Influence of Simulated Quinclorac Drift on the Accumulation and Movement of Herbicide in Tomato (*Lycopersicon esculentum*) Plants

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Quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) is a herbicide commonly used in rice, and its drift has been suspected of causing injury to off-target tomato fields throughout Arkansas. Studies were conducted to evaluate the effects of single and multiple simulated quinclorac drift applications on tomato plant growth and development. Residues extracted from tomato plants treated with 0.42 g of ai ha^{-1} were below the detection limit of liquid chromatography−double mass spectrometry (LC-MS/MS) analysis. Quinclorac residue levels and half-lives in tomato tissue increased as the application rate and number of applications increased. From 3 to 72 h after ^{14}C-quinclorac treatment of plants, most of the absorbed ^{14}C was retained in the treated leaf, and translocations of ^{14}C out of the treated leaf of vegetative and flowering tomato plant tissues were similar. Of the ^{14}C that translocated out of the treated leaf, the greatest movement was acropetally. The flower cluster contained 1% of the total absorbed ^{14}C, which suggests the potential for quinclorac translocation into tomato fruit. More extensive research will be required to understand the impact that quinclorac may have on tomato production in the area.

INTRODUCTION

Tomatoes (*Lycopersicon esculentum* Mill.) are only grown on about 500 ha throughout Arkansas, but accounted for > U.S. $17 000 000 in revenue in 2002 (*1*). Throughout the Mississippi Delta region of Arkansas, off-target movement of quinclorac has been suspected of causing problems with tomato production, resulting in economic losses to farmers. Tomatoes are extremely sensitive to quinclorac (*2*, *3*), and understanding the impact of quinclorac drift to off-target tomato fields has become an important issue in Arkansas.

Quinclorac is widely used because it is efficacious on many problem weeds in rice (*4−6*) and has a broad range of application timings (*7*). Quinclorac is commonly applied to Arkansas rice fields using fixed-winged aircraft, which has created concern among tomato growers. Tomato growers feel that the extensive use of quinclorac, coupled with a large potential for drift from aerial application (*8*), has resulted in repeated damage to their tomato crops (*9*). However, no conclusive information exists that explains why this problem continues because quinclorac application is restricted to distances > 6.4 km from tomato fields.

Survey studies were conducted at five tomato producer's fields throughout the Mississippi Delta region of Arkansas to evaluate quinclorac injury in these tomato fields and the relationship of the

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injury to levels of quinclorac residues in tomato tissue, soil, and air at the test sites as a result from drift (*9*). From mid-May until harvest, tomato plants at all sites displayed various degrees of abnormal growth symptoms. The most common symptoms were severe leaf curling and cupping, small plant size, lack of vigor, bloom abscission, and low fruit set and growth. Many of the observed foliar symptoms were consistent with those expected from quinclorac exposure. Furthermore, tomato plant tissues contained detectable quinclorac levels (LOD = 10 ppb) from the beginning of sampling (*9*). Quinclorac was detected more frequently and in higher amounts in the tissue samples taken during the early season, which also corresponded to the peak time for quinclorac application to rice. The ambient air above the tomato fields also contained detectable levels of quinclorac, but no quinclorac applications were reported within 6.4 km on many days that quinclorac was detected. Although these tomato plants were repeatedly exposed to low levels of quinclorac, no quinclorac was detected in soil samples from those fields. Bansal et al. (*9*) concluded that the specific sources of quinclorac found in the ambient air could not be determined.

In support of the growers' concerns, other data have shown that quinclorac can damage plants, reduce yields (*10*), and potentially accumulate in tomato fruit. Although responses of tomato to other herbicides have been evaluated, data on absorption and translocation of quinclorac in tomato have not been reported.

Quinclorac absorption and translocation vary depending on plant species. In general, quinclorac is readily absorbed by germinating seeds, roots, and leaves and is translocated both acropetally and basipetally in plants (*3, 11*). Leafy spurge (*Euphorbia eusala* L.) foliage rapidly absorbed ^{14}C-quinclorac (65% of the total applied within 4 h after treatment), but little additional absorption occurred from 4 to 44 h (*12*). The majority of the absorbed ^{14}C-quinclorac either remained in the treated leaf or was exuded by roots. Contrary to results with leafy spurge, 90% of the absorbed ^{14}C-quinclorac translocated out of the treated leaf of false cleavers (*Galium spurium* L.), with differing amounts translocating acropetally, basipetally, or via root exudation (*13*).

Rapid uptake of ^{14}C-quinclorac was observed in southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.], Kentucky bluegrass (*Poa pratensis* L.), (*14*), and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] (*15*). In barnyardgrass, 40−60% of the absorbed ^{14}C-quinclorac remained in the treated leaf, whereas only small amounts of this herbicide translocated to the roots or was exuded by the roots.

