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WEED SCIENCE

Fluometuron Carryover to Flue-Cured Tobacco Following Application to Cotton

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INTERPRETIVE SUMMARY

Tobacco and cotton are North Carolina's most valuable agronomic crops. Cotton acreage in North Carolina increased from 42,000 acres in 1978 to 1,060,000 acres in 2001. This 25-fold increase in cotton acreage has led to much more cotton being rotated with tobacco. Approximately half of North Carolina's flue-cured tobacco is grown in rotation with cotton. This rotation, while benign in most respects, has caused concern among growers that the commonly used cotton herbicide, fluometuron (Cotoran, Meturon), may injure tobacco grown the season following cotton.

An experiment was conducted at six sites in eastern North Carolina during 1995 through 1998 on soils commonly used for tobacco and cotton production to determine the potential for fluometuron applied to cotton to carry over to tobacco planted the following season. Conventionally tilled cotton was treated with fluometuron preemergence at 1.5 lb a.i. acre^{-1} broadcast or in a 50% band over the row (0.75 lb acre^{-1} planted). This treatment was followed by zero, one, or two postemergence-directed applications of fluometuron at 1.5 lb acre^{-1} in a 50% band. Total fluometuron applied ranged from 0.75 to 3.0 lb acre^{-1}. Tobacco was planted the following year.

Interveinal chlorosis (yellowing) on lower leaves was the most obvious symptom of fluometuron injury on tobacco. No chlorosis was noted when fluometuron was applied preemergence only. When applied both preemergence and postemergence, greater chlorosis was noted following broadcast preemergence application. Averaged over postemergence applications, 7 and 14% of tobacco plants exhibited chlorosis following banded and broadcast preemergence applications, respectively. The number of postemergence applications had a greater impact than the method of preemergence application. At five of six sites, 6% or less of the tobacco plants exhibited chlorosis following one preemergence application and one postemergence application. Three to 29% of the plants exhibited chlorosis following one preemergence and two postemergence applications. At the sixth site, 1, 20, and 67% of the plants exhibited chlorosis following one preemergence application and zero, one, and two postemergence applications, respectively. Necrosis (dead leaf tissue) was noted at only one of the six sites, where 13% of the plants exhibited minor necrosis on the lower, unharvestable leaves following the broadcast preemergence application and two postemergence applications. No necrosis was noted with other treatments. No tobacco stunting was observed, and fluometuron treatments did not affect tobacco yield or leaf quality.

A second experiment was conducted at four locations in 1996 and 1997 to determine the sensitivity of flue-cured tobacco to varying rates of fluometuron and to examine the response to fluometuron as affected by transplant type. Use of greenhouse-produced tobacco transplants has become common practice in recent years. Previous research has indicated greenhouse transplants may be more sensitive to some chemicals than plantbed transplants. Fluometuron at rates ranging from 0.03 to 1.5 lb acre^{-1} was incorporated immediately ahead of bed formation and transplanting. Tobacco was extremely sensitive to fluometuron, with 10% visible injury

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and 10% yield reduction resulting from fluometuron at only 0.07 and 0.08 lb acre^{-1}, respectively. Reductions in leaf quality also resulted from low rates of fluometuron. Greenhouse transplants were initially more sensitive to fluometuron than were plantbed transplants. This reaction probably was due to the greater root mass that remains intact on greenhouse transplants during removal from the trays in which they are grown. In contrast, most of the roots are stripped off plantbed transplants as they are pulled from the soil. By 4 wk after transplanting, however, greenhouse and plantbed transplants responded similarly to fluometuron (Griffin L.L.C., 2001).

These results indicate that tobacco is extremely sensitive to fluometuron. However, when applied according to label directions, the herbicide should not carry over in quantities sufficient to economically impact tobacco planted the following year. Chlorosis on the lower leaves may be observed, but this should not reduce tobacco yield or quality. Higher rates of fluometuron were required to cause stunting than to produce chlorosis, indicating that, contrary to growers' claims, fluometuron causes no "hidden" damage. This work also suggests that severe tobacco injury, as occasionally noted in growers' fields, probably results from misapplication of fluometuron.

ABSTRACT

Tobacco (*Nicotiana tabacum* L.) is commonly rotated with cotton (*Gossypium hirsutum* L.) in North Carolina. An experiment on coastal plain soils determined potential for fluometuron {*N*,*N*-dimethyl-*N′*-[3-(trifluoromethyl)phenyl]urea} applied to cotton to carry over to tobacco. Cotton received fluometuron preemergence at 1.7 kg a.i. ha^{-1} broadcast or in a 50% band over the row followed by zero, one, or two postemergence-directed applications at 1.7 kg ha^{-1} in a 50% band. Greater tobacco chlorosis was noted following broadcast preemergence application. At five of six sites, 6% or fewer plants exhibited minor chlorosis following preemergence and one postemergence application, while 3 to 29% were chlorotic following preemergence and two postemergence applications. At the sixth site, 1, 20, and 67% of plants exhibited chlorosis following preemergence and zero, one, and two postemergence applications, respectively. Necrosis on lower, unharvestable leaves was noted on 13% of plants at one site. No stunting was observed, and no treatment affected tobacco yield or leaf quality. A second experiment determined tobacco sensitivity to fluometuron was affected by transplant source. Fluometuron at 0.03 to 1.7 kg ha^{-1} was incorporated before transplanting greenhouse- and plantbed-produced transplants. Ten percent visible injury and 10% yield reduction occurred with fluometuron at 0.08 and 0.10 kg ha^{-1}, respectively. Greenhouse transplants initially exhibited greater response to fluometuron, but no difference between transplant sources was noted 4 wk after transplanting. Fluometuron applied to cotton according to label directions should not economically impact tobacco production the following year.

