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Article

# Mowing Associated to Chemical Control for Glyphosate-Resistant Cotton Stalk Destruction

*Roçada Associada ao Controle Químico para Destruição de Soqueiras de Algodoeiro Resistente ao Glyphosate*

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ABSTRACT - Post-harvest cotton stalk control is mandatory in many cotton producing countries, and the major methods used for this practice are mechanical and chemical (glyphosate and 2,4-D as the most usual herbicides applied), or a combination of both. However, the adoption of glyphosate-resistant cotton varieties by growers have required the development of alternative chemical treatments. Six trials were conducted to evaluate systems combining mowing and chemical control of glyphosate-resistant cotton stalks. Experiments conducted in 2014 were installed in randomized complete block design with nineteen treatments and four replicates. In 2015, the experiments were also conducted in randomized complete block design with eleven treatments and four replicates. Herbicide treatments were applied after cotton stalk mowing. Cotton stalk control varied according to rainfall regime after herbicide application. A single herbicide application to stub regrowth plants did not provide acceptable efficacy in cotton stalk destruction, independently of the treatment used. The best options for glyphosate-resistant cotton stalk control consisted of 2,4-D application immediately after mowing, followed by sequential application of combinations of 2,4-D with flumiclorac, carfentrazone or imazethapyr.

**Keywords:** crop residues, fallow management, herbicides, transgenic plants.

*RESUMO - O controle de soqueiras de algodoeiro é obrigatório em vários países produtores, e os métodos mais utilizados para essa prática são o controle mecânico e químico (glyphosate e 2,4-D são os herbicidas mais usualmente aplicados), ou a combinação de ambos. Apesar disso, a adoção de variedades de algodoeiro resistentes ao glyphosate pelos produtores tem requerido o desenvolvimento de tratamentos químicos alternativos. Seis experimentos foram conduzidos para avaliar sistemas associando roçada e controle químico de soqueiras de algodoeiro resistente ao glyphosate. Experimentos conduzidos em 2014 foram instalados no delineamento de blocos casualizados com dezenove tratamentos e quatro repetições. Em 2015, os experimentos também foram conduzidos no delineamento de blocos casualizados com onze tratamentos e quatro repetições. Os tratamentos herbicidas foram aplicados depois da roçada das soqueiras de algodoeiro. O controle variou em função do regime de precipitação depois da aplicação de herbicidas. A aplicação única de herbicidas em plantas rebrotadas não proporcionou eficácia aceitável na destruição de soqueiras de algodoeiro, independentemente do tratamento utilizado. As melhores opções para o controle de soqueiras de algodoeiro consistiram na aplicação de 2,4-D imediatamente após a roçada, seguido pela aplicação sequencial de associações de 2,4-D com flumiclorac, carfentrazone ou imazethapyr.*

**Palavras-chave:** resíduos culturais, manejo entressafra, herbicidas, plantas transgênicas.

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## INTRODUCTION

*Cotton* is a *perennial* plant grown commercially as annual summer crop. Cotton stalk occurs when a plant survives over winter and then regrows from the old root stock. As cotton stalks become progressively larger and more difficult to manage over time, they must be managed to prevent the problem.

The elimination of cotton stalk is essential for several reasons: because these plants may affect the growth of the successional crops by behaving as weeds (Greenberg et al., 2007), because they can serve as host for pests such as the boll weevil during the winter months (Azambuja and Degrande, 2014, Pimenta et al., 2016) and because growers can be financially charged due to the fines imposed by legislation in many countries.

In theory *cotton stalk* should not occur due to the requirement of *harvested cotton* to be controlled with adequate cultivation and soil disturbance as soon as practical after *harvest*. Although the root cutting associated to mechanical destruction of cotton stalk is probably one of the most effective alternatives, no-tillage growers are reluctant to use heavy cultivation to manage stalk cotton due to soil disturbance. Mechanical control limitations are also related to their low operational efficiency and to the difficulty in conducting this operation in rainy periods (Bianchini and Borges, 2013).

Advantages of chemical methods include not only the elimination of soil disturbance, but also improved operational efficiency, when compared to the mechanical destruction (Yang et al., 2006), and, additionally, provide fallow weed control in no-tillage areas. However, the results of chemical alternatives depend on the stalk vigor conditions for herbicide absorption, and usually two or sometimes three sequential applications are required to achieve acceptable efficiency. Another constraint for herbicides is the potential carryover for successional crops (Robinson and McNaughton, 2012). Mechanical methods without soil disturbance combined with herbicide use may be among the best alternatives in this case.