Overall, reports indicate that quinclorac movement differs among plant species, and it is difficult to predict quinclorac absorption and translocation in tomato plants. Furthermore, these reported studies do not provide insight as to the potential movement of herbicide toward or into the fruiting structures, which could create concerns among consumers and processors.

Although recent published data related to this residue study evaluated the effects of quinclorac on the growth and development of tomato plants (*10*), no studies have examined herbicide residues within the plants. Thus, our objectives were to develop a time course of the persistence of detectable quinclorac residues in tomato tissues exposed to simulated drift rates of quinclorac on young tomato plants and to examine the absorption and translocation of quinclorac in tomato plants.

MATERIALS AND METHODS

Field Studies. Field studies were conducted at the Main Experiment Station in Fayetteville, AR, in 1999 and 2000 to determine the effects of quinclorac exposure on tomato plant (var. 'Mountain Supreme') growth and development. The experimental design was a randomized complete block, with a factorial arrangement of treatments (quinclorac rate by number of quinclorac applications), and four replications. Plots were composed of a single row of plants, 12.3 m long, 0.45 m plant spacing, 2 m between plots, with 6 m alleys separating replications.

Each spring, the soil [Captina silt loam (fine-silty, mixed, mesic Typic Fragiudult) with 1.5% organic matter and a pH of 5.9] was fertilized according to soil test recommendations prior to bedding. In 1999, tomato seeds were planted in a greenhouse on April 30, and plants (ca. five-leaf stage) were transplanted into beds on June 4. In 2000, tomato seeds were planted in the greenhouse on April 20, and plants were transplanted into beds on May 24. Established plants were watered with drip-line irrigation and treated with azoxystrobin (fungicide) and λ-cyhalothrin (insecticide) for control of diseases and insects. Primary weed control was achieved with a broadcast application of sethoxydim (0.22 kg of ai ha^{-1}) and metribuzin (0.56 kg of ai ha^{-1}). Uncontrolled weeds were removed by hand.

Field Studies: Application of Simulated Drift. Previous reports indicated that drift applications of certain herbicides to tomato at or just prior to bloom were the most detrimental to yield (*16, 17*). Thus, quinclorac (Facet 75 DF) was initially applied when plants began blooming. In 1999, quinclorac was applied at 0.42, 4.2, and 42 g of ai ha^{-1}, but rates were adjusted in 2000 to represent lower drift rates of 0.42, 2.1, and 4.2 g of ai ha^{-1} that would be more comparable to actual field drift events. Each quinclorac rate was applied at midbloom of the first flower cluster, midbloom of the first cluster followed by an application 1 WAT, or midbloom of the first cluster followed by applications at 1 and 2 WAT. A 60 cm band was sprayed over the top of plants using a CO$_2$ backpack sprayer (8003 even flat-fan nozzle) calibrated to deliver 187 L ha^{-1} at 172 kPa. All treatments were made at 0600 h with zero wind velocity. Applications were initiated on July 12 and July 11 in 1999 and 2000, respectively. Ambient air temperatures were 20−25 °C, RH was 85−95%, and soil temperatures were 20−25 °C at all application times.

Field Studies: Sampling and Extraction. Single plants were randomly harvested from each plot at 0, 3, 7, 9, 10, 14, 17, 21, 28, 35, 42, 49, and 56 DAT. Plants were excised at the soil surface, and fresh weight was determined. The plant material (vegetation and fruit) was bagged, sealed, labeled, and placed in a freezer.

Tissue from some untreated tomato plants (harvested prior to any field treatments) was fortified with quinclorac to establish the stability of quinclorac in tomato tissues during transit to the analytical laboratory and also to serve as standards for quinclorac analysis in field-harvested tissue. Fortified samples were prepared by grinding leaf tissue in liquid nitrogen (mortar and pestle) and adding known amounts of quinclorac in acetone (1 mL) to plant tissue (10 g) to create standard fortified samples of 1000, 100, and 10 ppb (fresh weight basis). Fortified samples were created immediately after each harvest. Field and fortified tomato samples were packed with dry ice and shipped next-day airfreight to ADPEN Laboratories Inc. (Jacksonville, FL) for residue analysis.

Field Studies: Residue Analysis. All samples for residue analysis were analyzed by ADPEN Laboratories. Residues in tomato tissues were extracted according to a modified procedure (presently proprietary, BASF Corp., Research Triangle Park, NC) based on method A8902 (*18*). Generally, ground tomato tissue was treated with NaOH and extracted with acetone. This acetone extract was concentrated with a rotary evaporator and adjusted to pH 8.0 followed by partitioning with dichloromethane. The remaining aqueous layer was acidified to pH 1.0−2.0 and repartitioned with dichloromethane. This dichloromethane fraction was reduced to dryness (nitrogen stream), brought up in an alkaline solution, and further purified utilizing quaternary amine-based column chromatography. Final quantitative analyses of the samples were performed utilizing liquid chromatography with tandem mass spectrometry detection (SCIEX API 3000 triple-quadrupole systems; Applied Biosystems, Foster City, CA). ADPEN defined the LOD and LOQ as 3- and 10-fold greater than the "noise" level, respectively. The LODs for quinclorac in tomato tissue were 9 and 5 ppb and the LOQs were 30 and 17 in 1999 and 2000, respectively.

