ABSTRACT

CHAUDHARI, SUSHILA. Critical Period for Weed Control in Grafted Tomato (*Solanum lycopersicum*) and Herbicide Tolerance of Grafted Tomato and Eggplant (*Solanum melongena*). (Under the direction of Drs. Katherine M. Jennings and David W. Monks).

Field experiments were conducted to determine the critical period for weed control (CPWC) in non-grafted Amelia and Amelia grafted onto Maxifort tomato rootstock grown in plasticulture. The establishment treatments (EST) consisted of two seedlings of common purslane, large crabgrass and yellow nutsedge transplanted at 1, 2, 3, 4, 5, 6 and 12 wk after tomato transplanting (WAT) and remained until tomato harvest to simulate weeds emerging at different times during the season. The removal treatments (REM) consisted of the same weeds transplanted on the same d of tomato transplanting and removed at 2, 3, 4, 5, 6, 8, and 12 WAT to simulate weeds controlled at different times during the season. The beginning and end of the CPWC, based on a 5% yield loss of marketable tomato, was determined by fitting log-logistic and Gompertz models to the relative yield data representing REM and EST, respectively. The predicted CPWC, in the presence of a mixed population of weeds, was from 2.2 to 4.5 WAT in grafted tomato and from 3.3 to 5.8 WAT in non-grafted tomato. The length (2.3 or 2.5 wk) of CPWC in fresh market tomato was not affected by grafting, however, the CPWC management began and ended one wk earlier in grafted tomato than non-grafted tomato.

Greenhouse and field experiments were conducted to determine herbicide tolerance of grafted tomato. Although injury was observed from post-transplant applied herbicides in the greenhouse, no differences were observed in grafted and non-grafted tomato response including visual injury, plant height and fresh weight. Tomato injury at 3 wk after herbicide
application increased from 3 to 13, 1 to 37 and 2 to 86% as rate of halosulfuron, S-
metolachlor and metribuzin increased, respectively. In field experiments under plasticulture,
fomesafen, halosulfuron, napropamide, and trifluralin pre-transplant initially caused greater
injury to grafted tomato than non-grafted tomato regardless of rootstock (Anchor-T, Beaufort
or Maxifort). However, by 4 WAT, no injury was observed in grafted and non-grafted
tomato. A grafting by herbicide interaction was not observed for yield, and grafted A-
Maxifort tomato produced greater total and marketable yield than non-grafted Amelia
tomato. Grafted tomato exhibited similar tolerance to non-grafted tomato for all herbicides
applied post- and pre-transplant.

Greenhouse and field experiments were conducted to determine response of grafted
eggplant on tomato rootstock to fomesafen, halosulfuron, S-metolachlor, metribuzin,
napropamide, and trifluralin. No difference in injury from herbicides was observed in grafted
and non-grafted eggplant in greenhouse and field experiments. Metribuzin applied post-
transplant at 140 and 280 g ai ha\(^{-1}\) caused 94 and 100% injury to grafted and non-grafted
eggplant 4 WAT. In field experiments, pre-transplant fomesafen, S-metolachlor,
napropamide, and trifluralin caused less than 10% injury and no yield reduction in grafted
and non-grafted eggplant. However, metribuzin caused higher injury and yield reduction in
both grafted and non-grafted eggplant than other herbicides. Metribuzin at 550 g ha\(^{-1}\) caused
60 and 81% plant stand loss in 2013 and 2014, respectively. Halosulfuron reduced yield by
24% in both grafted and non-grafted eggplant compared to nontreated control in 2013 but did
not reduce yield in 2014. Grafted eggplant on tomato rootstocks exhibited similar tolerance
to non-grafted eggplant for all herbicides applied post- and pre-transplant.
Greenhouse experiments were conducted to determine the efficacy of metribuzin on drought-stressed grafted and non-grafted tomato. Drought stress treatments included no drought stress, 3 d of drought stress before with no drought stress after metribuzin application (3 d DSB), and 3 d of drought stress before with 3 d of drought stress after metribuzin application (3 d DSBA). Metribuzin was applied at 550 g ha\(^{-1}\). No difference in injury from metribuzin was observed in grafted and non-grafted plants. However, at 7 and 14 d after metribuzin treatment (DMT), less injury was observed on tomato plants that were 3 d DSBA (5 and 2% injury, respectively) than on plants that were 3 d DSB (15 and 8% injury, respectively) or those that were not subjected to drought stress (18 and 11% injury, respectively). Photosynthesis rate and stomatal conductance were reduced similarly in grafted and non-grafted tomato when subjected to drought stress before metribuzin application. Photosynthesis and stomatal conductance of tomato at 7 DMT (3 d after re-watering) was not different among drought stress treatments or metribuzin treatments. Grafted tomato demonstrated similar tolerance as non-grafted tomato to metribuzin under drought stress conditions.

Experiments were conducted to evaluate absorption and translocation of halosulfuron in grafted and non-grafted tomato and eggplant. No differences were observed between the transplant types with regard to absorption and translocation of \(^{14}\text{C}\)-halosulfuron. Absorption of \(^{14}\text{C}\)-halosulfuron increased with time, reaching 10 and 74% of applied herbicide at 6 and 96 h after treatment (HAT), respectively. Translocation of \(^{14}\text{C}\)-halosulfuron was limited to the treated leaf, which reached maximum (66% of applied) at 96 HAT, whereas minimal (< 4% of applied) translocation occurred in scion shoot, rootstock shoot, and root combined.
Results from this experiment indicate that grafting did not affect absorption and translocation of halosulfuron in tomato and eggplant.
Critical Period for Weed Control in Grafted Tomato \textit{(Solanum lycopersicum)} and Herbicide Tolerance of Grafted Tomato and Eggplant \textit{(Solanum melongena)}

by

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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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DEDICATION

I would like to dedicate this work to my parents for being the source of my inspiration and pride. They have always been there giving me love and support.
BIOGRAPHY

Sushila Chaudhari grew up on a farm in Sri Ganganagar, Rajasthan, India. After finishing high school, she was awarded the National Talent Scholarship from the Indian Government to obtain her B.S. (Hons.) in Agriculture from Punjab Agricultural University. She received her degree in 2008. She participated in many activities and was awarded many honors in sports, clay-modeling, and rangoli (a folk art in India). She was active in the National Service Scheme program organized by the university. Sushila earned her M.S. degree in weed science under the direction of Brent Sellers at the University of Florida. Her research focused on the management of paragrass (*Urochloa mutica*, an invasive weed) in the Florida Wetlands using chemical and cultural weed management strategies. In 2011, Sushila began her PhD program in weed science with Katie Jennings and David Monks at North Carolina State University. Her dissertation research focused on determining the critical period for weed control, and herbicide tolerance of grafted tomato and eggplant. Sushila provided leadership for additional research projects in blueberry, strawberry, sweet potato, bell pepper, tomato, and cucumber. Sushila also conducted tomato grafting and weed identification workshops for growers, extension agents, and visiting scholars from Mali and Senegal. Sushila has authored two peer reviewed journal publications. Sushila has presented at numerous professional meetings, including the Florida Weed Science Society, Florida Exotic Pest Plant Council Symposium, Weed Science Society of North Carolina (WSSNC), Northeastern Weed Science Society (NEWSS), Southern Weed Science Society (SWSS), Weed Science Society of America (WSSA), and American Society for Horticultural Science. She has won several awards including 1st place overall individual at the 2013 NEWSS weed
content, WSSNC and SWSS Outstanding Ph.D. Graduate Student, WSSNC Endowment Scholarship, SWSS Endowment Enrichment Scholarship, four travel grants, and six awards for poster and paper presentations. Her goal is to work in research and development contributing to cutting-edge research and addressing the critical needs of growers and weed science.
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I want to thank Dr. Rob Richardson and Dr. Travis Gannon for allowing me to use their laboratory for conducting the halosulfuron absorption and translocation study. I also thank Dr. Khalied Ahmed, Dr. Kyle Keller (BASF) and Mary Quiones-Lopez (BASF) for helping me with analysis of samples from the translocation and metabolism study. I want to thank Dr. Kent Burkey to provide the LI-6400 Portable Photosynthesis System and valuable suggestions for the experiment and Walt Pursley for assisting with the instrumentation. I am appreciative to all the staff at the Mountain Research Station, Waynesville, NC, Mountain Horticultural Crops Research and Extension Center, Mills River, NC, and Horticultural Crops Research Station, Clinton, NC for their help in taking care of my field studies and providing me great help during crop harvest. Also, I thank the USDA-NIFA-2009-2376 and
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CHAPTER 1

Critical Period for Weed Control in Grafted and Non-grafted Fresh Market Tomato

(In the format appropriate for submission to Weed Technology)
Critical Period for Weed Control in Grafted and Non-grafted Fresh Market Tomato

Sushila Chaudhari, Katherine M. Jennings, David W. Monks, David L. Jordan, and Christopher C. Gunter, and Frank J. Louws*

Field experiments were conducted to determine the critical period for weed control (CPWC) in non-grafted Amelia and Amelia grafted onto Maxifort tomato rootstock grown in plasticulture. The establishment treatments (EST) consisted of two seedlings of each common purslane, large crabgrass and yellow nutsedge transplanted at 1, 2, 3, 4, 5, 6 and 12 wk after tomato transplanting (WAT) and remained until tomato harvest to simulate weeds emerging at different times. The removal treatments (REM) consisted of the same weeds transplanted on the same d of tomato transplanting and removed at 2, 3, 4, 5, 6, 8, and 12 WAT to simulate weeds controlled at different times. The beginning and end of the CPWC, based on a 5% yield loss of marketable tomato, was determined by fitting log-logistic and Gompertz models to the relative yield data representing REM and EST, respectively. In both grafted and non-grafted tomato, plant above-ground dry biomass increased as establishment of weeds was delayed and tomato plant biomass decreased when removal of weeds was delayed. For a given time of weed removal and establishment, grafted plants produced higher biomass than non-grafted. The delay in establishment and removal of weeds resulted in weed biomass decrease and increase of the same magnitude regardless of transplant type, respectively. Increased growth of grafted tomato did not increase the ability of tomato plant to suppress weed growth over non-grafted tomato. The predicted CPWC was from 2.2 to 4.5 WAT in grafted tomato and from 3.3 to 5.8 WAT in non-grafted tomato. The length (2.3 or
2.5 wk) of CPWC in fresh market tomato was not affected by grafting, however, the CPWC management began and ended one wk earlier in grafted tomato than non-grafted tomato. Thus, weed management in grafted tomato should start earlier than non-grafted tomato to attain highest acceptable yields.

*Nomenclature: Common purslane, Portulaca oleracea L.; large crabgrass, Digitaria sanguinalis (L.) Scop.; Yellow nutsedge, Cyperus esculentus L.; Tomato, Lycopersicon esculentum L.

Key words: Removal, establishment, competition, interference, grafted tomato
Grafting is a technique to combine the shoot of a desirable fruit producing cultivar (scion) onto the disease-resistant rootstock or rootstock with another desirable characteristic, from another cultivar or species. The use of grafting is mentioned in ancient books written in 5th century China and 17th century Korea to increase the fruit size of gourd (Lee and Oda 2003). However, grafting was first introduced in Japan to increase yield and to manage fusarium wilt \([Fusarium oxysporum Schlecht. (emend. Snyd. & Hans.) f. sp. niveum (E.F. Sm.)]\) in watermelon \([Citrullus lanatus (Thunb.) Matsum. & Nakai]\) in 1920 (Tateishi 1927). Since then, vegetable grafting has become an important technique for production of cucurbiteaceae and solanaceous vegetables around the world where intensive cultivation occur using limited arable land (Bletsos 2005; Lee 2003). In 2008, more than 700 million grafted plants (cucurbiteaceae and solanaceous vegetables) were produced in Korea as well as in Japan (Lee et al. 2010).

Vegetable grafting has been used in the United States (US) greenhouse industry and by small acreage growers (Kubota et al. 2008) but has experienced renewed interest in the US as an alternative to methyl bromide (mandated by the US Clean Air Act and the Montreal Protocol on Ozone Depleting Substances) to control soilborne pests and diseases (Louws et al 2010). A survey conducted by the University of Arizona in 2002 and 2006 showed that more than 40 million grafted tomato seedlings are used annually in North American greenhouses (Kubota et al. 2008). However, no published report exists that estimated the use of grafted plants in field conditions in the US. Certain tomato rootstocks are known to improve resistance or tolerance against fusarium wilt [caused by \(Fusarium oxysporum\) f. sp. \(lycopersici\) (Sacc.) W.C. Snyder and H.N. Hans], verticillium wilt (caused by \(Verticillium\)
dahliae Kleb.), southern blight (caused by Sclerotium rolfsii Sacc.), and bacterial wilt (caused by Ralstonia solanacearum) and root-knot nematodes (Meloidogyne spp.) (Lee 1994; López-Pérez et al. 2006; Rivard et al. 2010; Rivard and Louws 2008). In addition to soilborne pest management, grafting is a promising tool to achieve greater fruit yield, increase nutrient uptake, and enhance tolerance to abiotic stresses such as thermal stress, salt stress, water stress and organic pollutants (Colla et al. 2010; Proietti et al. 2008; Schwarz et al. 2010).

Fresh market tomato was grown on 38,340 ha in the US and 1,380 ha in North Carolina in 2012 (USDA-NASS 2013). In 2012, the crop value was $37 million and North Carolina ranked 4th in the country in fresh market tomato production (USDA-NASS 2013). Fresh market tomato production in the plasticulture system consists of raised beds, fumigation, polyethylene mulch, and drip fertigation and is one of the primary production system by growers in the US. Polyethylene mulch plays an important role to achieve early tomato fruit maturity, high yield, and superior fruit quality (Jones et al. 1977; Sanders et al. 1996; Wien and Minotti 1987). Polyethylene mulch is also beneficial to reduce weed emergence and growth (Teasdale and Colacicco 1985).

In North Carolina, common purslane, large crabgrass and yellow nutsedge are listed among the ten most common weeds present in tomato (Webster 2010). Yellow nutsedge and common purslane are also considered among the top ten most troublesome weeds in North Carolina (Webster 2010). Yellow nutsedge primarily reproduces by underground tubers and its leaf tips can easily penetrate polyethylene mulch (Chase et al. 1998) and degrade the durability of the mulch. Season-long interference of yellow nutsedge reduced tomato shoot
biomass by 34% (Morales-Payan et al. 2003). Large crabgrass begins producing tillers and adventitious roots at height of 8 to 10 cm (Monks and Schultheis 1998). Once large crabgrass established tillers and adventitious roots, it becomes difficult to control and causes yield loss in vegetables and row crops (Monks and Schultheis 1998). The season-long presence of large crabgrass at a density of 55 plants m$^{-2}$ in direct seeded tomato caused 74% yield reduction (Monaco et al. 1981). Management of these weeds in tomato production is very important to produce good quality fruit and high yield (Zimdahl 2004). In the absence of weed control, tomato plant growth is inhibited and individual fruit size, number, and weight is reduced (Buckelew et al. 2006; Weaver and Tan 1983).

The critical period for weed control (CPWC) is the time in the cropping season during which weeds must be controlled (chemically, mechanically or hand removed etc.) to prevent yield and quality reductions in crops (Knezevic et al. 2002; Weaver and Tan 1983). The CPWC represents the overlap between two separately measured competition components (1) the critical timing of weed removal or maximum duration of time that a weed can grow and interfere with the crop before unacceptable yield loss is incurred, and (2) the critical weed-free period or minimum length of time that weed emergence must be prevented to ensure weed growth does not diminish crop yield (Knezevic et al. 2002; Weaver and Tan 1983). The CPWC for tomato has been determined under different conditions with varying results. Weaver and Tan (1983) reported CPWC in transplanted tomato for natural populations of mixed weed species from 4 to 5 wk after transplanting (WAT), the time period when tomato flowering and fruit set first occur. They also reported that a single but thorough weeding during this time period was sufficient to prevent yield loss in tomato. In field-seed processing
tomato, the critical period to control natural populations of mixed weed species was 7 to 9 wk after seeding (Weaver 1984). The critical purple nutsedge-free period in tomato and okra is from 3 to 5 and 3 to 7 WAT, respectively (William and Warren 1975). In a similar study authors reported that full-season purple nutsedge (Cyperus rotundus L.) interference reduced transplanted tomato yield by 53% (William and Warren 1975). In plasticulture tomato production systems, tomato should be maintained free of Eastern black nightshade (Solanum ptycanthum Dun.) 4 to 7 WAT to avoid greater than 20% yield loss (extra-large and jumbo grades) (Buckelew et al. 2006).

The critical period of weed interference is a key component in developing integrated pest management strategies (Swanton and Weise 1991). The CPWC of a crop varies with the aggressiveness of the crop or weed, crop cultivar, row spacing, planting density, weed species, weed density, environmental conditions and crop management (Agostinho et al. 2006; Knezevic et al. 2003; Martin et al. 2001; Norsworthy and Oliveira 2004; Seem et al. 2003). The beginning of CPWC in corn was delayed with the additional nitrogen application (Evans et al. 2003). An aggressive crop or crop cultivar often has a shorter CPWC than a less aggressive crop or crop cultivar. Crop cultivar differences in competitiveness with weeds were reported among tomato cultivars in response to velvetleaf (Abutilon theophrasti Medic.) competition (Ngouajio et al. 2001). Motis et al. (2004) reported that yellow nutsedge interference in bell-pepper (Capsicum annuum L.) was longer in the fall (1 to 7 WAT) as compared to spring (3 to 5 WAT) due to the fast early season growth of nutsedge in fall. The early season high temperature in fall (21 C) as compared to spring (10 C) favored rapid
growth of yellow nutsedge that resulted in stronger competitiveness of nutsedge with pepper in the fall.

Researchers have reported that grafted plants with a vigorous rootstock produce greater biomass compared to non-grafted plants (Khah et al. 2006; Turhan et al. 2011). The increase in plant vigor and yield of grafted plants is most likely attributed to a vigorous root system that allows an increase in water and minerals uptake (Kacjan-Marsic and Osvald 2004; Lee 1994; Leoni et al. 1990; Oda 1995). Increased vigor of grafted tomato over non-grafted tomato may have a substantial impact on the critical timing for weed control. Thus, the objective of this experiment is to evaluate the effect of grafting on critical period for weed control in plasticulture tomato using rootstock known to provide enhanced vigor.

