EFFECTS OF SIMULATED 2,4-D AND DICAMBA DRIFT ON FIELD-GROWN TOMATO PLANTS

A Thesis

by

MORGAN ELIZABETH HERMES

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Joshua A. McGinty
Co-Chair of Committee,	Scott A. Nolte
Committee Members,	Paul A. Baumann
	Joseph G. Masabni
	Gaylon D. Morgan
Head of Department,	David D. Baltensperger

August 2020

Major Subject: Agronomy

ABSTRACT

This study was conducted to examine the effects of simulated herbicide drift on field-grown tomato production. Field studies were conducted at College Station, Tx during the 2013 and 2014 growing season to examine the effects of 2,4-D, dicamba, and glyphosate drift on field-grown tomato plants. Herbicide resistant weeds are proliferating in crop cultures worldwide and new transgenic seed technologies have been developed that will aid in control of these pernicious weeds. Recently introduced low volatility formulations of dicamba and 2,4-D herbicides will reduce vapor drift. However, physical spray drift is a challenge many producers will encounter now that these new transgenic seed technologies have become commercially available.

The 2013 studies included 2,4-D at rates of 53, 27, 13 and 6.7 g ae ha^{-1}, dicamba at rates of 28, 14, 7.0 and 3.5 g ae ha^{-1} and glyphosate at rates of 43, 22, 11 and 5.4 g ae ha^{-1}. The 2014 studies included 2,4-D at rates of 106, 53, 27 and 13 g ae ha^{-1} and dicamba at rates of 56, 28, 14 and 7 g ae ha-1. Visual injury ratings were made based on considering the percent of plant biomass exhibiting epinasty. Visual plant injury confirmed that tomatoes were more susceptible to injury at earlier growth stages. As herbicide rates increased, the level of visual injury increased and plant biomass decreased for both application timings. Yield response was inconsistently impacted by rate and product.

DEDICATION

Dedicated to the memory of

Donald Vrana and

Eli Janak.

ACKNOWLEDGEMENTS

I would like to thank Dr. Baumann for making the opportunity to pursue a graduate degree possible. Graduate School has opened the door for many opportunities and has filled my life with abundant blessings.

I would like to thank Dr. McGinty for his help in the fields, with statistical analysis, thesis editing, and bringing this project to fruition. I would like to thank Dr. Nolte for his guidance, teaching and clarification. Additionally, I would like to thank committee members Dr. Masabni and Dr. Morgan for their continuous encouragement and support from the fields to completion.

Specifically, I want to thank Matt Matocha for his help and encouragement during this project, Johnathan Hernandez for helping me harvest all the tomatoes, the entire Janak family for their continuous encouragement, and my brother Collin Metting who helped me water, harvest and dry tomato plants. I would also like to thank my Bestie, Friends, Family, Auntie Mary, Mother, Father, and Granny for their continuous love and support.

Most importantly, I would like to thank my husband Richard and our amazing daughter Wiona. Richard has been very patient with me, always encouraging, and providing me with much needed emotional support, physical labor, and unconditional love over the years. Our family, including our sweet Labrador Cotton, has given me the strength to see this project through completion.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Paul Baumann, Dr. Joshua McGinty, advisor, Dr. Scott Nolte co-advisor and of the Department of Soil and Crop Sciences, Dr. Joseph Masabni of the Department of Horticultural Sciences and Dr. Gaylon Morgan with Cotton Incorporated.

Funding Source

Graduate study was supported by Texas A&M University Soil and Crop Science Weed Science Extension. This work was also made possible in part by a general chemical company funding. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Soil and Crop Science Department.

NOMENCLATURE

DAT	days after treatment
DMA	dimethylamine
2,4-D	2,4-dichlorophenoxyacetic acid
GR	glyphosate-resistant
IAA	indole-3-acetic acid
kPa	kilopascal
kph	kilometer per hour
L ha^{-1}	liter per hectare
PRE	pre-emergent
POST	post-emergent
WAT	weeks after transplanting

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Fresh and processed tomato account for more than $2 billion in annual farm cash receipts (USDA 2016). Fresh market tomatoes are one of the most popular fresh market vegetables consumed in the United States; however, three-fourths of the tomatoes consumed by Americans are in the form of processed tomatoes. Depending on the time of year, fresh and processed tomatoes will vary in profit potential. Many factors can contribute to this cost variation, especially greenhouse imports that are plentiful during winter months (USDA 2016). American field-grown tomatoes are now facing the consequential threats of some new herbicide technologies.

The recent emergence of weeds resistant to herbicides such as glyphosate application year after year for weed control in fields of herbicide-resistant crops has prompted serious concerns regarding the long-term availability of the facile and economically important weed control provided by current herbicide-resistant crop plants (Behrens et. al. 2007; Heap 2020).

The increased prevalence of herbicide resistant weeds to glyphosate and ALS herbicides has prompted seed and chemical manufacturers to pair older herbicides with multiple stacked transgenic herbicide resistant traits for large scale agronomic crops. Corteva Agriscience, formerly Dow AgroSciences, offers a low volatility formulation of 2,4-D with their Enlist™ weed control system. This weed control system consists of the use of Enlist One® and Enlist Duo® herbicides containing 2,4-D choline with Colex-D®

technology in cotton, corn, and soybean varieties possessing the Enlist (2,4-D tolerant) trait (Corteva Agriscience/Dow AgroSciences, Indianapolis, IN) (Anonymous 2017a, Anonymous 2017b). BASF, Bayer CropScience, Corteva, and Syngenta now offer low volatility formulations of dicamba (Engenia, Xtendimax, FeXapan, and Tavium, respectively) for use in dicamba resistant crops such as Xtend soybean and XtendFlex cotton, which is tolerant to glyphosate and glufosinate as well. Roundup PowerMAX®, for example, can be used as part of the Roundup Ready Xtend Crop System®.

These auxin tolerant herbicide technologies became commercially available in 2015 and are advertised as reducing physical spray drift and volatility. However, the increased use of herbicides, such as 2,4-D and dicamba, has the potential to increase risks of off-target movement onto high-value crops, such as tomato. The objectives of this study were to (1) Simulate 2,4-D and dicamba drift concentrations on field grown tomatoes and (2) Assess the impact of sub-lethal doses of these herbicides on crop growth and yield.

CHAPTER II

LITERATURE REVIEW

Glyphosate

Glyphosate [N-(phosphonomethyl) glycine] is a non-selective, postemergence herbicide (POST) herbicide. This has made glyphosate a popular choice among producers (Shaner 2014). Kniss (2017) evaluated 159 unique herbicides of these herbicides, glyphosate had a low acute toxicity for applicators and a ninety percent lower chronic toxicity. Released to market as an herbicide in the late 1970s, this chemical provided outstanding control of perennial broadleaf weeds and perennial grasses (Ross and Lembi 1999).

Glyphosate is classified as an inhibitor of aromatic amino acid biosynthesis that antagonizes the chloroplast enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) stopping the conversion of shikimate to the amino acids phenylalanine, tyrosine and tryptophan (Ross and Lembi 1999). In a study by Amrehein et al. (1980), a highly significant correlation was found between the reduction of anthocyanin formation and accumulation of shikimate in buckwheat. As concentrations of glyphosate increase, shikimate formation builds up and is then blocked; then phenylalanine is consequently reduced. Glyphosate symptoms develop slowly over one to three weeks depending upon the plant species, herbicide dose, and temperature. Symptoms include gradual yellowing starting with new tissue and continuing throughout other tissues in the plant (Ross and Lembi 1999).

In the United States, 1996 marked the year the glyphosate-resistance gene was introduced to market in soybeans, the following year the same gene was introduced in cotton, then in 1998 the gene was introduced in corn (Bradshaw et al. 1997; Ellis and Griffin 2002; Mendelson 1998). Glyphosate is the predominant herbicide used for weed control on a vast majority of corn and soybeans grown across the U.S. (USDA 2020). In the surrounding processing tomato production fields, complaints have occurred due to glyphosate drift causing injury (Kruger et al. 2012). In the same study, Kruger et al. (2012) also reported that flower abortion at the early bloom stage was more severe due to glyphosate injury.