Laboratory Studies. Laboratory experiments were conducted to evaluate quinclorac absorption and translocation in tomato plants at two growth stages: vegetative (4-leaf stage) and flowering (10-leaf stage). Experiments were conducted twice as a completely random design with four replications, and factors were arranged as a two-factor factorial (plant size by harvest time). Tomato seeds were planted in vermiculite and placed

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in a growth chamber until germination occurred (28/24 °C day/night; 16 h day length; 90% RH; PPFD 500 μmol m^{-2} s^{-1}). Seven-day-old seedlings to be treated at the 4-leaf stage were transferred to pots (350 mL) containing sterilized quartz sand, and seedlings to be treated at the flowering stage were transferred to larger pots (1500 mL) containing sterilized quartz sand. After transfer, plants were returned to the growth chamber until the desired growth stage was attained. Plants were fertilized weekly with water-soluble plant food (ca. 7 g L^{-1}) (Miracle-Gro, The Scotts Co., Marysville, OH).

Laboratory Studies: Herbicide Application. At the desired growth stage, the plants were treated with a broadcast application of quinclorac at 42 g of ai ha^{-1} (0.1× rate) containing nonionic surfactant (0.25% v/v) at 187 L ha^{-1} using a track sprayer in an enclosed spray chamber. Treated plants were taken to an isotope laboratory for application of ^{14}C-quinclorac (ring-6-^{14}C; specific activity = 83.47 MBq mg^{-1}; BASF Corp., Research Triangle Park, NC; **Figure 1**). The adaxial surface of the third leaf of four-leaf plants was spotted with four 1 μL droplets of ^{14}C-quinclorac (electronic microsyringe) in a combined formulation with spray solution (Facet 75 DF and surfactant) to deliver 416.67 Bq μL^{-1} (100 000 dpm total). The adaxial surfaces of the fifth and sixth leaves of flowering plants (below the flowering cluster) were each spotted with four 1 μL droplets (electronic microsyringe) to deliver 416.67 Bq μL^{-1} (200 000 dpm). After ^{14}C-quinclorac treatment, plants were placed in a growth chamber (28 °C; 16 h day length; 95% RH; PPFD 500 μmol m^{-2} s^{-1}) until harvest.

Laboratory Studies: Plant Sampling and Radiolabel Analysis. At 0, 3, 6, 12, 24, 48, and 72 HAT, plants were divided into sections: treated leaf; stems and leaves above the treated leaf; stems and leaves below the treated leaf; roots; and flowers when applicable. Treated leaves of each plant were rinsed with deionized water (4 mL) in a scintillation vial (20 mL) for 15 s to remove unabsorbed ^{14}C-quinclorac. Each leaf wash vial was then filled with 15 mL of Ultima Gold XR High Flashpoint Scintillation Cocktail (Packard Instrument Co., Meriden, CT). Plant tissues from the different sections of the four-leaf plants were left intact and oxidized using an OX-700 Biological Oxidizer (R. J. Harvey Instrument Corp., Hillsdale, NJ), and ^{14}CO$_2$ was trapped in scintillation vials containing Harvey Carbon-^{14} Cocktail (R. J. Harvey Instrument Corp.). Due to the large size of the flowering plants, tissues from the different plant sections were homogenized in liquid nitrogen (mortar and pestle) and subsampled before oxidizing and trapping. Radioactivity in samples was analyzed using a Packard TriCarb 2900 TR Liquid Scintillation Analyzer (Packard Instrument Co.). Count times were %2 s or 10 min, whichever occurred first, and quench was determined using the transformed Spectral Index of the Sample (tSIS) and the transformed Spectral Index of the External Standard (tSIE). Recovery of radioactivity was > 96% in four-leaf plants and > 92% for flowering plants.

Field and Laboratory Data Analysis. Data for field and laboratory studies were subjected to ANOVA, with partitioning appropriate for a factorial arrangement of treatments, and means were separated using Fisher's Protected LSD at the 5% probability level. The duplication of laboratory experiments was treated as a random variable; therefore, data were pooled over runs. All analyses were conducted using PROC MIXED (SAS, version 8, SAS Institute, Cary, NC).

Regression analysis for residue detection was conducted using fit of least-squares in SAS. Residue decay curves are illustrated as $Y = c \, e^{(-kt)}$, where Y is the predicted quinclorac residue level in tomato tissue at a given time, c is the maximum quinclorac concentration immediately following application, k is the rate of decay, and t is day(s) after application.
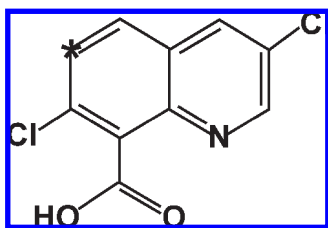
Figure 1. Structure of (ring-6-^{14}C)-quinclorac. *denotes the location of radiolabeled carbon.