**Materials and Methods**

Field experiments were conducted at the Horticultural Crops Research Station (35.02°N, 79°W; 48 m above sea level), near Clinton, NC in 2013 and 2014. Soil was a Norfolk sandy loam (fine loamy, kaolinitic, thermic Typic Kandiudults) with pH 5.7, CEC 3.9 meq per 100g and organic matter 0.9%. Transplant type included non-grafted Amelia (Harris Moran, P.O. Box 4938, Modesto, CA) and Amelia scion grafted onto Maxifort (DeRuiter, 800 North Lindbergh Blvd, St. Louis, MO) tomato rootstock. Amelia is a determinate hybrid tomato variety with large fruit that is popular in southeastern US (Kemble 2015). Maxifort is a commercially available tomato rootstock that is an interspecific hybrid of cultivated tomato and a wild-type, short-lived, perennial tomato plant (Solanum habrochaites S. Knapp & D.M. Spooner) from the western regions of Ecuador and Peru. This rootstock provides enhanced vigor of the grafted plant and confers resistance to tomato mosaic virus, fusarium wilt, corky
root, verticillium wilt, and root knot nematodes (Rivard and Louws 2006). Grafted plants were produced at North Carolina State University using the tube grafting technique described by Rivard and Louws (2006).

Beds (15 cm high by 76 cm wide on top) on 1.5-m centers were formed in a field four wk prior to transplanting, fumigated with chloropicrin at 174 kg ai ha$^{-1}$ plus 1,3-dichloropropene at 114 kg ai ha$^{-1}$ (Pic-Clor 60, Cardinal Professional Products, PO Box 782, Hollister, CA) and covered with black polyethylene mulch simultaneously in one operation. As beds were formed and fumigated, irrigation drip tape was placed 8 cm deep from the soil surface slightly off center of the bed. One d before transplanting, planting holes were punched in the middle of beds at 60 cm in-row spacing. Seven wk old tomato transplants (20 to 23 cm tall) were hand-planted on May 6, 2013 and May 19, 2014. Plot size was a single row 3.7 long by 1.5 m wide. Each plot contained six tomato plants either grafted or non-grafted.

Weed establishment and weed removal experiments were conducted adjacent to each other to determine the critical period for weed control (CPWC) as described by Motis et al. (2004). Each experiment (weed establishment or weed removal) was conducted in a randomized complete block design with a two-way factorial (2 × 7) arrangement of transplant type (Amelia and A-Maxifort), and 7 different timings of either weed establishment (EST) or weed removal (REM) treatments. Each treatment combination was replicated four times. In EST treatments, weeds were transplanted 1, 2, 3, 4, 5, 6 and 12 WAT in grafted and non-grafted tomato and remained until tomato harvest to simulate weeds emerging at different times during the season. In REM treatments, weeds were transplanted
on the same day of tomato transplanting and removed at 2, 3, 4, 5, 6, 8, and 12 WAT and then remained weed-free the rest of the growing season to simulate weed control beginning at different times during the season. Weed removal at 12 WAT represented the weedy (all season) treatment and weed establishment at 12 WAT represented the weed-free treatment.

A mixture of large crabgrass, common purslane, and yellow nutsedge were grown in the greenhouse for 23 ± 5 d (common purslane, large crabgrass) or 10 ± 3 d (yellow nutsedge) in 288-cell plug trays using commercial potting mix (Fafard 4P potting mix, Conrad Fafard Inc., 160 Agawam, MA) to ensure uniformity and to facilitate weed establishment similar to other studies (Buckelew et al. 2006; McGiffen et al. 1992). Weed seedlings were 6 to 8 cm tall at each planting time in both EST and REM treatments. Six weed seedlings, two of each weed species (yellow nutsedge, large crabgrass, and common purslane) were transplanted into each tomato planting hole at each weed transplanting time in both experiments. The area between rows was maintained weed-free by applying paraquat at 560 g ai ha⁻¹ 10 d before tomato transplanting and weeds were hand removed as needed. Weeds, other than yellow nutsedge, large crabgrass and common purslane, emerging in the holes in the polyethylene mulch where tomato was established were removed by hand throughout the season. Cultural practices for conventional tomato production in NC were followed (Kemble 2015).

Tomato plant height was measured from the soil surface to the most recent upper expanded tomato leaf immediately prior to implementation of REM and EST treatments at 2, 4, 6, and 8 WAT. Above-ground weed biomass was measured (oven-dried at 55°C for four d) at each weed removal from REM or at the final tomato harvest from EST. One tomato plant
per plot was harvested at 8 WAT and dried at 55 C for four d to measure tomato shoot biomass from EST and REM treatments. Tomato fruit with a minimum color classification of “breakers” to “turning” (USDA 1997) were hand-harvested weekly for 6 wk in 2013 and 4 wk in 2014. A mechanical grader was used to sort fruit according to US standards for grades [jumbo (≥8.8 cm in diameter), extra-large (7.3 to 8.8 cm), large (6.4 to 7.3 cm), medium (5.7 to 6.4 cm), small (5.4 to 5.7 cm), cull (< 5 cm or containing damage or defects)] (USDA 1997). Marketable fruit consisted of medium, large, extra-large, and jumbo grades (McAvoy and Freeman 2013); total fruit consisted of marketable grade plus small and cull grade. Relative marketable yield of each experimental plot was calculated as a percentage of the corresponding weed-free yield of each transplant type.

Tomato plant height, tomato plant biomass, weed biomass, marketable yield and relative yield were checked for homogeneity of variance before statistical analysis by plotting residuals. PROC MIXED of SAS (Version 9.3, SAS Institute, Cary, NC) was used to analyze the data from both years with yr, transplant type and treatments (EST and REM) as fixed factors and replications within yr as random effect. Means were separated using Fisher’s Protected LSD test at P ≤ 0.05 when appropriate. Interactions between yr, transplant type and treatments (EST and REM) combinations were evaluated at 0.05 significance level. Least square means for EST and REM treatments were averaged over years when interactions between transplant type and yr were not significant. Nonlinear regression analysis was applied to the least squares means using PROC NLIN in SAS to estimate coefficients for models to describe relative marketable yield, tomato plant biomass and weed biomass as a function of REM and EST treatments. The results from PROC NLIN in SAS were same as
SigmaPlot 10.0 (Systat Software, Inc. 225 W. Washington St., Suite 425, Chicago, IL), therefore SigmaPlot was used to make all the regression graphs.

A three-parameter logistic equation was fitted to describe the effect of REM treatments on marketable tomato relative yield (Knezevic et al. 2002). This equation was used to determine the beginning of the CPWC for each transplant type:

\[ Y = \left( \frac{1}{\exp[k \cdot (T - d)] + f} \right) + \left( \frac{f - 1}{f} \right) \times 100 \]  

(1)

where \( Y \) is relative yield (% of season-long weed-free yield), \( T \) is the time (x-axis expressed in WAT), \( d \) is the point of inflection (WAT), and \( k \) and \( f \) are constants. The three-parameter Gompertz equation was used demonstrate the effect of EST treatments on the relative marketable tomato yield and to determine the end of CPWC for each transplant type (Knezevic et al. 2002):

\[ Y = a \times \exp \left[ -b \times \exp(-c \times T) \right] \]  

(2)

Where \( Y \) is yield (% of season-long weed-free yield), \( a \) is the upper asymptote for tomato yield, \( b \) and \( c \) are constants, \( e \) is the base of natural logarithm, and \( T \) is time in wk after transplanting.

Nonlinear regression was used to describe relationship between REM and EST treatments, and weed biomass (Ahamdvand et al. 2006). The two parameter exponential growth model was used to describe the effect of REM treatments on weed biomass accumulation.

\[ Y = a \times \exp(b \times x) \]  

(3)

Where \( Y \) is the weed dry biomass, \( a \) is the maximum weed biomass, \( b \) is the asymptote of the curve and \( x \) is the duration of weed interference (in wk). Two parameter exponential decay equation was fitted to EST treatments and weed biomass accumulation:
\[ Y = a \exp(-b \cdot x) \quad (4) \]

Where \( Y \) is the weed dry biomass, \( a \) is the y-intercept, \( b \) is the asymptote of the curve and \( x \) is the duration of weed-free period (in wk). A nonlinear quadratic (\( Y = y_0 + ax + ax^2 \)) model used to describe the effect of REM and EST treatments on tomato plant biomass.

**Results and Discussion**

**Weeds Above-ground Dry Biomass.** Data were pooled across yr because the interactions between yr and transplant types were not significant for both EST and REM treatments. In both grafted and non-grafted transplants above-ground dry biomass of the weeds displayed an exponential decrease and exponential growth to EST and REM treatments, respectively (Figure 1.1). That is, above-ground dry biomass of weeds increased as weed removal was delayed. In contrast, above-ground dry biomass of weeds decreased as weeds establishment was delayed. These results are similar to those of Ahmadvand et al. (2009) who reported that total dry weight of weeds growing in potato (\( Solanum tuberosum \) L.) increased and decreased as duration of weed-infested and weed-free period increased, respectively. The increase and decrease in weed biomass with delay in REM and EST treatments, respectively, was similar in both grafted and non-grafted tomato. These results indicate that although grafted tomato is considered mostly vigorous relative to non-grafted tomato (Khah et al. 2006; Kacjan-Marsic’ and Osvald 2004; Romano and Paratore 2001), grafting did not affect weed growth and did not have any advantage in suppressing weed emergence or growth. Our results are in agreement with previous studies that indicated no difference in biomass of weeds in grafted and non-grafted tomato (Ghosheh et al. 2010). The non-limiting supply of resources
including water and nutrient in the plasticulture system may have contributed to weeds growing similarly for both grafted and non-grafted tomato.

**Tomato Height and Above-ground Dry Biomass.** No significant interactions for yr by transplant type for EST and REM for tomato height were observed. Therefore, data for tomato height were combined across yr. In EST, tomato height at 8 WAT was recorded from the season-long weed-free (EST= 12WAT) treatment (Table 1.1). Tomato plant height was similar in both grafted and non-grafted plants initially at 2 and 4 WAT in both EST and REM treatments. However, later in the season grafted plants grew taller than non-grafted plants (Table 1.1).

For above-ground dry biomass of tomato, no transplant type by yr interactions for REM and EST treatments were observed; therefore data were pooled over yr. The effect of EST and REM treatments, and transplant type was significant on plant above-ground dry biomass. In both transplant type, tomato above-ground dry biomass displayed a positive quadratic and negative quadratic response to EST and REM treatments, respectively. These observations indicated that above-ground dry biomass of tomato increased with delayed weed establishment and decreased when weed removal was delayed (Figure 1.2). For a given time of weed removal and establishment, grafted A-Maxifort tomato plants produced higher biomass than non-grafted Amelia. Other researchers have also reported that grafted plants were taller and more vigorous compared to non-grafted plants (Khah et al. 2006; Kacjan-Marsic’ and Osvald 2004; Romano and Paratore 2001).

Interference between tomato and weeds resulted in reduction of above ground dry biomass of tomato relative to the weed-free treatments. Grafted A-Maxifort tomato above-
ground dry biomass from weedy (REM = 12 WAT) and weed-free (EST = 12 WAT) treatments were 380 and 548 g plant\(^{-1}\). Likewise, non-grafted Amelia tomato above-ground dry biomass from weedy (REM = 12 WAT) and weed-free (EST = 12 WAT) treatments were 284 and 419 g plant\(^{-1}\). Garvey et al. (2013) have reported the increase and decrease in tomato plant shoot dry biomass when Palmer amaranth (*Amaranthus palmeri*) establishment and removal was delayed, respectively.

**Tomato Yield and Critical Period for Weed Control.** The yr by transplant type interaction was significant for season-long weed-free (EST = 12 WAT) but was not significant for season-long weedy (REM = 12 WAT) tomato marketable yield; therefore, data were presented by yr. In both yr, grafted A-Maxifort and non-grafted Amelia produced similar yield in season-long weedy plots (Table 1.2). Marketable yield in season-long weed-free treatment (EST = 12 WAT) was 11 and 36% greater in grafted A-Maxifort than non-grafted Amelia in 2013 and 2014, respectively. However, the yield increase in 2013 was not statistically significant. Grafting has been reported to have a positive yield response in tomato (Ghosheh et al. 2010; Khah et al. 2006). Lee and Oda (2003) theorized that the growth and yield increase are due to a vigorous root system of the rootstocks that improve uptake of water and minerals in grafted tomato compared with non-grafted plants.

The beginning and end of the CPWC in grafted and non-grafted tomato was determined based on a 5% acceptable yield loss level. The choice of 5% is an arbitrary measurement of yield loss, and the range of percent yield loss depends on the economics of weed management or the risk that the farmer is willing to take (Knezevic et al. 2002). In previous studies, a 5% acceptable yield-loss level was used to measure the CPWC in
different crops such as peanut (*Arachis hypogaea* L.), field and sweet corn (*Zea mays* L.) (Evans et al. 2003; Everman et al. 2008; Norsworthy and Oliveira 2004). It is assumed that a 5% yield loss is acceptable to tomato growers and the economics of tomato production.

Due to the lack of yr by transplant type interaction for the REM and EST, relative marketable data were combined over yr for each transplant type. The beginning and end of the CPWC, based on a 5% yield loss of marketable tomato, was determined by fitting log-logistic and Gompertz models to the relative yield data representing REM and EST, respectively (Figure 1.3). The parameters estimates of log-logistic and Gompertz models are listed in Table 3. At the 5% yield-loss level, CPWC was estimated from 2.2 to 4.5 and 3.3 to 5.8 WAT in grafted and non-grafted tomato, respectively. The beginning of the CPWC was estimated to be 2.2 and 3.3 WAT for grafted A-Maxifort and non-grafted Amelia, respectively (Figure 1.3). The beginning of CPWC was earlier in grafted tomato, indicating the initial poor competitive ability of grafted plants with weeds. Khah et al. (2006) suggested that grafted plants need a recovery period after grafting as they grow slow initially after transplanting. Similarly, Ghosheh et al. (2010) reported that non-grafted plants were taller than grafted plants at 16 days after transplanting when growing with naturally grown weed species in the field. The end of CPWC was 4.5 and 5.8 WAT in grafted A-Maxifort and non-grafted Amelia at 5% yield-loss level. The early end of CPWC with grafting may be attributed to rapid growth of grafted plants later in the season, which resulted in grafted tomato competitiveness with late established weeds. Season-long weedy interference (REM =12 WAT) resulted in 46 and 38% tomato-yield loss from grafted and non-grafted plants,
respectively. Garvey et al. (2013) reported a 52% decrease in tomato yield of non-grafted tomato after 10 wk of interference from Palmer amaranth.

This research shows that the length of CPWC (yellow nutsedge, large crabgrass and common purslane) was similar in grafted and non-grafted tomato at 2.3 (17 d) and 2.5 (18 d) wk, respectively. However, the onset of the CPWC was earlier in grafted tomato. Thus, weed control should begin at least one wk earlier in grafted tomato than non-grafted tomato. In addition, although not evaluated in our experiments, growers will need to also consider the potential of seed production with weeds that emerge outside the CPWC time period even though they may not affect fruit yield and quality.

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Table 1.1. Effect of weed removal (REM) and establishment (EST) treatments on grafted and non-grafted tomato plant height at Clinton, North Carolina

<table>
<thead>
<tr>
<th>Treatments x</th>
<th>Transplant type y</th>
<th>Tomato height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 WAT</td>
</tr>
<tr>
<td>Establishment</td>
<td>A-Maxifort</td>
<td>27 a</td>
</tr>
<tr>
<td></td>
<td>Amelia</td>
<td>29 a</td>
</tr>
<tr>
<td>Removal</td>
<td>A-Maxifort</td>
<td>28 a</td>
</tr>
<tr>
<td></td>
<td>Amelia</td>
<td>27 a</td>
</tr>
</tbody>
</table>

w Data pooled over 2013 and 2014.

x Means within column and within establishment or removal followed by the same letter are not significantly different according to Fisher’s Protected LSD test at P ≤ 0.05.

y Abbreviations: A-Maxifort, Amelia scion grafted onto Maxifort rootstock; WAT, wk after transplanting.

z In EST 8 WAT reading from season-long weed-free (EST =12 WAT) plots.
Table 1.2. Marketable yield of grafted and non-grafted tomato in season-long weedy (REM = 12 WAT) and season-long weed-free (EST = 12 WAT) treatments from 2013 and 2014 Clinton, North Carolina.

<table>
<thead>
<tr>
<th>Year</th>
<th>Transplant type</th>
<th>Marketable yield</th>
<th>Season-long weedy</th>
<th>Season-long weed-free</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>t ha⁻¹</td>
</tr>
<tr>
<td>2013</td>
<td>A-Maxifort</td>
<td>30 a</td>
<td>73 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Amelia</td>
<td>35 a</td>
<td>66 a</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>A-Maxifort</td>
<td>46 a</td>
<td>71 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Amelia</td>
<td>37 a</td>
<td>51 b</td>
<td></td>
</tr>
</tbody>
</table>

Means within column for each year, followed by the same letter are not significantly different according to Fisher’s Protected LSD test at P ≤ 0.05.

Abbreviations: A-Maxifort, Amelia scion grafted onto Maxifort rootstock.
Table 1.3. Parameter estimates for the three-parameter log-logistic model and Gompertz model for relative (% of weed-free check) marketable tomato yield.

<table>
<thead>
<tr>
<th>Transplant type</th>
<th>Log–logistic</th>
<th></th>
<th></th>
<th>Gompertz</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d</td>
<td>f</td>
<td>k</td>
<td>$R^2$</td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>A-Maxifort</td>
<td>41.9</td>
<td>1.859</td>
<td>0.058</td>
<td>0.99</td>
<td>102.0</td>
<td>0.642</td>
</tr>
<tr>
<td>Amelia</td>
<td>36.2</td>
<td>2.564</td>
<td>0.088</td>
<td>0.95</td>
<td>100.2</td>
<td>0.456</td>
</tr>
</tbody>
</table>

Log-logistic: $Y = \left[ \frac{1}{\exp[k \times (T - d) + f]} \right] + \left[ \frac{f - 1}{f} \right] \times 100$, where $Y$ is yield (% of season-long weed-free yield), $T$ is the time (x-axis expressed in WAT), $d$ is the point of inflection (WAT), and $k$ and $f$ are constants. Gompertz: $Y = a \times \exp[-b \times \exp(-c \times T)]$, where $Y$ is yield (% of season-long weed-free yield), $a$ is the upper asymptote for tomato yield, $b$ and $c$ are constants, $e$ is the base of natural logarithm, and $T$ is time in wk after transplanting.