Tobacco and cotton are North Carolina's most valuable agronomic crops (NCDACS, 2000a). Cotton production in North Carolina increased from 17,000 ha in 1978 to 429,150 ha in 2001 (NCDACS, 2000b, 2001). This 25-fold increase in cotton production has led to significant changes in crop rotations. An estimated 50% of North Carolina's flue-cured tobacco is grown in rotation with cotton (W.D. Smith, North Carolina State Univ., personal communication, 2001). This rotation, while benign in most respects, has caused concern among some growers that the commonly used cotton herbicide, fluometuron, may injure tobacco grown during the season following cotton.

Fluometuron, an apoplastically mobile phenylurea herbicide, is applied preemergence on all nontransgenic cotton in North Carolina to control broadleaf weeds (York and Culpepper, 2001). It usually is applied in combination with other herbicides such as pendimethalin [*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine], trifluralin [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine], clomazone {2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone}, or norflurazon {4-chloro-5-[methylamino]-2-[3-(trifluoromethyl)phenyl]-3 [2*H*]-pyridazinone}. Heavily infested fields usually require additional herbicides applied postemergence for optimum cotton yield, to avoid cotton grade reductions from foreign matter, and to reduce weed-related harvesting problems (Wilcut et al., 1995).

Fluometuron plus MSMA (monosodium methanearsonate) applied postemergence-directed can be an integral component of weed-management systems for nontransgenic cotton (Wilcut et al., 1995; Culpepper and York, 1997; York and Culpepper, 2001). Labeled rates of fluometuron range from 1.1 to 2.2 kg ha^{-1} per application, with one preemergence and two postemergence applications allowed in a growing season (Griffin, 2001).

North Carolina and other southeastern states have experienced a rapid shift to glyphosate-resistant cotton (Anonymous, 2000). The need for fluometuron in management systems for glyphosate-resistant cotton has been greatly reduced (Culpepper and York, 1998). However, some researchers think a residual herbicide may be beneficial in a glyphosate-based weed-management program (Askew and Wilcut, 1999), and some growers continue to use fluometuron preemergence in glyphosate-resistant cotton.

Fluometuron is moderately persistent in soil (Horowitz, 1969; Bouchard et al., 1982). Microbial degradation is primarily responsible for fluometuron dissipation from soil (Bozarth and Funderburk, 1971; Bouchard et al., 1982; Mueller et al., 1992), and climatic conditions that retard microbial activity result in longer persistence (Sharp et al., 1982; Rogers et al., 1985; Brown et al., 1996; Willian et al., 1997). Fluometuron is subject to leaching, especially in soils with low adsorptive capacity (LaFleur et al., 1973; Bouchard, 1981; Rogers et al., 1985, 1986; Hubbs and Lavy, 1990). However, leaching is much less important than microbial degradation (Rogers et al., 1985, 1986; Willian et al., 1997) in fluometuron dissipation.

Injury to wheat (*Triticum aestivum* L.) and hairy vetch (*Vicia villosa* Roth) planted in the fall or soybean [*Glycine max* (L.) Merr.], rice (*Oryza sativa* L.), corn (*Zea mays* L.), and cucumber (*Cucumis sativus* L.) planted in the spring following cotton treated with fluometuron during the preceding year has been observed on silt loam and silty clay soils (Rogers et al., 1986; Corbin et al., 1994; Johnson et al., 1995). Injury also has been observed on soybean and sorghum [*Sorghum bicolor* (L.) Moench] planted as a replacement crop 6 to 9 wk after cotton treated with fluometuron (Jackson et al., 1978). In other studies, carryover to soybean was not observed the year following fluometuron applied preemergence at 1.7 kg ha^{-1} (Chandler and Savage, 1980). Soybean planted the year following fluometuron applied preemergence at 5 kg ha^{-1} was visibly injured but yield was unaffected.

In the Mid-South region of the USA, the potential for fluometuron carryover on silt loam soils has been lower than that on silty clay soils (Rogers et al., 1986; Corbin et al., 1994). Little information is available on the carryover potential of fluometuron on sandy soils typical of the southeastern USA. Peanut (*Arachis hypogaea* L.) was not injured when planted the year following cotton treated with fluometuron at 2.2 kg ha^{-1} broadcast preemergence plus fluometuron banded postemergence-directed twice at 1.1 kg ha^{-1} (York, 1993).

Tobacco is sensitive to fluometuron and other substituted urea herbicides, but no studies have been conducted to correlate fluometuron residues in soil with tobacco injury. Fluometuron can injure cucumber at concentrations as low as 0.06 mg kg^{-1} on silt loam soils (Rogers et al., 1985). Fluometuron at 0.3 mg kg^{-1} has been detected in silt loam soils at the end of the growing season following one broadcast preemergence application and two banded postemergence-directed applications (Corbin et al., 1994). The impact that tobacco transplant source has on injury potential is unknown. Greenhouse production of tobacco transplants offers advantages (Smith et al., 2001), and growers have rapidly adopted this technology. Greenhouse transplants accounted for 93% of the transplants in North Carolina in 1999. Greenhouse transplants are often more sensitive than plantbed transplants to tobacco herbicides and systemic insecticides (Pate, 1998). The potential for increased sensitivity of these transplants to fluometuron residues needs to be examined.

The objectives of this research were to determine the potential for fluometuron to carry over to flue-cured tobacco planted the year following various fluometuron applications to cotton and to compare the sensitivity of flue-cured tobacco transplant types to fluometuron.

MATERIALS AND METHODS

Carryover Experiment

The 2-yr experiment was initiated in separate fields in 1995, 1996, and 1997 at the Upper Coastal Plain Research Station at Rocky Mount, NC, and the Lower Coastal Plain Research Station at Kinston, NC. Soils at each experimental site are

Table 1. Description of soils at experiment sites.