RESULTS AND DISCUSSION

Field Studies: 1999. Initial fortified sample analyses indicated that contamination occurred during the residue analysis procedure. Quinclorac levels in these samples were higher than expected (**Table 1**), most likely caused by overloading or inadequate purging of the LC column between samples. This problem was corrected by grouping subsequent samples by relative concentration and by increasing column wash times.

Quinclorac was not detected in untreated tomato plant or fruit tissues at any time (**Figure 2a**), indicating no cross-contamination between plots. Immediately after application, residues in plant tissues treated with quinclorac at 0.42 g ha^{-1} were detectable, but below the LOQ (**Figure 2a**). At 3 DAT, quinclorac was no longer detectable in the plant tissue. Quinclorac was again detected in plant tissues immediately after a second quinclorac application at 0.42 g ha^{-1} 7 DAT, but the levels were below the LOQ. Quinclorac was not detectable in tomato plants after the third quinclorac treatment at 0.42 g ha^{-1} 14 DAT. Quinclorac at 0.42 g ha^{-1} did not affect plant growth (*10*); thus, by 14 DAT, plants were much larger and the herbicide residues within the tomato tissues were probably more diluted.

Immediately after quinclorac application at 4.2 g ha^{-1}, quinclorac residue levels in plants were 79 ppb, but were below the LOQ at 3 DAT (**Figure 2b**). Residues were detectable up to 10 DAT, and the corresponding half-life of these residues was 2.3 days (according to the regression equation). Residues peaked at 63 ppb in plants after receiving a second quinclorac application at 4.2 g ha^{-1} 7 DAT (**Figure 2b**). As with the single application of quinclorac at 4.2 g ha^{-1}, residues in these samples were below the LOQ at 3 days after the second treatment and persisted for 10 days. Quinclorac half-life after the second application increased to 3.6 days. Tomato plants treated with a third application at 4.2 g ha^{-1} 14 DAT contained 53 ppb of quinclorac immediately after application (**Figure 2b**), and levels were detectable and quantifiable for 7 days after the application (half-life = 3.0 days). Furthermore, another study on the effects of quinclorac on tomato plants reported that this rate caused significant injury, reduction in biomass accumulation, and yield loss (*10*).
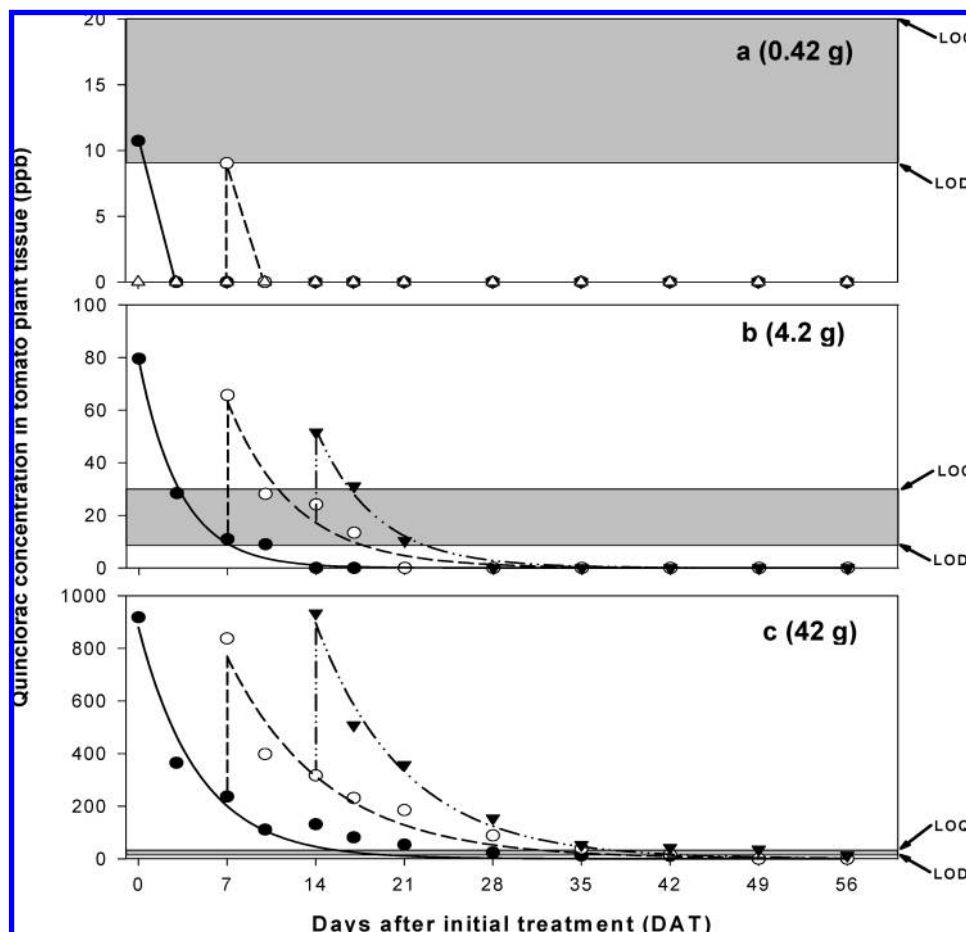
Quinclorac residue levels in tomato plants treated at 42 g ha^{-1} were 879 ppb immediately after application (**Figure 2c**). Quantifiable residues persisted in plant tissues until 28 DAT, and residues were detectable in plants until 42 DAT. The half-life of quinclorac in tomato tissues after a single quinclorac application at this high rate was 3.3 days. After a second application of 42 g ha^{-1} at 7 DAT, quinclorac peaked at 777 ppb and the half-life increased to 5.2 days. Quinclorac levels were 922 ppb after the third quinclorac application, and residues in tissues were detectable through 56 DAT. These higher residue levels were also associated with greater injury, biomass reduction, and yield loss compared to the lower rates as seen in an earlier published related study (*10*).