Currently, products such as Enlist Duo® (Corteva Agriscience/Dow Agroscience, Indianapolis, IN) combine glyphosate and 2,4-D choline to fight herbicide-resistant weeds (Anonymous 2017b). Herbicide resistant weeds, such as waterhemp and Palmer amaranth, are found predominantly in row crops and has shown a high amount of EPSP synthase inhibitor resistance across the United States (Heap 2020).

2,4-D

The herbicide 2,4-D (2,4-dichlorophenoxy acetic acid) can act as a plant growth regulator, inducing rooting and blossom set when applied at low rates (Senseman 2007; Shaner 2014). In 1941, 2,4-D was discovered, but early research remained confidential until the end of WWII. Effective at low rates and affordable to produce, 2,4-D proved to be a highly valuable herbicide (Ross and Lembi 1999).

2,4-D is similar in structure to indole acetic acid, a plant growth hormone. This herbicide comes in three forms, an ester that readily dissolves in an organic solvent, an amine salt that is more water soluble and an acid that is the parent compound (Shaner 2014). In plants affected by 2,4-D, epinasty is the first visual symptom after the herbicide is applied and is a downward twisting and curvature of the stems and leaves. Later, callus tissue develops, shoots and roots can become distorted, roots can appear from stem tissue and the phloem becomes broken or plugged, preventing movement from the leaves to the stems (Ross and Lembi 1999).

Dicots are more sensitive to auxin-type growth regulators than monocot plants. Occasionally monocots such as corn still undergo meristematic activity and can show symptoms and develop abnormal brace roots. (Ross and Lembi 1999).

The proliferation of herbicide resistant weeds has encouraged the development of new transgenic herbicide tolerance technologies that will aid control programs for these pernicious weeds. Also, programs employing the use of these tolerant traits alone or in combination with other herbicide resistance traits will allow rotation to herbicides that are effective for controlling resistant weeds (Behrens et al. 2007). Low volatility 2,4-D such as Enlist One^{TM} (Corteva Agriscience/Dow Agroscience, Indianapolis, IN) can now be used for broadleaf weed control over the top of corn, cotton, and soybeans (Anonymous 2017a).

Dicamba

Dicamba (3,6-dichloro-2-methoxybenzoic acid) is an auxin-type herbicide that mimics the effects of excess quantities of the natural plant hormone indole-3-acetic acid (IAA) when applied to dicotyledonous plants (Behrens et. al. 2007). The biosynthesis of IAA and cytokinins in higher plants is still poorly understood, and only in the case of ethylene has a receptor been identified (Kende and Zeevaart 1997). However, dicamba has been used for more than forty years to efficiently control most broadleaf weeds (Behrens et. al. 2007).

The Roundup Ready® Xtend Crop system is available for soybean and cotton production (Anonymous 2018b). Engenia® (BASF Corporation, Research Triangle Park, NC) is approved for weed control in dicamba-tolerant cotton, soybean, and asparagus. It can be used in conservation reserve programs for corn, cotton, fallow cropland, farmstead turf (noncropland) and sod farms, grass grown for seed, pasture, hay, rangeland, farmstead (noncropland), proso millet, small grain, sorghum, soybean, and sugarcane (Anonymous 2018a). Low volatility dicamba Xtendimax® with Vapor Grip Technology (Bayer/Monsanto Company, St. Louis, MO) is available for use in certain cropping systems, including dicamba-resistant cotton and soybean. Tavium® Plus VaporGrip® Technology (Syngenta, Greensboro, NC) is available for use in Roundup Ready 2 Xtend® Soybeans and Bollgard II® XtendFlex® Cotton. DuPont™ FeXapan® Plus VaporGrip® Technology (Anonymous 2018c) is available for use in Roundup Ready 2 Xtend® soybean. Tough to control or glyphosate resistant broadleaf weeds and the availability of new dicamba resistant crops have led to the widespread use of dicamba for POST weed control (USDA 2020).

Spray particle drift has been attributed to soybean injury even while using low volatility commercial dimethylamine (DMA) salt formulations of dicamba. However, when field conditions are right, vapor drift can still occur (Behrens 1979; Mueller and Steckel 2019).

Herbicide Drift

Spray drift from auxin herbicides can cause major damage to sensitive vegetable and ornamental crops. Many plant species provide a natural bioassay when it comes to off-target movement of herbicides. Results of off-target herbicide drift are highly visible and advertise to the community if a mistake was made during an application (Ross and Lembi 1999). Off-target movement can take place via volatilization and vapor drift, spray drift, particle movement in the air or through the soil and through groundwater (Ross and Lembi 1999).

Environmental conditions such as wind speed, relative humidity, and temperature; before, during, and following herbicide exposure play a key role determining crop sensitivity to herbicide drift (Egan et al. 2014). New resistant cultivars enable these compounds to be applied in tolerant crops at additional times during the growing season (including more POST applications), and over greatly expanded acreages. This has led to increased problems with off-target movement onto susceptible crops (Bradley 2017 and 2018). Over the last twenty-five years, herbicide use intensity increased in cotton, maize, rice, and wheat. Herbicide increases were more rapid in non-GE (genetically engineered) crops. Although GE crops have been previously implicated for increasing herbicide use (Kniss 2017).

Tomato

Tomato is a member of the Solanaceae family and is native to western South America. The wild tomato originally grew along the coast up to the Andes mountains, throughout Peru to Northern Chile and in the Galapagos Islands (Bergougnoux 2014). Tomatoes were originally imported from the Andean region to Europe in the 16th century and spread throughout the world and represent the most economically important vegetable crop worldwide. Fresh market tomatoes are highly valuable, many are also used in the processing industry in soup, paste, concentrate, juice, and ketchup. The tomato provides an incredible source of important nutrients such as lycopene, β-carotene and vitamin C, which all have positive impacts on human health. Its production and consumption have increased with population growth (Bergougnoux 2014). Tomatoes are not just a highly desirable garden crop. In 2011, almost 160 million tons of tomatoes were produced worldwide, making the tomato the seventh most important crop species (Bergougnoux 2014).

Commercial crop production has had issues with tolerance to glyphosate due to its use to control a wide range of weed species. Roundup has been so effective it has been widely used (Goldy 2016). Glyphosate resistance has forced producers to change the chemistry used in their operation. Herbicide drift research has been conducted on a wide variety of field crops and their response. The metabolism rate of an herbicide is dependent upon the plants ability to detoxify the herbicide and the type of herbicide used. Toxicity could be an issue in the event of dicamba or 2,4-D entering a plant and the plant not being able to break it down quickly (Romanowski 1974). Producers should be cautious when applying herbicides and be mindful of where herbicides are used in relation to nearby sensitive plant species. Tomatoes are very delicate and will react to even small amounts of herbicides (Goldy 2016).

A 2-year study by Jordan and Romanowski (1974) found that 2,4-D and dicamba applied to tomatoes at a later growth stage, while tomato fruit was at an immature green stage, did not significantly reduce yield. However, a study in 1971 indicated that dicamba reduced yield at the 0.02 kg/ha rate. Different cultivars were used in the 1971 and 1972 studies and may have contributed to the dicamba susceptibility. Early application of 2,4-D and dicamba have shown to have a detrimental effect on yield at early bloom. In 1972, dicamba caused an 84% decrease in yield at a rate of 0.1 kg/ha. The plants outgrew the herbicide effects but the late blooms did not set mature fruit before the end of the growing season. Internal deformation was observed for 60 percent of the dicamba treated tomato fruits and 40 percent for the 2,4-D treated tomato fruits at the second timing application, an immature green stage of fruit on the plants. Internal deformation was not observed at the first timing application, while plants were at full bloom. Injury to the tomato plants from 2,4-D and dicamba is difficult to distinguish between (Jordan and Romanowski 1974). Robbins and Taylor (1957) found that plants treated at full bloom had reduced yields, while plants treated at first bloom had delays but recovered when treated with 2,4-D at 0.002 kg/ha. Hemphill and Montgomery (1981) found distorted fruit shape and blotchy ripening when 2,4-D was applied at 0.0021 kg/ha and showed epinasty at the growing points. This was noticeable for 10 to 14 days after application. Higher rates caused severe epinasty, stunted growth, vein clearing and stem lesions. However, an increase in tomato yield was found at very low concentrations of 2,4-D. At 6.6 g/ha, yield was significantly increased but significantly decreased at 66 g/ha. This pattern was observed at each of the harvests at 71, 99, and 123 days after spraying. Fruit size contributed to an increase in yield promoted by early ripening with both rates of 2,4-D. Each year's study found a decrease in yield at higher rates and an increase at lower rates. At low rates of 2,4-D, larger fruit size was observed. At 6.6 g/ha, fruit number was not affected (Hemphill and Montgomery 1981).