Experiment	Location	Years	Soil series and textural category†	pH	Organic matter content‡
				%	
Carryover	Rocky Mount	1995–1996	Norfolk loamy sand	5.7	1.9
		1996–1997	Goldsboro fine sandy loam	5.5	1.6
		1997–1998	Norfolk loamy sand	6.0	1.9
	Kinston	1995–1996	Goldsboro fine sandy loam	5.5	2.5
		1996–1997	Norfolk loamy sand	5.7	2.2
		1997–1998	Goldsboro fine sandy loam	5.6	2.4
Fluometuron rate and transplant type	Rocky Mount	1996	Norfolk loamy sand	6.1	1.8
		1997	Goldsboro fine sandy loam	6.0	1.5
	Kinston	1996	Goldsboro fine sandy loam	5.6	2.4
		1997	Goldsboro fine sandy loam	6.1	2.4

† Norfolk loamy sand: fine-loamy, siliceous, thermic, Typic Paleudults. Goldsboro fine sandy loam: fine- loamy, siliceous, thermic, Aquic paleudults.

‡ Organic matter determined by the chromic acid colorimetric method (Nelson and Sommers, 1982).

described in Table 1. These soils, which have kaolinite as the predominant clay type, are typical of those used for cotton and tobacco production in the coastal plain of North Carolina. Corn was grown at all sites during the year preceding cotton.

Cotton was planted into conventionally prepared seedbeds during the first year of the experiment. Trifluralin at 0.6 kg a.i. ha^{-1} was incorporated with a field cultivator at Rocky Mount and with a disk at Kinston. Rows were then formed by bedding with in-row subsoiling. Cotton cv. DES 119 was planted 5 May, 3 May, and 7 May at Rocky Mount in 1995, 1996, and 1997, respectively. Cotton cv. Deltapine 51 was planted 12 May, 7 May, and 12 May at Kinston in 1995, 1996, and 1997, respectively.

The experimental design was a randomized complete block with treatments replicated five times at Kinston and four times at Rocky Mount. Cotton plots were 18 m long by eight rows wide with a 97-cm row spacing. Treatments consisted of fluometuron applied preemergence at 1.68 kg ha^{-1} as either a broadcast spray or in a 50% band over the row (0.84 kg ha^{-1} planted) followed by fluometuron applied postemergence-directed zero, one, or two times at 1.68 kg ha^{-1} in a 50% band. A no-fluometuron check also was included. The first postemergence-directed application was made 26 to 42 d after planting to three- to four-leaf cotton. The second postemergence-directed application was made 39 to 60 d after planting to 8- to 10-leaf cotton.

All treatments were applied with a CO_2-pressurized backpack sprayer. Fluometuron broadcast preemergence was applied with flat-fan nozzles delivering 190 L ha^{-1} at 170 kPa. Fluometuron banded preemergence was applied with a single even-spray, flat-fan nozzle per row, delivering 195 L ha^{-1} at 140 kPa. Fluometuron postemergence-directed was applied using two flat-fan nozzles per row delivering 260 L ha^{-1} at 140 kPa. A nonionic surfactant (Induce, mixture of alkyl aryl polyoxylkane ether and free fatty acids, Helena Chemical, Memphis, TN) at 0.25% (vol vol^{-1}) was included in the postemergence-directed sprays.

Normal cotton cultivation, fertilization, insect control, and defoliation practices were followed. The center four rows of each plot were harvested mechanically at all sites except Kinston in 1997. After cotton harvest, cotton stalks were shredded and test areas were disked once.

The land was disked once the following spring, and fenamiphos [ethyl 3-methyl-4-(methylthio) phenyl (1-methylethyl) phosphoramidate] at 6.8 kg a.i. ha^{-1}, chlorpyrifos [*O*,*O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] at 2.2 kg a.i. ha^{-1}, and metalaxyl [methyl *N*–(2,6-dimethylphenyl)-*N*-(methoxyacetyl)-DL-alaninate] at 1.1 kg a.i. ha^{-1} were incorporated by disking at Rocky Mount for insect and disease control. Fields at Kinston received only metalaxyl at 1.1 kg ha^{-1}. Using known reference points to ensure locating plots in the same area as in the previous year, tobacco rows were formed by bedding with in-row subsoiling. All tillage operations were performed parallel to the rows of the preceding cotton crop to minimize lateral movement of fluometuron to adjacent plots. No herbicides or fumigants were applied to tobacco to avoid known potential injury problems, which might mask the effects of fluometuron. All other practices were standard for tobacco production in eastern North Carolina.

Tobacco plots consisted of six rows spaced 1.2 m apart and centered over the previous year's cotton plots. Tobacco plot length was reduced to 12 m to compensate for any longitudinal movement of fluometuron by tillage implements. Greenhouse-produced tobacco cv. K-326 transplants were set in the field on 5 May, 13 May, and 15 May at Rocky Mount in 1996, 1997, and 1998, respectively, and at Kinston on 29 April, 6 May, and 7 May in 1996, 1997, and 1998, respectively. Tobacco was maintained weed-free by hand-hoeing and cultivation.

All data were collected from the center two tobacco rows. At 2, 4, and 6 wk after transplanting, the number of plants expressing fluometuron-induced chlorosis or necrosis, a stand count, and overall crop injury were recorded. Plants were considered chlorotic if there was any visible whitening or yellowing of interveinal leaf tissue or leaf margins characteristic of fluometuron injury (Skroch and Sheets, 1977). Plants were considered necrotic if there was any visible leaf necrosis. Overall injury, which included chlorosis, necrosis, and plant vigor, was estimated visually using a scale of 0 = no injury to 100 = complete death. Tobacco was hand-harvested three times at Rocky Mount in 1996 and 1998 and four times at the other locations. Cured leaves from individual harvests were weighed and graded separately. Grade index (Bowman et al., 1988) was recorded, and the weighted average value per kg was determined from a yearly market average for each grade.

Data were subjected to analysis of variance with partitioning appropriate for a two (preemergence) by three (postemergence) factorial treatment arrangement. A separate analysis of variance compared all fluometuron treatments with the no-fluometuron check. Data for number of chlorotic or necrotic plants and for overall visible injury were subjected to square-root transformation before analysis of variance. Nontransformed data for overall injury are presented. Data for number of chlorotic or necrotic plants were converted to a percentage of the total plants for presentation. Data were combined over locations and years when appropriate.