Table 1. Analysis of Tomato Plant Tissue Samples Fortified with Known Quinclorac Concentrations (Averaged over All Sampling Dates)

concn (ppb)	n^a	range^b (ppb)	av (ppb)	SD (ppb)	recovery (%)
			1999		
0	10	0−11	5	4	
10	11	6−37	12	6	120
100	10	60−118	83	12	83
1000	10	894−1496	1082	65	108
			2000		
0	10	0−3	0.3	0.9	
10	11	5−19	9	4	90

^{a} Number of samples tested. ^{b} Limit of quinclorac detection = 9 ppb. Limit of quantification = 27 ppb.

Figure 2. Quinclorac residue decay in tomato plant tissue as affected by quinclorac rate and application number in 1999: (**a**) ●, 0.42 g ha^{-1} treated at 0 DAT; ○, 0.42 g ha^{-1} treated at 0 and 7 DAT; ▼, 0.42 g ha^{-1} treated at 0, 7, and 14 DAT ; ▽, untreated check. (**b**) ●, 4.2 g ha^{-1} treated at 0 DAT, $Y = 78.76$ e$^{(-0.306d)}$, $R^2 = 0.99$; ○, 4.2 g ha^{-1} treated at 0 and 7 DAT, $Y = 63.45$ e$^{(-0.1904d)}$, $R^2 = 0.96$; ▼, 4.2 g ha^{-1} treated at 0, 7, and 14 DAT, $Y = 53.19$ e$^{(-0.232d)}$, $R^2 = 0.98$. (**c**) ●, 42 g ha^{-1} treated at 0 DAT, $Y = 878.82$ e$^{(-0.211d)}$, $R^2 = 0.97$; ○, 42 g ha^{-1} treated at 0 and 7 DAT, $Y = 777.32$ e$^{(-0.134d)}$, $R^2 = 0.96$; ▼, 42 g ha^{-1} treated 0, 7, and 14 DAT, $Y = 921.68$ e$^{(-0.169d)}$, $R^2 = 0.99$. $Y =$ predicted quinclorac concentration, and $d =$ days after initial treatment. Quinclorac residue decay was not modeled when plants were treated with 0.42 g ha^{-1} due to lack of detectable quinclorac in plant tissue over time. Gray regions on the illustrations depict data points above the limit of detection that could not be accurately quantified.

Half-lives of quinclorac residues in tomato tissue tended to increase slightly with higher rates and with multiple applications. This may be a result of slowed metabolic processes and reduced growth related to injury caused by higher rates and multiple applications (*10*), causing a relatively higher concentration of quinclorac in these plant tissues over time.

Field Studies: 2000. Quinclorac was not detectable in untreated tomato plants, indicating that cross-contamination did not occur (**Figure 3a**). In addition, quinclorac was below the detection level in plants treated with one, two, and three applications at 0.42 g ha^{-1} (**Figure 3a**). At the higher quinclorac rate of 2.1 g ha^{-1}, tissues in plants treated with one, two, and three applications contained residue levels between the LOQ and LOD only immediately after application. Residues were below the LOQ by 10 days after each application (**Figure 3b**).

Tomato plants treated with quinclorac at 4.2 g ha^{-1} contained residue levels of 21 ppb immediately after application (**Figure 3c**), and this amount was much less than that observed in 1999 (**Figure 2b**). Detectable quinclorac residues were 21 and 19 ppb in plants immediately after a second and third application at 4.2 g ha^{-1}, respectively (**Figure 3c**). Quinclorac levels rapidly declined in plants after each application, with residues persisting for only 3 days after each application. Multiple applications of quinclorac at 4.2 g ha^{-1} did not have a consistent effect on half-lives (2.4–4.5 days) in 2000.