Abbreviations: A-Maxifort, Amelia scion grafted onto Maxifort rootstock.
Figure 1.1. The influence of weed establishment (EST) and removal (REM) treatments on weed above-ground dry biomass in grafted and non-grafted combined over 2013 and 2014 at Clinton, North Carolina. Points represent observed mean data. Lines represent predicted values. EST_{A-Maxifort} = 1672\exp(-0.61x); R^2 = 0.96. EST_{Amelia} = 1503\exp(-0.47x); R^2 = 0.95. REM_{A-Maxifort} = 48\exp(0.28x); R^2 = 0.98. REM_{Amelia} = 59\exp(0.26x); R^2 = 0.96.
Figure 1.2. The influence of (A) weed establishment (EST), and (B) removal (REM) treatments on above-ground dry biomass of grafted A-Maxifort and non-grafted Amelia combined over 2013 and 2014 at Clinton, North Carolina. Points represent observed mean data. Lines represent predicted values. $EST_{A-Maxifort} = 365.33 + 26.69x - 0.94x^2; R^2 = 0.96$. $EST_{Amelia} = 296.21 + 18.29x - 0.68x^2; R^2 = 0.91$. $REM_{A-Maxifort} = 542.83 - 28.69x + 1.21x^2; R^2 = 0.87$. $REM_{Amelia} = 411.32 - 7.02x - 0.30x^2; R^2 = 0.93$. 
Figure 1.3. The influence of weed establishment (EST) and removal (REM) treatments on marketable yield (% of weed-free check) of (A) grafted 'A-Maxifort' and (B) non-grafted 'Amelia' tomato combined over 2013 and 2014, Clinton, North Carolina. Points represent observed mean data. Solid lines represent predicted values.
CHAPTER 2

Response of Grafted Tomato (Solanum lycopersicum) to Herbicides

(In the format appropriate for submission to Weed Technology)
Response of Grafted Tomato (*Solanum lycopersicum*) to Herbicides

Sushila Chaudhari, Katherine M. Jennings, David W. Monks, David L. Jordan, and Christopher C. Gunter, and Frank J. Louws *

Tomato grafting has gained increased attention in the United States as an alternative to methyl bromide to control soilborne pests and diseases. Although several herbicides are registered in tomato production, a lack of information exists on the effect of herbicides on grafted tomato. Greenhouse and field experiments were conducted to determine herbicide tolerance of grafted tomato. In greenhouse experiments, halosulfuron (27, 54, and 108 g ai ha$^{-1}$), metribuzin (250, 500, and 1000 g ai ha$^{-1}$), and S-metolachlor (1070, 2200, and 3200 g ai ha$^{-1}$) were applied post-transplant to non-grafted ‘Amelia’ and Amelia scion grafted onto ‘Maxifort’ or ‘RST-04-106-T’ tomato rootstocks. Although herbicide injury was observed, no differences were observed in grafted and non-grafted tomato response including visual injury, plant height and fresh weight. Tomato injury at 3 wk after herbicide application increased from 3 to 13, 2 to 86, and 1 to 37% as rate of halosulfuron, metribuzin, and S-metolachlor increased, respectively. In field experiments under plasticulture, herbicides applied pre-transplant included fomesafen (280 and 420 g ai ha$^{-1}$), halosulfuron (39 and 52 g ha$^{-1}$), metribuzin (280 and 550 g ha$^{-1}$), napropamide (1120 and 2240 g ai ha$^{-1}$), S-metolachlor (800 and 1060 g ha$^{-1}$), and trifluralin (560 and 840 g ai ha$^{-1}$). Amelia was used as the scion and the non-grafted control. ‘Anchor-T’, ‘Beaufort’ or Maxifort tomato were used as rootstocks for grafted plants. Fomesafen, halosulfuron, napropamide, and trifluralin initially caused greater injury to grafted tomato than non-grafted tomato regardless of rootstock
(Anchor-T, Beaufort or Maxifort). However, by 4 wk after transplanting, all grafted and non-grafted plants were recovered from herbicide injury. A transplant type by herbicide interaction was not observed for yield, but grafted A-Maxifort tomato produced greater total and marketable yield than non-grafted Amelia tomato. Grafted tomato exhibited similar tolerance as non-grafted tomato for all herbicides applied post- and pre-transplant.

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**Nomenclature:** Fomesafen; halosulfuron; metribuzin; napropamide; S-metolachlor; trifluralin; tomato, *Solanum lycopersicum* L.

**Key words:** Crop tolerance, fruit number and yield, methyl bromide alternatives.
Fresh market tomato is an important crop in North Carolina as this state ranked fourth in tomato production in the United States in 2012 with 1,380 planted ha and a gross value of $37 million (USDA-NASS 2013). Tomato growers have traditionally depended heavily on methyl bromide to manage soilborne pathogens and pests. Methyl bromide has been linked to ozone depletion, and its use in agriculture has been banned (as mandated by the U.S. Clean Air Act and the Montreal Protocol on Ozone Depleting Substances) (USEPA 2005). Tomato grafting was introduced in the United States as an alternative practice to methyl bromide to address soilborne diseases and pests. Grafting is a relatively new technique in solanaceous and cucurbitaceous crops in the United States (Sakata et al. 2007). A survey conducted by the University of Arizona in 2002 and 2006 showed that more than 40 million grafted tomato seedlings are used annually in North American greenhouses (Kubota et al. 2008). Grafting is successfully used in tomato production to manage fusarium wilt [caused by *Fusarium oxysporum* f. sp. *lycopersici* (Sacc.) W.C. Snyder and H.N. Hans], verticillium wilt (caused by *Verticillium dahliae* Kleb.), southern blight (caused by *Sclerotium rolfsii* Sacc.), and bacterial wilt (caused by *Ralstonia solanacearum*) and root-knot nematodes (*Meloidogyne* spp.) (Barrett et al. 2012; McAvoy et al. 2012; Rivard et al. 2010a, 2012). Grafting with specialized rootstocks has resulted in greater fruit yield and enhanced tolerance to abiotic stresses such as thermal, salt, and water stress and organic pollutants (Colla et al. 2010; Schwarz et al. 2010).

Effective weed management in tomato is critical to produce good quality fruit and yield (Zimdahl 2004); failure to do so can result in severe losses (Buckelew et al. 2006; Garvey et al. 2013; Weaver and Tan 1983). Weaver et al. (1987) reported that 20 nightshade
(Solanum spp.) plants per m\(^2\) can reduce yield up to 60% in transplanted tomato if not controlled. Palmer amaranth (Amaranthus palmeri) interference for 10 wk resulted in 53% yield reduction due to Palmer amaranth growing taller than the tomato and reducing the amount of sunlight reaching the tomato plant (Garvey et al. 2013).

Fumigation, herbicides, and hand removal are the primary methods of weed control in plasticulture tomato production. Several herbicides are registered for application to tomato (Kemble 2015). Tomato is tolerant of fomesafen applied pre-transplant at 280 to 840 g ha\(^{-1}\) (Mohseni-Moghadam and Doohan 2015). Fomesafen is primarily used in agronomic crops such as cotton (Gossypium hirsutum L.) and soybean [Glycine max (L.) Merr.], but recently it was registered pre-transplant application in tomato. Tomato has excellent tolerance of halosulfuron at 26 to 53 g ha\(^{-1}\) applied pre- or post-transplant or via drip irrigation (Adcock et al. 2008; Dittmar et al. 2012; Jennings 2010). Adock et al. (2008) reported that a higher rate of halosulfuron PRE (19.2 g ha\(^{-1}\)) was required to reduce yellow nutsedge (Cyperus esculentus L.) dry weights by 90% as compared to halosulfuron POST (17.1 g ha\(^{-1}\)). Additional research has documented that halosulfuron reduces yellow nutsedge and purple nutsedge (Cyperus rotundus L.) tuber production and viability (Molin et al. 1999; Nelson and Renner 2002). Excellent control of large crabgrass [Digitaria sanguinalis (L.) Scop.], pitted morningglory (Ipomoea lacunosa L.), eclipta (Eclipta prostrata L.), and redroot pigweed (Amaranthus retroflexus L.) was observed with S-metolachlor applied pre-transplant in plasticulture tomato (Adcock et al. 2008). These authors reported that S-metolachlor applied pre-transplant at 1140 g ha\(^{-1}\) followed by halosulfuron applied post-transplant at 53 g ha\(^{-1}\) reduced yellow nutsedge biomass and plastic punctures by 44% and 29%, respectively,
compared with polyethylene mulch alone. Metribuzin is applied pre- and post-transplant to control many broadleaf weeds in several agronomic and horticultural crops, including tomato (Anonymous 2015b). Tomato tolerance to metribuzin depends on several factors, including temperature, relative humidity, light intensity, plant size, and cultivars (Fortino and Splittstoesser 1974a, 1974b; Pritchard and Warren 1980). Napropamide is registered in tomato for soil incorporation and surface pre-transplant application to control many annual grasses and broadleaf weeds (Anonymous 2015a).

Previous studies have shown that crop cultivars may vary in their tolerance of herbicides (Bunnell et al. 2003; Porterfield et al. 2002). For example, metribuzin injury to tomato depends on plant size and cultivars (Fortino and Splittstoesser 1974a; Gawronski 1983). Frear et al. (1983) reported that in tomato seedlings 80% of absorbed $^{14}$C-metribuzin was metabolized within 24 hr after application. Differential metribuzin tolerance of tomato cultivars has been attributed to the rate of metabolism, which was reported at least two-fold greater in tolerant tomato seedling compared to susceptible (Stephenson et al. 1976). The effect of grafting on tolerance of herbicides in tomato is not fully understood, and most studies have focused on cucurbit. Under field conditions, watermelon [Citrullus lanatus (Thunb.) Matsum. & Nakai] grafted onto bottle gourds [Lagenaria siceraria (Mol.) Standl.] or interspecific hybrid squash (Cucurbita moschata Duch.) rootstocks had similar tolerance and yield response to clomazone, halosulfuron, S-metolachlor, and terbacil herbicides (Adkins 2011). Cohen et al. (2008) reported good tolerance of clomazone in non-grafted squash, but it caused bleaching on watermelon grafted onto squash rootstock. Ghosheh et al. (2010)
reported that grafted tomatoes under greenhouse conditions had relatively higher sensitivity to metribuzin and sethoxydim compared with non-grafted plants.

Grafted tomato plants cost more (approximately 43 to 74 cents more per plant) than non-grafted plants due to extra investment on potting media, seeding trays, rootstock seeds, grafting supplies and manual labor to perform grafting (Rivard et al. 2010b). Therefore, herbicide injury can become an even greater economic risk when using grafted plants. As grafted tomato becomes more common in the United States, farmers will need information on tolerance of grafted plants to herbicides. The objective of this research was to determine the tolerance of grafted tomato to commonly used herbicides under greenhouse and field conditions.

**Materials and Methods**

**Greenhouse Experiment.** The experiments were conducted at Marye Anne Fox Science Teaching Laboratory Greenhouses at North Carolina State University (35.79°N, 78.67°W) in Raleigh, NC in the spring of 2012 and 2014. Transplant types included non-grafted Amelia (Harris Moran, P.O. Box 4938, Modesto, CA) and Amelia scion grafted onto commercially available tomato cultivars Maxifort (DeRuiter, 800 North Lindbergh Blvd, St. Louis, MO) and RST-04-106-T (DP Seeds LLC., US Highway 95, Yuma, AZ) rootstocks (hereafter Amelia, A-Maxifort, and A-RST, respectively). Grafted plants were produced at North Carolina State University using the tube grafting technique (Rivard and Louws 2006). Plants were transplanted into 20 cm wide by 15 cm deep polyethylene pots (ITML Horticultural Products, Brantford, Canada). Soil for the first run of the experiment was nontreated Orangeburg sandy loam (fine-loamy, kaolinitic, thermic typic Kandiudults having
pH 6.2, CEC 4.9 meq per 100 g and 1.8% organic matter) collected from the Horticultural Crops Research Station near Clinton, NC. Screened topsoil (Rex H. Frazier Page road Garden Center, NC) used for the second run was a sandy clay loam with pH 6.3, CEC 3.8 meq per 100 g, and 0.9% organic matter. Herbicides were applied topically 9 to 10 d after transplanting when tomato plants were 16 to 19 cm tall with 5 to 7 leaves. Herbicides treatments included halosulfuron, metribuzin, and S-metolachlor at rates listed in Table 1. A nonionic surfactant (Scanner®, Loveland Products Inc., PO Box 1286, Greeley, CO) at 0.25% (v/v) was included with halosulfuron. A nontreated control was included for comparison. Herbicides were applied in a spray chamber equipped with a CO2-pressurized sprayer calibrated to deliver 187 L ha\(^{-1}\) with an 8002EVS nozzle (Teejet Technologies, Wheaton, IL) at 275 kPA. To avoid potential washing of herbicide from leaves, water was applied only to the soil surface after herbicide application. Plants were fertilized with 60 ml pot\(^{-1}\) of a 4 g L\(^{-1}\) fertilizer solution (Miracle-Gro® Fertilizer, The Scotts Company LLC, Marysville, OH) at 1, 3 and 5 wk after transplanting (WAT) to ensure optimum plant growth. Plants were watered twice to maintain optimum plant growth. The greenhouse was maintained at 24 ± 5 C under natural sunlight. The experiment was conducted using a factorial treatment arrangement of transplant type (Amelia, A-RST, and A-Maxifort) and herbicide treatments (3 herbicides with 3 rates of each and a nontreated control) in a randomized complete block design with four blocks containing single-plant replicates of each treatment.

Percent tomato injury was estimated visually 2 and 3 wk after herbicide application (WHA) using a scale from 0 to 100% (0% = no injury and 100% = plant death). Chlorosis, necrosis, and leaf deformation were considered in the visual injury estimates. Tomato height
was determined 2 and 4 WHA by measuring from the soil surface to the most recent expanded leaf. Plants were harvested 5 WHA and sectioned into roots and shoots for fresh weight determination.

**Field Experiment.** The experiments were conducted at the Mountain Horticultural Crops Research and Extension Center, Mills River, NC (82.56°W, 35.43°N, elevation 631 m) in 2012 and the Mountain Research Station, Waynesville, NC (82.96°W, 35.53°N, elevation 780 m) in 2013. Soils included a Bradson gravelly loam (sandy clay loam, oxidic, mesic Typic Hapludults) with pH 6.5, CEC 5.2 meq per100 g, and organic matter 3.7% in 2012 and a Rosman fine sandy loam (coarse-loamy, mixed, superactive, mesic Fluventic Humudepts) with pH 5.7, CEC 11.6 meq per 100 g, and organic matter 5.3% in 2013. Raised beds 15 cm high by 76 cm wide at the top were formed on 1.5-m centers at least 3 wk before tomato transplanting. In a single operation, beds were fumigated with chloropicrin at 174 kg ai ha$^{-1}$ plus 1,3-dichloropropene at 114 kg ai ha$^{-1}$ (Pic-Clor 60, Cardinal Professional Products, PO Box 782, Hollister, CA), a single drip tape was laid in the center of the bed approximately 8 cm below the soil surface, and beds were covered with black polyethylene mulch. Beds were fumigated to eliminate soilborne pests in an effort to focus specifically on crop response to various herbicides.

The experimental design was a split-block with treatments replicated four times. Within each block transplant types were randomized to row, and herbicide treatments (consisted of six herbicides with each at two rates and a nontreated control) were randomized to column (Stringer et al. 2012). Transplant types included non-grafted Amelia and Amelia scion grafted on commercially available cultivars Maxifort, Beaufort (DeRuiter, 800 North
Lindbergh Blvd, St. Louis, MO), or Anchor-T (American Takii, Natividad Road, Salinas, CA) tomato rootstocks (hereafter Amelia, A-Maxifort, A-Beaufort, and A-Anchor-T, respectively). Grafted plants were produced using the same methods as described earlier. Herbicides applied pre-transplant included fomesafen, halosulfuron, metribuzin, napropamide, S-metolachlor, and trifluralin at rates (lowest and highest recommended rate in tomato) shown in Table 1. One day before tomato transplanting, black polyethylene mulch used to trap the fumigant was removed. Herbicides were applied to the beds using a CO₂-pressurized backpack sprayer equipped with two 11002VS nozzles (TeeJet Technologies, Wheaton, IL) spaced 50 cm apart and calibrated to deliver 187 L ha⁻¹ of spray solution. After application, trifluralin was incorporated into the top 4 to 5 cm of soil using a tractor-mounted rototiller. Immediately after herbicide application, new polyethylene mulch was reapplied with care to avoid any disturbance of the previously formed beds. Planting holes were punched mechanically in the middle of beds and drip irrigation was started to provide sufficient moisture to incorporate the herbicides and support tomato establishment when transplanted. Seven wk-old (approximately 20 to 23 cm tall) grafted and non-grafted tomato plants were hand-transplanted on 31 May 2012 and 05 June 2013. Plots were single rows 1.5 m wide with five plants spaced 0.6 m apart. Weeds emerging from the crop hole in the polyethylene mulch were removed by hand as needed before weeds exceeded 1.3 cm tall. Standard cultural practices, including fertigation and insect and disease management, were followed as recommended by NC Cooperative Extension Service (Kemble 2015).

Tomato injury using the aforementioned scale of 0 to 100% was estimated visually at 1, 2, 3 and 4 WAT. Height of three plants in the center of plots was measured at 2 WAT both
years and 6 or 8 WAT in 2012 and 2013, respectively. In 2012, tomato harvest was performed only once 9 WAT due to bacterial wilt (*Ralstonia solanacearum*) incidence when tomato fruit was at least 3.8 cm in diameter. In 2013, tomato fruit meeting a minimum color classification of ‘‘breaker’’ to ‘‘turning’’ (USDA-AMS 1997) were hand-harvested once weekly for 5 wk. A mechanical grader was used to separate fruits according to the following USDA grade standards: jumbo (>8.8 cm diam), extra-large (7.3 to 8.8 cm), large (6.4 to 7.3 cm), medium (5.7 to 6.4 cm), small (5.0 to 5.7 cm), and cull (< 5 cm or containing damage or defects).