Fluometuron Rates and Transplant Type Experiment

The experiment was conducted at the Upper Coastal Plain Research Station at Rocky Mount, NC, and the Lower Coastal Plain Research Station at Kinston, NC, during 1996 and 1997. Soils for this experiment are described in Table 1. Corn was the preceding crop at each experimental site.

The experimental design was a split-plot with treatments replicated four times. Whole plots consisted of fluometuron at rates of 0, 0.035, 0.07, 0.14, 0.28, 0.56, 0.84, 1.12, and 1.68 kg ha^{-1}. Subplots consisted of two rows of plantbed or greenhouse transplants. Two border rows separated whole plots. Row spacing was 1.2 m and plots were 12 m in length. Fluometuron rates were assigned randomly in each block, and transplant types were assigned randomly within fluometuron rates. Fluometuron was applied as a broadcast spray using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles delivering 190 L ha^{-1} at 170 kPa. Fluometuron was incorporated by double disking at Kinston or a single pass of a field cultivator at Rocky Mount. Rows were then formed by bedding with in-row subsoiling. No fumigants or herbicides other than fluometuron were applied to the tobacco. Both greenhouse and plantbed tobacco cv. K 326 transplants were placed in the field 8 May and 29 April at Rocky Mount and Kinston, respectively, in 1996 and 13 May and 6 May at Rocky Mount and Kinston, respectively, in 1997. Transplants were produced according to standard practices (Smith et al., 2001). Tobacco was maintained weed-free by cultivation and hand-hoeing.

Data recorded at 2, 4, and 6 wk after transplanting included a stand count, the number of plants exhibiting chlorosis or necrosis, and a visual estimation of injury as described previously. The number of dead plants, the number of plants exhibiting chlorosis, and the number of plants exhibiting necrosis were summed and then divided by the total number of plants to obtain a variable referred to as percent dead or injured plants. This combined variable was necessary because the number of chlorotic or necrotic plants decreased as fluometuron rates increased and a greater number of plants died. Tobacco was harvested by hand three to four times, and each harvest was weighed and graded separately. Grade index and value per kg were determined as described previously. Value per ha was calculated from yield and value per kg.

Data were subjected to analysis of variance and were combined over locations and years because there were no treatment by location, treatment by year, or treatment by location by year interactions. Data were transformed as described previously; nontransformed data are presented. Quadratic equations were fitted for visible injury and yield loss. A generalized logistic model was fitted for data on dead or injured plants, value per kg, and quality index.

RESULTS AND DISCUSSION

Carryover Experiment

Cotton Response

No cotton injury from fluometuron preemergence was noted. Injury from fluometuron postemergence-directed never exceeded 5% (data not shown). Weed pressure was very light in cotton at Rocky Mount in 1995 and 1996 and at Kinston in 1996, and cultivation was sufficient to maintain all plots essentially weed-free. Yield of fluometuron-treated cotton at these locations did not differ from that of the no-fluometuron checks. Pooled over treatments, seed cotton yields at Rocky Mount in 1995 and 1996 and at Kinston in 1996 were 2190, 3320, and 2890 kg ha^{-1}, respectively. Cotton in the no-fluometuron plots at Kinston in 1995 and at Rocky Mount in 1997 was moderately infested with weeds. No differences were noted among yields of cotton receiving various fluometuron treatments, with yields averaging 2430 kg ha^{-1} at Kinston in 1995 and 2750 kg ha^{-1} at Rocky Mount in 1997. Yields of the no-fluometuron checks were reduced 24 and 18% at Kinston in 1995 and Rocky Mount in 1997, respectively. Cotton yield was not recorded at Kinston in 1997.

Tobacco Response

Conditions were generally good for initial survival of transplants, and fluometuron treatments the previous year had no effect on tobacco stand. Transplant survival was at least 97% at all sites.

A preemergence application method by numbers of postemergence applications interaction was not observed for percentage of tobacco plants exhibiting chlorosis or for overall tobacco injury. However, location and year by numbers of postemergence applications interactions prevented combining these data over years or locations. No year or location by preemergence application method interaction was observed.

The percentage of plants exhibiting chlorosis and overall injury increased between the 2- and 4-wk evaluations but remained generally constant between the 4- and 6-wk evaluations. Increased absorption of fluometuron probably occurred between 2 and 4 wk after transplanting due to expansion of the root system and increased transpiration of growing plants as they recovered from the shock of transplanting.

Pooled over numbers of postemergence fluometuron applications, there tended to be a greater percentage of tobacco plants exhibiting chlorosis 6 wk after transplanting following broadcast preemergence fluometuron, compared with banded preemergence fluometuron. However, a significant difference was noted only at Rocky

Table 2. Main effect of method of fluometuron preemergence application to cotton grown the year preceding tobacco on percentage of tobacco plants exhibiting chlorosis 6 wk after transplanting.†

Fluometuron preemergence application method	Kinston			Rocky Mount			Mean‡
	1996	1997	1998	1996	1997	1998	
				%			
Broadcast	12 a	2 a	13 a	11 a	13 a	42 a	14 a
Banded	8 a	0 a	6 a	8 a	6 a	16 b	7 b

† Data pooled over numbers of postemergence fluometuron applications. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at $P = 0.05$. Fluometuron applied broadcast or in a 50% band over the row of the preceding cotton crop at 1.68 kg ha^{-1}.

‡ Data pooled over locations and years. No preemergence application method by year or location interaction was observed.