CHAPTER III

MATERIAL AND METHODS

2013 Studies

Three field studies were conducted during the 2013 growing season to investigate the effects of herbicides commonly used in cotton and grain production on field-grown tomato. These studies included four rates of 2,4-D, dicamba, and glyphosate (Table 1) applied at two growth stage timings, in addition to untreated control plots. Each herbicide being evaluated was a separate study. Treatments were arranged in a randomized complete block design with four replications. The 2013 studies were located at the Texas A&M Research Farm near College Station, Texas. A “Roma” tomato variety was selected and grown on a Weswood silty clay loam. Plots consisted of two rows with 76.2 cm in width by 182.9 cm in length. Roma tomatoes were transplanted with six plants per plot, three plants on the right row and three plants on the left row of the plot. All data were collected season-long from three flagged plants, most representative of the plot as a whole. All studies were irrigated through drip irrigation lines placed in the plant rows. Water soluble 18-18-21 liquid fertilizer (The Scotts Company, Marysville, OH) was applied throughout the study. DuPont ™ Coragen® (chlorantraniliprole) insecticide was used to control insects throughout the study (DuPont Tamaki, Auckland, New Zealand). All herbicide treatments were made using a CO2 backpack sprayer. A study conducted by Banks and Schroder (2002) confirmed the need to use carrier volumes that are proportional to the herbicide dosage, thus maintaining constant herbicide concentration in the carrier, when conducting simulated herbicide drift research. Failure to do so could underestimate the potential for injury. Herbicide treatments were applied such that carrier volumes were proportional to the herbicide rate (Table 1). Treatments included 2,4-D (455 g ae L^{-1}) applied at 53, 27, 13, and 6.7 g ae ha^{-1}. Dicamba (350 g ae L^{-1}) was applied at 28, 14, 7.0, and 3.5 g ae ha^{-1}. Glyphosate (540 g ae L^{-1}) was applied at rates of 34, 17, 8, and 4.2 g ae/ha^{-1}. To simulate spray drift, four TeeJet (TeeJet Technologies) XR nozzle sizes were selected and calibrated at the pressures and speeds listed in Table 1 to deliver the selected carrier volumes for each treatment. The first application was made three weeks after transplanting, prior to the onset of fruit. The second application was made six weeks after transplanting at the beginning of fruiting.

Table 1. Herbicides, rates, carrier volumes, nozzles, pressure and speed used to simulate drift in 2013.

Herbicide	Rate g ae ha^{-1}	Carrier Volume L ha^{-1}	Nozzle	Pressure kPa	Speed kph
2,4-D	53	561	XR8005	400	3.2
2,4-D	27	281	XR8004	296	4.8
2,4-D	13	140	XR8002	200	4.8
2,4-D	6.7	70	XR8001	159	4.8
Dicamba	28	561	XR8005	400	3.2
Dicamba	14	281	XR8004	296	4.8
Dicamba	7.0	140	XR8002	200	4.8
Dicamba	3.5	70	XR8001	159	4.8
Glyphosate	34	561	XR8005	400	3.2
Glyphosate	17	281	XR8004	296	4.8
Glyphosate	8.4	140	XR8002	200	4.8
Glyphosate	4.2	70	XR8001	159	4.8
Nontreated control	-	-	-	-	-

Table 2. 2013 Environmental conditions at herbicide application

Application	Timing A	Timing B
Date	6/03/13	6/21/13
Time	3:30 p.m.	10:30 a.m.
Air Temperature (°C)	31.6	31.5
Soil Temperature at 12 cm depth (°C)	31.1	26.6
Relative Humidity (%)	37	56
Cloud Cover	0	40
Dew Presence (Yes/No)	No	No
Soil Surface	Dry	Moist
Soil Moisture	Excellent	Excellent

Injury ratings were made based upon the percent of the above-ground biomass exhibiting abnormalities such as bending, twisting, leaf cupping and/or drooping of stems and leaf petioles. Each injury rating was based on a 0 to 100% scale with 100% representing total death. The rating system is a standard basis when comparison is made to an untreated check (Truelove 1977). The field studies were evaluated at 3, 5, 7 and 14 days after treatment. Plants from which injury data were gathered were individually hand harvested and tomato fruits weighed. After the completion of the study, above ground plant biomass was collected, dried until a stable dry weight was achieved and weighed. Plant fresh weight, size, and dry weights were averaged for each plot from the three flagged plants. To evaluate the complete effect of the herbicide treatment, yield must be collected to represent the economic response of the crop to the treatment (Truelove 1977). Environmental conditions at application are shown in Table 2.

All analyses were conducted using JMP 14 (SAS Institute 2014). Data were subjected to analysis of variance (ANOVA) and means were separated using Fisher's Least Significant Difference (LSD).

2014 Studies

Four field studies were conducted in 2014 growing season. These studies included four rates of 2,4-D and dicamba (Table 3) applied at two timings with untreated controls in two separate studies at two locations; the Texas A&M Research Farm near College Station, Texas on a Weswood silty clay loam and the Texas A&M Horticulture Farm near College Station, Texas on a Robco loamy fine sand. A "Celebrity" tomato variety was selected and grown at both locations. Treatments were arranged in a randomized complete block design with four replications. Plot sizes were 61 cm in width by 4.6 m in length. Celebrity tomato was transplanted in rows with six plants per plot, and data were collected from the four center plants. All studies were received supplemental drip irrigation augmented with a Dosatron fertilizer injector to meet the adequate moisture and fertilizer needs. Each row was covered with a black plastic mulch layer, which helped to keep the beds moist in addition to reducing weed germination. DuPont ™ Coragen® insecticide was used to control insects throughout the study (DuPont Tamaki, Auckland, New Zealand). All herbicide treatments were applied using a CO_2 backpack sprayer. As an extra precaution, a plot shield was constructed from PVC pipe and frost barrier to prevent potential spray drift from plot to plot within the study. Herbicide treatments were applied such that carrier volumes were proportional to the herbicide rate (Table 3). Treatments included 2,4-D Amine (455 g ae L^{-1}) applied at 106, 53, 27, and 13 ae ha-1. Dicamba (350 g L^{-1}) was applied at 56, 28, 14, and 7.0 g ae ha^{-1}. To simulate spray drift, four TeeJet (TeeJet Technologies) XR nozzle sizes were selected and calibrated at the pressures and speeds listed in Table 3 to deliver the selected carrier volumes for each treatment. To maintain accurate speed, applications speeds were calibrated at known steps per minute and a metronome was utilized to maintain a consistent walking pace. Similar to the 2013 studies, the first application was made three weeks after transplanting, prior to the onset of fruit. The second application was made six weeks after transplanting at the beginning of fruiting. (Timings A and B, respectively). Environmental conditions at application are shown in Table 4.

Table 3. Herbicides, rates, carrier volumes, nozzles, pressure and speed used to simulate drift in 2014.