**Statistical Analyses.** PROC MIXED of SAS (Version 9.2, SAS Institute, Cary, NC) was used to analyze data and means were separated using Fisher’s Protected LSD test (P ≤ 0.05). All data were checked for homogeneity of variance before statistical analysis by plotting residuals. Data for percent visual injury from greenhouse and field experiments were subjected to arcsine square-root transformation. However, to facilitate the interpretation of results, back-transformed means are presented. In the greenhouse experiment, herbicide treatments, transplant type and their interaction were considered fixed effects in the model, whereas experiment run, replication within experiment run, and the combination of fixed effects by run interaction were random effects. In the field experiment, the analysis was implemented separately for each year with transplant type, herbicide treatment, and their interactions as fixed effects and the replication, replication × transplant type, and replication × herbicide treatment as random effects. The herbicide treatment factor was partitioned into main and interaction effects of individual herbicide and rate. The transplant type by herbicide interaction was also partitioned accordingly.
Results and Discussion

Greenhouse Experiment. The interaction of transplant type by herbicides and the main effect of transplant type were not significant for any response variable (visual injury, plant height, and plant fresh shoot and root biomass). Averaged over herbicide treatments, injury 2 WHA, injury 3 WHA, height 2 WHA, height 4 WHA, shoot fresh weight, and root fresh weight for the three transplant types ranged from 23 to 26%, 16 to 18%, 31 to 34 cm, 53 to 54 cm, 50 to 56 g, and 12 g, respectively (data not shown). The effect of herbicide treatments on each response variable was significant (Table 2). Lack of a transplant type by herbicide interaction indicated that grafting of tomato had no apparent effect on tolerance of tomato to herbicides in the greenhouse.

Tomato injury increased as the rate of halosulfuron, metribuzin, and S-metolachlor increased (Table 2). Halosulfuron caused lower injury than higher rates of metribuzin or S-metolachlor. Injury increased from 6% with halosulfuron at 27 g ha\(^{-1}\) to 16% with halosulfuron at 108 g ha\(^{-1}\). Dittmar et al. (2012) reported a linear increase in tomato injury from 13 to 28% (at 3 WHA) as the rate of halosulfuron applied post-transplant increased from 13 to 80 g ha\(^{-1}\) under greenhouse conditions. However, tomato tolerance to halosulfuron at 26 to 53 g ha\(^{-1}\) applied as a directed spray post-transplant was reported by Jennings (2010) and Dittmar et al. (2012) under field conditions. Metribuzin at 1000 g ha\(^{-1}\) injured tomato 82 and 87% at 2 and 3 WHA, respectively. It is well-documented that metribuzin applied post-transplant can cause moderate to severe injury to tomato, depending on cultivar, application rate, and weather conditions (Fortino and Splittstoesser 1974a, 1974b; Frank and Beste 1985; Freisen and Hamill 1978). Fortino and Splittstoesser (1974b) reported tomato injury...
increasing from 5 to 85% as the rate of metribuzin applied post-transplant to 15-cm seedlings increased from 280 to 1120 g ha\(^{-1}\), with the amount of injury being dependent on tomato cultivar. S-metolachlor at 3200 g ha\(^{-1}\) and metribuzin at 500 g ha\(^{-1}\) injured tomato similarly, with injury ranging from 51 to 53% and 37 to 45% at 2 WAT and 3 WAT, respectively. Greater injury was expected from these rates because these rates are higher than the recommended rates of S-metolachlor and metribuzin (except 500 g ha\(^{-1}\)) in tomato (Kemble 2015). Injury from all other treatments was 20% or less and 12% or less at 2 and 3 WAT, respectively. Metribuzin at 500 and 1000 g ha\(^{-1}\) reduced tomato height 55 to 65% and 43 to 75% at 2 WHA and 4 WHA, respectively. S-metolachlor at 3200 g ha\(^{-1}\) reduced tomato height 23 and 17% at 2 WHA and 4 WHA, respectively. Halosulfuron, regardless of rate, metribuzin at 250 g ha\(^{-1}\), and S-metolachlor at 1070 or 2200 g ha\(^{-1}\) did not affect tomato height. Each herbicide at one or more application rates reduced shoot and root fresh weight, except for halosulfuron, which did not reduce shoot fresh weight at any rate. The greatest impact on shoot and root fresh weight was noted with S-metolachlor at 3200 g ha\(^{-1}\) and metribuzin at 500 and 1000 g ha\(^{-1}\).

**Field Experiment.** Data were analyzed separately by each year, due to high incidence of bacterial wilt in 2012 that affected yield and lack of visual injury in 2013. Data were combined over herbicide rates as no differences between rates of any herbicide were noted for any variable during both yr. The herbicide by transplant type interaction was noted for visible tomato injury at Mills River in 2012. Greater injury was noted 1 WAT on grafted tomato transplants treated with fomesafen, halosulfuron, napropamide, and trifluralin relative to injury on non-grafted Amelia (Table 3). Except for napropamide, injury was similar
among the three grafted transplant types. A-Anchor-T treated with napropamide sustained more injury than A-Maxifort. By 2 WAT, greater injury on grafted transplants was noted only with halosulfuron. Recovery from injury occurred as the season progressed. At 3 WAT, 7, 5 and 4% injury was observed from halosulfuron applied to A-Anchor-T, A-Beaufort, A-Maxifort, respectively, whereas 2% or less injury was observed with other herbicides and transplant types (data not shown). No injury was observed with any treatment 4 WAT. In contrast to observations at Mills River in 2012, no visible injury to tomato was observed with any treatment at Waynesville in 2013 (data not shown). The differential response between years may be partially attributed to greater herbicide adsorption onto the higher organic matter soil at Waynesville that resulting in less herbicide being available to tomato (Parochetti 1973; Upchurch and Mason 1962).

An herbicide by transplant type interaction was not observed for tomato height, tomato yield, or tomato fruit number in either year. Additionally, the main effect of herbicides was not significant. Compared with the nontreated control, no herbicide impacted tomato height, yield, or fruit number (data not shown). Averaged over transplant types, tomato height with the various herbicides at Mills River in 2012 ranged from 35 to 36 cm and 77 to 84 cm at 2 WAT and 6 WAT, respectively. At Waynesville in 2013, tomato height ranged from 31 to 34 cm and 90 to 100 cm at 2 WAT and 8 WAT, respectively. Total fruit yield in 2012 ranged from 16 to 20 t ha⁻¹ (non-treated = 19 t ha⁻¹). In 2013, total fruit yield, marketable fruit yield, total fruit number, and marketable fruit number ranged from 79 to 92 t ha⁻¹, 67 to 78 t ha⁻¹, 311,000 to 341,000 fruit ha⁻¹, and 202,000 to 240,000 fruit ha⁻¹,
respectively. Values for the nontreated control for these same variables were 88 t ha\(^{-1}\), 76 t ha\(^{-1}\), 311,000 fruit ha\(^{-1}\), and 227,000 fruit ha\(^{-1}\), respectively.

The main effect of transplant type was significant for tomato height, yield, and fruit number. In 2012, A-Anchor-T was initially taller than Amelia but no differences in height were noted among transplant types at 6 WAT (Table 4). At 2 WAT in 2013, A-Beaufort was shorter than Amelia but similar to Amelia at 8 WAT. A-Anchor-T and A-Maxifort were shorter than Amelia at 8 WAT in 2013. There were no differences in total yield among transplant types in 2012. Yields were low in 2012 due to bacterial wilt and a single harvest. In 2013, greater marketable yield, total yield, marketable fruit number, and total fruit number were achieved with A-Maxifort compared with Amelia. Total yield of A-Beaufort was also greater than total yield of Amelia. With the lack of an herbicide by transplant type interaction for yield and lack of an effect of herbicides on yield, it must be concluded that differences in yield between transplant types, especially A-Maxifort, and Amelia were due to grafting.

Published research on response of grafted tomato to herbicides is very limited. Ghosheh et al. (2010) reported that grafted tomato had greater sensitivity than non-grafted tomato to mixtures of metribuzin and sethoxydim applied post-transplant. They attributed the reduced tolerance of grafted tomato to slower recovery of plants after grafting stress, leading to less metabolism of herbicides. In this study authors had observed plant responses only for one week after herbicide treatments. However, in our greenhouse experiments plant responses were observed from 2 to 5 WHA, and both grafted and non-grafted plants responded similarly. In our field experiment, differences between grafted and non-grafted tomato response to herbicides applied pre-transplant were primarily at 1 WAT. The grafted
plants likely recovered from grafting stress by 2 WAT and thereafter responded similarly to non-grafted plants in both the greenhouse and field experiment. Khah et al. (2006) suggested that grafted plants need a recovery period to begin growing vigorously after grafting. Similar to our results, Adkins (2011) reported that watermelons grafted onto bottle gourd and interspecific hybrid squash rootstocks had similar herbicide tolerance and yield response to terbacil, halosulfuron, clomazone and S-metolachlor applied pre-transplant and halosulfuron applied post-transplant under field conditions.

Tomato in our field experiment was grown under weed-free conditions, hence the results document that fomesafen, halosulfuron, metribuzin, napropamide, S-metolachlor, and trifluralin can be applied pre-transplant in plasticulture production without adversely affecting tomato yield. The results also demonstrated excellent tolerance of grafted tomato to these herbicides. We conclude that herbicides registered for non-grafted tomato can safely be used on grafted tomato in plasticulture systems. Future research should focus on the effect of grafting on herbicide absorption, translocation, and metabolism.

Acknowledgments

The authors express appreciation to the following individuals for their assistance with conducting this research: Dr. Stephen Meyers, Daniel Dayton, Nick Basinger, and the staff at the Mountain Horticultural Crops Research and Extension Center, Mills River and the Mountain Research Station, Waynesville, NC. Authors thank the USDA-NIFA-2009-2376 and USDA-SCRI-2011-51181-30963 for providing funding. Furthermore, authors thank Dr. Cavell Brownie for her assistance with data analyses.
Literature Cited


Frank JR, Beste CE (1985) Effects of metribuzin placement on the foliage of tomato (Lycopersicon esculentum) and jimsonweed (Datura stramonium). Weed Sci 31:445–449


Table 2.1. Herbicides used in field and greenhouse experiments.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Common name</th>
<th>Trade name</th>
<th>Experiment</th>
<th>Application rates</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fomesafen</td>
<td></td>
<td>Reflex®</td>
<td>Field</td>
<td>280 and 420</td>
<td>Syngenta Crop Protection LLC; Greensboro, NC syngentacroopprotection-us.com</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td></td>
<td>Sandea®</td>
<td>Greenhouse</td>
<td>27, 54, and 108</td>
<td>Gowan Company; Yuma, AZ; gowanco.com</td>
</tr>
<tr>
<td>Metribuzin</td>
<td></td>
<td>TriCor® DF</td>
<td>Greenhouse</td>
<td>250, 500, and 1000</td>
<td>United Phosphours Inc.; King of Prussia, PA; upi-usa.com</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Field</td>
<td>280 and 550</td>
<td></td>
</tr>
<tr>
<td>Napropamide</td>
<td></td>
<td>Devrinol® DF-XT</td>
<td>Field</td>
<td>1120 and 2240</td>
<td>United Phosphorus Inc.</td>
</tr>
<tr>
<td>S-metolachlor</td>
<td></td>
<td>Dual MAGNUM®</td>
<td>Greenhouse</td>
<td>1070, 2200, and 3200</td>
<td>Syngenta Crop protection LLC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Field</td>
<td>800 and 1060</td>
<td></td>
</tr>
<tr>
<td>Trifluralin</td>
<td></td>
<td>Treflan® HFP</td>
<td>Field</td>
<td>560 and 840</td>
<td>Dow AgroSciences LLC; Indianapolis, IN; dowagro.com</td>
</tr>
</tbody>
</table>
Table 2.2. Effect of herbicides on tomato in the greenhouse experiment$^z$.

<table>
<thead>
<tr>
<th>Herbicides</th>
<th>Rate</th>
<th>2 WHA$^z$</th>
<th>3 WHA</th>
<th>2 WHA</th>
<th>4 WHA</th>
<th>Shoot</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g ha$^{-1}$</td>
<td>%</td>
<td>cm</td>
<td>g</td>
<td>g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>halosulfuron</td>
<td>27</td>
<td>6 c</td>
<td>3 d</td>
<td>37 a</td>
<td>62 ab</td>
<td>13 cb</td>
<td></td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>12 c</td>
<td>7 d</td>
<td>36 a</td>
<td>59 a</td>
<td>14 abc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>108</td>
<td>16 c</td>
<td>12 cd</td>
<td>38 a</td>
<td>58 abc</td>
<td>13 bc</td>
<td></td>
</tr>
<tr>
<td>metribuzin</td>
<td>250</td>
<td>7 c</td>
<td>1 d</td>
<td>33 a</td>
<td>62 ab</td>
<td>14 abc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>53 ab</td>
<td>45 b</td>
<td>18 bc</td>
<td>28 cd</td>
<td>8 cd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>82 a</td>
<td>87 a</td>
<td>14 c</td>
<td>13 d</td>
<td>3 d</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>1070</td>
<td>4 c</td>
<td>0 d</td>
<td>40 a</td>
<td>66 ab</td>
<td>15 ab</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>20 bc</td>
<td>11 cd</td>
<td>39 a</td>
<td>60 ab</td>
<td>13 bc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3200</td>
<td>51 ab</td>
<td>37 bc</td>
<td>31 ab</td>
<td>42 bcd</td>
<td>7 cd</td>
<td></td>
</tr>
<tr>
<td>Nontreated</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40 a</td>
<td>63 a</td>
<td>73 a</td>
<td>20 a</td>
</tr>
</tbody>
</table>

$^y$ Data pooled over transplant types and two runs of experiment. Means within a column followed by the same letter are not different according to Fisher’s Protected LSD test at $P \leq 0.05$.

$^z$ WHA, wk after herbicide application.
Table 2.3. Visible injury of tomato 1 and 2 WAT as affected by transplant type and herbicides at Mills River in 2012.

<table>
<thead>
<tr>
<th>Transplant Type</th>
<th>Fomesafen</th>
<th>Halosulfuron</th>
<th>Metribuzin</th>
<th>Napropamide</th>
<th>S-metolachlor</th>
<th>Trifluralin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amelia</td>
<td>4 b</td>
<td>6 b</td>
<td>5 b</td>
<td>1 c</td>
<td>5 a</td>
<td>2 b</td>
</tr>
<tr>
<td>A-Anchor-T</td>
<td>9 a</td>
<td>16 a</td>
<td>13 a</td>
<td>7 a</td>
<td>10 a</td>
<td>6 a</td>
</tr>
<tr>
<td>A-Beaufort</td>
<td>8 a</td>
<td>15 a</td>
<td>14 a</td>
<td>4 a</td>
<td>8 ab</td>
<td>2 a</td>
</tr>
<tr>
<td>A-Maxifort</td>
<td>9 a</td>
<td>12 a</td>
<td>16 a</td>
<td>5 a</td>
<td>4 bc</td>
<td>5 a</td>
</tr>
</tbody>
</table>

\^{y} Data pooled over two rates of each herbicide. Means within a column followed by the same letter are not different according to Fisher’s Protected LSD Test at $P \leq 0.05$.

\^{z} Abbreviations: WAT, wk after transplanting; A-Anchor-T, Amelia scion grafted onto Anchor-T rootstock; A-Beaufort, Amelia scion grafted onto Beaufort rootstock; A-Maxifort, Amelia scion grafted onto Maxifort rootstock.
Table 2.4. Effect of transplant type on tomato height, fruit yield, and fruit number\(^z\).

<table>
<thead>
<tr>
<th>Transplant Type(^z)</th>
<th>Height</th>
<th>Yield</th>
<th>Fruit number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 WAT(^z)</td>
<td>6 WAT</td>
<td>2012</td>
</tr>
<tr>
<td>Amelia</td>
<td>35 b</td>
<td>83 a</td>
<td>36 a</td>
</tr>
<tr>
<td>A-Anchor-T</td>
<td>38 a</td>
<td>83 a</td>
<td>33 ab</td>
</tr>
<tr>
<td>A-Beaufort</td>
<td>34 b</td>
<td>81 a</td>
<td>30 b</td>
</tr>
<tr>
<td>A-Maxifort</td>
<td>36 ab</td>
<td>81 a</td>
<td>33 ab</td>
</tr>
</tbody>
</table>

\(^z\) Data pooled over herbicide treatment. Means within a column followed by the same letter are not different according to Fisher’s Protected LSD test at \(P \leq 0.05\).

\(^z\) Abbreviations: WAT, wk after transplanting; A-Anchor-T, Amelia scion grafted onto Anchor-T rootstock; A-Beaufort, Amelia scion grafted onto Beaufort rootstock; A-Maxifort, Amelia scion grafted onto Maxifort rootstock.
CHAPTER 3

Response of Eggplant (*Solanum melongena*) Grafted onto Tomato (*Solanum lycopersicum*) Rootstock to Herbicides

(In the format appropriate for submission to Weed Technology)
Response of eggplant (*Solanum melongena*) grafted onto tomato (*Solanum lycopersicum*) rootstock to herbicides

Sushila Chaudhari, Katherine M. Jennings, David W. Monks, David L. Jordan, and Christopher C. Gunter, and Frank J. Louws *

Tomato rootstocks have been successfully used for eggplant production. However, the safety of tomato herbicides has not been tested on grafted eggplant which is combination of two plants, tomato rootstock and eggplant scion. Greenhouse and field experiments were conducted to determine response of grafted eggplant on tomato rootstock to napropamide, metribuzin, halosulfuron, trifluralin, *S*-metolachlor and fomesafen herbicides. In greenhouse experiments herbicide treatments included halosulfuron (18, 36 g ai ha$^{-1}$) post-transplant, metribuzin (140, 280 g ai ha$^{-1}$) post or pre-transplant, and *S*-metolachlor (400, 800 g ai ha$^{-1}$) pre-transplant. In field experiments herbicide treatments included pre-transplant fomesafen (280, 420 g ai ha$^{-1}$), halosulfuron (39, 52 g ha$^{-1}$), metribuzin (280, 550 g ha$^{-1}$), napropamide (1120, 2240 g ai ha$^{-1}$), *S*-metolachlor (800, 1060 g ha$^{-1}$), and trifluralin (560, 840 g ai ha$^{-1}$).