The most commonly used herbicides for chemical cotton stalk destruction are 2,4-D and glyphosate, mostly because both are systemic in plants and present limited residual effect in soil (Ferreira et al., 2018). Systemic herbicides like these may reach the terminal root and shoot growth areas (Robinson et al., 2012), which is essential to control perennials, and provide an important tool when herbicides are sprayed on stem sections (right after mechanical mowing) or on very limited leaf area after crop harvest (Lemon et al., 2003). In some cases, the use of contact herbicides may be prioritized for a rapid defoliation effect, especially to reduce insect hosting.

Glyphosate-resistant (Roundup Ready - RR™ Flex™) cotton is a genetically modified crop containing a protein (CP4 EPSPS) which allows Roundup Flex™ cotton plants to tolerate applications of glyphosate over the top. A C4 EPSPS gene clone are present and expressed in Roundup Flex™ cotton, which confers tolerance to glyphosate application during vegetative growth, flowering and boll filling (Pline et al., 2002). The adoption of Roundup Flex™ cotton by farmers sharply restricts the benefits of glyphosate as an alternative for cotton stalk management (York et al., 2004). Thus, alternative systems are demanded by cotton growers. The objective of this study was to evaluate different systems combining mowing and herbicidal treatments for the stalk destruction of glyphosate-resistant cotton under different environments.

## MATERIAL AND METHODS

Six experiments were performed (four from July to December 2014 and two from July to October 2015) to assess the efficacy of chemical treatments for glyphosate-resistant (Roundup Flex™) cotton stalk destruction in different areas of cotton production in Brazil. In 2014, the experiments were conducted in Santa Helena de Goiás, Goiás (17°50’05"S, 50°34’53"W, 577 m altitude - E1); Nova Ponte, Minas Gerais (19°17’33’’S, 47°41’37’’W, 1000 m - E2); Primavera do Leste, Mato Grosso (15°31’38"S, 54°12’36"W, 620 m - E3); and Sorriso, Mato Grosso (12°45’50"S, 55°50’26"W, 395 m - E4). In 2015, the experiments were conducted in Primavera do Leste, Mato Grosso (15°31’36"S, 54°12’28"W, 699 m - E5); and Campo Verde, Mato Grosso (15°29’37"S, 55°01’36"W, 663 m - E6).

Soil samples were collected (0-20 cm layer) from all experimental areas before conducting the experiments. The physical and chemical characteristics, crop data, and climatic conditions at herbicide applications are outlined in Table 1. Rainfall data recorded during the experimental period are shown in Figure 1.

***Table 1*** **-** Physical and chemical characteristics of soil samples from the experimental areas, crop data and climatic conditions at the time of treatment application

| | E1[(1)] | E2 | E3 | E4 | E5 | E6 |
|---|---|---|---|---|---|---|
| | Soil physical and chemical characteristics | | | | | |
| pH ($H_2O$) | 6.5 | 4.9 | 6.4 | 5.5 | 6.3 | 6.4 |
| OM (mg $dm^{-3}$) | 3.2 | 3.4 | 2.3 | 2.7 | 2.4 | 2.8 |
| Clay (g $kg^{-1}$) | 440 | 287 | 333 | 580 | 316 | 383 |
| Silt (g $kg^{-1}$) | 50 | 125 | 107 | 150 | 90 | 107 |
| Sand (g $kg^{-1}$) | 510 | 588 | 560 | 270 | 594 | 510 |
| | Crop data | | | | | |
| Variety | BRS 371 RF | DP 1240 B2RF | IMA 5675 B2RF | IMA 5675 B2RF | IMA 5675 B2RF | IMA 5675 B2RF |
| Spacing (m) | 0.76 | 0.8 | 0.9 | 0.9 | 0.9 | 0.9 |
| Mowing height (m) | 0.1 to 0.25 | 0.1 to 0.15 | 0.15 to 0.2 | 0.15 to 0.2 | 0.2 to 0,3 | 0.2 to 0.3 |
| | Application A | | | | | |
| Date | 08/02 | 08/21 | 08/06 | 07/15 | 08/10 | 07/31 |
| Temp (ºC) | 29 | 29.8 | 28.3 | 31.2 | 27.5 | 24.6 |
| RH (%) | 52 | 68.8 | 65 | 50 | 48.3 | 56.2 |
| WS (km $h^{-1}$) | 1.1 | 6.1 | 1.2 | 2.2 | 2.4 | 3.1 |
| | Application B | | | | | |
| Date | 08/23 | 09/16 | 08/25 | 08/15 | 08/31 | 08/25 |
| Temp (ºC) | 24 | 31.1 | 26.5 | 30.4 | 29.7 | 30.4 |
| RH (%) | 40 | 65.4 | 55 | 38.5 | 50.6 | 44.7 |
| WS (km $h^{-1}$) | 1.8 | 5.3 | 0 | 1.8 | 1.2 | 2.8 |
| | Application C | | | | | |
| Date | 09/12 | 10/13 | 08/25 | 08/15 | - | - |
| Temp (ºC) | 28 | 28.7 | 26.5 | 30.4 | - | - |
| RH (%) | 50 | 72.5 | 55 | 38.5 | - | - |
| WS (km $h^{-1}$) | 1.5 | 4.5 | 0 | 1.8 | - | - |