Herbicide	Rate g ae ha^{-1}	Carrier Volume L ha^{-1}	Nozzle	Pressure kPa	Speed kph
2,4-D	106	1122	XR8006	414	2.2
2,4-D	53	561	XR8003	414	2.2
2,4-D	27	281	XR8004	262	4.8
2,4-D	13	140	XR8002	262	4.8
Dicamba	56	1122	XR8006	414	2.2
Dicamba	28	561	XR8003	414	2.2
Dicamba	14	281	XR8004	262	4.8
Dicamba	7	140	XR8002	262	4.8
Nontreated control	-	-	-	-	-

Table 4. 2014 Environmental conditions at herbicide application

------------------TAMU HORTICULTURE FARM------------------		
Application	**Timing A**	**Timing B**
Date	5/2/14	5/23/14
Time	6:50 AM	8:00 AM
Air Temperature (°C)	10.5	31
Soil Temperature at 12 cm depth (°C)	17.2	26.6
Relative Humidity (%)	77.0	83.0
Cloud Cover	0	100
Dew Presence (Yes/No)	No	Yes
Soil Surface	Dry	Moist
Soil Moisture	Fair	Excellent

------------------TAMU RESEARCH FARM------------------		
Application	**Timing A**	**Timing B**
Date	5/02/14	5/23/14
Time	10:00	6:45AM
Air Temperature (°C)	22.2	30.6
Soil Temperature at 12 cm depth (°C)	18.8	26.6
Relative Humidity (%)	27	97.1
Cloud Cover	15	100
Dew Presence (Yes/No)	No	Yes
Soil Surface	Dry	Moist
Soil Moisture	Fair	Excellent

Injury ratings were based upon the percent of the above-ground biomass exhibiting abnormalities such as bending, twisting, leaf cupping and/or drooping of stems and leaf petioles. Each injury rating was based on a 0 to 100% scale with 100% equaling total death. Again, the rating system is a standard basis when comparison is made with an untreated check (Truelove 1977). Each field study was evaluated at 3, 5, 7 and 14 days after treatment. Plants from which injury data were gathered were individually hand harvested and tomatoes were sized and weighed. After the completion of the study, above ground plant biomass was collected, dried until a stable dry weight was achieved and weighed.

While this study was conducted drift from the herbicide Status® (BASF Corporation, Research Triangle Park, NC) took place from a neighboring corn field.

All analyses were conducted using JMP 14 (SAS Institute 2014). Data was subjected to analysis of variance (ANOVA) and means were separated using Fisher's LSD.

CHAPTER IV

RESULTS

Roma Tomato

2013 2,4-D

A significant rate by timing interaction was detected for injury at 3, 5, and 7 DAT and for plant biomass (Table 5), thus those data were not analyzed separately for the main effects of rate or timing. Rate had an effect on 14 DAT injury and yield, while there was a significant main effect of timing on 14 DAT injury.

Table 5. Analysis of variance for main effects and interactions on injury, yield and biomass 2,4-D at Texas A&M Research Farm, 2013.

Source	Injury					
	3DAT	5DAT	7 DAT	14 DAT	Yield	Plant Biomass
Rate	***	***	***	***	*	**
Timing	NS	NS	**	**	NS	*
Rate X Timing	***	***	***	NS	NS	*

*, **, *** signify p< 0.05, 0.01, and 0.001, respectively.

Injury caused by 2,4-D in 2013 ranged from 7.5 to 77.5% at 3 DAT, 7.5 to 80% at 5 DAT and 12.5 to 86.3% at 7 DAT for the first application timing (Table 6). Injury from the second application timing ranged from 25 to 63.8% at 3 DAT, 25 to 63.8% at 5 DAT and 25 to 63.8% at 7 DAT. Seven days after treatment, epinasty was greatest with 53 g ae ha^{-1} and 27 g ae ha^{-1} applied at timing A (86.3 and 76.3%, respectively). The two highest rates 53 g ae ha^{-1} and 27 g ae ha^{-1} resulted in significantly greater injury than that observed from the two lower rates, for both timings. Plant biomass ranged from 516 to

945 kg ha^{-1} for the first application timing. At the second application timing, biomass ranged from 1,571 to 1,146 kg ha^{-1}.

Table 6. Injury, yield, and biomass of tomato treated with 2,4-D as influenced by rate and application time at Texas A&M Research Farm in 2013.

		Injury					
Rate	Timing	3 DAT*	5 DAT	7 DAT	14 DAT	Yield	Plant Biomass
g ha^{-1}		%				kg ha^{-1}	kg ha^{-1}
53	A	77.5 a	80 a	86.3 a	72.5	242	708 def
27	A	68.8 ab	71.3 ab	76.3 b	58.8	604	580 ef
13	A	12.5 e	16.3 ef	23.8 e	30	811	516 f
6.7	A	7.5 ef	7.5 fg	12.5 f	22.5	866	945 cdef
0	A	0 f	0 g	0 g	0	1,766	1910 a
53	B	63.8 b	63.8 b	63.8 c	60	787	1134 bcd
27	B	46.3 c	46.3 c	46.3 d	41.3	823	1146 bcd
13	B	30 d	30 d	30 e	25	1,313	1094 bcde
6.7	B	25 d	25 de	25 e	22.5	1,772	1571 ab
0	B	0 f	0 g	0 g	0	1,556	1442 abc

*Means followed by the same letter within a column are not significantly ($p \leq 0.05$) different. ^{A} 3 weeks after transplanting ^{B} 6 weeks after transplanting

Effects of rate on injury ranged from 22.5 to 66.3% at 14 DAT. Injury was greatest with the 53 g ae ha^{-1} rate. Rates of 13 g ae ha^{-1} or less did not significantly reduce yield relative to the nontreated control. Effects of rate on yield caused by 2,4-D in 2013 ranged from 515 to 1,661 kg ha^{-1}. Effects of timing on injury ranged from 29.8 to 36.8% at 14 DAT. Timing A at 53 g ae ha^{-1} showed the greatest injury 7 DAT. Timing A at 6.7 g ae ha^{-1} showed the lowest injury 3 DAT. Injury was greater following Timing A (36.8%) than Timing B (29.8%). See Table 7.

Table 7. Effect of 2,4-D simulated drift rates on 14 DAT tomato injury and yield at Texas A&M Research Farm, 2013.

Main Effect	Injury 14 DAT*	Yield kg ha^{-1}
Rate		
53	66.3 a	515 c
27	50 b	713 bc
13	27.5 c	1,062 abc
6.7	22.5 c	1,319 ab
0	0 d	1,661 a
Timing		
A	36.8 a	
B	29.8 b	

*Means followed by the same letter within a column are not significantly different ($p \leq 0.05$). ^{A}3 weeks after transplanting ^{B}6 weeks after transplanting

2013 Dicamba

A significant rate by timing interaction was detected for injury at 3, 5, 7 and 14 DAT (Table 8), thus these data were not analyzed for the main effects of rate or timing separately. Rate had an effect on biomass, while timing had an effect on yield and tomato biomass.

Table 8. Analysis of variance for main effects and interactions from dicamba on injury, yield and biomass at Texas A&M Research Farm, 2013.

Source	Injury				Yield	Plant Biomass
	3DAT	5DAT	7 DAT	14 DAT		
Rate	***	***	***	***	NS	**
Timing	***	***	***	NS	*	***
Rate * Timing	***	***	***	**	NS	NS

*, **, *** signify $p \leq 0.05$, 0.01, and 0.001, respectively.

Injury caused by dicamba in 2013 ranged from 7.5 to 66.3% at 3 DAT, 10 to 68.8% at 5 DAT, 13.8 to 75% at 7 DAT and 32.5 to 77.5% at 14 DAT for the first application timing. Injury from the second application timing ranged from 30 to 67.5 % at 3 DAT, 30 to 70% at 5 DAT, 35 to 75 % at 7DAT and 31.3 to 68.8 % at 14 DAT. Timing A at 28 g ae ha^{-1} showed the greatest injury 14 DAT. Timing A at 3.5 g ae ha^{-1} showed the least injury, had the highest yield, and biomass at 3 DAT. Timing B at 14 g ae ha^{-1} had the least biomass. See Table 9.

Table 9. Injury, yield and biomass of tomato treated with dicamba as influenced by rate and application time at Texas A&M Research Farm, 2013.