The eggplant cultivar ‘Santana’ was used as the scion and non-grafted control, while two hybrid tomatoes ‘RST-04-106-T’ and ‘Maxifort’ were used as rootstocks for grafted plants. No difference in injury from herbicides was observed in grafted and non-grafted eggplant in greenhouse and field experiments. Metribuzin post-transplant at 140 and 280 g ha$^{-1}$ caused 94 and 100% injury to grafted and non-grafted eggplant 4 wk after treatment. In field experiments, pre-transplant fomesafen, napropamide, *S*-metolachlor, and trifluralin caused
less than 10% injury and no yield reduction in grafted and non-grafted tomato. However, metribuzin caused injury and yield reduction in both grafted and non-grafted eggplant. Metribuzin at 550 g ha\(^{-1}\) caused 60 and 81% plant stand loss in 2013 and 2014, respectively. Halosulfuron reduced yield 24% in both grafted and non-grafted eggplant compared to nontreated control in 2013 but did not reduce yield in 2014. Grafted eggplant on tomato rootstocks exhibited similar tolerance to non-grafted eggplant for all herbicides applied post- and pre-transplant.

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**Nomenclature:** Fomesafen; halosulfuron; metribuzin; napropamide; S-metolachlor; trifluralin; eggplant, *Solanum melongena* L.; tomato, *Solanum lycopersicum* L.

**Key words:** Application method, rootstock, grafting, crop tolerance.
Grafting is an important technique globally for vegetable production (Lee and Oda 2003). Grafted plants are used extensively to manage biotic problems such as [caused by *Fusarium oxysporum* f. sp. *lycopersici* (Sacc.) W.C. Snyder and H.N. Hans], southern blight (caused by *Sclerotium rolfsii* Sacc.), and bacterial wilt (caused by *Ralstonia solanacearum*) and root-knot nematodes (*Meloidogyne* spp.) as well as tolerance to various abiotic stresses, including suboptimal temperatures (Zijlstra and den Nijs 1987; Venema et al. 2008), heat (Abdelmageed and Gruda 2009), excessive water (Black et al. 2003) and salinity (Fernández-García et al. 2002). Research has demonstrated that compatibility between rootstock and scion plays an important role to improve crop plant performance, although poor compatibility may lead to reduction in fruit quality, yield and possible plant collapse (Lee 1994; Traka-Mavrona 2000). Interspecific grafting using a rootstock and scion from different species in Solanaceous crops has been reported in literature (Moncada et al. 2013).

Moncada et al. (2013) used tomato hybrid *Solanum torvum* as the rootstock for eggplant and reported that yield and quality of eggplant fruit were primarily influenced by scion cultivar. Grafted eggplant on ‘Heman’ tomato rootstock in the greenhouse and the field produced 34 and 43% more fruit, respectively, than the non-grafted controls (Khah 2011). However, in a similar study eggplant grafted on ‘Primavera’ tomato rootstock produced 21% more fruit in the greenhouse and 5% less fruit in the field compared to the non-grafted controls. Likewise, tomato scion on eggplant rootstock has also been studied. Black et al. (2003) recommended eggplant accessions ‘EG195’ and ‘EG203’ as rootstocks for tomato production under flooding or waterlogged soils, bacterial wilt, root-knot nematode, and
tomato fusarium wilt. These data suggest that selection of scion to rootstock is critical to address specific abiotic and biotic threats in tomato and eggplant.

Weed management with herbicide can be challenging in interspecific grafted eggplant where the rootstock is a tomato and the scion is an eggplant compared to non-grafted eggplant. The rootstock tolerance to herbicides may or may not confer tolerance to the entire plant. Baker and Warren (1962) reported that squash (Cucurbita moschata Duch.) required 6 to 8 times greater dosage for 50% inhibition of growth compared to cucumber (Cucumis sativus L.). Root application of $^{14}$C-amiben on reciprocal grafts of cucumber and squash indicated that tolerance of amiben to either species depends on rootstock. $^{14}$C-amiben was translocated more in either scion when grafted onto cucumber rootstock than on squash. In another study, Jiang et al. (2013) reported that glyphosate-resistance can be transferred from soybean [Glycine max (L.) Merr.] rootstock having glyphosate resistance to non-transgenic soybean scion and the resulting plants survived glyphosate application. However, glyphosate-resistant transfer is unidirectional from root to shoot because plants with non-transgenic rootstock and glyphosate-resistant scion were killed by glyphosate application. In contrast, Cohen et al. (2008) reported that clomazone did not injur Cucurbita rootstock but caused injury to non-grafted watermelon [Citrullus lanatus (Thunb.) Matsum. & Nakai], and watermelon scion grafted onto Cucurbita rootstock.

More herbicides are registered in tomato than eggplant. Only nine herbicides including bensulide, carfentrazone, clethodim, dacthal, glyphosate, halosulfuron, napropamide, paraquat, and sethoxydim are registered for eggplant in southeastern United
States (Kemble 2015). It is important to know if herbicides registered for tomato including fomesafen, halosulfuron metribuzin, napropamide, S-metolachlor and trifluralin are safe to apply to grafted eggplant. Tolerance of grafted eggplant to herbicides registered for application in the production of eggplant and tomato is widely unknown. Therefore, the objective of this experiment was to determine the response of grafted eggplant to post- and pre-transplant herbicides registered in non-grafted tomato and eggplant.

**Material and Methods**

**Greenhouse Experiment.** Experiments were conducted at Marye Anne Fox Science Teaching Laboratory Greenhouses at North Carolina State University (35.79°N, 78.67°W) in Raleigh, NC in spring 2012 and 2014. Eggplant ‘Santana’ (Siegers Seed Company, 13031 Reflections Dr., Holland, MI) was used as non-grafted and scion in grafted plants. Commercially available tomato ‘Maxifort’ (DeRuiter, 800 North Lindbergh Blvd, St. Louis, MO) and ‘RST-04-106-T’ (DP Seeds LLC., US Highway 95, Yuma, AZ) were used as rootstock for grafted plants. Grafted plants were produced at North Carolina State University’s phytotron using the tube grafting technique described by Rivard and Louws (2006). Herbicide treatments included halosulfuron post-transplant (19 and 39 g ai ha⁻¹), metribuzin pre-transplant (140 and 280 g ai ha⁻¹), and S-metolachlor pre-transplant (400 and 800 g ai ha⁻¹). A nontreated control was included for comparison. Metribuzin post-transplant at 140 and 280 g ha⁻¹ was included during second run of experiment. Nonionic surfactant (Scanner®, Loveland Products Inc., PO Box 1286, Greeley, CO) at 0.25% (v/v) was included with halosulfuron. Plants were transplanted into 20 cm diameter and 15 cm deep
polyethylene pots (ITML Horticultural Products, Brantford, Canada) containing non-treated Orangeburg sandy loam (fine-loamy, kaolinitic, thermic typic Kandiudults) field soil obtained from the Horticultural Crops Research Station near Clinton, NC with pH 6.2, CEC 4.9 meq per 100g and 1.8% organic matter. Pre-transplant herbicides were applied to the soil surface in pots and plants were transplanted immediately after application. Post-transplant herbicides were applied 8 to 10 d after plants were transplanted corresponding to plant height of 10 cm with 4 to 5 leaves. Herbicides were applied using a spray chamber equipped with a CO₂-pressurized sprayer calibrated to deliver 187 L ha⁻¹ with an 8002 EVS nozzle tip (Teejet Technologies, Springfield, IL) at 275 kPa. All plants received pre-transplant treatments were watered lightly twice daily for one wk to incorporate soil-applied herbicides and to avoid leaching of herbicides through the pots. In post-transplant treatments to avoid potential washing of herbicide from leaves, water was applied only to the soil surface after herbicide application. Pots were watered as needed to maintain optimum plant growth. Pots were maintained weed-free by hand removing emerged weeds weekly. Plants were fertilized with 60 ml pot⁻¹ of a 4 g L⁻¹ fertilizer solution (Miracle-Gro® Fertilizer, The Scotts Company LLC, Marysville, OH) at 1 and 3 wk after herbicide application (WHA) to ensure optimum plant growth. Experiments were conducted in a greenhouse with natural sunlight (during spring) and temperatures of 24 ± 5 C.

The experiment was conducted using a factorial arrangement of transplant type (Santana, S-RST, and S-Maxifort) and herbicide treatments (3 herbicides with 2 rates of each and a nontreated control) in a randomized complete block design with four single-plant
replications of each treatment. Plant height (distance from soil surface to last fully expanded true leaf) and percent visual injury (0 to 100% scale with 0 = no injury to 100% = plant death) were determined at 4 WHA and 1, 2, and 4 WHA, respectively. Chlorosis, necrosis, and leaf deformation were included in the visual estimates. Destructive harvest of plants (shoots cut at the soil surface) was conducted 5 WHA to determine plant fresh biomass.

**Field Experiment.** The experiment was conducted during 2013 at Mountain Research Station, Waynesville, NC (82.96°W, 35.53°N, elevation 780 m). Soil was a Rosman Fine Sandy Loam (coarse-loamy, mixed, superactive, mesic fluventic Humudepts) with pH 5.7, CEC 11.6 meq per 100g and organic matter 5.3%. Experiment was repeated in 2014 at the Horticultural Crops Research Station, Clinton, NC (35.02°N, 79°W; 48 m above sea level). Soil was Norfolk sandy loam (fine loamy, kaolinitic, thermic typic Kandiudults) with pH 5.7, CEC 3.1 meq per 100g and organic matter 0.9%. Raised beds (76 cm wide by 15 cm high) were prepared at least 4 wk before eggplant transplanting by bedding and fumigating with a mixture of 174 kg ai ha⁻¹ plus 1,3-dichloropropene at 114 kg ai ha⁻¹ (Pic-Clor 60, Cardinal Professional Products, PO Box 782, Hollister, CA). In the same operation, a single drip irrigation tape was laid in the center of the bed approximately 8 cm below the soil surface and beds were covered with black polyethylene mulch.

The experimental design was a split-block with treatments replicated four times. Within each block transplant types were randomized to row, and herbicide treatments were randomized to column (Stringer et al. 2012). The herbicide treatments consisted of six herbicides with each at two rates and a nontreated control. The Santana eggplant was used as
the non-grafted treatment and scion in grafted plants. Commercially available tomato rootstock Maxifort was used as the rootstock for grafted (S-Maxifort) plants. Grafted plants were produced using the tube grafting technique described by Rivard and Louws (2006).

Herbicide treatments included fomesafen, halosulfuron metribuzin, napropamide, S-metolachlor, and trifluralin at rates mentioned in Table 3.1. These herbicide rates were lowest and highest recommended rates for tomato (Kemble 2015). One d before transplanting eggplant, black polyethylene mulch that was used to trap the fumigant was removed, pre-transplant herbicides applied to soil surface, and new polyethylene mulch applied to the treated beds. Herbicide treatments were applied in water using a CO$_2$ backpack sprayer equipped with two 11002VS nozzles (TeeJet Technologies, Wheaton, IL) on 50 cm spacing calibrated to deliver 187 L ha$^{-1}$ of spray solution at 269 kPa pressure. After application, trifluralin herbicide was incorporated into the top 4 to 5 cm of soil using a tractor mounted rototiller. Immediately after applying the polyethylene mulch, transplant holes were mechanically punched through the black polyethylene mulch at 60 cm row plant spacing and slightly off center of beds. Seven wk old (approximately 13 to 15 cm tall) grafted and non-grafted eggplant was hand transplanted on 5 June 2013 and 6 May 2014. Plots were single-row plantings consisting of five plants in 2013 and six plants in 2014 of each type of eggplant (grafted, non-grafted). Plot size was 1.5 by 9.1 m long row. Weeds emerging from the crop hole in the polyethylene mulch and prior to reaching 2.5 cm tall were removed by hand as needed. Standard plasticulture eggplant production practices were followed (Kemble
Weather data was collected by weather stations maintained by the NC State Climate Office at each respective research station.

Visual estimates of percent eggplant injury including chlorosis, necrosis, and leaf deformation (scale of 0% = no injury to 100% = plant death) were taken 1 and 4 WAT. The height of 3 (2013) and 4 plants (2014) in the center of plots was measured two times during the season at 2 (early season), and 8 (late season) WAT. Eggplant was harvested six times by removing marketable size fruit that was at least 10 cm diameter at the widest point and 15 cm in length (USDA-AMS 2013). In 2014, destructive harvest of one eggplant plant per plot was conducted after final eggplant fruit harvest. Plants were dried in a drying oven at 55 C for four d to determine above-ground biomass.

Statistical Analyses. Analysis of variance was conducted using the PROC MIXED procedure in SAS (Version 9.2, SAS Institute, Cary, NC) to test the effects of transplant type, herbicide and their interactions. Treatment means were separated using Fisher’s Protected LSD test (P ≤ 0.05). Data for percent visual injury from greenhouse and field experiments were subjected to arcsine square-root transformation. However, to facilitate the interpretation of results, back-transformed means are presented. In the greenhouse experiment, herbicide treatments, transplant type and their interaction were considered fixed effects in the model, whereas experiment run, replication within experiment run, and the combination of fixed effects by run interaction were random effects. In the field experiment, the analysis was implemented separately for each year with transplant type, herbicide treatment, and their interactions as fixed effects and the replication, replication × transplant type, and replication
× herbicide treatment as random effects. The herbicide treatment factor was partitioned into main and interaction effects of individual herbicide and rate. The transplant type by herbicide interaction was also partitioned accordingly.

**Results and Discussion**

**Greenhouse Experiment.** The main effect of transplant type, and interaction effects between transplant type and herbicide treatments were not significant for visual injury. No greater than 1% visible injury were observed with pre-transplant S-metolachlor in grafted and non-grafted eggplant (data not shown). Initially at 1 WHA, post-transplant halosulfuron caused higher injury as compared to pre-transplant metribuzin (Table 3.2). However, plants recovered from halosulfuron injury by 4 WHA and injury from pre-transplant metribuzin (280 g ha\(^{-1}\)) was higher (60%) (Table 3.2). Plants treated with post-transplant metribuzin at 140 and 280 g ha\(^{-1}\) were injured 29 and 50% at 1 WHA and increased to 94 and 100% by 4 WHA (Table 3).

The interaction between transplant type and herbicide treatment was not significant for plant height and fresh biomass. No height and plant fresh biomass data were collected from post-transplant metribuzin treatments because most plants were dead by 2 WHA. Grafted eggplant S-Maxifort and S-RST were taller (26 and 25 cm, respectively) compared to non-grafted eggplant (19 cm) (Table 3.2). Fresh plant biomass of non-grafted eggplant was 41 and 33% lower than grafted S-Maxifort and S-RST, respectively (Table 3.2). Bletsos (2006) reported greater plant height, stem diameter and root biomass of grafted plants than non-grafted control plants when eggplant ‘Tsakoniki’ scion was grafted onto *Solanum*
torvum tomato rootstock. Khah (2011) also reported that eggplant ‘Rima’ scion grafted onto hybrid tomato rootstocks ‘Heman’ (*Lycopersicon hirsutum* L.) and ‘Primavera’ (*Lycopersicon esculentum* Mill.) was significantly taller than non-grafted control. Pre-transplant metribuzin at 280 g ha\(^{-1}\) reduced plant height 48% and plant fresh biomass 73% compared to the nontreated control. None of the other herbicide treatments caused a negative effect on plant height or fresh biomass.

**Field Experiment.** The interaction of yr by transplant type by herbicide was significant for crop injury, height and yield so data were presented by yr. Injury was 3% or less with S-metolachlor, napropamide, and trifluralin in grafted S-Maxifort and non-grafted Santana eggplant (data not shown). Metribuzin was more injurious than either halosulfuron or fomesafen regardless of rate (Table 3.4). Injury from metribuzin at 280 g ha\(^{-1}\) (14 and 48%) and 550 g ha\(^{-1}\) (20 and 71%) was greater than halosulfuron at 39 g ha\(^{-1}\) (2 and 11%) and 52 g ha\(^{-1}\) (2 and 10%)\(^{1}\) and 4 WAT, respectively in 2013. Similar pattern of injury was observed in 2014 from halosulfuron and metribuzin (Table 3.4). No injury was observed from fomesafen in 2013. However, in 2014 injury from fomesafen at 280 and 480 g ha\(^{-1}\) was 8 and 12% at 1 WAT and 1 and 3% at 4 WAT. Metribuzin at 550 g ha\(^{-1}\) caused 60 and 81% plant stand loss in 2013 and 2014, respectively (Table 3.4). Aliyu and Lagoke (1995) also reported plant stand loss of ‘Scarlet’ eggplant from metribuzin mixtures with diphenamid (250 plus 1000 g ha\(^{-1}\)) and S-metolachlor (250 plus 1000 g ha\(^{-1}\)). The difference between fomesafen and metribuzin injuries between yr may be partially attributed to difference in organic matter (OM) at Waynesville (OM 5.3%) and Clinton (OM 0.9%). It has been well studied that
sorption of metribuzin increased with increasing soil organic matter (Majumdar and Singh 2007). The bioavailability of metribuzin and fomesafen decreases with an increase in organic matter content (Anonymous 2015; Gonese and Weber 1998; Rauch et al. 2007). Thus, more injury occurred at Clinton where soils had lower organic matter and less injury at Waynesville where soil had higher organic matter.

Effect of herbicide rates were not significant both yr for height, plant above-ground dry biomass, yield and number, therefore data was combined over rates for each herbicide (Table 3.5). In 2013, main effect of transplant type and herbicide treatments was significant for yield and fruit number (Table 3.5). Grafted plants produced 55 and 44% lower yield and number, respectively, as compared to non-grafted eggplant. Treatments of halosulfuron and metribuzin resulted in 24% and 68% yield reduction, and 24% and 69% reduction in fruit number, respectively in grafted and non-grafted eggplant. No adverse impact on eggplant yield was observed from fomesafen, napropamide, S-metolachlor, and trifluralin.

In 2014, main effect of transplant type and interactions were not significant except for height at 8 WAT where transplant type were significant (Table 3.6). None of the other herbicide treatments caused a negative impact on above-ground plant biomass, yield and fruit number except metribuzin which caused 42%, 69% and 79% reduction in above-ground plant biomass, yield and number, respectively relative to the nontreated control.

The yield difference in grafted and non-grafted eggplant in 2013 may be partially attributed to high rainfall as the field was flooded much of the season and the soil stayed saturated. Previous recommendations to use eggplant rootstock have occurred if flooding or
waterlogged soils are anticipated in the growing season, because eggplant can withstand short term waterlogged conditions and tomato cannot (Black et al. 2003). Eggplant accessions EG195 and EG203 are recommended to use as rootstock for tomato production under flooding or waterlogged soils, bacterial wilt, root-knot nematode, and tomato fusarium wilt (Black et al. 2003). Eggplant prefers a warm climate with daily mean temperature of 26 C and minimum temperature should not be less than 18 C (Swaider et al. 1992). Temperature was cooler at Waynesville than Clinton during the eggplant growing period (Figure 1). The minimum and average temperature at Clinton was within the range of 18 to 26 C during most growing months which is ideal for eggplant growth. However, at Waynesville minimum and average temperatures were below 17 and 21 C during most of growing season. Therefore, the warmer condition at Clinton was likely the reason for high plant growth (height) and yield during 2014 as compared to 2013.

