when it germinated before wheat. Ryegrass was at a disadvantage when both emerged simultaneously. However, severe populations can reduce wheat tillering, cause lodging, and interfere with harvesting due to the weed's later maturity (Justice et al. 1994). Severe infestations also decrease harvesting efficiency, contaminate grain, and reduce test weight.

Wheat growers have had few options to control Italian ryegrass. Growers have relied primarily upon the herbicide diclofop {(±)-2-[4-(2,4-dichlorophenoxy)phenoxy] propanoic acid}. Diclofop was first available to North Carolina growers under an emergency exemption in October of 1980 and then under federal registration in 1982.[1] Diclofop has been used successfully to control Italian ryegrass in wheat (Brewster et al. 1977; Khodayari et al. 1983). Diclofop applied preemergence or postemergence

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[1]Davis, C. 2001. Personal communication. Food and Drug Protection Division, Pesticide Section, North Carolina Department of Agriculture, Raleigh.

controlled Italian ryegrass well in North Carolina experiments (Liebl and Worsham 1987a). With diclofop being the only option growers had for Italian ryegrass control for many years, it was used continuously.

Existence of biotypes of Italian ryegrass not controlled by diclofop at field rates was first noted in Oregon in 1987 (Stanger and Appleby 1989). Italian ryegrass resistance to diclofop has also been reported in North Carolina (Heap 2002). Beginning about 1990, growers began to have failures with diclofop, and soon it became obvious that resistance to diclofop had evolved. Diclofop-resistant Italian ryegrass biotypes are now widespread in North Carolina, and options for control are limited.

Research has been conducted using flurtamone {(($\pm$)-5-(methylamino)-2-phenyl-4-[3-(trifluoromethyl)phenyl]-3(2*H*)-furanone)}, chlorsulfuron {(2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] benzenesulfonamide)}, chlorsulfuron plus metsulfuron {(2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino] sulfonyl]benzoic acid)}, metribuzin {(4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one)}, and other compounds as alternatives to diclofop with mixed results (Bridges 1990; Justice et al. 1994; Klingman and Peeper 1989; Lee et al. 1999; Liebl and Worsham 1987a).

Chlorsulfuron is registered for suppression of Italian ryegrass in wheat when applied preemergence at 35 g ai/ha (Anonymous 1999a). Chlorsulfuron controlled Italian ryegrass from 73 to 98% when applied preemergence at 18 and 35 g/ha (Griffin 1986). Variable control of Italian ryegrass was reported in Oklahoma (10 to 70%) with chlorsulfuron at 18 and 26 g/ha applied preemergence (Justice et al. 1994). Control was poor when Italian ryegrass emerged before herbicide activation by rainfall.

Sulfosulfuron {(1-(2-ethylsulfonylimidazo-[1,2a]pyridin-3-ylsulfonyl)-3-(4,6-dimethoxypyrimidin-2-yl)urea)} was registered in 1999 to control Italian ryegrass and other weeds in spring and winter wheat (Anonymous 1999a). In Idaho, sulfosulfuron applied postemergence to wheat at 35 g ai/ha controlled 2- to 3- and 6- to 8-leaf Italian ryegrass 45 and 65%, respectively (Rauch and Thill 1999).

BAY MKH 6562 (1-*H*-1,2,4-triazole-carboxamide, 4,5-dihydro-3-methoxy-4-methyl-5-oxo-*N*-[[2-(trifluoromethoxy)phenyl]sulfonyl]-sodium salt) is being developed to control or suppress Italian ryegrass and other weeds in wheat (Anonymous 1999b). In Idaho, 30 g ai/ha of MKH 6562 applied to 2- to 3-leaf and 6- to 8-leaf wheat controlled Italian ryegrass 66 and 52%, respectively (Rauch and Thill 1999). In North Carolina, the only labeled alternatives for diclofop-resistant Italian ryegrass control is a pre-mixture of chlorsulfuron plus metsulfuron and metribuzin.

A pre-packaged mixture of chlorsulfuron plus metsulfuron (5:1 w/w) is registered for suppression of Italian ryegrass when applied preemergence (PRE) at 26 g ai/ha (Anonymous 1999a). Chlorsulfuron plus metsulfuron can limit re-cropping to soybeans [*Glycine max* (L.) Merr.] due to plant-back restrictions (Anonymous 1999a). Double-cropping soybeans behind wheat is a common practice in North Carolina. Applying chlorsulfuron plus metsulfuron would eliminate this practice unless sulfonylurea-tolerant soybeans were planted.

In Louisiana, metribuzin applied at 420 g ai/ha controlled 2- to 4-leaf Italian ryegrass 97 to 98% but increased wheat yield in only 1 of 2 years because of wheat injury (Griffin 1986). Wheat yields have been variable in all research where metribuzin has been applied because of crop injury (Griffin 1986; Kinfe and Peeper 1991). Due to unacceptable crop injury and yield losses, metribuzin is not recommended for Italian ryegrass control in North Carolina. Inconsistent Italian ryegrass control has led to weed control problems for growers selecting between Italian ryegrass control options. Other options are needed for successful control of Italian ryegrass in North Carolina.

Imidazolinone-tolerant wheat, a non-transgenic cultivar, has been developed. Imidazolinone-tolerant wheat was identified by screening M^2 seed (Newhouse et al.

1992). Seeds of the winter wheat cultivar Fidel were mutagenized by imbibing seeds with sodium azide (Newhouse et al. 1992). The seed were then planted in the field, and the progeny were harvested at maturity. This generation of seeds was germinated in the presence of imazethapyr {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid}. Plants that survived were further screened by postemergence treatments of imazethapyr (Newhouse et al. 1992). Four plants, known as FS 4 plants, survived these treatments. It is not known whether the four selections represent the same or different mutational events (Newhouse et al. 1992). The herbicide tolerance trait from selected plants was inherited as a single dominant or semidominant gene (Shaner et al. 1984).

Imidazolinone herbicides inhibit activity of acetolactate synthase (ALS) (4.1.3.18), the first enzyme in the pathway for the synthesis of the branched-chain amino acids valine, leucine, and isoleucine (Stidham 1991). Once in the phloem and translocated to the site of action, imidazolinones inhibit ALS, causing death of meristematic cells resulting in plant death (Little and Shaner 1991). Imidazolinone herbicides have good flexibility in timing of application, low use rates, and low mammalian toxicity (Newhouse et al. 1992). Although death takes several weeks, imidazolinone herbicides control a wide spectrum of dicotyledonous and monocotyledonous weeds, including several winter annual grass species. The imidazolinone herbicide targeted for use with the imidazolinone-tolerant wheat is imazamox {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid}.

Imazamox controls a broad spectrum of annual grass weeds, including jointed goatgrass [*Aegilops cylindrica* (L.) Host.], downy brome (*Bromus tectorum* L.), wild oat (*Avena fatua* L.), Italian ryegrass, and others (Ball and Walenta 1997; Belles and Thill 1998; Gamroth et al. 1997; Neider and Thill 1997). However, imazamox is only marginally effective on wild garlic (*Allium vineale*) and some broadleaf species, including cutleaf evening primrose (*Oenothera laciniata*) and dandelion (*Taraxacum officinale*) (Anonymous 2002).

It would be advantageous to mix imazamox with commonly used broadleaf herbicides in order to broaden the spectrum of weed control and eliminate the time and expense of separate spray applications. Tank-mixture decisions depend primarily on weed density, weed species and size, rotational crop restrictions, interactions between herbicides, resistance management strategies, and cost effectiveness (Nelson et al. 1998).

Certain broadleaf herbicides can negatively affect the activity of Italian ryegrass herbicides. Researchers have found the efficacy of diclofop on wild oat was lower when tank mixed with chlorsulfuron (O'Sullivan and Kirkland 1984), MCPA {(4-chloro-2-methylphenoxy)acetic acid} (Olson and Nalewaja 1977), tribenuron {2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino] sulfonyl]benzoic acid} (Baergh et al. 1996), or 2,4-D {(2,4-dichlorophenoxy) acetic acid} (Fletcher and Drexler 1980; Todd and Stobbe 1980).

Tank mixtures of imazamox with commonly used broadleaf herbicides could broaden the spectrum of weed control in imidazolinone−tolerant wheat. There is, however, little information on antagonism with imazamox mixed with commonly used broadleaf herbicides.

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CHAPTER 2

Italian Ryegrass (*Lolium multiflorum*) Control in Imidazolinone-Tolerant Wheat (*Triticum aestivum*)[1]

KEVIN C. CLEMMER and ALAN C. YORK[2]

Abstract: Italian ryegrass is the most problematic weed of small grains in North Carolina. After many years of continuous use, much of the Italian ryegrass in the state is now resistant to diclofop. A field experiment was conducted at three locations to determine control of Italian ryegrass and response of imidazolinone-tolerant wheat to imazamox and other herbicides. Imazamox ammonium salt applied POST in the fall to 3- to 4-leaf Italian ryegrass at 35 to 53 g ae/ha controlled Italian ryegrass 90 to 100% 10 wk after treatment (WAT). Late-season control ranged from 83 to 98% at two locations and 24 to 55% at the third location. Late-season control from spring-applied imazamox on 1- to 3-tiller ryegrass ranged from 53 to 58% at one location and 7 to 16% at the other locations. Split application of imazamox at 27 g/ha in the fall and 27 g/ha in the spring was less effective than fall-applied imazamox at 53 g/ha at two of three locations. However, split application was more effective than spring application. Fall-applied imazamox was less effective than fall-applied diclofop on diclofop-susceptible Italian ryegrass but more effective on mixed populations of diclofop-resistant and -susceptible biotypes. Pendimethalin applied PRE at 1120 g ai/ha increased late-season control 10 to 33 percentage points when used in combination with fall-applied imazamox at 35 g/ha.

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Imazethapyr ammonium salt at 70 g ae/ha was less effective than imazamox, while imazethapyr at 47 g/ha plus imazapyr isopropylamine salt at 16 g ae/ha and imazamox were similarly effective. Imazapic ammonium salt at 70 g ae/ha and imazamox at 53 g/ha were similarly effective at two locations, while imazapic was more effective at the third location. Imidazolinone herbicides caused only minor, temporary chlorosis on the wheat. In greenhouse experiments, a diclofop-susceptible biotype of Italian ryegrass was more sensitive to imazamox than a diclofop-resistant biotype.

Nomenclature: chlorsulfuron, {(2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide)}; diclofop, {((±)-2-[4-(2,4-dichlorophenoxy) phenoxy] propanoic acid)}; flurtamone, {((±)-5-(methylamino)-2-phenyl-4-[3-(trifluoromethyl)phenyl]-3(2*H*)-furanone)}; imazamox, {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid}; imazapic, {(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-methyl-3-pyridinecarboxylic acid}; imazapyr, {(±)-2-[4,5-dihydro-4-methyl-4-(1-methyl ethyl)-5-oxo-1*H*-imidazol-2-yl]-3- pyridinecarboxylic acid}; imazethapyr, {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid}; metribuzin, {4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one}; metsulfuron, {2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino] sulfonyl]benzoic acid}; pendimethalin, {*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitro-benzenamine}; Italian ryegrass, *Lolium multiflorum* L. #[3] LOLMU; wheat, *Triticum aestivum* L.

Additional index words: Clearfield wheat, diclofop, herbicide-resistant biotypes,

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[3]Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

imazamox, imazapic, imazapyr, imazethapyr, pendimethalin.

Abbreviations: ALS, acetolactate synthase; ANOVA, analysis of variance; DAT, days after treatment; I_{80}, rate required for 80% control or 80% fresh weight reduction; IMI-tolerant, imidazolinone-tolerant; POST, postemergence; PRE, preemergence; WAT, weeks after treatment.

INTRODUCTION

Italian ryegrass is the most problematic weed of small grains in North Carolina. Severe populations can reduce wheat tillering, cause lodging, and delay harvesting due to the weed's later maturity (Justice et al. 1994). Severe infestations also decrease harvesting efficiency, contaminate grain, and reduce test weight. Yield losses of 30% are common when Italian ryegrass is left uncontrolled, while researchers have shown yields can be reduced greater than 50% (Lee et al. 1999). Liebl and Worsham (1987b) reported a 5% yield loss for every 10 Italian ryegrass plants/m^2.