(1) Abbreviations: E1, Santa Helena de Goiás (2014); E2, Nova Ponte (2014); E3, Primavera do Leste (2014); E4, Sorriso (2014); E5, Primavera do Leste (2015); E6, Campo Verde (2015); OM, Organic matter; Temp, Temperature; RH, Relative air humidity; WS, Wind speed.

## Experiments conducted in 2014

The experimental design was a completely randomized blocks with 19 treatments (Table 2) and four replicates. For 2,4-D amine (DMA 806 BR™, Dow AgroSciences, Indianapolis, IN; http://dowagro.com), doses are expressed as g of acid equivalent per hectare (g a.e. $ha^{-1}$), whereas for flumiclorac (Radiant™, Valent U.S.A. Corporation, Walnut Creek, CA; http://sumitomochemicalamerica.com/valent/), and imazethapyr (Pivot™, BASF Corporation Agricultural Products, Research Triangle Park, NC; http://agro.basf.com), doses are expressed as g of active ingredient per hectare (g a.i. $ha^{-1}$). The herbicide treatments were defined considering that soybean would be the successional crop, and the four sites were chosen to provide different rainfall conditions after herbicide application.

The plot area was different in each location (E1 = 22.8 $m^2$, E2 = 32 $m^2$, and E3 = E4 = 25.2 $m^2$), but for all sites % control and stub regrowth of cotton plants was evaluated in the two central plot rows. All experiments were installed in commercial crops of Roundup Flex™ cotton, and the main crop data are outlined in Table 1. Prior to first herbicide application, cotton was mowed with a tractor-mounted offset rotary mower. A first group of herbicide treatments was composed by two sequential applications (A and C) and a second group was composed by one single application (B).