Grafted eggplant responded similarly to non-grafted eggplant for tolerance of S-metolachlor, napropamide, fomesafen, and trifluralin. There were also no differences between grafted and non-grafted eggplant with halosulfuron and metribuzin. Previous research found over 51% growth reduction in eggplant from foliar applied 26 g ha\(^{-1}\) halosulfuron 12 DAT (Flanders and Culpepper 2002). Drip application of halosulfuron from 39 and 52 g ha\(^{-1}\) reduced yield at least 4% and 33%, respectively (Webster and Culpepper 2005). Metribuzin rates used in this experiment, have been reported safe to tomato but not eggplant (Kemble 2015; Fortino and Splittstoesser 1974). The findings in this experiment indicated that tomato rootstock tolerance of metribuzin and halosulfuron was not transferred
to the eggplant scion. Similar results were obtained by Cohen et al. (2008) in which they reported that clomazone was safe for *Cucurbita* rootstock but caused injury to non-grafted watermelon, and watermelon scion grafted onto *Cucurbita* rootstock. The results indicate that grafting does not impart eggplant tolerance to halosulfuron and metribuzin herbicides which are registered in tomato. Although metribuzin and halosulfuron are registered in tomato, these herbicides could injure grafted eggplant on tomato rootstock. The pre-transplant S-metolachlor, napropamide, fomesafen, and trifluralin were safe for both grafted and non-grafted eggplant, and when registered would be very useful for weed control in grafted eggplant.

**Acknowledgments**

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Table 3.1. Herbicides used in field and greenhouse experiments.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Common name</th>
<th>Trade name</th>
<th>Experiment</th>
<th>Application rates</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fomesafen</td>
<td>Reflex®</td>
<td>Field</td>
<td>Field</td>
<td>280 and 420</td>
<td>Syngenta Crop Protection LLC; Greensboro, NC syngentacroopprotection-us.com</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td>Sandea®</td>
<td>Greenhouse</td>
<td>Field</td>
<td>19 and 39</td>
<td>Gowan Company; Yuma, AZ; gowanco.com</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>TriCor® DF</td>
<td>Greenhouse</td>
<td>Field</td>
<td>140 and 280</td>
<td>United Phosphours Inc.; King of Prussia, PA; upi-usa.com</td>
</tr>
<tr>
<td>Napropamide</td>
<td>Devrinol® DF-XT</td>
<td>Field</td>
<td>1120 and 2240</td>
<td>United Phosphorus Inc.</td>
<td></td>
</tr>
<tr>
<td>S-metolachlor</td>
<td>Dual MAGNUM®</td>
<td>Greenhouse</td>
<td>Field</td>
<td>400 and 800</td>
<td>Syngenta Crop protection LLC</td>
</tr>
<tr>
<td>Trifluralin</td>
<td>Treflan® HFP</td>
<td>Field</td>
<td>560 and 840</td>
<td>Dow AgroSciences LLC; Indianapolis, IN; dowagro.com</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2. Effect of transplant type and herbicides on eggplant injury, eggplant height and fresh biomass in greenhouse experiments, Raleigh, North Carolina<sup>w</sup>.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Treatment</th>
<th>Rate</th>
<th>Visual injury&lt;sup&gt;x&lt;/sup&gt;</th>
<th>Fresh biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g ha&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>1 WHA</td>
<td>2 WHA</td>
</tr>
<tr>
<td>Transplant type (T)&lt;sup&gt;y&lt;/sup&gt;</td>
<td>Santana</td>
<td>-</td>
<td>4 a</td>
<td>22 a</td>
</tr>
<tr>
<td></td>
<td>S-Maxifort</td>
<td>-</td>
<td>7 a</td>
<td>12 a</td>
</tr>
<tr>
<td></td>
<td>S-RST</td>
<td>-</td>
<td>7 a</td>
<td>15 a</td>
</tr>
<tr>
<td>Herbicide (H)&lt;sup&gt;z&lt;/sup&gt;</td>
<td>Halosulfuron</td>
<td>19</td>
<td>13 a</td>
<td>11 b</td>
</tr>
<tr>
<td></td>
<td>Halosulfuron</td>
<td>39</td>
<td>16 a</td>
<td>15 ab</td>
</tr>
<tr>
<td></td>
<td>Metribuzin</td>
<td>140</td>
<td>1 b</td>
<td>5 b</td>
</tr>
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<td></td>
<td>Metribuzin</td>
<td>280</td>
<td>1 b</td>
<td>40 a</td>
</tr>
<tr>
<td></td>
<td>S-metolachlor&lt;sup&gt;z&lt;/sup&gt;</td>
<td>400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>S-metolachlor&lt;sup&gt;z&lt;/sup&gt;</td>
<td>800</td>
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<td>-</td>
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<tr>
<td></td>
<td>Nontreated</td>
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<td>-</td>
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<tr>
<td>T×H</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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</tbody>
</table>

<sup>w</sup>Data pooled over two runs.

<sup>x</sup>Means within columns for main effects (transplant type or herbicide) followed by the same letter are not significantly different according to Fisher’s Protected LSD test at P ≤ 0.05.

<sup>y</sup>Abbreviations: S-Maxifort, Santana scion grafted onto Maxifort rootstock; S-RST, Santana scion grafted onto RST-04-106-T rootstock; WHA, wk after herbicide application; NS, not significant.

<sup>z</sup>S-metolachlor and the nontreated control were not included in analysis for visual injury.
Table 3.3. Effect of transplant type and post-transplant metribuzin on eggplant injury in greenhouse experiment, Raleigh, North Carolina.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Treatment</th>
<th>Visual injury&lt;sup&gt;y&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 WHA</td>
</tr>
<tr>
<td>Transplant type&lt;sup&gt;z&lt;/sup&gt;</td>
<td>Santana</td>
<td>37 a</td>
</tr>
<tr>
<td></td>
<td>S-Maxifort</td>
<td>34 a</td>
</tr>
<tr>
<td></td>
<td>S-RST</td>
<td>46 a</td>
</tr>
<tr>
<td>Herbicide</td>
<td>Metribuzin (140 g ha&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>29 b</td>
</tr>
<tr>
<td></td>
<td>Metribuzin (280 g ha&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>50 a</td>
</tr>
</tbody>
</table>

<sup>y</sup>Means within columns for main effects (transplant type or herbicide) followed by the same letter are not significantly different according to Fisher’s Protected LSD test at P ≤ 0.05.

<sup>z</sup>Abbreviations: S-Maxifort, Santana scion grafted onto Maxifort rootstock; S-RST, Santana scion grafted onto RST-04-106-T rootstock; WHA, wk after herbicide application.
Table 3.4. Effect of pre-transplant metribuzin, halosulfuron, and fomesafen on visual eggplant injury and plant stand loss in 2013 and 2014 field experiments\textsuperscript{w}.

<table>
<thead>
<tr>
<th>Herbicide\textsuperscript{y}</th>
<th>Rate (g ha\textsuperscript{-1})</th>
<th>Visual injury\textsuperscript{x}</th>
<th>Plant stand loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 WAT %</td>
<td>4 WAT %</td>
<td>2013 2014</td>
</tr>
<tr>
<td>Metribuzin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>14 a</td>
<td>43 a</td>
<td>25 a 66 a</td>
</tr>
<tr>
<td>550</td>
<td>20 a</td>
<td>56 b</td>
<td>60 b 81 a</td>
</tr>
<tr>
<td>Halosulfuron</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>2 b</td>
<td>4 d</td>
<td>- -</td>
</tr>
<tr>
<td>52</td>
<td>2 b</td>
<td>6 cd</td>
<td>- -</td>
</tr>
<tr>
<td>Fomesafen\textsuperscript{z}</td>
<td>280</td>
<td>8 cd</td>
<td>- -</td>
</tr>
<tr>
<td>420</td>
<td>-</td>
<td>12 c</td>
<td>- -</td>
</tr>
</tbody>
</table>

\textsuperscript{w}Data pooled over transplant type.

\textsuperscript{x}Means within a column followed by the same letter are not significantly different according to Fisher’s Protected LSD test at P ≤ 0.05.

\textsuperscript{y}Nontreated control, napropamide, S-metolachlor, and trifluralin are not included in the analysis.

\textsuperscript{z}In 2013 both rates of fomesafen not included in analysis.
Table 3.5. Effect of transplant type and herbicides on eggplant height, fruit yield, and fruit number in 2013, Waynesville, North Carolina.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Treatment</th>
<th>Height* cm</th>
<th>2 WAT</th>
<th>8 WAT</th>
<th>Fruit Yield</th>
<th>Fruit Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transplant type (T)</td>
<td>Santana</td>
<td>14 a</td>
<td>93 a</td>
<td>84 a</td>
<td>124 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S-Maxifort</td>
<td>15 a</td>
<td>103 b</td>
<td>37 b</td>
<td>69 b</td>
<td></td>
</tr>
<tr>
<td>Herbicide (H)</td>
<td>Fomesafen</td>
<td>16 a</td>
<td>100 a</td>
<td>71 a</td>
<td>112 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Halosulfuron</td>
<td>14 a</td>
<td>102 a</td>
<td>49 c</td>
<td>82 c</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Metribuzin(^z)</td>
<td>-</td>
<td>-</td>
<td>21 d</td>
<td>33 d</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Napropamide</td>
<td>15 a</td>
<td>97 a</td>
<td>64 abc</td>
<td>99 abc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S-metolachlor</td>
<td>14 a</td>
<td>94 a</td>
<td>57 abc</td>
<td>94 abc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trifluralin</td>
<td>14 a</td>
<td>99 a</td>
<td>54 bc</td>
<td>89 bc</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nontreated</td>
<td>14 a</td>
<td>98 a</td>
<td>67 ab</td>
<td>108 ab</td>
<td></td>
</tr>
<tr>
<td>T × H</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

*Means within columns for main effects (transplant type or herbicide) followed by the same letter are not significantly different according to Fisher’s Protected LSD test at P ≤ 0.05.

\(^x\) Abbreviations: S-Maxifort, Santana scion grafted onto Maxifort rootstock; WAT, wk after treatment; NS, not significant.

\(^y\) Data is pooled over two rates for each herbicide.

\(^z\) Metribuzin was not included in analysis for height data.
Table 3.6. Effect of transplant type and herbicides on eggplant height, plant biomass, fruit yield, and fruit number in 2014, Clinton, North Carolina.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Treatment</th>
<th>Height&lt;sup&gt;w&lt;/sup&gt;</th>
<th>Plant biomass</th>
<th>Fruit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 WAT 8 WAT cm</td>
<td>g plant&lt;sup&gt;1&lt;/sup&gt;</td>
<td>t ha&lt;sup&gt;1&lt;/sup&gt; ha&lt;sup&gt;1&lt;/sup&gt; × 10&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Transplant type (T)&lt;sup&gt;x&lt;/sup&gt;</td>
<td>Santana</td>
<td>16 a 98 b</td>
<td>639 a</td>
<td>95 a 194 a</td>
</tr>
<tr>
<td></td>
<td>S-Maxifort</td>
<td>15 a 114 a</td>
<td>726 a</td>
<td>96 a 226 a</td>
</tr>
<tr>
<td>Herbicide (H)&lt;sup&gt;y&lt;/sup&gt;</td>
<td>Fomesafen</td>
<td>16 a 104 a</td>
<td>715 a</td>
<td>102 a 210 a</td>
</tr>
<tr>
<td></td>
<td>Halosulfuron</td>
<td>15 a 106 a</td>
<td>643 a</td>
<td>98 a 197 a</td>
</tr>
<tr>
<td></td>
<td>Metribuzin&lt;sup&gt;z&lt;/sup&gt;</td>
<td>- -</td>
<td>427 b</td>
<td>32 b 63 b</td>
</tr>
<tr>
<td></td>
<td>Napropamide</td>
<td>16 a 108 a</td>
<td>715 a</td>
<td>103 a 213 a</td>
</tr>
<tr>
<td></td>
<td>S-metolachlor</td>
<td>15 a 105 a</td>
<td>621 a</td>
<td>97 a 197 a</td>
</tr>
<tr>
<td></td>
<td>Trifluralin</td>
<td>15 a 106 a</td>
<td>666 a</td>
<td>98 a 199 a</td>
</tr>
<tr>
<td></td>
<td>Nontreated</td>
<td>16 a 106 a</td>
<td>734 a</td>
<td>103 a 239 a</td>
</tr>
<tr>
<td>T × H</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

<sup>W</sup>Means within columns for main effects (transplant type or herbicide) followed by the same letter are not significantly different according to Fisher’s Protected LSD test at P ≤ 0.05.

<sup>x</sup>Abbreviations: S-Maxifort, Santana scion grafted onto Maxifort rootstock; WAT, wk after treatment; NS, not significant.

<sup>y</sup>Data pooled over two rates for each herbicide.

<sup>z</sup>Metribuzin was not included in analysis for height data.
Figure 3.1. Weather data including monthly average temperature, minimum temperature, and precipitation during eggplant growing season from Waynesville (2013) and Clinton (2014), North Carolina.
CHAPTER 4

Response of Drought-stressed Grafted and Non-grafted tomato (*Solanum lycopersicum*) to Metribuzin

(In the format appropriate for submission to Weed Technology)
Response of drought-stressed Grafted and Non-grafted tomato (*Solanum lycopersicum*) to Metribuzin

Sushila Chaudhari, Katherine M. Jennings, David W. Monks, David L. Jordan, and Christopher C. Gunter, and Frank J. Louws*

Greenhouse experiments were conducted in Raleigh, NC to determine the efficacy of metribuzin on drought-stressed grafted and non-grafted tomato. The tomato cultivar ‘Amelia’ was used as the scion and non-grafted control, while two hybrid tomatoes ‘Beaufort’ and ‘Maxifort’ were used as rootstocks for grafted plants. Drought stress treatments included no drought stress, 3 d of drought stress before with no drought stress after metribuzin application at (3 d DSB), and 3 d of drought stress before with 3 d of drought stress after metribuzin application (3 d DSBA). Metribuzin was applied at 550 g ai ha\(^{-1}\). No difference in injury from metribuzin was observed in grafted and non-grafted plants. However, at 7 and 14 d after metribuzin treatment (DMT), less injury was observed on tomato that were 3 d DSBA (5 and 2% injury, respectively) than on plants that were 3 d DSB (15 and 8% injury, respectively) or those that were never drought-stressed (18 and 11% injury, respectively).

Photosynthesis rate and stomatal conductance were reduced similarly in grafted and non-grafted tomato when subjected to drought stress before metribuzin application.

Photosynthesis and stomatal conductance of tomato at 7 DMT (3 d after re-watering) was not different among drought stress treatments or metribuzin treatments. Grafted tomato
demonstrated similar tolerance to metribuzin as non-grafted tomato under drought stress conditions.

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**Nomenclature:** Metribuzin; tomato, *Solanum lycopersicum* L.

**Key words:** Rootstock, grafting, photosynthesis, stomatal conductance.
Vegetable grafting is very common practice in Asiatic and European countries for growing solanaceous and cucurbitaceous crops (Kubota et al. 2008; Lee et al. 2010). However, grafting is a relatively new technique in the United States (Sakata et al. 2007). Tomato grafting has emerged in the United States as an alternative practice to methyl bromide to address soil borne diseases and pests (Louws et al. 2010). Surveys conducted by the University of Arizona in 2002 and 2006 showed that more than 40 million grafted tomato seedlings are used annually in North American greenhouses (Kubota et al. 2008). Grafting is successfully used in tomato production to manage fusarium wilt [caused by *Fusarium oxysporum* f. sp. *lycopersici* (Sacc.) W.C. Snyder and H.N. Hans], verticillium wilt (caused by *Verticillium dahliae* Kleb.), southern blight (caused by *Sclerotium rolfsii* Sacc.), and bacterial wilt (caused by *Ralstonia solanacearum*) and root-knot nematodes (*Meloidogyne* spp.) (Barrett et al. 2012; McAvoy et al. 2012; Rivard et al. 2010a; 2012). Grafting with certain rootstocks has resulted in greater fruit yield, and enhanced tolerance to abiotic stresses such as thermal, salt, and water-stress and organic pollutants (Colla et al. 2010; Proietti et al. 2008; Schwarz et al. 2010). Djidonou et al. (2013) has reported improved irrigation water and nitrogen use efficiency using grafted plants in tomato production systems.

Metribuzin, a triazinone and photosystem II (PS II) inhibitor herbicide (Senseman 2007), is registered PRE and POST at 280 to 550 g ha\(^{-1}\) for controlling annual broadleaf weeds in tomato (Anonymous 2015). Metribuzin can cause injury to tomato, including stunting, and marginal leaf chlorosis and necrosis under certain environmental conditions.
(Fortino and Splittstoesser 1974 a, b; Friesen and Hamill 1978). Tomato plants are more sensitive to metribuzin injury when growing in high temperature (27 C), high relative humidity (80%) or low light intensity (6,500 lx) before its application (Fortino and Splittstoesser 1974 a, b; Phatak and Stephenson 1973). McNaughton (2013) reported lower visual injury to tomato plants from glyphosate drift followed by metribuzin application under drought stress compared to non-stress conditions in greenhouse.

Metribuzin injury to tomato also depends on tomato plant size and cultivars (Fortino and Splittstoesser 1974; Gawronski 1983). Small plants are more sensitive to metribuzin injury than larger plants. Frear et al. (1983) reported that in tomato seedlings 80% of absorbed $^{14}$C-metribuzin was metabolized within 24 hr after application. Differential metribuzin tolerance of tomato cultivars had been attributed to the rate of metabolism, which was reported at least two-fold greater in tolerant tomato seedling compared to susceptible (Stephenson et al. 1976).

The effect of metribuzin on non-grafted tomato under different environmental conditions has been well studied as mentioned above. As grafted tomato becomes popular in the United States, it is important to understand the effect of metribuzin on grafted tomato. Grafted tomato plants cost more (approximately 43 to 74 cents more per plant) than non-grafted plants due to extra investment on potting media, seeding trays, rootstock seeds, grafting supplies and manual labor to perform grafting (Rivard et al. 2010b), hence metribuzin injury could become an even greater economic risk when using grafted plants. Therefore, objective of this experiment was to determine the response of grafted and non-
grafted tomato to metribuzin POST under drought stress and no stress conditions in greenhouse.