Table 3. Main effect of method of fluometuron preemergence application to cotton grown the year preceding tobacco on visible injury to tobacco plants 6 wk after transplanting.†

Fluometuron preemergence application method	Kinston			Rocky Mount			
	1996	1997	1998	1996	1997	1998	Mean‡
				%			
Broadcast	5 a	4 a	7 a	7 a	7 a	16 a	8 a
Banded	3 a	1 a	1 a	3 a	5 a	6 b	4 b

† Data pooled over numbers of postemergence applications of fluometuron. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at $P = 0.05$. Fluometuron applied broadcast or in a 50% band over the row of the preceding cotton crop at 1.68 kg ha^{-1}.

‡ Data pooled over locations and years. No preemergence application method by year or location interaction was observed.

Mount in 1998, where 42 and 16% of the plants exhibited chlorosis following broadcast and banded applications, respectively (Table 2). Averaged over years, locations, and numbers of postemergence applications, 14 and 7% of the tobacco transplants exhibited chlorosis following broadcast and banded preemergence applications, respectively. Similar trends were noted for overall injury to tobacco (Table 3). At Rocky Mount in 1998, overall injury was 16 and 6% with broadcast and banded applications of fluometuron, respectively. Averaged over locations, years, and numbers of postemergence fluometuron applications, overall injury was 8 and 4% with broadcast and banded preemergence applications, respectively. Data for overall injury percentage were of lower magnitude than data for the percentage of plants exhibiting chlorosis. Plants were counted as chlorotic if any chlorosis was visible. Chlorosis was confined to the lower, unharvestable leaves, and the severity of symptoms was mild. Mild chlorosis did not weigh heavily in the estimation of overall visible injury.

Numbers of postemergence applications had a greater impact on tobacco than methods of preemergence application. Little to no overall injury or chlorosis was noted at Kinston in 1997 (Tables 4, 5). At Kinston in 1996 and 1998 and at Rocky Mount in 1996 and 1997, overall injury percentage and the percentage of plants exhibiting chlorosis did not differ between zero and one postemergence application of fluometuron. Increased injury percentage and a greater percentage of plants exhibiting chlorosis were noted with the second postemergence application. Six to 29% of the plants at these locations were chlorotic, and the overall injury percentage was estimated to be 8 to 13% following two postemergence applications. In addition to increasing the overall amount of fluometuron applied, the second postemergence application was made 39 to 60 d after planting. Later application reduces the time the herbicide is subject to degradation. Additionally, conditions for microbial degradation may be less favorable during mid-season because of higher temperatures and typically lower soil moisture (Rogers et al., 1985). At Rocky Mount in 1998, the percentage of plants exhibiting chlorosis and overall injury increased with each additional postemergence

Table 4. Main effect of numbers of postemergence-directed applications of fluometuron to cotton grown the year preceding tobacco on percentage of tobacco plants exhibiting chlorosis 6 wk after transplanting.†

Numbers of postemergence-directed applications of fluometuron	Kinston			Rocky Mount			
	1996	1997	1998	1996	1997	1998	Mean‡
				%			
0	0 b	0 a	0 b		0 b	0 b	1 c
1	0 b	0 a	1 b		6 b	5 b	20 b
2	29 a	3 a	6 a		27 a	23 a	67 a

† Data pooled over methods of preemergence application of fluometuron. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at $P = 0.05$. Fluometuron postemergence-directed at 1.68 kg ha^{-1} in a 50% band over the row of the preceding cotton crop.

Table 5. Main effect of numbers of postemergence-directed applications of fluometuron to cotton grown the year preceding tobacco on visible injury to tobacco plants 6 wk after transplanting.†

Numbers of postemergence-directed applications of fluometuron	Kinston			Rocky Mount			
	1996	1997	1998	1996	1997	1998	Mean‡
	%						
0	2 b	3 a	2 b		1 b	1 b	1 c
1	2 b	2 a	3 b		3 b	4 b	8 b
2	8 a	3 a	11 a		12 a	13 a	24 a

† Data pooled over methods of preemergence application of fluometuron. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at $P = 0.05$. Fluometuron postemergence-directed at 1.68 kg ha^{-1} in a 50% band over the row of the preceding cotton crop.

application. Sixty-seven percent of the plants exhibited chlorosis following two postemergence applications, and the overall injury percentage was estimated to be 24%.

No necrosis was noted at Kinston in any year or at Rocky Mount in 1996 or 1998. Necrosis was noted at Rocky Mount in 1997 only when tobacco was planted following one broadcast preemergence application of fluometuron and two postemergence applications. Thirteen percent of the plants in this system exhibited necrosis. The necrosis was minor and was confined to the unharvestable lower leaves, and thus did not impact tobacco quality. No stunting was observed with any treatment. Treatments did not affect tobacco yield, grade index, or value per kg (data not shown). Pooled over treatments, locations, and years, tobacco yield was 3335 kg ha^{-1}, grade index was 68, and value was \$3.84 kg^{-1}.

Microbial degradation is the primary method of fluometuron dissipation (Bozarth and Funderburk, 1971; Mueller et al., 1992). Soil moisture during the warmer months of the year would, therefore, be the primary factor determining persistence. Cumulative rainfall May through October was above normal in 1995 and 1996 at both locations (Table 6). However, the above-normal rainfall was not evenly distributed. Greater-than-normal rainfall was received in June and October 1995; whereas, below-normal rainfall was received during the other 4 mo. Rainfall was above normal during July, September, and October 1996 but below normal during May, June, and August. Most of the above-normal precipitation in 1995 and 1996, and especially in 1995, came from heavy rainfall events where rainfall greatly exceeded the soils' moisture-holding capacities, and most of the water ran off. Considering that, plus the below-normal precipitation during at least half of the warm months, overall soil moisture

Table 6. Monthly rainfall totals.