		Injury					
Rate	Timing	3 DAT*	5 DAT	7 DAT	14 DAT	Yield	Plant Biomass
g ae ha^{-1}		%				kg ha^{-1}	kg ha^{-1}
28	A	66.3 a	68.8 a	75 a	77.5 a	734	953
14	A	50 b	51.3 b	57.5 b	51.3 c	750	1,121
7	A	25 d	26.3 d	33.8 d	38.8 d	763	1,400
3.5	A	7.5 e	10 e	13.8 e	32.5 e	902	1,733
0	A	0 f	0 f	0 f	0 f	1,402	2,133
28	B	67.5 a	70 a	75 a	68.8 b	465	1,062
14	B	52.5 b	55 b	58.8 b	52.5 c	405	718
7	B	38.8 c	40 c	41.3 c	40 d	377	952
3.5	B	30 d	30 d	35 d	31.3 e	666	1,110
0	B	0 f	0 f	0 f	0 f	609	1,249

*Means followed by the same letter within a column are not significantly different ($p<0.05$). ^{A}3 weeks after transplanting ^{B}6 weeks after transplanting

When the main effect of rate was analyzed, dry weight ranged from 920 to 1,420 kg ha^{-1}. Effects of timing on yield ranged from 504 to 910 kg ha^{-1} and 1,018 to 1,468 kg ha^{-1} for dry weight. Yield less impacted by Timing A (910 kg ha-1) than Timing B (504 kg ha-1). Biomass was less impacted by Timing A (1,468 kg ha-1) than Timing B (1,018 kg ha^{-1}), while the nontreated (1,691 kg ha^{-1}) The greatest biomass reduction occurred from the 28 and 14 g ae ha^{-1} rates (1,008 and 920 kg ha-1, respectively). See Table 10.

Table 10. Effect of dicamba simulated drift rates on yield and biomass at Texas A&M Research Farm, 2013.

Main Effect Rate	Yield	Plant Biomass
g ae ha^{-1}	kg ha^{-1}	kg ha^{-1}
28		1,008 c
14		920 c
7		1,176 bc
3.5		1,421 b
0		1,691 a
Timing		
A	910 a	1,468 a
B	504 b	1,018 b

2013 Glyphosate

Rate had a significant impact on injury at 14 DAT (Table 11). A significant rate by timing interaction was detected for dry weight. Injury at 3, 5, and 7 DAT as well as tomato yield was not significantly impacted by the main effects of rate and timing, or their interaction.

Table 11. Analysis of variance for main effects and interactions from glyphosate on injury, yield and biomass at Texas A&M Research Farm, 2013.

Source	Injury				Yield	Plant Biomass
	3 DAT	5DAT	7 DAT	14 DAT		
Rate	NS	NS	NS	***	NS	NS
Timing	NS	NS	NS	NS	NS	NS
Rate X Timing	NS	NS	NS	NS	NS	*

*, **, *** signify $p < 0.05$, 0.01, and 0.001, respectively.

Tomato biomass ranged from 962 to 1,356 kg ha^{-1} for the first application timing. At the second application timing, plant biomass ranged from 1,070 to 2,033 kg ha^{-1}. Numerical difference in injury due to glyphosate never exceeded 4%, regardless of the rate or application timing. While not significant, the 34 g ae ha^{-1} rate had the highest injury for Timing A and B at 14 DAT. Numerical differences at the 4.2 g ae ha^{-1} rate had the least injury for Timing A and B at 3, 5, and 7 DAT and the 34 g ae ha^{-1} rate had the highest yield for Timing B. While not significant, the 17 g ae ha^{-1} rate had the lowest yield for Timing A. Timing B resulted in the highest biomass at the 8.4 g ae ha^{-1} rate. Timing A resulted in the lowest biomass at the 34 g ae ha^{-1} rate. See Table 12.

Table 12. Injury, yield and biomass of tomato treated with glyphosate at Texas A&M Research Farm, 2013.

Rate	Timing	Injury 3 DAT*	 5 DAT	 7 DAT	 14 DAT	Yield	Plant Biomass
g ae ha^{-1}		%				kg ha^{-1}	kg ha^{-1}
34	A	0	0	3	4	640	962 c
17	A	0	0	2	3	560	1194 bc
8.4	A	0	0	1	2	795	1069 bc
4.2	A	0	0	0	1	941	1356 abc
0	A	0	0	0	0	779	1305 bc
34	B	0	2	3	4	1234	1710 ab
17	B	0	1	2	3	845	1210 bc
8.4	B	0	0	1	2	1175	2033 a
4.2	B	0	0	0	1	882	1070 bc
0	B	0	0	0	0	318	782 c

*Means for the same main effect followed by a different letter are significantly (p<0.05) different. ^{A}3 weeks after transplanting ^{B} 6 weeks after transplanting

The 34 g ae ha^{-1} rate resulted in the greatest injury at 14 DAT (4%). Injury decreased significantly with each decrease in rate (3, 2, 1, and 0% for rates of 17, 8.4, 4.2 g ae ha^{-1}, and the nontreated plots, respectively). See Table 13.

Table 13. Effect of Glyphosate simulated rates on 14 DAT tomato injury at Texas A&M Research Farm, 2013.

Main Effect Rate	Injury 14 DAT
g ae ha^{-1}	%
34	4 a
17	3 b
8.4	2 c
4.2	1 d
0	0 e

Celebrity Tomato

2014 2,4-D River Bottom

A significant rate by timing interaction was detected for injury at 3, 5, and 7 DAT (Table 14), thus these data were not analyzed for the main effects of rate or timing separately. 2,4-D rate had a significant effect on yield, while the main effects and their interaction were not significant for biomass.

Table 14. Analysis of variance for main effects and interactions from 2,4-D on injury, yield and biomass at Texas A&M Research Farm, 2014.

	Injury				
Source	3 DAT	5 DAT	7 DAT	Yield	Plant Biomass
Rate	***	***	***	***	NS
Timing	***	***	***	NS	NS
Rate X Timing	***	***	*	NS	NS

*, **, *** signify $p< 0.05$, 0.01, and 0.001, respectively.

Injury caused by 2,4-D in 2014 ranged from 0.3 to 13.8 % at 3 DAT, 5.0 to 46.3% at 5 DAT and 12.5 to 63.8 % at 7 DAT for the first application timing. At the second application timing injury ranged from 15.0 to 42.5 % at 3 DAT, 21.3 to 62.5 % at 5 DAT and 33.8 to 70 % at 7 DAT. Timing A at 106 g ae ha^{-1} showed the most injury 7 DAT. Timing A at 13 g ae ha^{-1} showed the least injury 3 DAT. While not significant, Timing A at 13 g ae ha^{-1} resulted in the greatest biomass and 106 g ae ha^{-1} resulted in the least biomass. See Table 15.

Table 15. Injury, yield and biomass of tomato treated with 2,4-D as influenced by rate and application time at Texas A&M Research Farm, 2014.

Rate	Timing	Injury			Plant Biomass
		3 DAT*	5 DAT	7 DAT	
g ae ha^{-1}			%		kg ha^{-1}
106	A	13.8 c	46.3 b	63.8 ab	1,204
53	A	6.2 d	62 a	45 c	1,294
27	A	1.3 de	11.3 e	30 d	1,373
13	A	0.3 e	5.0 f	12.5 e	1,700
0	A	0 e	0 e	0 f	1,500
106	B	42.5 a	62.5 a	70 a	1,290
53	B	30.0 b	50.0 b	57.5 b	1,513
27	B	27.5 b	36.3 c	46.3 c	1,500
13	B	15.0 c	21.3 d	33.8 d	1,676
0	B	0 e	0 e	0 f	1,360

*Means for the same main effect followed by a different letter are significantly ($p<0.05$) different. [A] 3 weeks after transplanting [B] 6 weeks after transplanting

Yield ranged from 4,737 to 9,614 kg ha^{-1} in 2014. Yield was greatest in the nontreated plots (9614 kg ha^{-1}) and least with the 106 and 53 g ae ha^{-1} rates (4,737 and 5,803 kg ha^{-1}, respectively). Effects of rate on yield caused by 2,4-D in 2014 ranged from 4,737 to 7,639 kg ha^{-1}. A rate of 27 g ae ha^{-1} resulted in the greatest biomass. A rate of 106 g ae ha^{-1} resulted in the lowest biomass. (Table 16).

Table 16. Effect of 2,4-D simulated rates on tomato yield at Texas A&M Research Farm, 2014.

Main Effect Rate	Yield
g ae ha^{-1}	kg ha^{-1}
106	4,737 c
53	5,803 bc
27	7,639 b
13	7,287 b
0	9,614 a

2014 2,4-D Horticulture Farm

A significant rate by timing interaction was detected for injury at 3, 5, and 7 DAT and for plant biomass (Table 17), thus these data were not analyzed for the main effects of rate or timing separately. There was a significant main effect of rate and timing on 14 DAT epinasty. Yield and plant biomass were not impacted by herbicide rate, timing, or the interaction of the two.