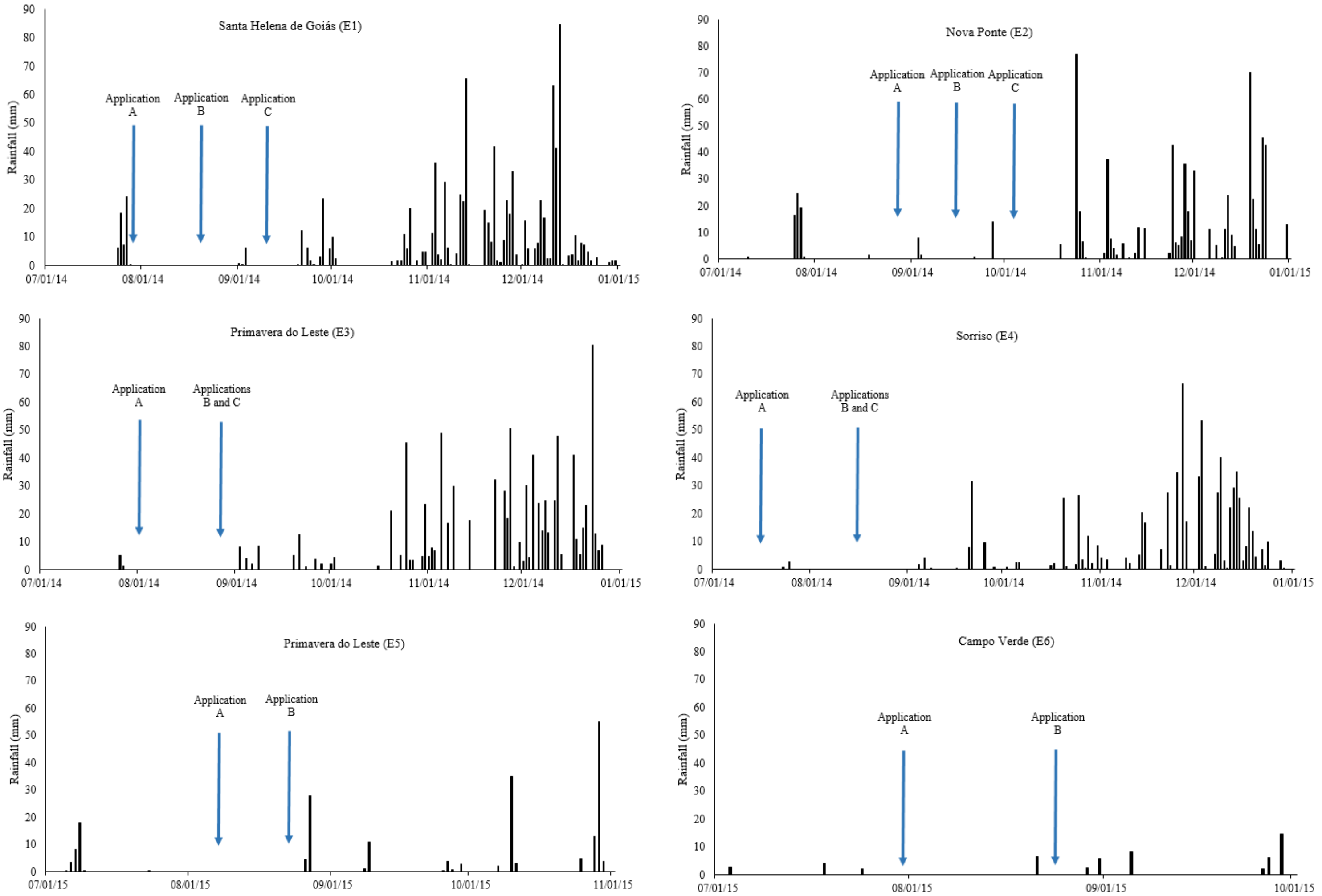


***Figure 1*** **-** Rainfall (mm) during the experimental period in 2014 and 2015. A, B, and C are the time points when the herbicides were applied in the experiments (Table 1).

For all sites, application A was performed within a maximum of 30 minutes after mowing. Applications B and C were performed when the cotton plants had a stub length ranging from 5 to 10 cm, which occurred from 19 to 31 days after mowing (Application B – single application treatments) and from 19 to 53 days after Application A (for sequential applications treatments), considered in this case the Application C.

A $CO_2$-pressurized backpack sprayer equipped with a boom with six XR-110.02 flat fan nozzles spaced 0.5 m apart was used at constant pressure in all applications. The volume of herbicide solution application was 200 L $ha^{-1}$ for E1 and 150 L $ha^{-1}$ for the other three sites. Table 1 also outlines the data for all applications for each site where the experiments were conducted.

Visual estimates of regrowth were recorded using a 0 to 100 scale; where 0 = no control and 100 = complete control. Additionally, the number of plants and the number of plants with stub regrowth per plot were recorded and data were converted to percent stub regrowth for analysis. Such evaluations were performed 20 and 90 days after mowing (DAM) for E1 and E2, and 20 and 50 DAM for E3 and E4.

The length of the stub plants considered alive were measured in the last evaluation of each experiment (90 DAM for E1 and E2 and 50 DAM for E3 and E4) as an additional efficacy criterion. To determine whether the plants were alive, they were bevel cut (at a height ranging from 5 to 10 cm from the plant base) and visually assessed to determine whether the stem tissues were moist. The stub length values of the dead plants were counted as zero.