Month	Average†	Kinston			Rocky Mount		
		1995–1996	1996–1997	1997–1998	1995–1996	1996–1997	1997–1998
	cm						
May	10.8	7.0	8.1	5.2	5.6	9.3	3.6
June	11.1	42.9	7.6	2.7	30.8	8.8	7.2
July	14.4	5.9	24.5	14.0	8.4	18.0	12.5
August	13.7	11.7	6.9	6.2	11.0	13.0	4.1
September	10.7	6.1	25.3	12.1	9.4	20.7	17.6
October	7.8	15.0	14.7	3.4	15.0	11.8	4.2
November	7.5	8.2	10.0	12.0	12.0	6.0	11.1
December	8.5	4.7	8.6	8.8	5.4	9.2	7.3
January	10.4	8.8	6.3	14.1	10.7	6.8	15.0
February	9.6	4.4	40	15.3	6.2	6.8	5.1
March	10.5	11.7	8.3	8.0	8.4	6.3	13.1
April	8.3	7.1	7.8	11.2	8.1	9.2	10.7

† Thirty-year (1961-1990) average monthly rainfall, averaged over five reporting stations (Goldsboro, Kinston, Smithfield, Williamston, and Wilson, NC) in the central coastal plain of North Carolina (SRCC, 2000).

conditions probably were not greater than normal. Precipitation during the cooler months, November through April, was below normal in both years preceding the tobacco crops.

Sorption of fluometuron is correlated primarily with soil organic matter content (Mueller et al., 1992; Willian et al., 1997), and fluometuron can leach in sandy, low organic matter soils (Bouchard et al., 1986; Rogers et al., 1986; Essington et al., 1995). We speculated that leaching did not contribute greatly to overall fluometuron dissipation in this experiment. Most fluometuron typically remains in the upper portion of the soil profile (Baldwin et al., 1975; Hance et al., 1981; Nicholls et al., 1982; Willian et al., 1997). Additionally, fluometuron has not been detected in surficial aquifers following normal field use on coarse-textured soils whereas other herbicides, such as atrazine [6-chloro-*N*-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4-diamine], have been detected under similar conditions (Wade et al., 1998). Leaching during periods of saturated-soil conditions in summer months would probably be offset by upward movement of the herbicide through the soil profile via capillary transport during drier periods (Hubbs and Lavy, 1990; Weber et al., 1999). Leaching also was minimized during the cooler months, November through April, in 1995–1996 and 1996–1997, due to below-normal precipitation (Table 6).

The 1997 growing season was drier than normal at both locations, and may explain why more fluometuron symptoms were noted on tobacco in 1998 (Tables 2–5). Rainfall during May through October 1997 was only two-thirds normal (Table 6). Rainfall was near normal during July and September at Kinston but much below normal during the other 4 mo. At Rocky Mount, rainfall in September was 164% of normal but only 33 to 87% of normal during the other 5 mo.

Temperature also can influence microbial degradation of herbicides. Average daily temperatures, pooled over the months of May through October, were 1ºC above normal at Kinston in 1995 and 1996, about normal at Kinston in 1997 and Rocky Mount in 1995 and 1996, and 1ºC below normal at Rocky Mount in 1997. Average daily temperatures November to April were 0.3 to 1.3ºC above normal at Kinston in each year, about normal at Rocky Mount in 1997–1998, and 0.6 to 2.6ºC below normal at Rocky Mount in 1995–1996 and 1996–1997. These relatively minor deviations from normal should have had little impact on fluometuron dissipation (Rogers et al., 1985).

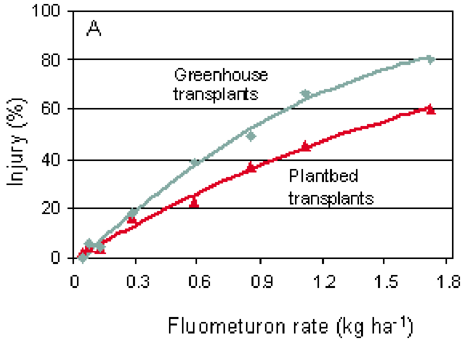
Fluometuron can be applied one to three times per season at rates of 1.12 to 2.24 kg ha^{-1} per application (Griffin L.L.C., 2001). Hence, the rates and numbers of fluometuron applications in our experiment were within the limits defined by the label. It is possible, but unlikely, that greater injury to tobacco would have been observed if fluometuron had been applied for 2 or more years consecutively before planting tobacco. Rogers et al. (1985) reported no buildup of fluometuron over 3 yr. Brown et al. (1996) reported that 5 to 10% of the fluometuron initially applied was present 1 yr after application. However, with residual levels of 10% 1 yr after application, continued use of the same rates would result in only 11.1% residual 1 yr after three consecutive-use seasons.

Greater injury to tobacco may have been observed if other herbicides having a similar mode of action — such as diuron [*N*'-(3,4-dichlorophenyl)-*N*,*N*-dimethylurea], linuron [*N*'-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea], or prometryn [*N*,*N*'-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine] — had been applied in addition to the fluometuron (Corbin et al., 1994). However, this is an unlikely scenario. Diuron, linuron, and prometryn typically are applied as postemergence-directed sprays (York and Culpepper, 2001). Growers would rarely make two postemergence applications of fluometuron plus a postemergence application of one of these other herbicides. Diuron, linuron, and prometryn are viewed as alternatives to fluometuron applied postemergence (York and Culpepper, 2001).

Fluometuron Rate and Transplant-Type Experiment

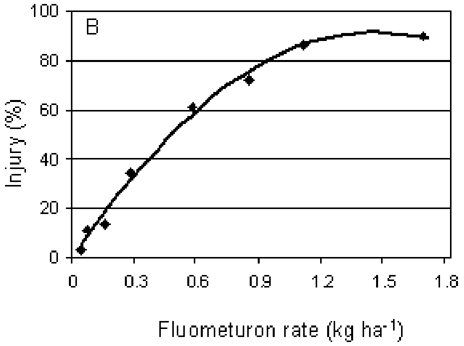
Lack of treatment by year or treatment by location interactions allowed pooling of data over years and locations. A fluometuron rate by transplant-type interaction was noted for percentage of dead or injured plants and for overall injury 2 wk after transplanting. Neither a fluometuron rate by transplant-type interaction nor a main effect of transplant types was observed for these variables at 4 or 6 wk after transplanting or for tobacco yield, grade index, or value per kilogram. However, the main effect of fluometuron rates was significant for dead or injured plants and overall injury at 4 and 6 wk after transplanting and for tobacco yield, grade index, and value per kilogram.