Diclofop, first available to North Carolina growers under an emergency exemption in October of 1980 and then under federal registration in 1982[4], applied PRE or POST has been used successfully to control Italian ryegrass in wheat (Brewster et al. 1977; Khodayari et al. 1983; Liebl and Worsham 1987a). Diclofop was the only acceptable option for control for many years, and growers used it continuously. Biotypes of Italian ryegrass resistant to field rates of diclofop were first reported in Oregon in 1987 (Stanger and Appleby 1989). Italian ryegrass resistant to diclofop was reported in North Carolina in 1990 (Heap 2002). Diclofop-resistant Italian ryegrass is now widespread in North Carolina, and options for control are limited.

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[4]Davis, C. 2001. Personal communication. Food and Drug Protection Division, Pesticide Section, North Carolina Department of Agriculture, Raleigh.

Research has been conducted using flurtamone, chlorsulfuron, chlorsulfuron plus metsulfuron, metribuzin, and other compounds as alternatives to diclofop with mixed results (Bridges 1990; Justice et al. 1994; Klingman and Peeper 1989; Lee et al. 1999; Liebl and Worsham 1987a). Prior to the recent registration of imazamox, the only alternatives for diclofop-resistant Italian ryegrass control in North Carolina were chlorsulfuron plus metsulfuron and metribuzin.

A pre-packaged mixture of chlorsulfuron plus metsulfuron (5:1 w/w) applied PRE at 26 g ai/ha is registered for suppression of Italian ryegrass (Anonymous 1999). Italian ryegrass control by chlorsulfuron plus metsulfuron has been variable in North Carolina (A.C. York, unpublished data). Chlorsulfuron plus metsulfuron also can limit re-cropping flexibility due to plant-back restrictions for soybeans (*Glycine max*) (Anonymous 1999). Wheat tolerance of metribuzin, at rates necessary to control Italian ryegrass, has generally been inadequate in North Carolina.[5] In Louisiana, metribuzin applied at 420 g ai/ha controlled 2- to 4-leaf Italian ryegrass 97 to 98% but increased wheat yield in only 1 of 2 yr because of wheat injury (Griffin 1986).

Non-transgenic, imidazolinone-tolerant (IMI-tolerant) wheat has recently been commercialized. IMI-tolerant wheat was identified by screening M_2 seed (Newhouse et al. 1992). Seeds of the winter wheat cultivar Fidel were mutagenized by imbibing with sodium azide. The seed were then planted in the field, and the progeny were harvested at maturity. This generation of seeds was germinated in the presence of imazethapyr. Plants that survived were further screened for tolerance to imazethapyr applied POST. Four plants, known as FD 4 plants, survived these treatments. It is not known whether the four selections represent the same or different mutational events (Newhouse et al.

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[5]Lewis, W.M. 2001. Personal communication. Professor Emeritus, Crop Science Department, North Carolina State University, Raleigh.

1992). The herbicide tolerance trait from selected plants was inherited as a single dominant or semidominant gene (Shaner et al. 1984).

Imidazolinone herbicides inhibit activity of acetolactate synthase (ALS) (4.1.3.18), the first enzyme in the pathway for the synthesis of the branched-chain amino acids valine, leucine, and isoleucine (Stidham 1991). Once in the phloem and translocated to the site of action, imidazolinones inhibit ALS, causing death of meristematic cells resulting in plant death (Little and Shaner 1991). Imidazolinone herbicides have good flexibility in timing of application, low use rates, and low mammalian toxicity (Newhouse et al. 1992). Although death takes several weeks, imidazolinone herbicides control a wide spectrum of dicotyledonous and monocotyledonous weeds, including several winter annual grass species.

Imazamox is the imidazolinone herbicide targeted for use on IMI-tolerant wheat. Imazamox controls a number of annual grass weeds, including jointed goatgrass [*Aegilops cylindrica* (L.) Host.], downy brome (*Bromus tectorum* L.), wild oat (*Avena fatua* L.), Italian ryegrass, and others (Anonymous 2002; Ball and Walenta 1997; Belles and Thill 1998; Gamroth et al. 1997; Neider and Thill 1997).

The objective of this study was to evaluate wheat response and Italian ryegrass control by imazamox applied POST as affected by rate and time of application and by pendimethalin applied PRE. Additional objectives were to compare control by imazamox with that of other imidazolinone herbicides and diclofop, and to compare the response of diclofop-susceptible and -resistant biotypes to imazamox.

MATERIALS AND METHODS

Field Experiment. The experiment wase conducted on private farms near Alamance and Whitsett, NC during the 1999-2000 season and on the Central Crops Research Station at Clayton, NC in 2000-01. Soils included Mecklenburg clay loam (fine, mixed, active, thermic Hapludalfs) with 1.8% organic matter and pH 5.8 at Alamance, Enon clay loam (fine, mixed, active, thermic Ultic Hapludalfs) with 1.3% organic matter and pH 5.3 at Whitsett, and Gilead sandy loam (fine, kaolinitic, thermic, Aquic Hapludalfs) with 1.4% organic matter and pH 6.0 at Clayton.

The Alamance location was heavily infested with diclofop-susceptible Italian ryegrass. The initial Italian ryegrass density was 3,000 plants/m^2, but this number decreased over time due to intraspecific competition. However, the Italian ryegrass gave 100% ground coverage throughout the season. The Whitsett location had a mixture of diclofop-resistant and -susceptible Italian ryegrass biotypes at a density of 150 plants/m^2. The Clayton location had a light infestation of diclofop-susceptible ryegrass. To augment the population, diclofop-resistant Italian ryegrass was spread over the field after wheat planting and lightly covered using a culti-packer. The resulting Italian ryegrass density at that location was 80 plants/m^2.

An experimental line of IMI-tolerant wheat, 'CV 9804', was planted into conventionally prepared seedbeds on 27 October, 1 November, and 6 November at Alamance, Whitsett, and Clayton, respectively. Row spacing was 19 cm and plot size was 1.5 by 15 m. The experimental design was a randomized complete block with treatments replicated four times.

Treatments included the following: imazamox at 35, 44, and 53 g/ha applied POST in the fall or spring; imazamox at 27 g/ha applied in the fall followed by imazamox at 27 g/ha applied in the spring; diclofop at 800 g/ha applied in the fall or 1120 g/ha applied in the spring; pendimethalin applied PRE at 1120 g ai/ha followed by imazamox applied POST at 35 g/ha in the fall or spring; pendimethalin applied PRE followed by diclofop applied POST at 800 g/ha in the fall or 1120 g/ha in the spring; and imazapic at 70 g/ha, imazethapyr at 70 g/ha, and imazethapyr plus imazapyr at 47 plus 16 g/ha applied in the fall.

Pendimethalin was applied the same day as wheat planting. Fall and spring POST treatments were applied approximately 4 and 16 wk after planting, respectively. Wheat and Italian ryegrass each had 3 to 4 leaves at time of fall applications. Spring applications were made to 2- to 4-tiller wheat and 2- to 3-tiller Italian ryegrass. All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles calibrated to deliver 140 L/ha at 147 kPa and 4.8 km/h. All POST treatments except diclofop included 30% urea ammonium nitrate solution at 2.5% (v/v) and a nonionic surfactant[6] at 0.25% (v/v).

Weed control and wheat injury from fall-applied treatments were estimated visually 4, 6, 10, 15, and 22 WAT. Weed control and wheat injury from spring-applied treatments were estimated 4 and 10 WAT. The 22-WAT evaluation for fall-applied treatments was made at the same time as the 10-WAT evaluation for spring-applied treatments. A scale of 0 (no control or injury) to 100% (complete control or crop death) was used. Foliar chlorosis, stunting, and population reductions were considered in making the visual estimates. Yield was not recorded as agreements with the seed supplier required destruction of the wheat prior to maturity.

Data for Italian ryegrass control with fall-applied imazamox at 53 g/ha, spring-applied imazamox at 53 g/ha, and the split application of 27 g/ha in the fall and spring were subjected to analysis of variance (ANOVA). In a separate ANOVA, Italian ryegrass control with fall-applied diclofop and all the imidazolinone herbicides was compared. Data from fall and spring applications of imazamox and diclofop were subjected to ANOVA with partitioning appropriate for a four (herbicide) by two (time of application) factorial treatment arrangement. Data for imazamox and diclofop applied POST in the

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[6]Induce (mixture of alkyl polyoxylkane ether, free fatty acids, and isopropanol). Helena Chemical Co., 5100 Poplar Avenue, Memphis, TN 38137.

fall and spring with and without pendimethalin PRE were subjected to a separate ANOVA with partitioning for a two (pendimethalin rates) by four (POST herbicides) factorial treatment arrangement. Means were separated using Fisher's Protected LSD test at P = 0.05. Nontransformed data are presented as arcsine square root transformation of visual estimates did not affect conclusions.

Greenhouse Experiment. The experiment was conducted in a greenhouse at North Carolina State University from September 1999 to March 2000 and from September 2000 to February 2001. Plants were grown with approximate day/night temperatures of 20/10 C and were watered overtop daily. Sunlight was supplemented with metal halide lamps (300 mol m^{-2} s^{-1} photosynthetic photon flux) set on a 12-h photoperiod. Italian ryegrass seed were planted in 12-cm round pots containing a loamy sand soil (82% sand, 8% silt, 8% clay) with 1.3% organic matter and pH 5.6.

Individual pots were planted with diclofop-susceptible Italian ryegrass seed collected in Johnston County, NC or diclofop-resistant seed collected in Union County, NC. Following seedling emergence, the grass was thinned to five plants per pot. All pots received 20 ml of a 15 g/L commercial greenhouse fertilizer[7] solution at 14 d after planting and 14 d after treatment (DAT).

Treatments applied to each biotype included imazamox at 0, 5, 10, 15, 20, 25, 30, 35, 40, and 60 g/ha and diclofop at 0, 60, 120, 180, 240, 300, 360, 480, 600, 1200, and 1800 g/ha. Imazamox treatments included 30% urea ammonium nitrate solution at 2.5% (v/v) and a nonionic surfactant[6] at 0.25% (v/v). Herbicides were applied using a spray chamber equipped with a single even-spray, flat-fan nozzle calibrated to deliver 160 L/ha at 200 kPa and 2.4 km/h when Italian ryegrass was 9 to 12 cm tall with 1 to 3 leaves.

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[7]Fertilizer, Peters Professional All Purpose 20-20-20, Scotts-Sierra Horticultural Products Co., 14111 Scottslawn Road, Marysville, OH 43041.

Visual estimates of control were recorded 14 and 28 DAT using the scale mentioned previously. Plants were clipped at the soil level and shoot fresh weight was recorded 28 DAT.

The experimental design was a randomized complete block with treatments replicated four times, and the test was repeated twice. Data were subjected to ANOVA and nonlinear regression analysis. Parameter estimates and R^2 values were determined according to Draper and Smith (1981). From the fitted regressions, the rate of imazamox and diclofop required for 80% visible control or fresh weight reduction (I_{80}) was determined. The I_{80} values for imazamox were compared using ANOVA followed by single degree of freedom contrasts.

RESULTS AND DISCUSSION

Field Experiment. *Weed Control.* Treatment by location interactions prevented pooling data across locations. A significant application timing by herbicide interaction occurred for fall and spring applications of imazamox and diclofop at all locations. Italian ryegrass control at Clayton 4 WAT and late in the season was similar with diclofop applied in the fall and spring (Table 1). Control ranged from 67 to 69% 4 WAT and 57 to 61% late in the season. It was observed that about 60% of the plants were controlled completely while the remainder were unaffected. This response is expected with a mixed population of diclofop-susceptible and -resistant biotypes. Diclofop was somewhat more effective 4 WAT when applied in the fall at Whitsett. However, most of the Italian ryegrass at this location appeared to diclofop-resistant, and very poor late-season control was obtained regardless of time of application.