**Materials and Methods**

Experiments were conducted at the Marye Anne Fox Science Teaching Laboratory Greenhouse at North Carolina State University (35.79°N, 78.67°W) in Raleigh, NC in March 2014 and repeated in May 2014. Transplant type included non-grafted ‘Amelia’ (Harris Moran, P.O. Box 4938, Modesto, CA), and Amelia scion grafted on commercially available tomato ‘Beaufort’ or ‘Maxifort’ (DeRuiter Seeds, 800 North Lindbergh Blvd, St. Louis, MO) rootstocks (hereafter Amelia, A-Beaufort, and A-Maxifort, respectively). Grafted plants were produced at NC State University’s phytotron using the tube grafting technique (Rivard and Louws 2006). Plants were transplanted into 20 cm wide by 15 cm deep polyethylene pots (ITML Horticultural Products, Brantford, ON, Canada) using a 1:1 (v/v) mix of sand (Screened Topsoil, Rex H. Frazier Page Rd. Garden Center, NC) and commercial potting mix (Fafard 4P potting mix, Conrad Fafard Inc., 160 Agawam, MA). The resulting soil mix contained organic matter 4.2%, CEC 4.9 meq per 100g, and pH 6. Plants were watered twice daily except when drought stress treatments were applied.

At 15 d after transplanting, appropriate drought stress treatments were induced when plants were 27 to 32 cm tall (first experiment) and 38 to 42 cm tall (second experiment). Three drought stress treatments were: no drought stress, 3 d of drought stress before and no drought stress after metribuzin application (3 d DSB), and 3 d of drought stress before and 3 d of drought stress after metribuzin application (3 d DSBA). Plants subjected to drought
stress conditions did not receive water for at least 2 days when first visible wilting occurred and then drought stress was maintained by providing limited water (160 to 180 ml pot\(^{-1}\) d\(^{-1}\)) to the soil surface. Similar method was used by Zhou et al. (2007) and McNaughton (2013) to achieve drought-stressed plants. Drought stress symptoms of tomato included yellowing, stunting, inhibition of leaf size and number. Metribuzin was applied at 0 or 550 g ai ha\(^{-1}\). Metribuzin was applied in a spray chamber with a CO\(_2\) pressurized sprayer calibrated to deliver 187 L ha\(^{-1}\) with an 8002EVS nozzle (Teejet Technologies, Springfield, IL) at 275 kPa pressure. Plants subjected 3 d DSB received similar amounts of water as no drought stress plants after metribuzin application. However, plants subjected to 3 d DSBA only received limited water 160 to 180 ml pot\(^{-1}\) d\(^{-1}\) for next three consecutive days and then received similar amount of water as no drought stress plants. All pots were watered on soil surface with care after POST metribuzin application to avoid potential washing of metribuzin from leaves. All plants were fertilized with 100 ml pot\(^{-1}\) of a 4 g L\(^{-1}\) fertilizer solution (Miracle-Gro® Fertilizer, Scotts Company LLC, Marysville, OH) at 7, 13 and 30 d after transplanting to ensure optimum plant growth. The greenhouse was maintained at 23 ± 5 C, and under natural sunlight. The experiment was conducted in a randomized complete block design with an three-way factorial (3 × 3 × 2) arrangement of transplant type (Amelia, A-Beaufort, and A-Maxifort), drought stress treatments (no drought stress, 3 d DSB, and 3 d DSBA), and metribuzin rates (0 and 550 g ha\(^{-1}\)) with four replications of each treatment. The experiment was conducted twice.
Photosynthetic rate (μmol CO$_2$ m$^{-2}$ s$^{-1}$) and stomatal conductance (mol H$_2$O m$^{-2}$ s$^{-1}$) were measured with a Licor 6400 Portable Photosynthesis System (LI-6400 Portable Photosynthesis System, LI-COR Biosciences, P.O. Box 4425, Lincoln, NE). These measurements were recorded to document the physiological stress associated with the drought and metribuzin in both grafted and non-grafted tomato. The light source was set at 1500 μmol m$^{-2}$ s$^{-1}$ and the reference CO$_2$ was set to 400 μmol. Photosynthetic rate and stomatal conductance were measured on tomato before starting drought stress treatments, after 3 d of drought stress but before metribuzin application, 3 d after metribuzin application (last day of drought stress), and 7 d after metribuzin application (3 d after re-watering). Measurements were taken on the third fully expanded leaf that was 2 cm$^2$ from the top of each plant between 10:00 and 15:00 hours Eastern Standard Time. Each measurement was taken over a 30-second period of time. There were three replicate plants per treatment and six measurements were taken per plant.

Tomato visual injury (included marginal leaf chlorosis and necrosis) was determined at 7 and 14 d after metribuzin treatment (DMT) and plant height were measured at 7 and 21 DMT. The scale for tomato visual injury was 0 to 100% with 0% = no injury and 100% = crop death. Plants were harvested by cutting at the soil surface 21 DMT and dried at 55 C for two days to determine above-ground plant biomass.

All data were subjected to ANOVA using the PROC MIXED procedure of SAS 9.2 (SAS Institute, Cary, NC) to test for treatment effects and interactions. Means were separated using Fisher’s Protected LSD test at P ≤ 0.05 when appropriate. Data were checked for
homogeneity of variance and normality using residual plots. Transplant type, drought stress, and metribuzin treatments and all interactions were considered fixed effects in the model. Experiment run, replication within run and treatment by run interaction were considered random effects, when data combined for both experimental runs. However, only replication was considered random effects, when data not combined for both experimental runs.

**Results and Discussion**

In both experiment runs, the drought stress symptoms partially disappeared when stressed plants were provided with adequate water, and the new growth that developed later did not show any stress symptoms. No metribuzin injury was observed in the second run. The bigger plant size at the time of metribuzin application in the second run could be the reason for no observed injury. Fortino and Splittstoesser (1974) reported that the small plants are more sensitive to metribuzin injury than larger tomato plants. In the first experiment run, no difference in injury was observed between grafted and non-grafted tomato plants, however injury was significantly lower on plants that had 3d DSBA (5 and 2% at 7 and 14 DMT, respectively) as compared to no drought-stressed plants (18 and 11% at 7 and 14 DMT, respectively) (Table 4.1). Plants that had 3d DSB showed similar level of injury as no drought-stressed plants. Increased tolerance of velvetleaf (*Abutilon theophrasti* Medik.) to glyphosate (Zhou et al. 2007) and green foxtail (*Setaria viridis* L. Beauv.) to fenoxaprop, fluazifop-P, haloxyfop, and sethoxydim (Boydston 1990) has been reported under drought stress conditions. McNaughton (2013) also reported lower injury on tomato from glyphosate (90 g ae ha⁻¹) drift followed by metribuzin (250 g ha⁻¹) when grown under soil moisture
limiting conditions as compared to non-limiting conditions. Drought stress has been shown to decrease absorption and translocation of herbicides including picloram in Russian knapweed (*Acroptilon repens* L. DC.), haloxyfop in johnsongrass (*Sorghum halepense* L. Pers.) and large crabgrass (*Digitaria sanguinalis* L. Scop.), and glyphosate in common milkweed (*Asclepias syriaca* L.) (Morrison et al. 1995; Peregoy et al. 1990; Waldecker and Wyse 1985). Metribuzin primarily translocates through the xylem tissue in plants (Fortino and Splittstoesser 1974). Therefore, the lower injury to 3 d DSBA plants in our experiment could be attributed to the decreased metribuzin translocation in stressed plants. However, metribuzin activity on 3 d DSB plants can be reversed somewhat by watering, therefore equal injury was reported as no drought-stressed plants.

Tomato plant height and biomass data were analyzed separately from both experiment runs because of significant treatment (transplant type, drought stress, and metribuzin rate) by run interactions. Differences between the two experiments might have been due to the different plant size used in the experiments. The interactions between main effects of transplant type, drought stress and metribuzin treatment were not significant for both plant height and biomass except for plant height at 7 DMT from the first experiment run (Table 4.2). At 7 DMT, the effect of transplant type and metribuzin treatment was not significant on plant height; however, both drought stress treatments (3 d DSB and 3 d DSBA) significantly reduced the plant height relative to no stress treatment. At 21 DMT, the effect of transplant type and drought stress on plant height was inconsistent from first run to the second. In the first run, both transplant type and drought stress treatment did not affect plant
height, but the effects were significant in the second run (Table 4.2). In the second run, the grafted plants A-Beaufort and A-Maxifort (67 and 68 cm, respectively) were shorter than non-grafted plants (73 cm), and plants receiving 3 d DSBA treatment (65 cm) had reduced height as compared to plants that received no drought stress (73 cm). The metribuzin treatment reduced the plant height significantly, at 21 DMT in both runs. The effect of transplant type was only significant in the first run, where the dry weight of grafted A-Beaufort (23 g) was higher than non-grafted Amelia (21 g), and that of grafted A-Maxifort (19 g) was lower than non-grafted Amelia. Drought stress affected plant dry weight only in the second run, where the 3 d DSBA treatment reduced the plant dry weight relative to no stress (20 g).

Photosynthesis and stomatal conductance of tomato before drought stress ranged from 21.7 to 23.6 μmol CO₂ m⁻² s⁻¹ and 0.49 to 0.58 mol H₂O m⁻² s⁻¹, respectively (data not shown). Photosynthesis and stomatal conductance was reduced in tomato plants subjected to 3 d of drought stress relative to non-stressed plants (Table 4.3). The reduction in photosynthesis and stomatal conductance confirms that the plants that were in stress treatments were in stress conditions before metribuzin application.

No difference was observed between photosynthesis and stomatal conductance of grafted and non-grafted tomato at 3 and 7 DMT; therefore data were pooled over transplant type (Table 4.4). At 3 DMT, nontreated plants subjected to no drought stress and 3 d DSB had higher photosynthesis (16.8 and 16.5 μmol CO₂ m⁻² s⁻¹, respectively) than 3 d DSBA (5.3 μmol CO₂ m⁻² s⁻¹). However, metribuzin treated plants subjected to no drought stress and 3 d
DSBA had lower photosynthesis (11.6 and 5.2 μmol CO$_2$ m$^{-2}$s$^{-1}$, respectively) compared to 3 d DSB plants (16.7 μmol CO$_2$ m$^{-2}$s$^{-1}$). The effect of metribuzin treatments did not affect stomatal conductance at 3 DMT. However, drought stress had significant effect; both no stress and 3 d DSB had higher stomatal conductance than 3 d DSBA (Table 4.4). No effect of drought stress treatment and metribuzin treatments was observed on photosynthesis and stomatal conductance of tomato plants 7 DMT (3 d after re-watering). Previous studies show that drought stress reduces photosynthesis, stomatal conductance, respiration and transpiration in tomato (Brix 1962; Nguyen 2012; Rao et al. 2000).

These results show that there was no difference observed in grafted and non-grafted tomato in terms of metribuzin injury, photosynthesis and stomatal conductance under either drought stress or no drought stress conditions. Visible metribuzin injury was more pronounced when tomato were grown under either no drought stress or 3 d DSB than 3 d DSBA. No difference in height of grafted and non-grafted tomato plants occurred in the first run, however, in the second run, the grafted plants were shorter than the non-grafted plants. The 3 d DSBA metribuzin application negatively affected plant height and dry weight. Photosynthesis rate and stomatal conductance of plants were negatively impacted with drought stress, however this effect disappeared after re-watering plants. These experiment results are important to know that the influence of drought stress on metribuzin tolerance in tomato is not affected by grafting. Higher tolerance of tomato from metribuzin would be expected when applied under drought stress conditions.
Acknowledgments

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Table 4.1. Effect of transplant type and drought stress treatments on tomato visual injury from metribuzin POST.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Treatment</th>
<th>Visual injury^x</th>
<th>7  DMT^y</th>
<th>14 DMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transplant type (T)^z</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amelia</td>
<td>13 a</td>
<td>7 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-Beaufort</td>
<td>14 a</td>
<td>6 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-Maxifort</td>
<td>12 a</td>
<td>6 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drought stress (D)^z</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No drought stress</td>
<td>18 a</td>
<td>11 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3d DSB</td>
<td>15 a</td>
<td>8 b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3d DSBA</td>
<td>5 b</td>
<td>2 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T × D</td>
<td>NS</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^x 0 = no injury and 100 = plant death.

^y Means within columns for main effects (transplant type or drought stress) followed by same letters not significantly different according to Fisher’s protected least significant difference LSD test at P ≤ 0.05.

^z Abbreviations: 3 d DSB, 3 d of drought stress before with no drought stress after metribuzin; 3 d DSBA, 3 d of drought stress before with 3 d of drought stress after metribuzin; A-Beaufort, Amelia scion grafted onto Beaufort rootstock; A-Maxifort, Amelia scion grafted onto Maxifort rootstock; DMT, d after metribuzin treatment; NS, not significant.
Table 4.2. Effect of transplant type, drought stress and metribuzin on tomato plant height and dry weight.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Treatment</th>
<th>Height</th>
<th></th>
<th>Dry weight</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7 DMT</td>
<td>21 DMT</td>
<td></td>
<td>21 DMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exp. 1</td>
<td>Exp. 2</td>
<td>Exp. 1</td>
<td>Exp. 2</td>
</tr>
<tr>
<td>Transplant type (T)</td>
<td>Amelia</td>
<td>40 a</td>
<td>52 a</td>
<td>68 a</td>
<td>73 a</td>
</tr>
<tr>
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<td>A-Beaufort</td>
<td>40 a</td>
<td>48 a</td>
<td>66 a</td>
<td>68 b</td>
</tr>
<tr>
<td></td>
<td>A-Maxifort</td>
<td>39 a</td>
<td>49 a</td>
<td>65 a</td>
<td>67 b</td>
</tr>
<tr>
<td>Drought stress (D)</td>
<td>No drought stress</td>
<td>44 a</td>
<td>54 a</td>
<td>64 a</td>
<td>73 a</td>
</tr>
<tr>
<td></td>
<td>3 d DSB</td>
<td>39 b</td>
<td>49 b</td>
<td>66 a</td>
<td>70 a</td>
</tr>
<tr>
<td></td>
<td>3 d DSBA</td>
<td>38 b</td>
<td>46 c</td>
<td>69 a</td>
<td>65 b</td>
</tr>
<tr>
<td>Metribuzin (M)</td>
<td>Nontreated</td>
<td>41 a</td>
<td>51 a</td>
<td>69 a</td>
<td>72 a</td>
</tr>
<tr>
<td></td>
<td>550 g ha⁻¹</td>
<td>39 a</td>
<td>49 a</td>
<td>64 b</td>
<td>67 b</td>
</tr>
<tr>
<td></td>
<td>T × D</td>
<td>*</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>T × M</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>D × M</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>T × M × D</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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</tr>
</tbody>
</table>
Table 4.2 continued

Means within columns for main effects (transplant type, drought stress or metribuzin) followed by same letters not significantly different according to Fisher’s protected least significant difference LSD test at $P \leq 0.05$.

Abbreviations: 3 d DSB, 3 d of drought stress before with no drought stress after metribuzin; 3 d DSBA, 3 d of drought stress before with 3 d of drought stress after metribuzin; A-Beaufort, Amelia scion grafted onto Beaufort rootstock; A-Maxifort, Amelia scion grafted onto Maxifort rootstock; DMT, d after metribuzin treatment; NS, not significant.
Table 4.3. Effect of transplant type and drought stress on photosynthesis and stomatal conductance of tomato plant measured at 3 d after drought stress, but before metribuzin application.

<table>
<thead>
<tr>
<th>Drought stress (D)</th>
<th>Transplant type (T)yz</th>
<th>Photosynthesis (µmol CO₂ m⁻² s⁻¹)</th>
<th>Stomatal conductance (mol H₂O m⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amelia</td>
<td>A-Beaufort</td>
<td>A-Maxifort</td>
</tr>
<tr>
<td>No drought stress</td>
<td>18.6 a</td>
<td>21.5 a</td>
<td>18.0 a</td>
</tr>
<tr>
<td>3 d drought stress</td>
<td>2.9 b</td>
<td>3.6 b</td>
<td>2.8 b</td>
</tr>
<tr>
<td>T × D</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Means within columns followed by same letters not significantly different according to Fisher’s protected least significant difference LSD test at P ≤ 0.05.

Abbreviations: A-Beaufort, Amelia scion grafted onto Beaufort rootstock; A-Maxifort, Amelia scion grafted onto Maxifort rootstock; NS, not significant.
Table 4.4. Effect of drought stress and metribuzin on photosynthesis and stomatal conductance of tomato plant measured at 3 and 7 d after metribuzin application (DMT).²

<table>
<thead>
<tr>
<th></th>
<th>Metribuzin</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nontreated</td>
<td>550 g ha⁻¹</td>
<td>Nontreated</td>
</tr>
<tr>
<td></td>
<td>Photosynthesis</td>
<td></td>
<td>Stomatal conductance</td>
</tr>
<tr>
<td>Drought stress (D)</td>
<td>µmol CO₂ m⁻²s⁻¹</td>
<td>mol H₂O m⁻²s⁻¹</td>
<td>µmol CO₂ m⁻²s⁻¹</td>
</tr>
<tr>
<td>No drought stress</td>
<td>16.8 a</td>
<td>11.6 b</td>
<td>0.28 a</td>
</tr>
<tr>
<td>3 d DSB</td>
<td>16.5 a</td>
<td>16.7 a</td>
<td>0.26 a</td>
</tr>
<tr>
<td>3 d DSBA</td>
<td>5.3 b</td>
<td>5.2 c</td>
<td>0.06 b</td>
</tr>
<tr>
<td>D × M*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 DMT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No drought stress</td>
<td>20.1 b</td>
<td>24.2 a</td>
<td>0.30 a</td>
</tr>
<tr>
<td>3 d DSB</td>
<td>21.4 ab</td>
<td>23.9 a</td>
<td>0.30 a</td>
</tr>
<tr>
<td>3 d DSBA</td>
<td>22.9 a</td>
<td>23.0 a</td>
<td>0.31 a</td>
</tr>
<tr>
<td>D × M</td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Data pooled over transplant type. Means within columns and within 3 or 7 DMT followed by same letters not significantly different according to Fisher’s protected least significant difference LSD test at P ≤ 0.05.