A generalized logistic, nonlinear model was fitted to the means for percentage of dead or injured plants on the basis of the log of the fluometuron rate. This transformation improved the fit of the prediction equation. Estimates of visible injury assessed overall plant damage, including chlorosis, necrosis, reductions in vigor, and plant death. Quadratic equations fitted means for percentage of overall injury to fluometuron rates. Greater rates of fluometuron were necessary to achieve a given level of overall injury (Fig. 1) compared with the same percentage of dead or injured plants (Fig. 2) because plants were counted as chlorotic even if only small areas of the leaves exhibited chlorosis. Mild chlorosis did not weigh heavily in the estimation of overall injury.

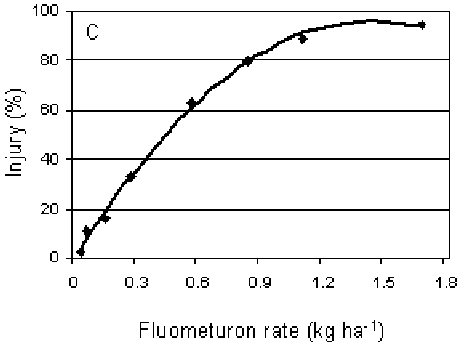


(A) $Y_{\text{plantbed}} = -0.13 + 49.3X - 7.96X^2$; $r^2 = 0.992$

$Y_{\text{greenhouse}} = -2.6 + 80.4X - 18.41X^2$; $r^2 = 0.995$

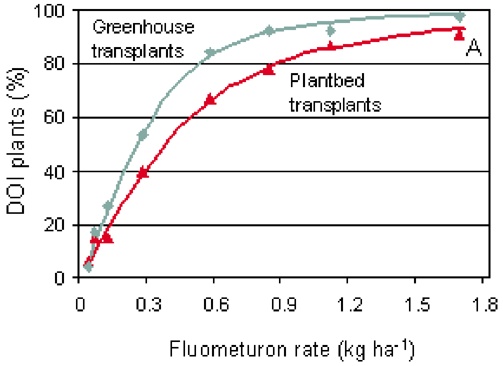


(B) $Y = 1.11 + 124.9X - 43.05X^2$; $r^2 = 0.980$



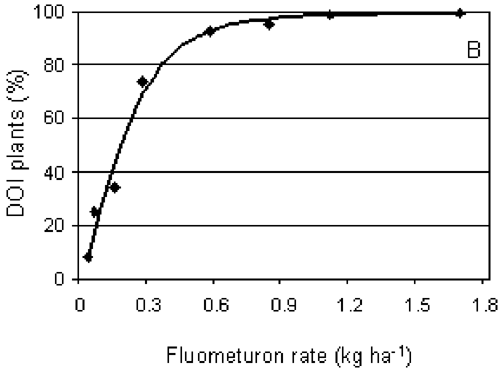
(C) $Y = 0.19 + 133.5X - 46.38X^2$; $r^2 = 0.996$

Fig. 1. Effect of fluometuron rates on visible injury of tobacco in fluometuron rate and transplant-type experiment. (A) 2 wk after transplanting; (B) 4 wk after transplanting; (C) 6 wk after transplanting. Data for 4 and 6 wk after transplanting are pooled over transplant types.

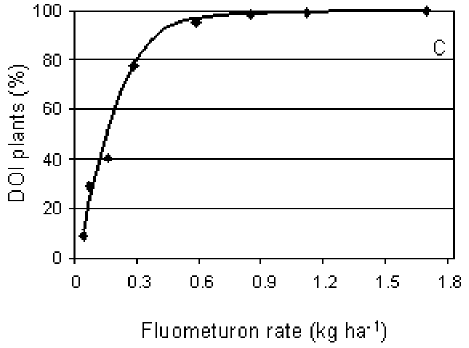


(A) $Y_{\text{plantbed}} = 100(1/(1 + 0.42*\exp(-4.51[\log X]))^{0.51})$; $r^2 = 0.994$

$Y_{\text{greenhouse}} = 100(1/(1 + 0.14*\exp(-5.51[\log X]))^{0.43})$; $r^2 = 0.997$



(B) $Y = 100(1/(1 + 0.05*\exp(-6.19[\log X])^{0.38})$; $r^2 = 0.994$



(C) $Y = 100(1/(1 + 0.02*\exp(-7.37[\log X])^{0.29})$; $r^2 = 0.994$

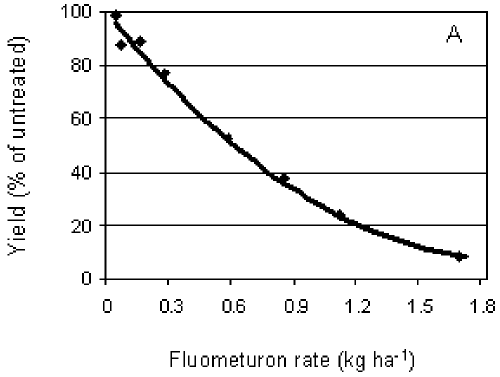
Fig. 2. Effect of fluometuron rates on percentage of dead or injured tobacco plants in fluometuron rate and transplant-type experiment. (A) 2 wk after transplanting; (B) 4 wk after transplanting; (C) 6 wk after transplanting. Data for 4 and 6 wk after transplanting are pooled over transplant types.