Diclofop was much more effective when applied in the fall at Alamance (Table 1). Complete control by fall-applied imazamox was noted 10 WAT. Control decreased to 90% by late-season due to ryegrass emergence after herbicide application. Diclofop applied in the spring controlled Italian ryegrass only 3% late in the season.

Imazamox was more effective on Italian ryegrass when applied in the fall as compared with spring applications. Italian ryegrass control 4 WAT with imazamox was similar with fall and spring applications at Alamance (Table 1). A rate response was noted only with the fall applications, where control 4 WAT with imazamox at 53 g/ha exceeded control by imazamox at 35 or 44 g/ha. Control by imazamox progressed slowly, and peaked about 10 WAT. Control 10 WAT with fall-applied imazamox at Alamance was at least 90% whereas control 10 WAT with spring-applied imazamox (late-season rating) was 10% or less. Control by fall-applied imazamox decreased between 10 WAT and late-season due to new weed emergence and regrowth on treated plants (Table 1 and Figure 1). Control late in the season by fall-applied imazamox at 53 g/ha was only 55% compared with 90% control by diclofop.

Italian ryegrass control by imazamox at Whitsett and Clayton was more effective with the fall applications at both 4 WAT and late in the season (Table 1). Control by fall-applied imazamox was 22 to 37 and 28 to 82 percentage points greater at 4 WAT and late in the season, respectively, than with spring-applied imazamox. A response to imazamox rates was noted only late in the season at Whitsett, where imazamox applied in the fall at 53 g/ha was more effective than imazamox at 35 g/ha. Control by the fall applications decreased much less between 10 WAT and late in the season at Clayton and Whitsett than at Alamance (Table 1 and Figure 1). This may have been at least partially due to the extremely heavy Italian ryegrass infestation at Alamance and the resulting poorer spray coverage on individual plants.

There was no advantage of split applications of imazamox as compared with a fall application. Late-season Italian ryegrass control at Clayton by split applications of imazamox at 27 g/ha in the fall and spring was similar to control by imazamox at 53 g/ha applied in the fall and greater than control by 53 g/ha applied in the spring (Figure 2). At

Alamance and Whitsett, split applications were less effective than fall application but more effective than spring application. Pendimethalin at 1120 g/ha controlled Italian ryegrass less than 20% 4 WAT and 2% or less late in the season at Alamance and Whitsett (Table 2). At Clayton, pendimethalin alone controlled Italian ryegrass 77 and 57% 4 WAT and late in the season, respectively. Each location received adequate rainfall or irrigation for herbicide application. The Alamance and Whitsett locations received 2 cm of rainfall 6 and 1 d after planting, respectively (Table A-1). The Clayton location received 2.5 cm of water via irrigation 1 d after planting (Table A-2). The lighter-textured soil at Clayton may have been a contributing factor to the better control by pendimethalin at that location. However, the shallow planting of Italian ryegrass seed at that location was likely the primary reason for better control by pendimethalin.

The effect of pendimethalin was variable when used in combination with POST herbicides. Although pendimethalin alone gave essentially no control at Alamance, it increased control 23 and 33 percentage points 4 WAT and late in the season, respectively, when used in combination with fall-applied imazamox (Table 2). Pendimethalin had no effect on control when used in combination with spring-applied imazamox or with fall- or spring-applied diclofop. At Whitsett, pendimethalin increased control 4 WAT 20 to 22 percentage points when used in combination with fall- or spring-applied imazamox or fall-applied diclofop. By late in the season, the only response to pendimethalin was an increase of 10 percentage points when used in combination with fall-applied imazamox. Although pendimethalin alone had poor activity on Italian ryegrass at Alamance and Whitsett, it was generally noted that pendimethalin stunted the weed. The response to pendimethalin used in combination with POST herbicides may have been due to the weeds being smaller when treated with POST herbicides in the presence of pendimethalin. At Clayton, pendimethalin significantly increased control only when used in combination with spring-applied imazamox. However, there was a trend for increased control when pendimethalin was used in combination with all POST herbicides and application timings.

Imazethapyr at 70 g/ha was the least effective of the imidazolinone herbicides. At all evaluation dates at all locations, fall-applied imazethapyr controlled Italian ryegrass less than fall-applied imazamox at 35 g/ha (Table 3). Italian ryegrass control by fall-applied imazethapyr plus imazapyr was similar to control by fall-applied imazamox at 53 g/ha at each evaluation data at each location except 4 WAT at Alamance. Late-season control by imazethapyr plus imazapyr was similar to or greater than control by imazamox at 35 or 44 g/ha at each location. Control by fall-applied imazapic at 70 g/ha was similar to control by fall-applied imazamox at 53 g/ha at each evaluation at Whitsett and Clayton. Control by imazapic and imazamox at 53 g/ha also was similar at 4 and 10 WAT at Alamance. However, imazapic was the most effective of the imidazolinones late in the season at Alamance, where control by imazapic was 93% compared with 55% by imazamox at 53 g/ha and 48% by imazethapyr plus imazapyr. Barber et al. (2001) also reported greater Italian ryegrass control by imazapic than by imazamox, imazaquin, or imazethapyr applied POST to Italian ryegrass of similar size. Imazapic was the only imidazolinone herbicide that controlled Italian ryegrass late in the season at Alamance as well as diclofop.

Wheat Injury. Slight visible wheat injury (less than 5%) was observed 4 WAT with the imidazolinone herbicides (data not shown). Wheat injury appeared primarily as chlorosis. The injury was transitory, and no injury was noted by 6 WAT. No injury was noted at any time with diclofop.

Greenhouse Experiment. Diclofop at rates up to 1800 g/ha did not give any visible control or fresh weight reduction of diclofop-resistant Italian ryegrass (data not shown). Visible control of the diclofop-susceptible biotype by diclofop and both biotypes by imazamox was best described by a rectangular hyperbola (Figures 3, 4, and 5). Shoot fresh weight reduction of the susceptible biotype by diclofop and both biotypes by imazamox was best described by a sigmoidal curve (Figures 6, 7, and 8).

The diclofop-resistant biotype appeared to be somewhat more tolerant of imazamox than was the diclofop-susceptible biotype. The I_{80} values for visible control and shoot fresh weight reduction of the resistant biotype were 47 and 41% greater, respectively (Table 4). It must be emphasized that this study focused on only one biotype of diclofop-resistant and one biotype of diclofop-susceptible Italian ryegrass. Additional experiments are needed to determine if diclofop-susceptible and -resistant biotypes collected from other areas of the state and region show a similar response.

Results from these field and greenhouse studies and other studies (Clemmer and York, unpublished data) suggest use of imazamox in an IMI-tolerant wheat cultivar can be a suitable alternative to diclofop where diclofop-resistant Italian ryegrass is present. Timely application of imazamox will be critical for acceptable Italian ryegrass control. Other studies have shown that imazamox is most effective when applied before Italian ryegrass exceeds the three-leaf stage (Clemmer and York, unpublished data). Control of Italian ryegrass while it is still small will also reduce competition with the crop.

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Table 1. Effect of rate and time of application of imazamox and diclofop on Italian ryegrass control. Field experiment.[a]

	Application		Alamance			Whitsett			Clayton		
Herbicide	Rate	Timing	4 WAT[b]	10 WAT	Late[c]	4 WAT	10 WAT	Late	4 WAT	10 WAT	Late
	g/ha		%								
Imazamox	35	Fall	23 cd	90 b	24 cde	55 ab	98 a	88 b	87 a	91 a	83 a
Imazamox	44	Fall	24 cd	92 b	31 c	67 a	99 a	91 ab	92 a	94 a	85 a
Imazamox	53	Fall	40 b	98 a	55 b	68 a	100 a	98 a	94 a	98 a	88 a
Diclofop	800	Fall	63 a	100 a	90 a	32 c	70 b	5 de	67 b	70 b	57 b
Imazamox	35	Spring	26 c		7 ef	33 c		8 cde	58 bc		55 b
Imazamox	44	Spring	35 bc		10 def	41 bc		13 cd	55 c		53 b
Imazamox	53	Spring	32 bc		9 def	41 bc		16 c	61 bc		58 b
Diclofop	1120	Spring	14 d		3 f	11 d		1 e	69 b		61 b

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] WAT, weeks after treatment.

[c] Late-season evaluation made 22 and 10 WAT for fall and spring applications, respectively.

Table 2. Effect of pendimethalin applied PRE on Italian ryegrass control by imazamox and diclofop applied POST. Field experiment.[a]

POST herbicide	Application timing	Alamance				Whitsett				Clayton			
		4 WAT[b]		Late[c]		4 WAT		Late		4 WAT		Late	
		- Pend[d]	+ Pend	- Pend	+ Pend	- Pend	+ Pend	- Pend	+ Pend	- Pend	+ Pend	- Pend	+ Pend
		%											
Imazamox	Fall	23 cd	46 b	24 c	57 b	55 b	77 a	88 b	98 a	87 ab	98 a	83 abc	95 a
Imazamox	Spring	26 c	23 cd	7 d	4 d	33 c	54 b	8 cd	16 c	58 c	88 ab	55 c	86 ab
Diclofop	Fall	63 a	74 a	90 a	87 a	32 c	52 b	5 d	14 cd	67 c	78 bc	57 c	67 c
Diclofop	Spring	14 d	23 cd	3 d	8 cd	11 d	25 cd	1 d	3 d	69 c	77 bc	61 c	73 bc

[a] Means within an evaluation period and location followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] WAT, weeks after treatment.

[c] Late-season evaluation made 22 and 10 weeks after fall and spring applications, respectively.

[d] Pend = pendimethalin PRE at 1120 g/ha. Pendimethalin applied alone controlled Italian ryegrass 2, 19, and 77% 4 WAT at Alamance, Whitsett, and Clayton, respectively, and 2, 0, and 57%, respectively, late in the season.

Table 3. Comparison of imidazolinone herbicides for control of Italian ryegrass. Field experiment.[a]

	Application	Alamance			Whitsett			Clayton		
Herbicide	rate	4 WAT[b]	10 WAT	Late[c]	4 WAT	10 WAT	Late	4 WAT	10 WAT	Late
	g/ha	%								
Imazamox	35	23 c	90 c	24 d	55 a	98 a	88 b	87 a	91 a	83 a
Imazamox	44	24 c	92 bc	31 cd	67 a	99 a	91ab	92 a	94 a	85 a
Imazamox	53	40 b	98 a	55 b	68 a	100 a	98 a	94 a	98 a	88 a
Imazethapyr	70	12 d	50 d	3 e	37 b	65 b	16 c	71 b	62 b	54 b
Imazethapyr	47	28 c	100 a	48 bc	68 a	100 a	99 a	86 a	96 a	96 a
+ imazapyr	+ 16									
Imazapic	70	43 b	97 ab	93 a	63 a	100 a	100 a	94 a	100 a	97 a
Diclofop	800	63 a	100 a	90 a	32 b	70 b	5 d	67 b	70 b	57 b

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] WAT, weeks after treatment.

[c] Late-season evaluation made 22 and 10 WAT for fall and spring applications, respectively.

Table 4. Rates of imazamox and diclofop required for 80% visible control or shoot fresh weight reduction (I_{80}) of Italian ryegrass. Greenhouse experiement.[a]

Herbicide	Italian ryegrass biotype	Visible control	Shoot fresh weight reduction
		g/ha	
Diclofop	Susceptible	507	388
Imazamox	Resistant	53[b]	41[c]
Imazamox	Susceptible	36	29

[a] Data pooled over runs.

[b] Significantly different from imazamox on susceptible biotype at P = 0.0001.

[c] Significantly different from imazamox on susceptible biotype at P = 0.0001.