Table 17. Analysis of variance for main effects and interactions from 2,4-D on injury, yield and biomass at Texas A&M Horticulture Farm, 2014.

	Injury					
Source	3 DAT	5 DAT	7 DAT	14 DAT	Yield	Plant Biomass
Rate	***	***	***	***	NS	NS
Timing	***	***	***	*	NS	NS
Rate X Timing	***	***	***	NS	NS	NS

*, **, *** signify $p< 0.05$, 0.01, and 0.001, respectively.

Injury caused by 2,4-D in 2014 ranged from 3.8 to 7.5% at 3 DAT, 4.5 to 15% at 5 DAT and 8.8 to 32.5% at 7 DAT for the first application timing (Table 18). Injury from the second application timing ranged from 11.3 to 52.5% at 3 DAT, 18.8 to 65% at 5 DAT and 23.8 to 68.8% at 7 DAT. Timing B at 106 g ae ha^{-1} showed the most injury 14 DAT. Timing A at 27 g ae ha^{-1} showed the least injury 3 DAT and 13 g ae ha^{-1} showed the least injury at 3 and 5 DAT. While not significant, timing A had higher yield data across all treatments with the exception of rate zero. A rate of 13 g ae ha^{-1} 2,4-D had the highest yield for timing A at 13368 kg ha^{-1}. Timing B at 106 g ae ha^{-1} had the least yield. While not significant, plant biomass ranged from 492 to 550 kg ha^{-1} for the first application timing. At the second application timing biomass ranged from 520 to

611 kg ha^{-1}. Timing B at 106 g ae ha^{-1} had the greatest biomass and Timing A at 53 g ae ha^{-1} had the least biomass. (Table 18)

Table 18. Injury, yield and biomass of tomato treated with 2,4-D as influenced by rate and application time at Texas A&M Horticulture Farm, 2014.

		Injury					
Rate	Timing	3 DAT*	5 DAT	7 DAT	14 DAT	Yield	Plant Biomass
g ha^{-1}		%				kg ha^{-1}	kg ha^{-1}
106	A	7.5 e	15 d	32.5 d	57.5	10,049	511
53	A	3.8 f	8.8 e	23.8 e	42.5	11,922	505
27	A	0 g	4.5 f	13.8 f	30	10,922	537
13	A	0 g	0 g	8.8 f	21.3	13,368	550
0	A	0 g	0 g	0 g	0	11,271	492
106	B	52.5 a	65 a	68.8 a	73.8	9,553	611
53	B	38.8 b	45 b	57.5 b	51.3	10,367	520
27	B	28.8 c	33.8 c	43.8 c	42.5	10,496	606
13	B	11.3 d	18.8 d	23.8 e	17.5	11,048	598
0	B	0 g	0 g	0 g	0	11,613	600

*Means for the same main effect followed by a different letter are significantly (p<0.05) different. ^{A} 3 weeks after transplanting ^{B} 6 weeks after transplanting

Injury ranged from 19.4 to 65.6% at 14 DAT. Injury increased significantly with increasing rates of 2,4-D. Injury was greatest with the 106 g ae ha^{-1} rate (65.6%) Injury was greatest with Timing B (37%), versus Timing A (30.3%). See Table 19.

Table 19. Effect of 2,4-D simulated rates and timing on 14 DAT tomato injury at Texas A&M Horticulture Farm, 2014.

Main Effect g ae ha^{-1}	14 DAT Epinasty %	
Rate		
106	65.6	a
53	46.9	b
27	36.3	c
13	19.4	d
0	0	e
Timing		
A	30.3	b
B	37.0	a

2014 Dicamba River Bottom

A significant rate by timing interaction was detected for injury at 3, 5, and 7 DAT (Table 20), thus these data were not analyzed for the main effects of rate or timing separately. There was a significant main effect of rate on yield. Plant biomass was not impacted by the main effects evaluated.

Table 20. Analysis of variance for main effects and interactions from dicamba on injury, yield and biomass at Texas A&M Research Farm, 2014.

Source	Injury				Plant
	3DAT	5DAT	7 DAT	Yield	Biomass
Rate	***	***	***	***	NS
Timing	***	***	**	NS	NS
Rate X Timing	***	***	***	NS	NS

*, **, *** signify $p < 0.05$, 0.01, and 0.001, respectively.

Injury caused by dicamba in 2014 ranged from 4.5 to 13.8% at 3 DAT, 5 to 43.8% at 5 DAT and 12.5 to 72.5% at 7 DAT for the first application timing (Table 21). Injury from the second application timing ranged from 13.8 to 46.3% at 3 DAT, 22.5 to 65% at 5 DAT and 33.8 to 62.5% at 7 DAT. Timing A at 56 g ae ha^{-1} showed the highest injury 7 DAT. Timing A at 28 g ae ha^{-1} and 7 g ae ha^{-1} showed the least injury 3 DAT. While not significant, timing A had the highest yield data at rate zero at 13,233 kg ha^{-1}. Yield ranged from 6,251 to 13,233 kg ha^{-1} for the first application timing. Yield was the highest for Timing B at 7 g ae ha^{-1}. Yield was the least for Timing A at 56 g ae ha^{-1}. At the second application timing biomass ranged from 7,971 to 10,997 kg ha^{-1}. While not significant, plant biomass ranged from 1,736 to 2,074 kg ha^{-1} for the first application timing. At the second application timing biomass ranged from 1,627 to 2,837 kg ha^{-1}. Biomass was the highest at Timing B at 28 g ae ha^{-1} and the least at 13 g ae ha^{-1}. (Table 21)

Table 21. Injury, yield and biomass of tomato treated with dicamba as influenced by rate and application time at Texas A&M Research Farm, 2014.

Rate	Timing	Injury 3 DAT*	 5 DAT	 7 DAT	Yield	Plant Biomass
g ae ha^{-1}			%		kg ha^{-1}	kg ha^{-1}
56	A	13.8 d	43.8 b	72.5 a	6,251	2,051
28	A	4.5 e	30 d	57.5 b	7,429	1,938
14	A	0 f	11.3 f	23.8 f	8,954	2,012
7	A	0 f	5 g	12.5 g	9,906	1,736
0	A	0 f	0 h	0 h	13,233	2,074
56	B	46.3 a	65 a	62.5 b	8,515	1,935
28	B	37.5 b	47.5 b	50 c	7,971	2,366
14	B	26.3 c	38.8 c	41.3 d	9,079	2,837
7	B	13.8 d	22.5 e	33.8 e	10,434	1,627
0	B	0 f	0 h	0 h	10,997	1,700

*Means for the same main effect followed by a different letter are significantly ($p<0.05$) different. ^{A} 3 weeks after transplanting ^{B} 6 weeks after transplanting

Yield ranged from 7,383 to 12,115 kg ha^{-1}. Again, yield was the highest in the nontreated plots at 12,115 kg ha^{-1}. Yield was least with the 56 and 28 g ae ha^{-1} rates (7,383 and 7,700 kg ha^{-1}, respectively). See Table 22.

Table 22. Effect of dicamba simulated rates on tomato yield at Texas A&M Research Farm, 2014.

Main Effect g ae ha^{-1}	Yield kg ha^{-1}	
Rate		
56	7,383	c
28	7,700	c
14	9,017	bc
7	10,170	ab
0	12,115	a

2014 Dicamba Horticulture Farm

A significant rate by timing interaction was detected for epinasty at 3, 5, and 7 DAT and for plant biomass (Table 23), thus these data were not analyzed for the main effects of rate or timing separately. There was a significant main effect of rate and timing on 14 DAT injury, while plant biomass was affected by herbicide timing.

Table 23. Analysis of variance for main effects and interactions from dicamba on injury, yield and biomass at Texas A&M Horticulture Farm, 2014.

	Injury					
Source	3DAT	5DAT	7 DAT	14 DAT	Yield	Plant Biomass
Rate	***	***	***	***	NS	NS
Timing	***	***	***	**	NS	**
Rate X Timing	***	***	**	NS	NS	NS

*, **, *** signify p< 0.05, 0.01, and 0.001, respectively.