One factor that may have caused lower quinclorac residue levels in 2000 compared to 1999 is rainfall events occurring within 2 days after the second and third quinclorac applications in 2000 (**Figure 4**). These rainfall events may have washed some unabsorbed herbicide from the leaves, thereby limiting uptake and lowering residue concentration and detection. Another factor that may have influenced residue levels is plant size. Results from a related published study indicated that plants in 1999 were much larger (weight basis) and appeared to have more leaf area than plants in 2000 (*10*). These larger plants may have intercepted more quinclorac spray per unit of mass, resulting in higher concentrations of quinclorac in the plant tissues.

Overall, there was no accumulation of quinclorac residues in tomato tissues as a result of multiple applications. Over 50% of the parent compound was metabolized within 5 days after an application. Conversely, quinclorac metabolism was < 10% over a similar period of time in other plants (*11, 19*). This rapid detoxification of quinclorac by tomato plants may explain their ability to recover from early injury (*10*). Furthermore, injury ratings indicated that tomato plants were sensitive to quinclorac at levels (0.42 g ha^{-1}) (*10*) resulting in residue levels in tomato tissue that could not be detected by analysis (**Figures 2** and **3**). Improving the sensitivity of quinclorac detection techniques would aid in understanding the relationships of quinclorac residues to drift rate, injury, growth, and yield.
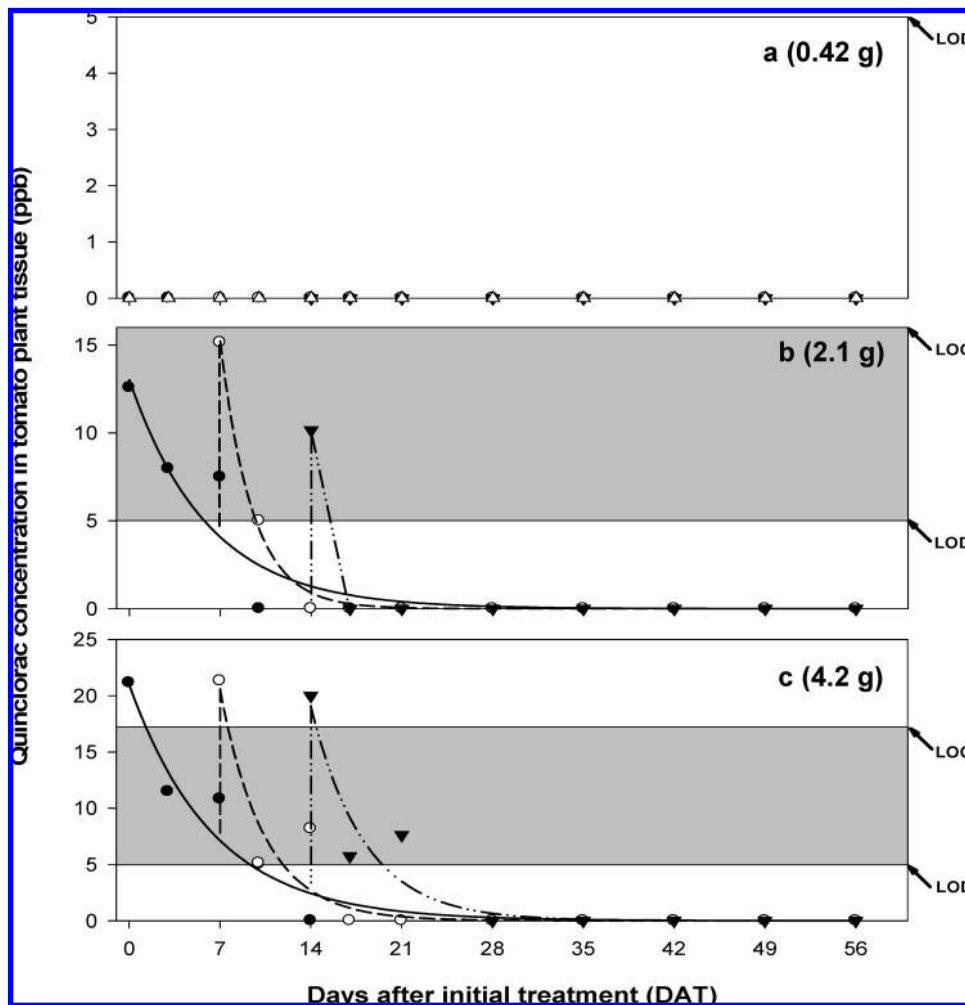
Figure 3. Quinclorac residue decay in tomato plant tissue as affected by quinclorac rate and application number in 2000: **a)** ●, 0.42 g ha^{-1} treated at 0 DAT; ○, 0.42 g ha^{-1} treated at 0 and 7 DAT; ▼, 0.42 g ha^{-1} treated at 0, 7, and 14 DAT; ▽, untreated check. (**b**) ●, 2.1 g ha^{-1} treated at 0 DAT; ▼ 2.1 g ha^{-1} treated at 0, 7, and 14 DAT, no function. (**c**) ●, 4.2 g ha^{-1} treated at 0 DAT, $Y = 20.99\,e^{(-0.154d)}$, $R^2 = 0.95$; ○, 4.2 g ha^{-1} treated at 0 and 14 DAT, $Y = 20.53\,e^{(-0.291d)}$, $R^2 = 0.90$; ▼, 4.2 g ha^{-1} treated at 0, 7, and 14 DAT, $Y = 19.31\,e^{(-0.267d)}$, $R^2 = 0.91$. Quinclorac residue decay was not modeled when plants were treated with 0.42 g ha^{-1} due to lack of detectable quinclorac in plant tissue over time. Gray regions on the illustrations depict data points above the limit of detection that could not be accurately quantified.