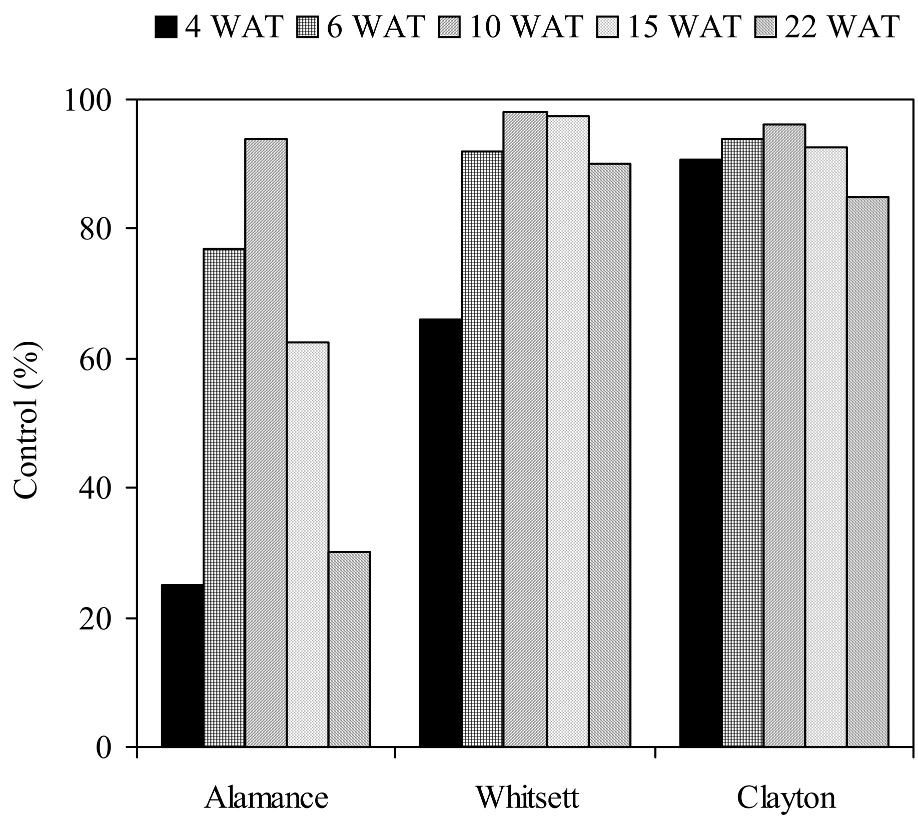

Figure 1. Italian ryegrass control at various weeks after treatment (WAT) with fall-applied imazamox at 44 g/ha.

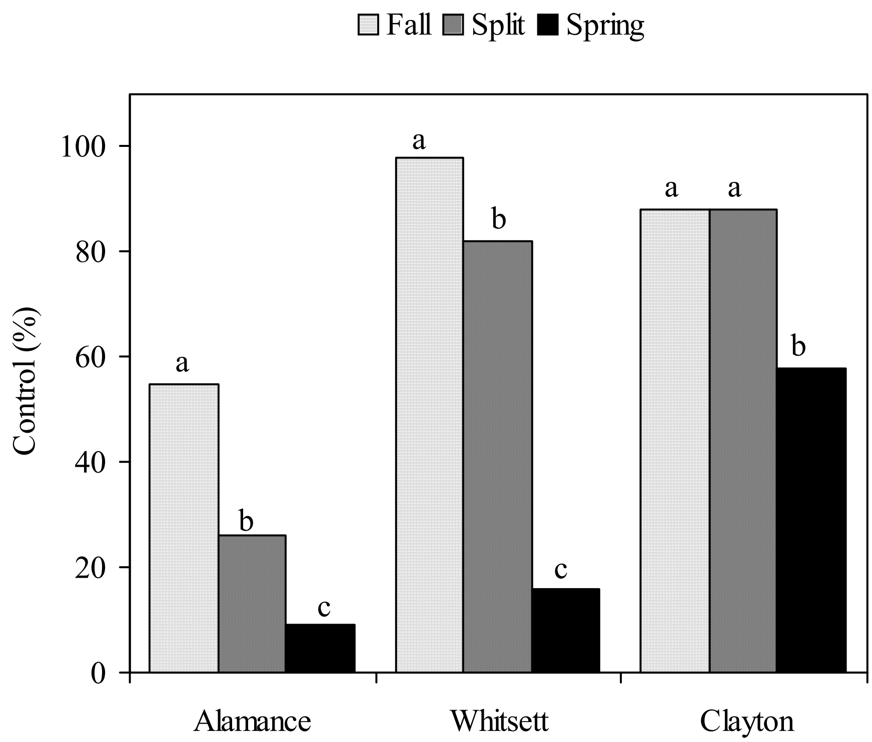

Figure 2. Late-season Italian ryegrass control by imazamox applied in the fall or spring at 53 g/ha or a split application of 27 g/ha in fall and spring. Bars within a location with the same letter are not different according to Fisher's Protected LSD at P = 0.05.

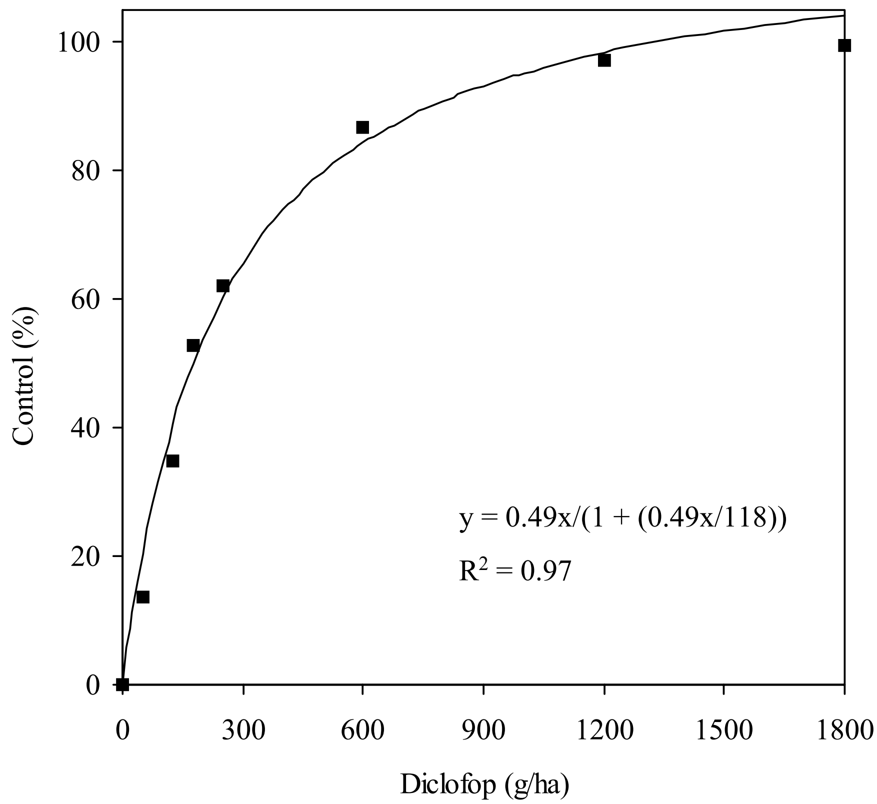

Figure 3. Control of diclofop-susceptible Italian ryegrass 28 days after treatment with diclofop. Greenhouse experiment.

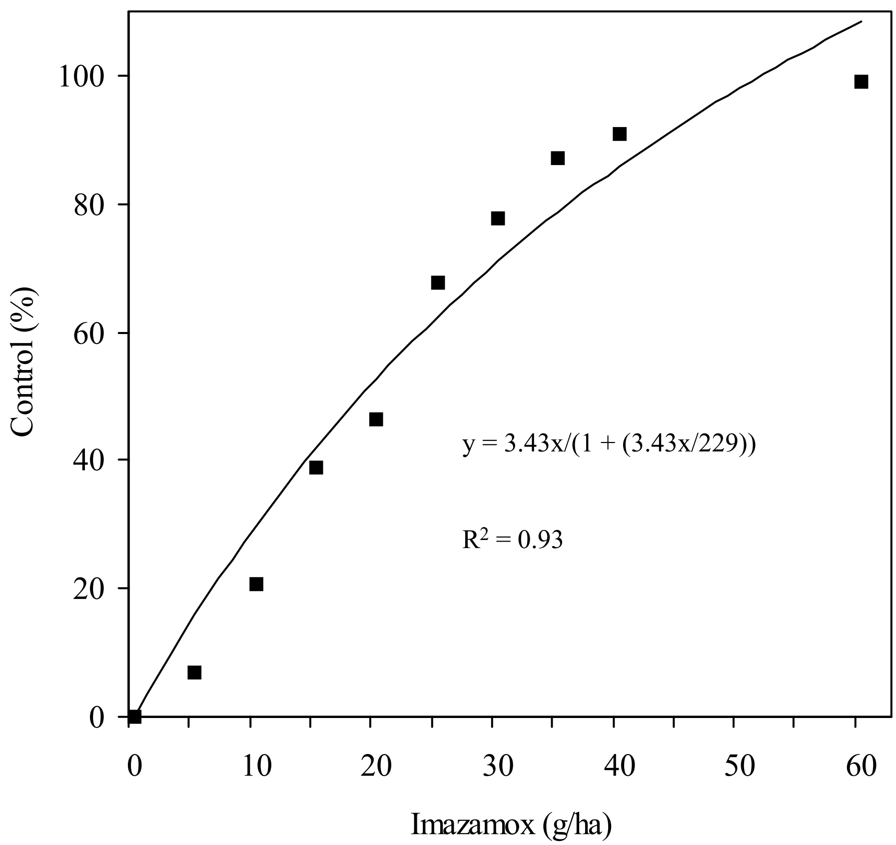

Figure 4. Control of diclofop-susceptible Italian ryegrass 28 days after treatment with imazamox. Greenhouse experiment.

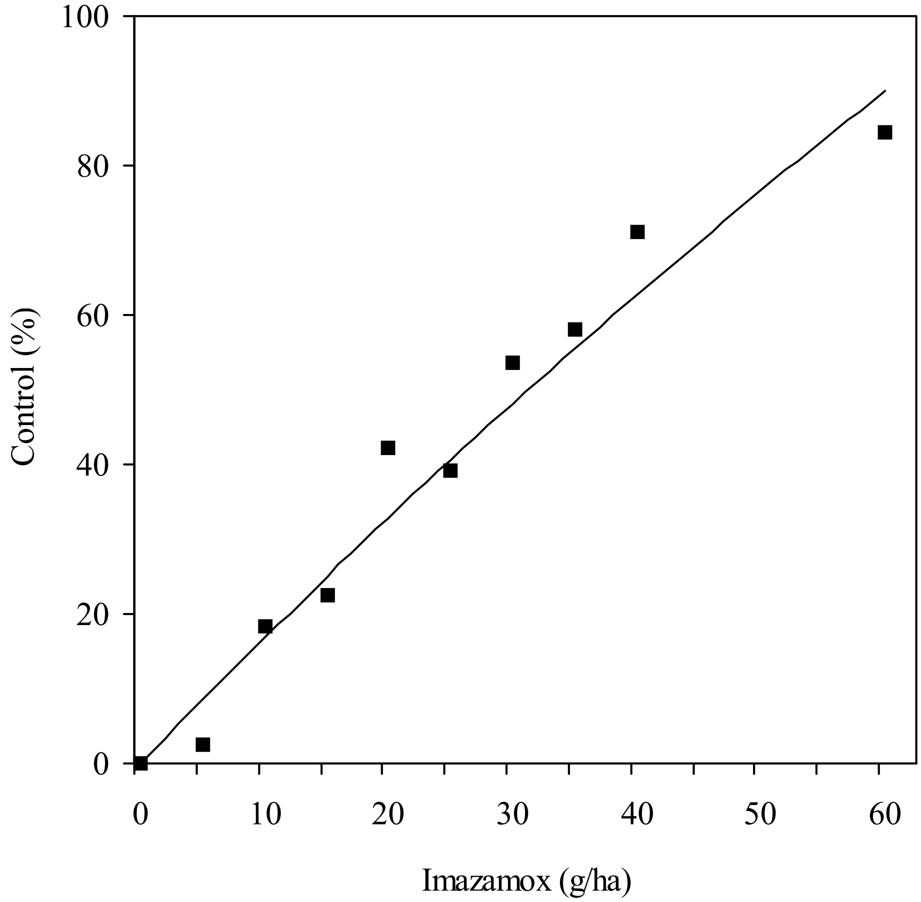

Figure 5. Control of diclofop-resistant Italian ryegrass 28 days after treatment with imazamox. Greenhouse experiment.