The overall injury percentage and the percentage of dead or injured plants increased as the fluometuron rate increased (Figs. 1, 2). Greenhouse transplants exhibited a greater response to fluometuron than plantbed transplants did at 2 wk after transplanting, and this differential response increased as the fluometuron rate increased. The rate of fluometuron necessary to injure or kill 20, 50, and 80% of the plants was 0.13, 0.37, and 0.87 kg ha^{-1}, respectively, for plantbed transplants compared with 0.09, 0.25, and 0.52 kg ha^{-1} for greenhouse transplants.

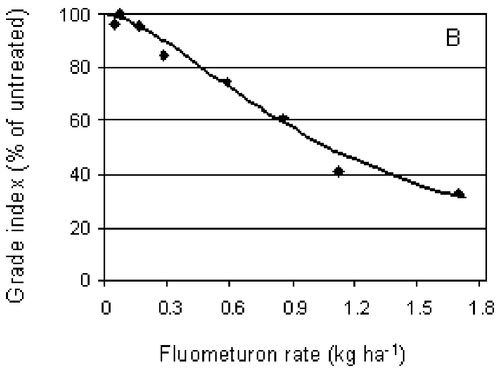
The greater response of greenhouse transplants to fluometuron at 2 wk after transplanting was probably due to differences in root mass at and shortly after transplanting. The rootball, which contains many fine roots, remains intact as greenhouse transplants are removed from the tray in which they were grown. In contrast, most of the roots are stripped off as plantbed transplants are pulled from the soil. The greater root mass on greenhouse transplants leads to greater absorption of water, nutrients, and herbicides shortly after transplanting (Pate, 1998). Lack of a fluometuron by transplant-type interaction and a significant main effect of transplant types at 4 and 6 wk after transplanting indicates the plantbed transplants produced new roots and absorbed fluometuron in amounts similar to that for greenhouse transplants after the 2-wk evaluation.

The rate of fluometuron necessary to produce a given percentage of overall injury or dead or injured plants decreased between the 2- and 4-wk evaluations but remained relatively constant between 4 and 6 wk after transplanting (Figs. 1, 2). For example, the rate of fluometuron that caused 60% overall injury at 4 and 6 wk after transplanting was 0.59 and 0.56 kg ha^{-1}, respectively, compared with 1.01 and 1.67 kg ha^{-1} for greenhouse and plantbed transplants, respectively, at 2 wk after transplanting.

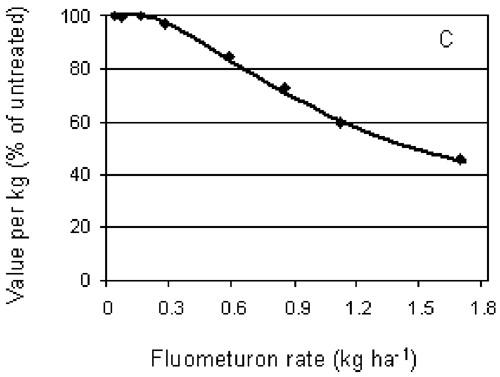
Tobacco yield decreased as fluometuron rate increased (Fig. 3). Yield was reduced 10 and 50% by fluometuron at 0.10 and 0.60 kg ha^{-1}, respectively. Tobacco quality, measured by grade index, and tobacco value per kg also decreased as fluometuron rate increased. Value per ha was reduced 10% by fluometuron at 0.09 kg ha^{-1} (data not shown).



(A) $Y = 98.95 - 96.4X + 25.6X2$; $r^2 = 0.993$



(B) $Y = 100(1 - 1/(1 + 1.25*\exp(-3.91[\log X])^{\wedge}0.92)$; $r^2 = 0.980$



(C) $Y = 100(1 - 1/(1 + 0.25*\exp(-2.62[\log X])^{\wedge}4.64)$; $r^2 = 0.999$

Fig. 3. Effect of fluometuron rates on tobacco yield (A), grade index (B), and value per kilogram (C) in fluometuron rate and transplant-type experiment. Data pooled over transplant types.

Minor fluometuron symptoms, primarily chlorosis on lower leaves, were apparent before substantial overall injury occurred. Additionally, the percentage of dead or injured plants was always greater than the percentage yield reduction at any given rate of fluometuron. This result would imply there would be no “hidden” yield or vigor reductions in the absence of chlorosis. Fluometuron does not directly affect root growth. It kills susceptible plants by causing lipid peroxidation in older leaf tissue (WSSA, 1994). Root systems should function normally as long as fluometuron levels in the plant did not affect above-ground growth, and plant vigor would not be affected until fluometuron levels were elevated to the point where chlorosis impaired leaf functions. Similar results were reported for cucumber, where low concentrations of fluometuron caused leaf chlorosis without reductions in fresh weight (Rogers et al., 1986).

In the carryover experiment with tobacco on soils similar to those in the transplant-type experiment, chlorosis on tobacco leaves was greatest following fluometuron broadcast preemergence and two postemergence-directed fluometuron applications. However, tobacco yields were unaffected by fluometuron treatments. Results of the fluometuron rate and transplant-type experiment suggest that fluometuron levels in the soil at time of tobacco planting in the carryover experiment were in the range of 0.06 to 0.10 kg ha^{-1} because these levels produced chlorosis on tobacco while having little to no effect on yield.

This research demonstrates that flue-cured tobacco is very sensitive to fluometuron. However, fluometuron at low levels can induce injury symptoms on tobacco without reducing yields. Greenhouse transplants are more sensitive to soil residues of fluometuron than conventional plantbed transplants are early in the season. Use of greenhouse transplants has increased dramatically in recent years, and the initial greater sensitivity of these transplants to fluometuron may partially explain growers' increased concerns about fluometuron carryover to tobacco. However, differences between transplant types in response to fluometuron are not evident by 4 wk after transplanting. Fluometuron applied preemergence plus twice postemergence-directed in a band to cotton should not adversely affect the yield, quality, or net returns of tobacco grown the following year. These results suggest that severe fluometuron injury to tobacco, as occasionally noted in growers' fields, probably results from misapplication of fluometuron.

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