Laboratory Studies. Absorptions of ^{14}C-quinclorac into the treated leaf of four-leaf and flowering tomato plants were similar through 24 HAT (**Figure 5**). At 48 and 72 HAT, absorption of ^{14}C-quinclorac was greater in vegetative plants compared to flowering plants. Similarly, Lym (*20*) reported that absorption of the auxin-type herbicide ^{14}C-fluoroxypyr was greater in vegetative leafy spurge plants compared to flowering plants. Throughout our tests, the largest portion of ^{14}C-quinclorac remained in the treated leaf of tomato plants (**Table 2**), which was also observed in honeyvine milkweed [*Ampelamus albidus* (Nutt.) Britt.] treated with ^{14}C-2,4-D (*21*).

The greatest movement of ^{14}C out of the treated leaf was acropetally in both vegetative and flowering tomato plants (**Table 2**). This pattern was also observed in ^{14}C-quinclorac-treated leafy spurge (*12*) and ^{14}C-2,4-D treated tomato plants (*22*). At 48 and 72 HAT, vegetative tomato plants had more ^{14}C in leaves and stems above the treated leaf than flowering plants. This may be due to greater flow of assimilates toward the apical meristem of young plants to support growth compared to slower growing, older plants. Similarly, acropetal translocation of other auxin-type herbicides was also greater in other young broadleaf plants compared to older plants (*23, 24*).

Translocation of ^{14}C into the flowers of the tomato plants could also be a factor influencing differential acropetal translocation in the two stages of tomato plant growth. The flower clusters were in the region of the plant above the treated leaf. ^{14}C movement into tomato plant flowers increased with time, and a maximum of 1% of the total absorbed ^{14}C-quinclorac occurred in flowers 72 HAT (**Table 2**). Pline et al. (*25*) also found that 0.2–3.7% of ^{14}C-glyphosate translocated to the squares (reproductive structures) of cotton.

Translocation of ^{14}C-quinclorac to leaves and stems below the treated leaf was more rapid through 6 HAT in vegetative plants (13% of the total absorbed ^{14}C) than in flowering plants (9% of the total absorbed ^{14}C) (**Table 2**). Contrary to the early harvest times (3 and 6 HAT), more radioactivity (16% of the total absorbed ^{14}C-quinclorac) was detected below the treated leaf of the flowering plants compared to the vegetative tomato plants (9% of the total absorbed ^{14}C-quinclorac) at 72 HAT. Similarly, more ^{14}C-2,4-D moved basipetally in flowering versus vegetative ironweed (*Vernonia baldwinii* Torr.) plants (*24*), and more ^{14}C-picloram (another auxin-type herbicide) moved basipetally in 16-week-old field bindweed plants compared to 5- or 7-week-old plants (*23*).