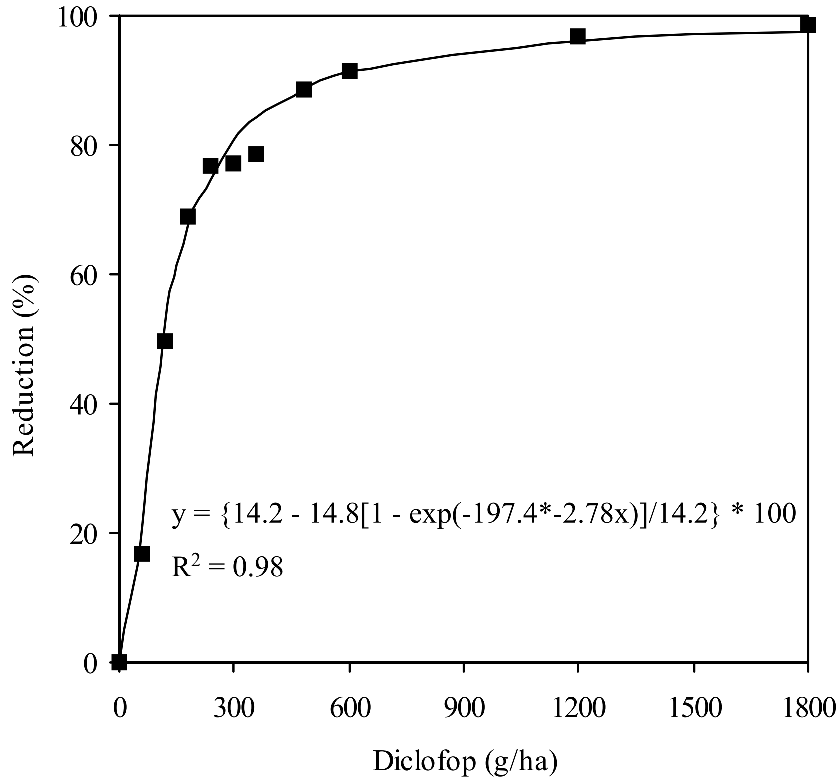

Figure 6. Diclofop-susceptible Italian ryegrass shoot fresh weight reduction 28 days after treatment with diclofop. Greenhouse experiment.

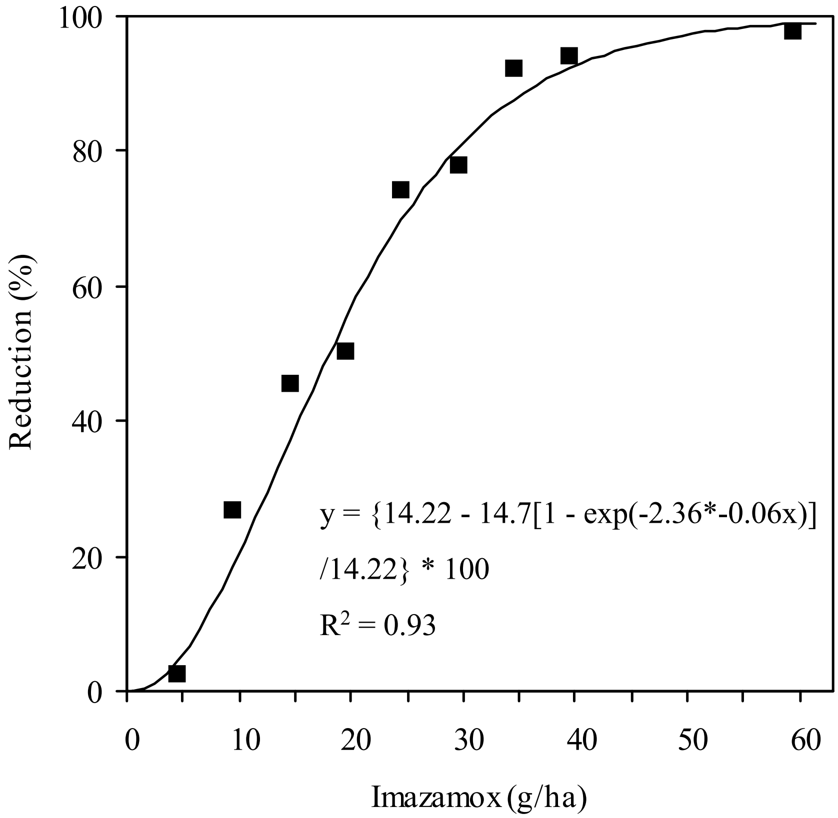

Figure 7. Diclofop-susceptible Italian ryegrass shoot fresh weight reduction 28 days after treatment with imazamox. Greenhouse experiment.

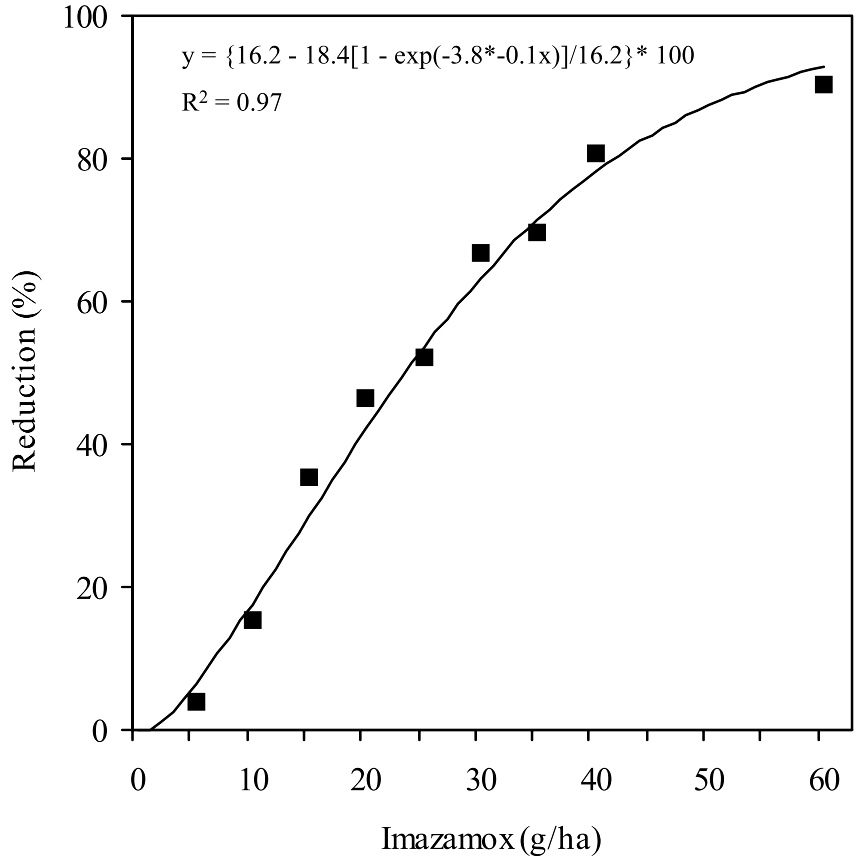

Figure 8. Diclofop-resistant Italian ryegrass shoot fresh weight reduction 28 days after treatment with imazamox. Greenhouse experiment.

CHAPTER 3

Italian Ryegrass (*Lolium multiflorum*) Control by Imazamox as Affected by Mixtures and Time of Application[1]

KEVIN C. CLEMMER and ALAN C. YORK[2]

Abstract. Imazamox controls Italian ryegrass in imidazolinone-tolerant (IMI-tolerant) wheat but is only marginally effective on some broadleaf species. A fallow-area field experiment was conducted at three locations in North Carolina to determine control of Italian ryegrass by imazamox as affected by imazamox rate, weed size at application, and mixtures with the broadleaf herbicides 2,4-D, dicamba, and thifensulfuron plus tribenuron. Interactions of imazamox rate, weed size, and broadleaf herbicides were not observed. Italian ryegrass control 56 d after treatment (DAT) increased as imazamox rate increased. Imazamox ammonium salt at 44 g ae/ha controlled Italian ryegrass 67% at two locations and 91% at the third location. Control decreased as the weed size at application increased. Control of two-leaf, four-leaf, and two-tiller weeds ranged from 86 to 95, 54 to 94, and 24 to 71%, respectively. Small increases in control were sometimes noted with mixtures of imazamox and 2,4-D dimethylamine salt at 530 g ae/ha or thifensulfuron plus tribenuron at 18 plus 9 g ai/ha, while minor decreases were sometimes noted with mixtures of imazamox and dicamba diglycolamine salt at 140 g ae/ha. In a greenhouse experiment, mixing 2,4-D with imazamox did not affect Italian ryegrass control. Dicamba reduced control, while thifensulfuron plus tribenuron increased ryegrass.

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Nomenclature: chlorsulfuron, {2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide}; 2,4-D, {(2,4-dichlorophenoxy)acetic acid; dicamba, 3,6-dichloro-2-methoxybenzoic acid}; diclofop, {(±)-2-[4-(2,4-dichlorophenoxy)phenoxy] propanoic acid}; imazamox, {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid}; MCPA, {(4-chloro-2-methylphenoxy)acetic acid}; thifensulfuron, {3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2- thiophenecarboxylic acid}; tribenuron, {2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2- yl)methylamino]carbonyl]amino] sulfonyl]benzoic acid}; Italian ryegrass, *Lolium multiflorum* Lam. Marshall #[3] LOLMU; wheat, *Triticum aestivum* L.

Additional index words: Dicamba, herbicide interactions, LOLMU, tribenuron, thifensulfuron, *Triticum aestivum*, 2,4-D, wheat.

Abbreviations: ANOVA, analysis of variance; DAT, days after treatment; I_{80}, rate required for 80% visible control or 80% fresh weight reduction; IMI-tolerant, imidazolinone-tolerant; POST, postemergence.

INTRODUCTION

Italian ryegrass continues to be the most problematic weed of small grains in North Carolina. Severe populations can reduce wheat (*Triticum aestivum*) tillering, cause lodging, and delay harvesting due to the weed's later maturity (Justice et al. 1994). Severe infestations also decrease harvesting efficiency, contaminate grain, and reduce test weight. Yield losses of 30% are common when Italian ryegrass is left uncontrolled, and researchers have reported yield reductions greater than 50% (Lee et al. 1999). Liebl

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[3]Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

and Worsham (1987b) reported a 5% yield loss for every 10 Italian ryegrass plants/m^2.

Diclofop, first available to North Carolina growers under an emergency exemption in October of 1980 and then under federal registration in 1982[4], applied PRE or POST controls Italian ryegrass in wheat (Brewster et al. 1977; Khodayari et al. 1983; Liebl and Worsham 1987a). Diclofop was the only acceptable option for control for many years, and growers used it continuously. Biotypes of Italian ryegrass not controlled by diclofop were first reported in Oregon in 1987 (Stanger and Appleby 1989). Italian ryegrass resistant to diclofop was reported in North Carolina in 1990 (Heap 2002). Diclofop-resistant Italian ryegrass is now widespread in North Carolina, and options for control are limited.

Imazamox is a imidazolinone herbicide recently registered for POST annual grass and broadleaf weed control in IMI-tolerant wheat (Anonymous 2002a). Imidazolinone herbicides inhibit acetolactate synthase (ALS, 4.1.3.18), an enzyme necessary for biosynthesis of leucine, valine, and isoleucine biosynthesis (Stidham and Singh 1991). Once in the phloem and translocated to the site of action, imidazolinones cause death of meristematic cells and ultimately plant death (Little and Shaner 1991). Imidazolinone herbicides have good flexibility in timing of application, low usage rates, and low mammalian toxicity (Newhouse et al. 1992).