***Table 2*** **-** Herbicide treatments evaluated for glyphosate-resistant (Roundup Flex™) cotton stalk destruction. 2014

| Treatment (g a.i. or a.e. ha$^{-1}$) | | |
|---|---|---|
| Application A[(1)] (After mowing) | Application B[(2)] (Single application) | Application C[(3)] (Sequential application) |
| 2,4-D amine (1340)[(4)] | - | - |
| 2,4-D amine (1675) | - | - |
| 2,4-D amine (1340) | - | 2,4-D amine (670) |
| 2,4-D amine (1675) | - | 2,4-D amine (670) |
| 2,4-D amine (1340) | - | 2,4-D amine (335) + flumiclorac (60) |
| 2,4-D amine (1675) | - | 2,4-D amine (335) + flumiclorac (60) |
| 2,4-D amine (1340) | - | 2,4-D amine (670) + flumiclorac (60) |
| 2,4-D amine (1675) | - | 2,4-D amine (670) + flumiclorac (60) |
| 2,4-D amine (1340) | - | flumiclorac (60) |
| 2,4-D amine (1675) | - | flumiclorac (60) |
| 2,4-D amine (1340) | - | 2,4-D amine (670) + imazethapyr (106) |
| - | 2,4-D amine (670) | - |
| - | 2,4-D amine (1005) | - |
| - | 2,4-D amine (1340) | - |
| - | 2,4-D amine (670) + flumiclorac (60) | - |
| - | 2,4-D amine (1005) + flumiclorac (60) | - |
| - | 2,4-D amine (670) + imazethapyr (106) | - |
| - | flumiclorac (60) | - |
| Control without herbicide | | |

[(1)] Application A: Performed within a maximum of 30 minutes after mowing. [(2)] Application B: Performed only in single-application treatments.[(3)] Application C: Performed in treatments with Application A (Sequential application). [(4)] All treatments were applied with 0.5% v v$^{-1}$ Assist™ (BASF Corporation Agricultural Products, Research Triangle Park, NC; http://www.agro.basf.com) except for the treatments with flumiclorac using 0.5% v v$^{-1}$ Lanzar™ (Arysta Lifescience, Cary, NC; http://www.arysta-na.com/us).

## Experiments conducted in 2015

The experimental design used was completely randomized blocks with 11 treatments (Table 3) and four replicates. The herbicide treatments were defined considering the results of the experiments from the previous year. For 2,4-D amine (DMA 806 BR™, Dow AgroSciences) and glyphosate (Roundup WG™, Monsanto, St. Louis, MO; http://monsanto.com) doses are expressed as g a.e. ha$^{-1}$, whereas for paraquat (Gramoxone 200™, Syngenta, Wilmington, DE; http://syngenta-us.com/), glufosinate (Finale™, Bayer CropScience, Research Triangle Park, NC; http://www.cropscience.bayer.us), carfentrazone (Aurora™, FMC Corporation, Philadelphia, PA; http://fmccrop.com/grower), flumiclorac (Radiant™, Valent U.S.A. Corporation), and saflufenacil (Heat™, BASF Corporation Agricultural Products) doses are expressed as g a.i. ha$^{-1}$.

***Table 3*** **-** Herbicide treatments evaluated for glyphosate-resistant (Roundup Flex™) cotton stalk destruction. 2015

| Treatments (g a.i. or a.e. ha$^{-1}$) | |
|---|---|
| Application A[(1)] (After mowing) | Application B[(2)] (Sequential application) |
| 2,4-D amine (1340) | 2,4-D amine (670) |
| 2,4-D amine (1340) | 2,4-D amine (670) + paraquat (400) |
| 2,4-D amine (1340) | 2,4-D amine (670) + glyphosate (1440) |
| 2,4-D amine (1340) | 2,4-D amine (1340) + glyphosate (1440) |
| 2,4-D amine (1340) | 2,4-D amine (670) + glufosinate (400) |
| 2,4-D amine (1340) | 2,4-D amine (670) + carfentrazone (28) |
| 2,4-D amine (1340) | 2,4-D amine (670) + flumiclorac (60) |
| 2,4-D amine (1340) | 2,4-D amine (1005) + flumiclorac (60) |
| 2,4-D amine (1340) | 2,4-D amine (1340) + flumiclorac (60) |
| 2,4-D amine (1340) | 2,4-D amine (670) + saflufenacil (49) |
| Control without herbicide | |

[(1)] Application A: Performed within a maximum of 30 minutes after mowing. [(2)] Application B: Performed 20 days after Application A (Sequential application). [(3)] All treatments were applied with 0.5% v v$^{-1}$ Lanzar™ (Arysta Lifescience, Cary, NC; http://www.arysta-na.com/us).