Injury caused by 2,4-D in 2014 ranged from 2.5 to 5.5% at 3 DAT, 5 to 21.3% at 5 DAT and 7.5 to 33.8% at 7 DAT for the first application timing (Table 24). Injury from the second application timing ranged from 11.3 to 38.8% at 3 DAT, 10 to 53.8% at 5 DAT and 12.5 to 57.5% at 7 DAT. Timing A had the highest injury at 56 g ae ha^{-1} 14 DAT. Timing A had the least amount of injury at 14 g ae ha^{-1} and 7 g ae ha^{-1} 3 DAT in addition to Timing B at 7 g ae ha^{-1} 3DAT. While not significant, timing B had the highest yield data at rate 14 g ae ha^{-1}and 7 g ae ha^{-1} at 16,460 and 17,077 kg ha^{-1}. Yield ranged from 13,821 to 17,077 kg ha^{-1} for the first application timing. While not significant, plant biomass ranged from 538 to 619 kg ha^{-1} for the first application timing. At the second application timing biomass ranged from 581 to 818 kg ha^{-1}. Timing B had the highest yield and biomass at 7 g ae ha^{-1}. Timing A had the least yield and biomass at 28 g ha^{-1}. (Table 24)

Table 24. Injury, yield and biomass of tomato treated with dicamba as influenced by rate and application time at Texas A&M Horticulture Farm, 2014.

		Injury					
Rate	Timing	3 DAT*	5 DAT	7 DAT	14 DAT	Yield	Plant Biomass
g ae ha^{-1}		%				kg ha^{-1}	kg ha^{-1}
56	A	5.5 d	21.3 d	33.8 c	61.3	13,316	561
28	A	2.5 de	12.5 e	25 d	52.5	13,135	562
14	A	0 e	5 fg	15 e	32.5	12,621	538
7	A	0 e	0 g	7.5 ef	22.5	14,694	619
0	A	0 e	0 g	0 f	0	16,274	578
56	B	38.8 a	53.8 a	57.5 a	48.8	13,821	701
28	B	22.5 b	38.8 b	45 b	37.5	15,479	738
14	B	11.3 c	27.5 c	32.5 cd	30	16,460	744
7	B	0 e	10 ef	12.5 e	17.5	17,077	818
0	B	0 e	0 g	0 f	0	15,968	581

*Means for the same main effect followed by a different letter are significantly ($p<0.05$) different. ^{A}3 weeks after transplanting ^{B}6 weeks after transplanting

Injury in response to dicamba rate ranged from 20 to 55% at 14 DAT. Injury was greatest with the 56 g ae ha^{-1} rate (55%) and decreased with decreasing rates of 28, 14, and 7 g ae ha^{-1}, and the nontreated plots (45, 31.3, 20, and 0%, respectively). Injury in response to application timing ranged from 26.8 (Timing B) to 33.8% (Timing A) at 14

DAT. Biomass in response to application timing ranged from 571 (Timing A) to 717 kg ha-^{1} (Timing B). See Table 25.

Table 25. Effect of dicamba simulated rates on 14 DAT tomato injury and yield at Texas A&M Horticulture Farm, 2014.

Main Effect Rate	14 DAT	Plant Biomass
g ae ha^{-1}	%	kg ha^{-1}
56	55 a	
28	45 b	
14	31.3 c	
7	20 d	
0	0 e	
Timing		
A	33.8 a	571 b
B	26.8 b	717 a

CHAPTER V

CONCLUSIONS

Discussion

The objective of these studies was to determine the effects of simulated drift of several commonly used herbicides on field-grown tomato. With glyphosate, significant injury was observed 14 DAT, however yield was not significantly impacted. Plant biomass was affected by the herbicide rates examined in this study. At the second application timing, the 34 and 8.4 g ae ha^{-1} rates resulted in the highest biomass recorded. Jeffries et al. (2014) found the most insight on the effect of simulated drift rates and application timing on plant growth based upon the plant above-ground biomass. Cedergreen (2008) found that glyphosate gave 25% increase in biomass at harvest when compared with the control barley plants. In this study, as glyphosate rate decreased, so did the observed level of injury. The results of these studies indicated that a significant yield loss did not occur, even at the highest drift concentration of glyphosate. Seasonal variability was observed, although not statistically significant, where a numerical difference was observed between the first and second application timing. Tomato plants treated with glyphosate exhibited low percentages of injury. At the highest (34 g ae ha^{-1}) rate plants expressed only 4% injury. Gilreath et al. (2001) found that with rates less than 10 g ha^{-1} of glyphosate foliar injury was generally mild. As the simulated drift concentration amount decreased, so did the level of injury observed. These results were expected due to the increase of herbicide applied.

Significant differences were not found amongst yield for either application timings. These results do not agree with Romanoski (1980) who found significant yield reductions only with early application of 0.10 kg ha^{-1} of glyphosate. Due to these findings, combined with low percent injury observed, the study was omitted for the following year.

2,4-D at 53 g ae ha^{-1} rate caused significant injury at 7 DAT in 2013. This agrees with the findings of Hemphill and Montgomery (1981) and Jordan and Romanowski (1974) who reported severe epinasty between 10 to 14 DAT. The results of this study indicated that yield decreased as the rate of 2,4-D increased. These findings correspond with those of Hemphill and Montgomery (1981) and Jordan and Romanowski (1974). Biomass data did not follow the same trend of yield data. All treatments with the exception of the untreated showed an increase in weight from the second application timing.

In 2014, at the River Bottom site, the most severe injury in response to 2,4-D took place at 7 DAT for the second application timing at the 106 g ae ha^{-1} rate. The impact of 2,4-D rate on tomato yield increased as the rate of 2,4-D decreased. With the exception of the 13 g ae ha^{-1} rate, a slight increase of 4% was found between the 13 g ae ha^{-1} rate and the 27 g ae ha^{-1} rate. A 51 g ae ha^{-1} percent decrease in yield was noted for the 106 g ae ha^{-1} rate. The slight 4% increase in yield due to the 27 g ae ha^{-1} rate applied may have been the result of biphasic response on the plant leading back to the principal of hormesis, thus producing a slight increase in fruit production and increasing yield.

In 2014 at the Horticulture Farm, the most severe injury in response to 2,4-D took place at 14 DAT for the second application timing at 106 g ae ha^{-1} rate. This is in agreement with the findings of Hemphill and Montgomery (1981) and Jordan and Romanowski (1974) that found that severe epinasty took place between 10 to 14 DAT. The results of this study indicated that yield decreased as the rate of 2,4-D increased. Numeric differences were noted for yield and biomass, but were not significant.

In 2013, the most severe injury in response to dicamba took place at 14 DAT for the first application timing. This agrees with the finding of Jordan and Romanowski (1974) and Hemphill and Montgomery (1981). The second application timing had the most severe epinasty ratings at 7 DAT this may have been due to the plant being more mature. These results agree with those of Gilreath et al. (2001) who found that plants that were more mature and treated at a later timing were less susceptible to foliar injury. The 3.5 rate resulted in the highest biomass recorded, perhaps as a result of hormesis. Plant biomass was reduced by 40% at the (28 g ae ha^{-1} rate) and 46% with the (14 g ae ha^{-1} rate). Andersen et al. (2004) found that soybean biomass and plant height was reduced by 70 and 66% with rates of dicamba between 0.0056 - 0.056 kg ae ha^{-1}.

In 2014 at the River Bottom site, the most severe injury took place at 7 DAT for the first application timing of dicamba. This agrees with the finding of Jordan and Romanowski (1974). The second application timing had severe epinasty ratings at 5 DAT, again, this may have been due to the plant being more mature. Plant yield was the highest in the untreated check but second highest at (7 g ae ha^{-1} rate). Plant yield was reduced by 39% at the (56 g ae ha^{-1} rate) and 36% with the (28 g ae ha^{-1} rate). Numeric differences were noted for biomass but not significant.