Imazamox controls a broad spectrum of annual grass weeds, including jointed goatgrass [*Aegilops cylindrica* (L.) Host.], downy brome (*Bromus tectorum* L.), wild oat (*Avena fatua* L.), Italian ryegrass, and others (Ball and Walenta 1997; Belles and Thill 1998; Gamroth et al. 1997; Neider and Thill 1997). However, imazamox is only marginally effective on wild garlic (*Allium vineale* L.) and some broadleaf species such as cutleaf

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[4]Davis, C. 2001. Personal communication. Food and Drug Protection Division, Pesticide Section, North Carolina Department of Agriculture, Raleigh.

evening primrose (*Oenothera laciniata*) and dandelion (*Taraxacum officinale*) (Anonymous 2002a).

It would be advantageous to mix imazamox with other commonly used wheat herbicides to control wild garlic or to broaden the spectrum of broadleaf weeds controlled, thus eliminating the time and expense of separate applications. There is, however, little information on efficacy of imazamox mixed with commonly used wheat herbicides. Certain broadleaf herbicides mixed with diclofop can negatively affect Italian ryegrass control (York et al. 2000). Others have found the efficacy of diclofop on wild oat was reduced when tank mixed with chlorsulfuron (O'Sullivan and Kirkland 1984), MCPA (Olson and Nalewaja 1977), tribenuron (Baergh et al. 1996), or 2,4-D (Fletcher and Drexler 1980; Todd and Stobbe 1980).

The objective of this research was to determine the effect of mixing 2,4-D, dicamba, and thifensulfuron plus tribenuron with imazamox on Italian ryegrass control.

MATERIALS AND METHODS

Field Experiment. The experiment was conducted on private farms near Alamance, NC during the 1999-2000 season and at the Cherry Farm Unit in Goldsboro, NC in 2000-01. The experiment was conducted in two adjacent fields at Alamance with a Mecklenburg clay loam soil (fine, mixed, active, thermic Hapludalfs) with 1.8% organic matter and pH 5.8. Soil at Goldsboro was a Goldsboro loamy sand (fine-loamy, siliceous, thermic Aquic Paledults) with 1.4% organic matter and pH 5.4.

The test sites were disked and smoothed, and Italian ryegrass was allowed to establish; no crop was planted. All locations were infested with diclofop-susceptible Italian ryegrass. Both sites at Alamance had an initial Italian ryegrass density greater than 1,000 plants/m^2. The density decreased over time due to intraspecific competition, but Italian ryegrass gave 100% ground coverage all during the experiment. The initial weed density was 150 plants/m^2 at Goldsboro. The experimental design was a randomized complete block with treatments replicated four times. Plot size was 2 by 6 m with an untreated strip between plots.

Treatments included a factorial arrangement of imazamox rates, broadleaf herbicides, and application timings. Imazamox rates were 0, 27, 35, and 44 g/ha. Broadleaf herbicides were none, dicamba at 140 g/ha, thifensulfuron at 18 g/ha plus tribenuron at 9 g/ha, and 2,4-D at 530 g/ha. Application timings were two-leaf, four-leaf, and two-tiller Italian ryegrass.

All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles calibrated to deliver 140 L/ha at 147 kPa and 4.8 km/h. All POST treatments included 30% urea ammonium nitrate solution at 2.5% (v/v) and a nonionic surfactant[5] at 0.25% (v/v).

Weed control was estimated visually 28 and 56 DAT. A scale of 0 (no control) to 100% (complete control) was used. Foliar chlorosis, stunting, and population reductions were used in making the visual estimates. Data were subjected to analysis of variance (ANOVA) with partitioning appropriate for the factorial treatment arrangement. Non-transformed data are presented as arcsin square root transformation did not affect conclusions. Data from the two sites at Alamance were pooled. A treatment by location interaction prevented pooling data from Alamance and Goldsboro. Means for significant main effects and interactions were separated with the appropriate Fisher's Protected LSD test at P = 0.05.

Greenhouse Experiment. Studies were conducted in a greenhouse at North Carolina State University from September 1999 to March 2000 and from September 2000 to February 2001. Plants were grown with approximate day/night temperatures of 20/10 C

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[5]Induce (mixture of alkyl polyoxylkane ether, free fatty acids, and isopropanol). Helena Chemical Company., 5100 Poplar Avenue, Memphis, TN 38137.

and were watered overtop daily. Sunlight was supplemented with metal halide lamps (300 μmol m^{-2} s^{-1} photosynthetic photon flux) set on a 12-h photoperiod.

Diclofop-susceptible Italian ryegrass seed collected from Johnston County, NC, were planted in 12-cm round pots containing a loamy sand soil (82% sand, 8% silt, 8% clay) with 1.3% organic matter and pH 5.6. Following seedling emergence, the grass was thinned to five plants per pot. All pots received 20 ml of a 15 g/L commercial greenhouse fertilizer[6] solution at 14 d after planting and 14 DAT.

Treatments included imazamox at 0, 5, 10, 20, 30, 40, 50, and 70 g/ha arranged factorially with no broadleaf herbicide, dicamba at 140 g/ha, thifensulfuron at 18 g/ha plus tribenuron at 9 g/ha, and 2,4-D at 530 g/ha. All treatments included 30% urea ammonium nitrate solution at 2.5% (v/v) and a nonionic surfactant[5] at 0.25% (v/v). The experimental design was a randomized complete block with treatments replicated four times. The experiment was repeated three times. Herbicides were applied using a spray chamber equipped with a single even-spray, flat-fan nozzle calibrated to deliver 160 L/ha at 200 kPa and 2.4 km/h when Italian ryegrass was 9 to 12 cm tall with 1 to 3 leaves.

Visual estimates of control were recorded 14 and 28 DAT using the scale mentioned previously. Plants were clipped at soil level 28 DAT and shoot fresh weight was recorded. Data were pooled over runs and subjected to ANOVA with basic partitioning for the factorial treatment arrangement. Nonlinear regression analysis was performed for each herbicide combination. To fit the nonlinear regression analysis, the rectangular hyperbola equation was used to describe percent control or shoot fresh weight as a function of rate. Parameter estimates and R^2 values were determined according to Draper and Smith (1981). From the fitted regressions, the rate of imazamox required for 80% visible control or shoot fresh weight reduction (I_{80}) when applied alone and in mixture

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[6]Fertilizer, Peters Professional All Purpose 20-20-20, Scotts-Sierra Horticultural Products Co., 14111 Scottslawn Road, Marysville, OH 43041.

with broadleaf herbicides was determined. The I_{80} values for imazamox applied alone and with broadleaf herbicides were compared using ANOVA followed by single degree of freedom contrasts.

RESULTS AND DISCUSSION

Experiment 1. There were no interactions of imazamox rate by weed size, imazamox rate by broadleaf herbicide, weed size by broadleaf herbicide, or imazamox rate by weed size by broadleaf herbicide. However, main effects of each treatment factor were significant.

Italian ryegrass control was not affected by dicamba and 2,4-D applied alone regardless of weed size at application (data not shown). Thifensulfuron plus tribenuron controlled Italian ryegrass less than 5% at Alamance. At Goldsboro, thifensulfuron plus tribenuron controlled Italian ryegrass approximately 20% at 56 DAT regardless of weed size at time of treatment. The primary effect noted on Italian ryegrass from thifensulfuron plus tribenuron was a reduction in height.

A main effect of imazamox application rates was noted at each location, where control increased as the herbicide application rate increased (Table 1). A main effect of weed size at time of herbicide application also was noted at each location. At Alamance, Italian ryegrass control decreased with each successive increase in weed size at time of application (Table 2). At 56 DAT, each delay in application reduced control about 30%. Greater than 80% control was obtained only when herbicides were applied to two-leaf Italian ryegrass. Control at Goldsboro was similar when herbicides were applied to 2- and 4-leaf weeds. However, control decreased 13 and 23 percentage points at 28 and 56 DAT, respectively, when application was delayed until the two-tiller stage. In other research, smaller Italian ryegrass was also more effectively controlled by imazamox (Clemmer and York, unpublished data). Greater and more rapid control at Goldsboro compared to Alamance may be a reflection of higher temperatures as mentioned previously. Temperature plays an important role in the activity of the imidazolinone herbicides (Malefyt and Quakenbush 1991). One would anticipate more rapid activity of the herbicide under higher temperatures. The much greater Italian ryegrass density at Alamance may also have been a factor. The dense stand of weeds at Alamance may have resulted in less spray coverage or less herbicide per plant.

No adverse effect on Italian ryegrass control was noted when either 2,4-D or thifensulfuron plus tribenuron was mixed with imazamox (Table 3). Thifensulfuron plus tribenuron mixed with imazamox increased control 2 to 5 percentage points 28 DAT at all locations. It also increased control seven percentage points 56 DAT at Alamance. Italian ryegrass control was increased six percentage points 56 DAT at Alamance and two percentage points 28 DAT at Goldsboro when 2,4-D was mixed with imazamox. Dicamba mixed with imazamox affected Italian ryegrass control only at 28 DAT at Goldsboro, where control was reduced two percentage points (Table 3). However, control by imazamox plus dicamba was numerically less than control by imazamox alone at all other locations and evaluation dates.

Greenhouse Experiment. Greenhouse results were generally similar to those from the field experiment. Results of regression analysis are shown in Figures 1 through 8. Based upon I_{80} values, Italian ryegrass control was unaffected when 2,4-D was mixed with imazamox (Table 4). However, a greater I_{80} value for combinations of imazamox plus dicamba indicates a reduction in Italian ryegrass control when dicamba was mixed with imazamox. Similarly, a smaller I_{80} value for combinations of imazamox plus thifensulfuron plus tribenuron indicates control was increased with this combination.

Imazamox applied to IMI-tolerant wheat may be a feasible alternative to control diclofop-resistant Italian ryegrass. Results from the current study and others (Clemmer and York, unpublished data) show that imazamox effectively controls both diclofop-susceptible and -resistant Italian ryegrass if applied when the weed is small (Clemmer and York, unpublished data).

Although imazamox also controls certain winter annual broadleaf weeds, there are some species not controlled (Anonymous 2002a). Additionally, imazamox does not control wild garlic. Hence, there will be situations where growers would desire to mix another herbicide with imazamox to control wild garlic or expand the spectrum of broadleaf weeds controlled. Results of our research indicate dicamba may reduce Italian ryegrass control when mixed with imazamox. However, our results indicate that either 2,4-D or thifensulfuron plus tribenuron would be suitable herbicides to mix with imazamox. As demonstrated in this experiment (Table 1), imazamox is most effective when applied to smaller Italian ryegrass. The imazamox manufacturer recommends imazamox application to ryegrass in the 3- to 4-leaf stage (Anonymous 2002a). Thifensulfuron plus tribenuron can be applied to wheat from the two-leaf stage until the flag leaf is visible (Anonymous 2002b). Hence, a combination of imazamox plus thifensulfuron and tribenuron could be applied when the Italian ryegrass was at an appropriate stage for treatment. In contrast, 2,4-D should be applied to wheat after the fully tiller stage but before stem elongation (York et al. 2000). At this growth stage of wheat, Italian ryegrass will typically also be tillered. In other research (Clemmer and York, unpublished data), imazamox applied in the fall when wheat and Italian ryegrass had 3 to 4 leaves was more efficacious than when applied in the spring to tillered wheat and tillered Italian ryegrass. However, in other research in North Carolina (York, unpublished data), wheat injury was unacceptable with mixtures of thifensulfuron plus tribenuron and imazamox. Thus, it appears that imazamox should be applied alone when treating Italian ryegrass. Additional research is needed to determine the effect of sequential applications of imazamox and thifensulfuron plus tribenuron.

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Table 1. Main effects of imazamox rates on Italian ryegrass control. Field experiment.[a]

	Alamance[b]		Goldsboro	
Imazamox rates	28 DAT[c]	56 DAT	28 DAT	56 DAT
g/ha	%			
27	36 c	44 c	90 c	83 b
35	41 b	53 b	91 b	86 ab
44	45 a	67 a	94 a	91 a

[a]Data pooled over broadleaf herbicides and weed sizes at application. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b]Data pooled over two sites.

[c]DAT, days after treatment.