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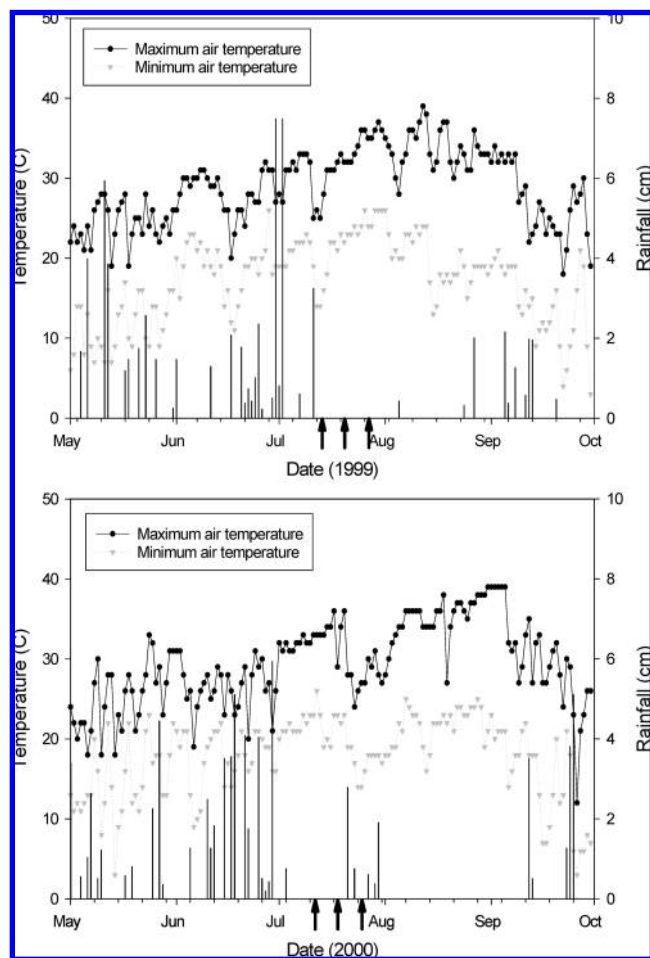
Figure 4. Air temperature and rainfall for the 1999 and 2000 growing seasons. Arrows indicate the approximate application times of quinclorac to tomato plants.
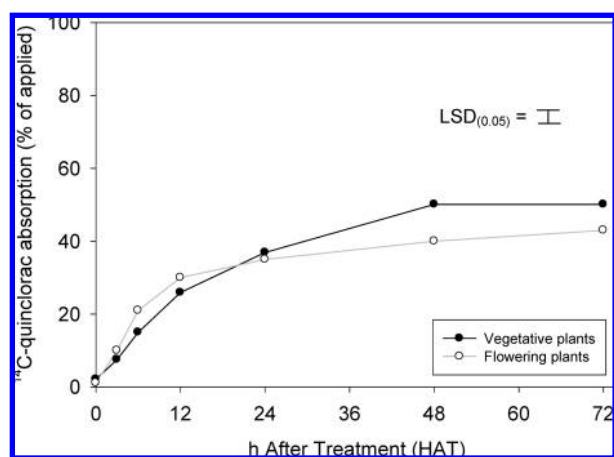
Figure 5. Absorption of ^{14}C-quinclorac by leaves of vegetative and flowering tomato plants over time. LSD used to make comparisons among and between HAT. Differences in absorption between vegetative and flowering plants are significant at 48 and 72 HAT.

Levels of ^{14}C in the roots of the vegetative and flowering tomato plants were similar until 72 HAT (**Table 2**). At 72 HAT, 12% of the total absorbed ^{14}C was found in flowering tomato plant roots versus 9% in vegetative plant roots. Likewise, more ^{14}C-2,4-D translocated to the roots of flowering ironweed compared to vegetative plants (*24*).

Table 2. ^{14}C-Quinclorac Translocation in Vegetative and Flowering Tomato Plants

h after treatment	growth stage	distribution of radioactivity (% of absorbed)				
		treated leaf	above treated leaf	below treated leaf	roots	flowers
3	vegetative	75	6	15	5	NA[a]
	flowering	78	4	9	4	0.1
6	vegetative	64	16	13	7	NA
	flowering	69	15	9	7	0.1
12	vegetative	62	19	9	9	NA
	flowering	60	19	11	10	0.3
24	vegetative	61	20	10	10	NA
	flowering	56	21	12	10	0.7
48	vegetative	55	25	11	9	NA
	flowering	51	22	13	10	0.9
72	vegetative	54	27	9	9	NA
	flowering	47	24	16	12	1.0
	LSD (0.05)	3	2	3	2	0.2

[a] NA, data not applicable because vegetative plants did not have flowers.

In both vegetative and flowering plants, the majority of the quinclorac remained in the treated leaf. The greatest movement of ^{14}C was acropetally, but some ^{14}C was found throughout the plant. Overall, ^{14}C translocations are similar in vegetative and flowering tomato plants, but quantities of ^{14}C in similar regions of the different size plants varied with time. A possible explanation for this is that young actively growing plants may be more efficiently transporting the herbicide, together with assimilates, to new growth and leaf expansion areas, whereas physiological changes in flowering plants cause reallocation of more assimilates to areas other than meristematic tissues.

In conclusion, quinclorac use for weed control in Arkansas rice will most likely continue, which will create a potential for off-target drift to commercial tomato production areas. Residue data indicated that quinclorac was rapidly metabolized. This metabolism explains why tomato plants in a related study were able to outgrow injury symptoms and produce yields comparable to untreated tomato plants (*10*). Additionally, absorption and translocation data showed that tomato growth stage influenced quinclorac and/or metabolite movement within the plant and that quinclorac and/or its metabolites translocated into the flowers. Further research will be needed to better understand quinclorac translocation and metabolism in tomato flowers and fruit.

ABBREVIATIONS USED

ai, active ingredient; ANOVA, analysis of variance; DAT, days after initial treatment; HAT, hours after treatment; LOD, limit of detection; LOQ, limit of quantification; ppb, parts per billion; PPFD, photosynthetic photon flux density; WAT, weeks after initial treatment.

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