In 2014 at the Horticulture Farm, injury was greater following the first application timing of dicamba. This agrees with the finding of Jordan and Romanowski (1974). This study did not reveal a significant difference in yield. These findings do not agree with Jordan and Romanowski (1974) or Kruger et al. (2012). Both found a reduction in yield. This is likely due to the higher rates of dicamba used in their studies. Jordan and Romanowski (1974) used dicamba rates of 0, 0.002, 0.02, and 0.2 kg ha^{-1} in 1971 and 0, 0.001, 0.01, and 0.1 kg ha^{-1}. Kruger et al. applied dicamba at 0, 0.56, 1.87, 5.6, 18.7, 56 and 187 g ha^{-1}. The second application timing had higher biomass then the first.

Conclusion

The potential risks with increased use of 2,4-D and dicamba herbicides, at higher concentrations, may still pose a threat to sensitive crops. Off-target drift will be an additional concern to many producers. Herbicide drift is a current problem across the United States but particularly effects niche crops such as tomatoes shown in this study. Best spray practices must be maintained in order to prevent physical and volatile herbicide drift. This study confirmed that small concentrations of herbicide may produce significant visual injury and negatively impact tomato biomass production and fruit yield in many cases. However, in other cases (such as the 2014 trials), yield was not impacted by drift rates of 2,4-D and dicamba even though visible injury was significant. The use of sensitive crop registries can be a great preventive step in evading direct damage.

Producers can also work with their insurance provider for individual crop insurance programs. Currently, new herbicide technologies have been released to reduce off-target drift while working to eliminate herbicide-resistant weeds species. Grower compliance to herbicide labels is vital to reduce herbicide drift. Some products require applicators licenses in order to apply. This study has revealed that minute amounts of 2,4-D and dicamba drift can result in significant injury and yield loss in tomato, thus herbicide applicators will need to be vigilant and adhere to product application requirements to minimize the risk of damage occurring to neighboring sensitive crops.

REFERENCES

Amrhein, N., Schab, J. & Steinrücken, H.C. 1980. The mode of action of the herbicide glyphosate. Naturwissenschaften 67:356-357.

Andersen S. M., S. A. Clay, and L. J. Wrage. 2004. Soybean foliage residues of dicamba and 2,4-D and correlation to application rates and yield. Agron. J. 96:750-760.

Anonymous (2017a) Enlist One® with Colex-D® Label. Available at https://www.enlist.com/content/dam/dpagco/enlist/na/us/en/files/Enlist%20One%20Herbicide%20Specimen%20Label.pdf. Accessed: April 13, 2020.

Anonymous (2017b) Enlist Duo®with Colex-D® Label. Available at https://www.enlist.com/content/dam/dpagco/enlist/na/us/en/files/Enlist%20Duo%20Specimen%20Label.pdf. Accessed: April 13, 2020.

Anonymous (2018a) Engina® Label. Available at https://www.engeniastewardship.com/documents/2019_Engenia_Herbicide_Label.pdf. Accessed: April 13, 2020.

Anonymous (2018b) Xtendimax® with Vaporgrip Technology® Label. Available at http://xtendimaxapplicationrequirements.com/Documents/2_35008S2-40%20XtendiMax%20VaporGrip%20Tech%20DFU%20Label.pdf. Accessed: April 13, 2020.

Anonymous (2018c) DuPont™ FeXapan® Plus VaporGrip® Technology Label. Available at http://www.cdms.net/ldat/ldDJ1002.pdf. Accessed: July 3, 2020.

Banks P. A. and J. Schroeder. 2002. Carrier volume affects herbicide activity in simulated spray drift studies. Weed Technol. 16:833-837.

Behrens M. R., N. Mutlu, S. Chakraborty, R. Dumitru, W. Z. Jiang, B. J. LaVallee, P. L. Herman, T. E. Clemente, and D. P. Weeks. 2007. Dicamba resistance: Enlarging and preserving biotechnology-based weed management strategies. Science 316:1185-1188.

Bergougnoux V. 2014. The history of tomato: From domestication to biopharming. Biotechnology Advances 32:170-189.

Bradley K. W. 2017. A Final Report on Dicamba-Injured Soybean Acres. Available at https://ipm.missouri.edu/IPCM/2017/10/final_report_dicamba_injured_soybean/. Accessed: June 13, 2020.

Bradley K. W. 2018. July 15 Dicamba Injury Update. Different Year, Same Questions. Available at https://ipm.missouri.edu/IPCM/2018/7/July-15-Dicamba-injury-update-different-year-same-questions/. Accessed: June 13, 2020.

Bradshaw L. D., B. H. Wells, S. L. Kimball, and S. R. Padgette. 1997. Perspectives on glyphosate resistance. Weed Technology: A Journal of the Weed Science Society of America 11:189-198.

Cedergreen N. 2008. Herbicides can stimulate plant growth. Weed Res. 48:429-438.

Egan J. F., K. M. Barlow, and D. A. Mortensen. 2014. A meta-analysis on the effects of 2,4-D and dicamba drift on soybean and cotton. Weed Sci. 62:193-206.

Ellis J. M. and J. L. Griffin. 2002. Soybean (glycine max) and cotton (gossypium hirsutum) response to simulated drift of glyphosate and glufosinate. Weed Technol. 16:580-586.

Gilreath J. P., C. A. Chase, and S. J. Locascio. 2001. Crop injury from sublethal rates of herbicide. III. pepper. Hortscience 36:677-681.

Gilreath J. P., B. M. Santos, C. A. Chase, and S. J. Locascio. 2006. Influence of soil fumigation on 2,4-D and dicamba carryover in fresh market tomato. Crop Protection 25:1095-1100.

Goldy R. 2016. Protecting Tomatoes from Herbicide Drift. Available at https://www.canr.msu.edu/news/protecting_tomatoes_from_herbicide_drift. Accessed: December 5, 2019.

Heap. 2020. International Survey of Herbicide Resistant Weeds. Available at http://www.weedscience.org. Accessed: April 14, 2020.

Hemphill D. D. and M. L. Montgomery. 1981. Response of vegetable crops to sublethal application of 2,4-D. Weed Sci. 29:632-635.

Jeffries M. D., D. J. Mahoney, and T. W. Gannon. 2014. Effect of simulated indaziflam drift rates on various plant species. Weed Technol. 28:608-616.

Jordan T. N. and R. R. and Romanowski. 1974. Comparison of dicamba and 2,4-D injury to field grown tomatoes. Hortscience 9:74-75.

Kende H. and J. A. D. Zeevaart. 1997. The five "classical" plant hormones. Plant Cell 9:1197-1210.

Kniss A. R. 2017. Long-term trends in the intensity and relative toxicity of herbicide use. Nat Commun 8:14865-14865.

Kruger G. R., W. G. Johnson, D. J. Doohan, and S. C. Weller. 2012. Dose response of glyphosate and dicamba on tomato (lycopersicon esculentum) injury. Weed Technol. 26:256-260.

Mendelson J. 1998. Roundup: The world's biggest-selling herbicide. Ecologist 28:270-275.

Mueller T. C. and L. E. Steckel. 2019. Dicamba volatility in humidomes as affected by temperature and herbicide treatment. Weed Technol. 33:541-546.

Robbins, W. A. and Taylor, W. S. 1957. Injury to canning tomatoes caused by 2,4-D. Proc. Am. Soc. Hortic. Sci. 70:373-378.

Romanowski R. R. 1980. Simulated drift studies with herbicides on field-grown tomato. Hortscience 15:793-794.

Ross M. A. and C. A. Lembi. 1999. Applied weed science. Second ed. Prentice Hall, Upper Saddle River, New Jersey.

Schaner D. L., ed. 2014. Herbicide Handbook. Tenth ed. Lawrence, KS: Weed Science Society of America. Pp. 16-19, 139-141, 240--242,

Senseman S. A., ed. 2007. Herbicide Handbook. Ninth ed. Lawrence, KS: Weed Science Society of America. Pp. 15, 322-328, 335-338.

Truelove B., ed. 1977. Research Methods in Weed Science. Second Edition ed. Auburn, Alabama: Southern Weed Science Society. Pp. 221.

United States Department of Agriculture. 2016. Tomatoes. Available at http://www.ers.usda.gov/topics/crops/vegetables-pulses/tomatoes.aspx. Accessed: February 05, 2016.

United States Department of Agriculture. 05, 2020. Agricultural Chemical use Program. Available at https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/. Accessed: June 13, 2020.