Table 2. Main effects of weed size at time of herbicide application on Italian ryegrass control. Field experiment.[a]

Italian ryegrass size at application	Alamance[b] 28 DAT[c]	Alamance[b] 56 DAT	Goldsboro 28 DAT	Goldsboro 56 DAT
	%			
2-leaf	46 c	86 a	96 a	95 a
4-leaf	43 b	54 b	96 a	94 a
2-tiller	33 c	24 c	83 b	71 b

[a]Data pooled over imazamox rates and broadleaf herbicides. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b]Data pooled over two sites.

[c]DAT, days after treatment.

Table 3. Main effects of broadleaf herbicides on Italian ryegrass control. Field experiment.[a]

	Alamance[c]		Goldsboro	
Broadleaf herbicide[b]	28 DAT[d]	56 DAT	28 DAT	56 DAT
	——— % ———			
None	39 bc	52 b	91 b	86 ab
2,4D	42 ab	58 a	93 a	89 a
Dicamba	37 c	49 b	89 c	80 b
Thifensulfuron + tribenuron	44 a	59 a	93 a	92 a

[a]Data pooled over imazamox rates and weed sizes at application. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b]Herbicide rates: 2,4-D, 530 g/ha; dicamba, 140 g/ha; thifensulfuron plus tribenuron, 18 + 9 g/ha.

[c]Data pooled over two sites.

[d]DAT, days after treatment.

Table 4. Rates of imazamox required for 80% visible control (I_{80}) or 80% shoot fresh weight reduction when mixed with broadleaf herbicides. Greenhouse experiment.[a]

	Visible control		Shoot fresh weight reduction	
Broadleaf herbicide[b]	I_{80}	P > F[c]	I_{80}	P > F
	g/ha		g/ha	
None	32		28	
2,4-D	26	0.2161	27	0.7144
Dicamba	49	0.0138	33	0.0413
Thifensulfuron + tribenuron	18	0.0254	20	0.0143

[a]Data pooled over runs. All treatments included 0.25% (v/v) nonionic surfactant and 2.5 L/ha 30% urea ammonium nitrate.

[b]Broadleaf herbicide application rates: 2,4-D, 530 g/ha; dicamba, 140 g/ha; thifensulfuron plus tribenuron, 18 + 9 g/ha.

[c]P-value for testing that I_{80} for imazamox plus broadleaf herbicide is the same as for imazamox alone.

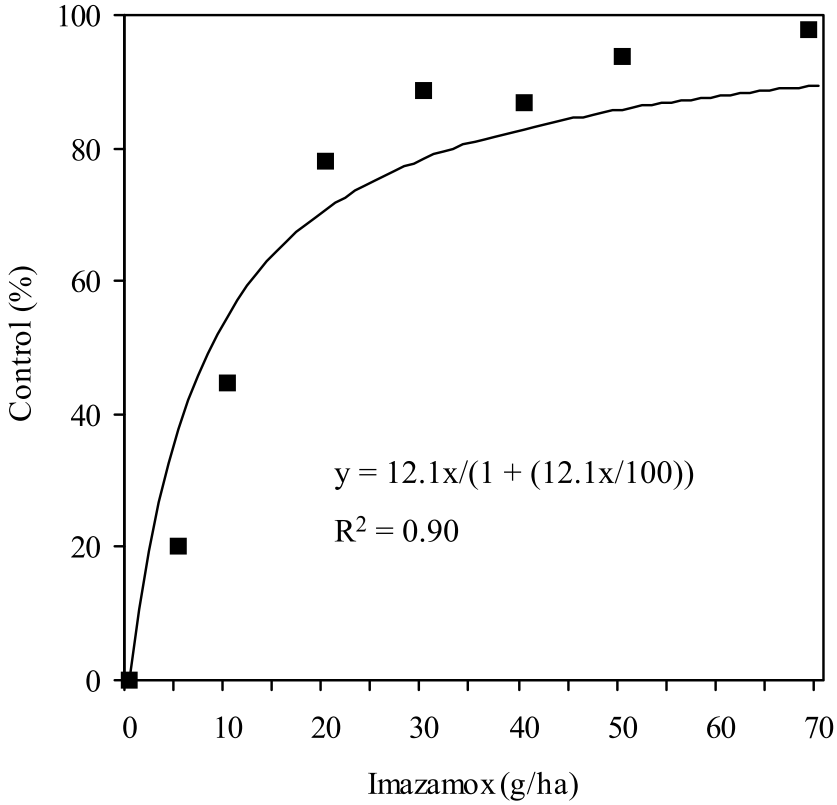

Figure 1. Italian ryegrass control 28 days after treatment with imazamox. Greenhouse experiment.

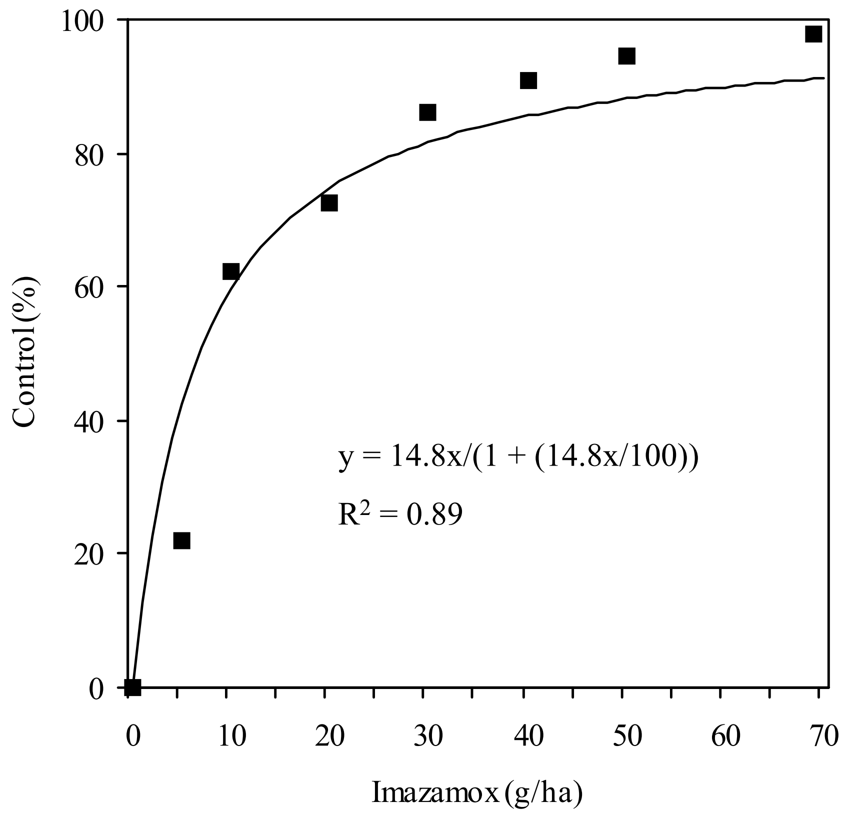

Figure 2. Italian ryegrass control 28 days after treatment with imazamox plus 530 g/ha 2,4-D. Greenhouse experiment.

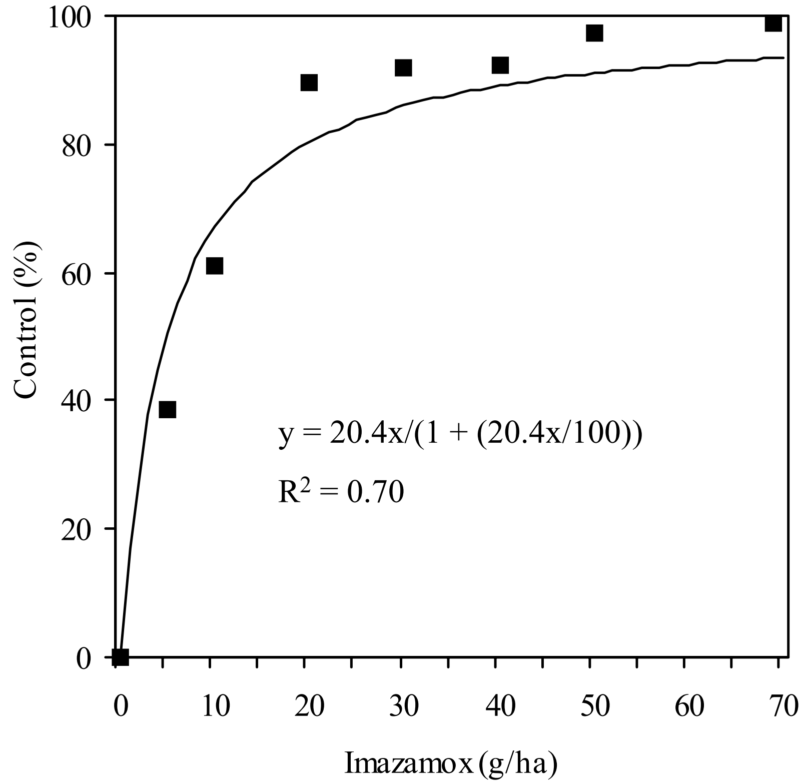

Figure 3. Italian ryegrass control 28 days after treatment with imazamox plus 18 g/ha thifensulfuron plus 9 g/ha tribenuron. Greenhouse experiment.

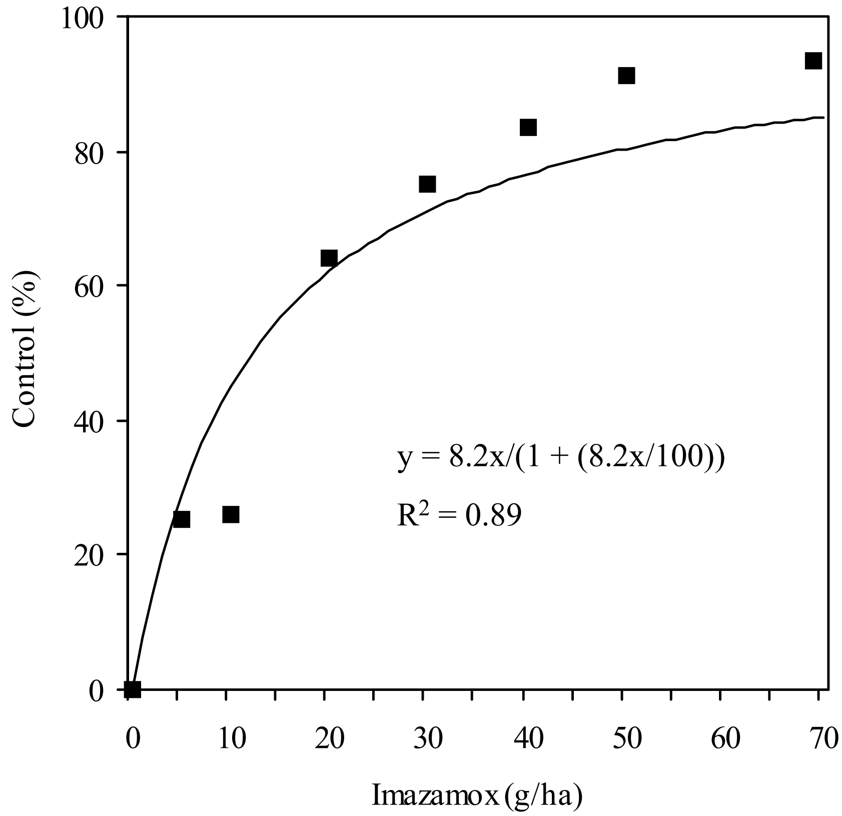

Figure 4. Italian ryegrass control 28 days after treatment with imazamox plus 140 g/ha dicamba. Greenhouse experiment.