² Abbreviations: 3 d DSB, 3 d of drought stress before with no drought stress after metribuzin; 3 d DSBA, 3 d of drought stress before with 3 d of drought stress after metribuzin; NS, not significant.
Figure 4.1. Tomato plant at time of metribuzin application: (A) Amelia (B) A-Beaufort (C) A-Maxifort. In each panel the plant on left is no drought stress and plant on right is 3 d of drought stress.
CHAPTER 5

Absorption and Translocation of Halosulfuron in Grafted Eggplant (*Solanum melongena*) and Tomato (*Solanum lycopersicum*)

(In the format appropriate for submission to Weed Technology)
Absorption and Translocation of Halosulfuron in Grafted Eggplant (Solanum melongena) and Tomato (Solanum lycopersicum)

Sushila Chaudhari, Katherine M. Jennings, David W. Monks, David L. Jordan, and Christopher C. Gunter, and Frank J. Louws *

Experiment was conducted to evaluate absorption and translocation of halosulfuron in grafted and non-grafted tomato and eggplant. Transplant type included non-grafted tomato cultivar ‘Amelia’, non-grafted eggplant cultivar ‘Santana’, Amelia scion grafted onto Maxifort tomato rootstock (A-Maxifort) and Santana scion grafted onto Maxifort rootstock (S-Maxifort). Plants were treated POST with commercially formulated halosulfuron at 39 g ai ha⁻¹ followed by ¹⁴C-halosulfuron under controlled laboratory conditions at North Carolina State University, Raleigh, NC. Amount of ¹⁴C-halosulfuron was quantified in leaf wash, treated leaf, scion shoot, rootstock shoot and root at 6, 12, 24, 48, and 96 h after treatment (HAT) by using liquid scintillation spectrometry. No differences were observed between transplant types with regard to absorption, and translocation of ¹⁴C-halosulfuron. Absorption of ¹⁴C-halosulfuron increased with time, reaching 10 and 74% of applied at 6 and 96 HAT, respectively. Translocation of ¹⁴C-halosulfuron was limited to the treated leaf, which reached maximum (66% of applied) at 96 HAT, whereas minimal (< 4% of applied) translocation occurred in scion shoot, rootstock shoot, and root combined. Results from this experiment indicate that grafting did not affect absorption and translocation of halosulfuron in tomato and eggplant.
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**Nomenclature:** Halosulfuron; eggplant, *Solanum melongena* L.; tomato, *Solanum lycopersicum* L.

**Key words:** Rootstock, interspecific, intraspecific.
Grafting is a technique to combine the shoot of a desirable fruit producing cultivar (scion) onto the soilborne disease-resistant rootstock or rootstock with another desirable production characteristic, from another cultivar or closely related species. The use of grafting is a very old technique to manipulate plant growth and was mentioned in ancient books written in 5th century China and 17th century Korea to increase the fruit size of gourd (Lee and Oda 2003). However, grafting was first introduced for disease control in Japan to increase yield and to manage fusarium wilt [Fusarium oxysporum Schlecht. (emend. Snyd. & Hans.) f. sp. niveum (E.F. Sm.)] in watermelon [Citrullus lanatus (Thunb.) Matsum. & Nakai] in 1920 (Tateishi 1927). Since then, vegetable grafting has become an important technique for production of cucurbitaceous and solanaceous vegetables around the world where intensive cultivation occur using limited arable land (Besri 2003; Bletsos 2005; Lee 2003). In 2008, more than 700 million grafted plants (cucurbits and solanaceous vegetables) were produced in Korea as well as in Japan (Lee et al. 2010). The use of grafted plants has increased in the United States as an environmentally safe alternative to methyl bromide (banded by Montreal Protocol) fumigation to manage soilborne diseases and pests (Louws et al. 2010). More than 40 million grafted tomato seedlings are produced annually in North American greenhouses (Kubota et al. 2008).

As the production of grafted plants increases worldwide (Kubota et al. 2008; Lee et al. 2010), breeders and seed companies are incorporating desired traits to develop new rootstocks to improve yield and fruit quality, and tolerance to many biotic and abiotic stresses including insect, diseases, salt stress, drought, waterlogged soils and temperature
(Barrett et al. 2012; Guan et al. 2012; King et al. 2010; 2008; Savvas et al. 2010; Schwarz et al. 2010). The use of interspecific (closely related species) and intraspecific (same species) rootstock to achieve the desired characteristics plants is very common in grafting. Eggplant accessions EG195 and EG203 are recommended to use as rootstocks for tomato production under flooding or waterlogged soils, in fields with soilborne problems such as bacterial wilt (caused by *Ralstonia solanacearum*), fusarium wilt [caused by *Fusarium oxysporum* f. sp. *lycopersici* (Sacc.) W.C. Snyder and H.N. Hans], and root-knot nematodes (*Meloidogyne* spp.) (Black et al. 2003).

Grafted plants are a combination of two different plants either interspecific or intraspecific so it is important to know the herbicidal selectivity of the whole plant. Differential absorption, translocation, and metabolism play an important role in herbicide selectivity in plant species (Gallaher et al. 1999; Askew and Wilcut 2002; Sidhu et al. 2014) because these processes affect the amount of the herbicide delivered to the site of action (Owen 1989). Baker and Warren (1962) found that the scion tolerance to amiben (3-amino-2,5-dichlorobenzoic acid) applied via a nutrient solution, was dependent upon type of rootstock (sensitive vs. tolerant to herbicide). Non-grafted cucumber (*Cucumis sativus* L.), and squash (*Cucurbita moschata* Duch.) or cucumber scion grafted on cucumber rootstock had a much greater concentration of radiolabeled amiben in the shoot compared to non-grafted squash or when squash plant used as rootstock. On the contrary, minor differences in translocation of absorbed atrazine and no difference in translocation of glyphosate reported based on rootstock in grafted watermelon (Adkins 2011).
However, the impact of grafting on herbicide absorption and translocation has not been studied in solanaceous crops. An understanding of herbicide absorption and translocation may further explain the difference and similarity in herbicide sensitivity for grafted and non-grafted solanaceous crops as reported by Ghosheh et al. (2010) and from chapter (2 and 3), respectively. The objective of this research was to compare the absorption and translocation of foliar-applied radiolabeled halosulfuron in grafted and non-grafted tomato and eggplants.

**Materials and Methods**

**Plant Materials.** The intraspecific grafted plants were tomato scion grafted onto tomato rootstock and interspecific grafted plants were eggplant scion grafted onto tomato rootstock. Eggplant cultivar ‘Santana’ (Siegers Seed Company, 13031 Reflections Dr., Holland, MI) and tomato cultivar ‘Amelia’ (Harris Moran, P.O. Box 4938, Modesto, CA) were used as non-grafted plants and as the scion in grafted plants. Commercially available tomato rootstock ‘Maxifort’ (DeRuiter, 800 North Lindbergh Blvd, St. Louis, MO) was used as the rootstock for grafted plants. Transplant type included non-grafted Amelia, non-grafted Santana, Amelia scion grafted onto Maxifort tomato rootstock (A-Maxifort), and Santana scion grafted onto Maxifort rootstock (S-Maxifort). Grafted plants were produced by following the ‘Japanese top-grafting’ or ‘tube-grafting’ method described in the NC Cooperative Extension Bulletin (Rivard and Louws 2006). Six wk old plants were transplanted into pots (750 ml volume) with commercial potting mix (Fafard 4P potting mix, Conrad Fafard Inc., 160 Agawam, MA). Plants were fertilized with 30 ml pot⁻¹ of a 4 g L⁻¹
fertilizer solution (Miracle-Gro® Fertilizer, The Scotts Company LLC, Marysville, OH) immediately after transplanting to ensure optimum plant growth. Plants were watered as needed with overhead irrigation. The greenhouse was maintained at 29 ± 3 C under natural sunlight.

**Absorption and Translocation.** Ten d after transplanting, plants were at the desired stage (5 to 6 leaves) for herbicide treatment. Prior to treatment with radiolabeled halosulfuron, plants were sprayed with commercially formulated halosulfuron at 39 g ai ha⁻¹ plus 0.25% v/v nonionic surfactant (Scanner®, Loveland Products Inc., PO Box 1286, Greeley, CO). Herbicide was applied in a spray chamber with a CO₂ pressurized sprayer calibrated to deliver 187 L ha⁻¹ with an 8002 EVS nozzle (Teejet Technologies, Springfield, IL) at 275 kPa. Radiolabeled (¹⁴C-pyrazole) halosulfuron, with specific activity 40 mCi mmol⁻¹ and 98.2% radioactive purity was foliar applied as described by McElroy et al. (2004).

Immediately following the commercial halosulfuron application, the adaxial surface of a fully expanded second-youngest leaf of each plant was spotted ten 1-μl droplets with a micropipett (Hamilton® Microliter Pipetter, Hamilton Co., Reno, NV) of ¹⁴C-halosulfuron. Radioactive spotting solution was a 1:1 v/v mixture of deionized water and acetone, 0.25% nonionic surfactant, and 363 Bq μl⁻¹ (first run) and 340 Bq μl⁻¹ (second run) radioactivity of ¹⁴C-halosulfuron. Acetone was added as the primary solvent to facilitate the stability of ¹⁴C-halosulfuron (McElroy et al. 2004). From this point, plants were sub-irrigated to prevent washing of the herbicide from the leaf surface.
Plants were harvested at 6, 12, 24, 48 and 98 h after treatment (HAT). Soil from plant roots was hand-removed by gentle shaking and plants were divided into treated leaf, shoot and root. In grafted plants shoots were divided into scion-shoot (plant shoot above graft union) and rootstock-shoot (plant shoot below graft union). Plants (replications) were also spotted with a radiolabeled herbicide solution and harvested after 10 s to test the efficacy of the leaf wash technique. Treated leaves were rinsed with 20 ml of a 1:1 v/v mixture of methanol-deionized water and 0.25% v/v nonionic surfactant to remove unabsorbed herbicide. A 1-ml aliquot of the leaf rinsate was added to 15 ml of scintillation cocktail (ScintiVerse® SX1 8-4 Universal Liquid Scintillation Cocktail, Fisher Scientific, Fair Lawn, NJ) and radioactivity was quantified by liquid scintillation spectrometry (LSS) (Packard TRI-CARB 2100TR Liquid Scintillation Spectrometer, Packard Instrument Company, Downers Grove, IL). All plant parts were then placed in paper bags and dried at 50 C for 4 d, combusted for 2 min in a biological sample oxidizer (Model OX-500, R.J. Harvey Instrument Corp., Hillsdale, NJ) and radioactivity trapped as \(^{14}\text{CO}_2\) was quantified by LSS.

The experiment was conducted using a factorial arrangement of transplant type (Amelia, Santana, A-Maxifort, and S-Maxifort) and harvest interval (6, 12, 24, 48 and 98 HAT) in a randomized complete block design with four single-plant replicates per treatment. Percent absorption was calculated from the fraction of total applied \(^{14}\text{C}\)-halosulfuron not recovered in the leaf wash. The percent translocation in each plant part was calculated by dividing the radioactivity in that plant part by the total amount applied. Data from both experiments were analyzed with PROC MIXED (SAS 9.2 Institute Inc., Cary, NC).
Translocation data for scion-shoot, rootstock-shoot and root were subjected to arcsine square-root transformation. However, to facilitate the interpretation of results, back-transformed means are presented. Data from both runs were combined because run by transplant type by harvest interval interaction was not significant. Harvest interval and transplant plant type were considered fixed effects in the model. Replication, experimental run, and their interaction were considered random effects. Where appropriate, treatment means were separated using Fisher’s Protected LSD test at $P \leq 0.05$. Nonlinear regression analysis was performed on absorption and leaf wash means data using SigmaPlot 10 (Systat Software Inc., San Jose, CA) to report the effect of harvest intervals.

**Results and Discussion**

Total absorption in a single plant was cumulative $^{14}$C-label in treated leaf, shoot (scion-shoot and rootstock-shoot in grafted plants), and root. No significant difference was observed between different transplant types for absorption of $^{14}$C-label, therefore data were pooled over transplant type. Plant absorption of $^{14}$C-label increased over time and followed an exponential rise pattern, while the amount of $^{14}$C-label in leaf wash decreased exponentially over time (Figure 5.1). Initial absorption was rapid and reached 42% by 24 HAT and then gradually increased to 60 and 70% at 48 and 96 HAT, respectively. Buker (2002) reported similar results when studying absorption of $^{14}$C-label in tomato and pepper, showing 40% and 60% absorption at 24 and 72 HAT, respectively.

The interaction between transplant type and harvest interval was not significant, but the effect of transplant type on percent translocation (measured as percent of applied) was
significant in rootstock-shoot and root, and harvest interval was significant in all plant parts but root (Table 5.1). Most of the $^{14}$C-label applied to the leaf stayed in the leaf and only a limited amount (< 4%) was translocated to other plant parts combined. In rootstock-shoot, grafted eggplant S-Maxifort had higher translocation than grafted tomato A-Maxifort.

Similarly, in root, eggplant had higher translocation than tomato regardless of grafting. The contrast between tomato and eggplant (averaged over grafting) showed that the eggplant had higher translocation in shoot as well (Table 5.1). The percent translocation increased with time in shoot (from 0.33 to 2.66%) and rootstock-shoot (0.06 to 0.54%) (Table 5.1).

Although differences in translocation occurred between transplant types, and harvest intervals, the actual amount translocated to plant parts other than treated leaf was < 2% in most cases, which made these differences less important (Table 5.1).

Our experiment confirms the results of Buker (2002) in pepper (*Capsicum annuum* L.) and tomato, and Isaacs et al. (2006) in common lambsquarters (*Chenopodium album* L.), that the translocation of foliar applied $^{14}$C-halosulfuron to other plant parts is very low. Less than 0.8% of absorbed $^{14}$C-halosulfuron translocated above and below the treated leaf and to the root in both tomato and pepper (Buker 2002). Isaacs et al. (2006) reported that less than 4% translocation of $^{14}$C-halosulfuron combinations with 2,4-D out of treated leaf in common lambsquarters at 72 HAT. Troxler et al. (2007) reported that less than 4% of applied $^{14}$C-trifloxysulfuron moved out of the treated leaves of tobacco (*Nicotiana tabacum* L.). Askew and Wilcut (2002) reported that majority of foliar-applied $^{14}$C-trifloxysulfuron remained in the treated leaves of peanut (*Arachis hypogaea* L.), cotton (*Gossypium* hirsutum L.), and
sicklepod \[Senna \text{obtusifolia} \text{ (L.) Irwin and Barnaby}\], and < 2% translocated to other plant parts. In contrast, McElroy (2004) reported that \(^{14}\text{C}\)-halosulfuron and \(^{14}\text{C}\)-trifloxysulfuron were able to translocate (43 and 29%, respectively) from the treated leaf to other plant parts of \text{Kyllinga}\text{spp.}.

Since the contrast statements showed that there was no difference in \(^{14}\text{C}\)-herbicide translocation in grafted and non-grafted plants regardless of either tomato or eggplant. This indicates that grafting does not inhibit movement of halosulfuron to different parts of the plant. Similar to these results, Adkins (2011) reported no difference in glyphosate and atrazine movement in grafted and non-grafted watermelon plants. The similar absorption and translocation could also explain the similar herbicide tolerance level of grafted and non-grafted tomato and eggplant in field and greenhouse experiments as reported Chapter 2 and 3.

In conclusion, grafting does not appear to impact absorption and translocation of foliar applied halosulfuron in grafted (interspecific and intraspecific) plants. Future research should investigate the impact of grafting on absorption and translocation of soil applied herbicides using different type of rootstocks.

Acknowledgments

The authors thank Dr. Khalied Ahmed, Shawn Beam, and Samuel McGowen for their assistance with conducting this research, and Drs. Rob Richardson and Travis Gannon for providing space and equipments in their laboratory for conducting the experiment. Authors
thank the USDA-NIFA-2009-2376 and USDA-SCRI-2011-51181-30963 for providing funding. Furthermore, authors thank Dr. Cavell Brownie for her assistance with data analysis.
Literature Cited


Table 5.1. The percentage of $^{14}$C-label translocated in different plant parts\textsuperscript{xy}.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Treatment</th>
<th>Treated leaf</th>
<th>Scion-shoot</th>
<th>Rootstock-shoot</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transplant type (T)\textsuperscript{z}</td>
<td>Amelia</td>
<td>41 a</td>
<td>0.97 a</td>
<td>-</td>
<td>0.29 b</td>
</tr>
<tr>
<td></td>
<td>Santana</td>
<td>40 a</td>
<td>1.51 a</td>
<td>-</td>
<td>0.56 a</td>
</tr>
<tr>
<td></td>
<td>A-Maxifort</td>
<td>38 a</td>
<td>0.88 a</td>
<td>0.06 b</td>
<td>0.26 b</td>
</tr>
<tr>
<td></td>
<td>S-Maxifort</td>
<td>40 a</td>
<td>1.45 a</td>
<td>0.61 a</td>
<td>0.49 a</td>
</tr>
<tr>
<td>Contrast\textsuperscript{c}</td>
<td>Grafted vs. Non-grafted Tomato vs. Eggplant</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NS</td>
<td>*</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>Harvest interval (H)</td>
<td>HAT\textsuperscript{z}</td>
<td>6</td>
<td>13 c</td>
<td>0.33d</td>
<td>0.06 b</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>25 bc</td>
<td>0.61 cd</td>
<td>0.09 b</td>
<td>0.27 a</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>37 b</td>
<td>1.43 bc</td>
<td>0.38 a</td>
<td>0.43 a</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>57 a</td>
<td>1.58 ab</td>
<td>0.44 a</td>
<td>0.48 a</td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>66 a</td>
<td>2.66 a</td>
<td>0.54 a</td>
<td>0.56 a</td>
</tr>
<tr>
<td></td>
<td>T × H</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>*</td>
</tr>
</tbody>
</table>

\textsuperscript{z} Pooled analysis over two experimental runs.

\textsuperscript{y} Means within column for main effects (transplant type or harvest interval) with the same letter are not significantly different according to Fisher’s Protected LSD (P ≤ 0.05).

\textsuperscript{z} Abbreviations: A-Maxifort and S-Maxifort, Amelia and Santana scion grafted onto Maxifort rootstock, respectively; HAT, h after treatment; NS, not significant.
Figure 5.1. Percentage of $^{14}$C-label absorbed in plants and remaining in the leaf wash during 96 h period. Means are average from two runs across all transplant type.

$$Y_a = 72(1 - \exp(-0.03X)) \quad R^2 = 0.99$$  
$$Y_w = 26 + 72\exp(-0.03X) \quad R^2 = 0.99$$