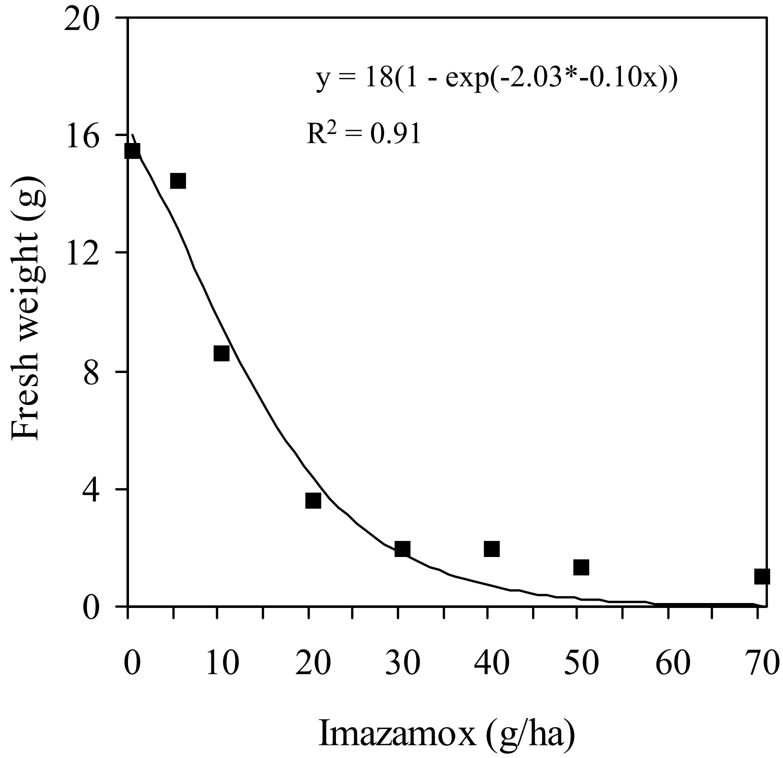

Figure 5. Italian ryegrass shoot fresh weight 28 days after treatment with imazamox. Greenhouse experiment.

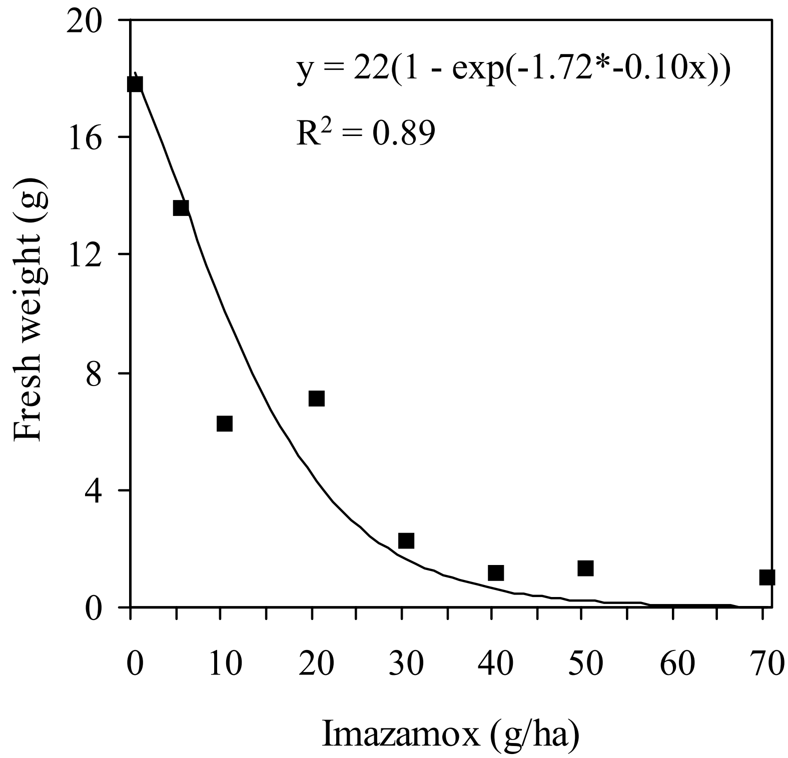

Figure 6. Italian ryegrass shoot fresh weight 28 days after treatment with imazamox plus 530 g/ha 2,4-D. Greenhouse experiment.

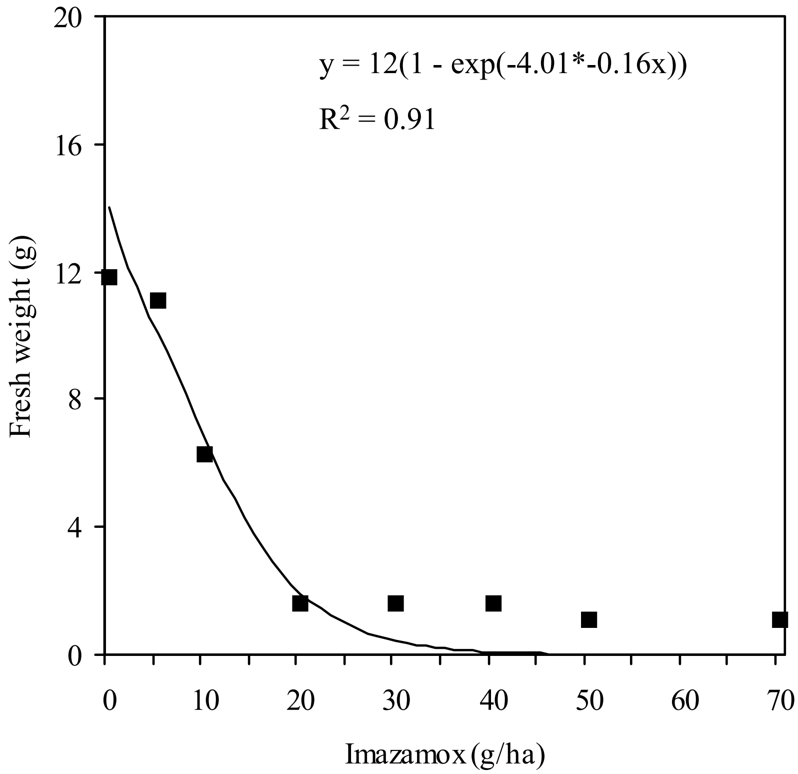

Figure 7. Italian ryegrass shoot fresh weight 28 days after treatment with imazamox plus 18 g/ha thifensulfuron plus 9 g/ha tribenuron. Greenhouse experiment.

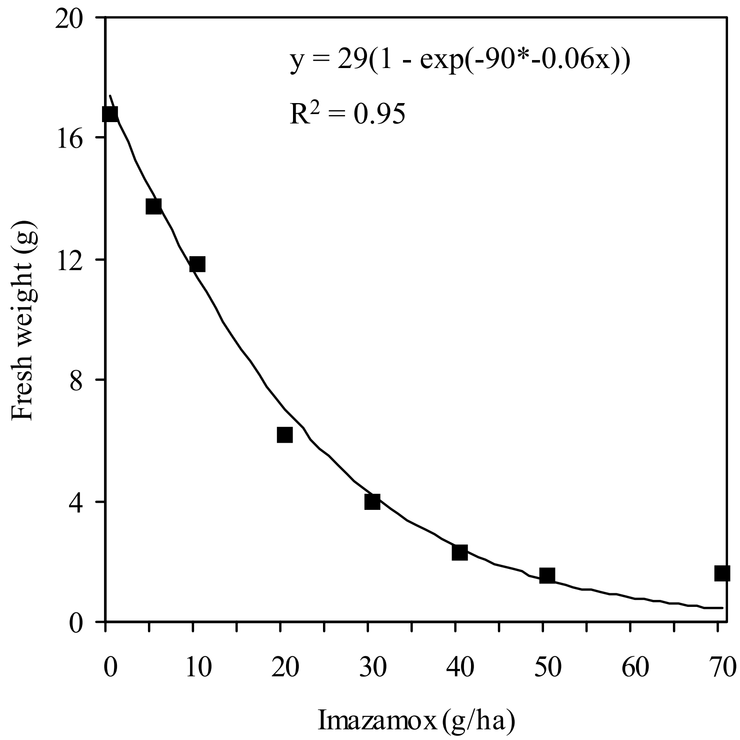

Figure 8. Italian ryegrass shoot fresh weight 28 days after treatment with imazamox plus 140 g/ha dicamba. Greenhouse experiment.

APPENDIX

Table A-1. Daily precipitation (cm), Alamance and Whitsett, NC. 1999-2000.[a,b]

Day	November	December	January	February	March	April
1	-[c]	-	-	-	-	-
2	2.03	-	-	-	-	-
3	-	-[e]	-	-	-	1.02
4	-	-	1.27	-	-	1.02
5	-	-	-	-	-	-
6	-	0.64	-	-	-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	2.29
9	-	-	2.29	-	-	-
10	-	1.14	1.52	-	-	-
11	-	-	-	-	1.02	-
12	Trace	-	-	2.54	-	-
13	-	0.51	-	1.27	-	-
14	-	1.52	-	-	-	5.33
15	-	-	-	-	-	-
16	-	-	-	-	6.1	-
17	-	-	-	-	-	-
18	-	-	11.43[f]	1.65	-	1.27
19	-	0.51	-	-	8.38	-
20	Trace	0.25	6.35[f]	-	-	-
21	0.03	1.27	-	-	-	-
22	Trace	-	-	-	-	-
23	-	-	3.81	-	-[g]	-
24	Trace	-	-	-	-	-
25	0.03	-	27.94[f]	-	0.51	1.25
26	4.06	-	-	-	-	-
27	-	-	-	0.38	1.02	0.76
28	-	-	-	-	-	3.56
29	-[d]	-	-		-	0.25
30	-	-	3.81		0.25	-
31		-	-		-	
Totals	6.15	5.84	58.42	5.84	17.28	16.75

Table A-1. Continued.

[a]Rainfall recorded by Joyce Clemmer, approximately 3 km from each location.

[b]PRE herbicide applied at Alamance on 27 October. No rainfall until 2 November.

[c]PRE herbicide applied at Whitsett.

[d]Fall POST herbicide applied at Alamance.

[e]Fall POST herbicide applied at Whitsett.

[f]Snow fall accumulation.

[g]Spring POST herbicide applied at Alamance and Whitsett.

Table A-2. Daily precipitation (cm), Clayton, NC. 2000-2001.[a]

Day	November	December	January	February	March	April
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	-	-	-	0.58	-	1.6
5	0.25	-	-	0.56	-	-
6	-[b]	-	-	-	-	-
7	2.54	-	-	-	-	-
8	-	-	0.56	-	-	-
9	0.18	-	-	-	-	-
10	-	-	-	-	-	-
11	-	-	-	-	-	-
12	-	0.58	0.33	1.12	-	-
13	-	-	-	-	-	-
14	0.38	-	-	-	-[d]	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-
17	-	1.83	-	1.32	-	-
18	-	-	-[c]	-	-	-
19	0.69	0.43	1.42	-	-	-
20	1.3	-	1.27	-	-	-
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	-	-	-	-	-	1.47
25	2.97	-	-	-	-	1.91
26	-	-	-	-	-	-
27	-	-	-	-	-	-
28	-	-	-	-	-	-
29	-	-	-		3.81	-
30	-	-	-		-	-
31		-	-		0.76	
Totals	8.31	2.84	3.58	3.58	4.57	4.98

Table A-2. Continued.

[a]Rainfall recorded on site.

[b]PRE herbicide applied at Clayton.

[c]Fall POST herbicide applied at Clayton.

[d]Spring POST herbicide applied at Clayton.

Table A-3. Daily precipitation (cm), Goldsboro, NC. 2001.[a]

Day	January	February	March	April
1	-	-	-[b]	0.76
2	-	-	-	-
3	-	-	0.51	-
4	-	-	2.03	-
5	-	1.14	-	-
6	-	-	-	-
7	0.38	-	-	-
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	0.38	0.64	-	-
13	-	0.25	0.15	0.46
14	0.38	0.2	0.38	-
15	-	-	1.14	-
16	-	2.03	-	-
17	-	-	-	0.51
18	-	-	-	-
19		[b]	-	-
20	0.64	-	6.86	-
21	-	-	0.81	-
22	-	0.2	-	-
23	-	-	-	-
24	-	-	-	-
25	-	-	-	1.27
26	-	-	-	-
27	-	-	-	-
28	-	-	-	-
29	[b]		4.01	-
30	0.3		-	-
31	-		0.25	
Totals	8.31	2.84	3.58	3.58

Table A-3. Continued.

[a]Rainfall recorded on site.

[b]Herbicides applied.