The plot area for both experiments was 21 $m^2$. Similar to the trials conducted in 2014, the 2015 experiments were installed in Roundup Flex™ cotton area, control and regrowth of cotton stalk was evaluated in the two central plot rows, and before first herbicide application cotton was mowed with a tractor-mounted offset rotary mower. Application A was performed within a maximum of 30 minutes after mowing. Application B were performed when the cotton plants had a stub length ranging from 5 to 10 cm, which occurred 20 days after mowing in both locations.

In both locations, all applications were performed with a $CO_2$-pressurized backpack sprayer equipped with a boom with six XR-110.02 flat fan nozzles spaced 0.5 m apart, and the volume of herbicide solution application used was 150 L $ha^{-1}$. The data for each application performed in the experiments are presented in Table 1.

The number of plants with or without stub regrowth per plot was recorded at 20, 35 and 50 DAM in the both experiments and data were converted to percent regrowth for analysis.

### Statistical analysis

Data were subjected to analysis of variance using the F test, and when significant, the means were compared using the Scott-Knott test ($p \leq 0.05$). Treatments with two sequential herbicide applications (Applications A and C) were compared with the single-application treatments (Application B) using the Scheffe's test ($p \leq 0.05$). All statistical tests were performed using the SISVAR program (Ferreira, 2011).

$\hat{C}$ = Applications A + C *versus* Application B

$\hat{C}$ = T3 + T4 + T5 + T6 + T7 + T8 + T9 + T10 + T11 - T12 - T13 - T14 - T15 - T16 - T17 - T18

## RESULTS AND DISCUSSION

### Experiments conducted in 2014

A similar pattern of high (≥89%) initial control (20 DAM) was observed in all experiments, when the 2,4-D was applied immediately after mowing (Application A), with no significative differences among doses (Tables 4, 5, 6 and 7).

The good performance observed when 2,4-D was applied immediately after cotton mowing resulted most likely from the redistribution inside the plants after herbicide absorption by the vascular bundles exposed after mowing (Senseman, 2007; Mithila et al., 2011). Despite the marked efficacy observed in Application A at 20 DAM, the destruction of cotton crop residues is challenging due to the high resprouting capacity of these plants. Thus, new herbicide applications or the adoption of new mechanical control measures are usually required (Bianchini and Borges, 2013).

An important factor should be considered before interpreting the data from the final rating of the cotton stalk control performed at the different sites (experiments). The experiments conducted in Mato Grosso state (E3 and E4) differed from the experiments conducted in Santa Helena de Goiás and Nova Ponte (E1 and E2) because the mowed plants for which the Application B and C treatments were planned had similar stub lengths at the same time; therefore, these applications were performed on the same date for these sites. The analysis of these data alone could suggest that applying 2,4-D immediately after mowing in the experiments conducted in Mato Grosso showed no advantages compared with the treatments without herbicides for cotton stalk management. However, the analysis of the control data, percentages of stub plants, and stub lengths clearly showed the benefits of Application A.

The final control evaluation (90 DAM) in Santa Helena de Goiás and Nova Ponte clearly indicated superior cotton stalk control in treatments with sequential herbicide applications compared with treatments with a single application to stub plants (Tables 4 and 5). For improved levels of stalk control at 90 DAM, a second spraying with 2,4-D alone at application C was more efficient than the application of flumiclorac. Mixtures of 2,4-D and flumiclorac or imazethapyr provided control similar to 2,4-D alone.

***Table 4*** **-** Control and stub lengths of glyphosate-resistant cotton stalks as a function of the application of herbicide treatments. Santa Helena de Goiás (E1), 2014

| Treatment (g a.i. or a.e. $ha^{-1}$) | | | Evaluations (DAM[1]) | | |
|---|---|---|---|---|---|
| Application A (After mowing) | Application B (Single application) | Application C (Sequential application) | % control | | SL (cm) |
| | | | 20 | 90 | 90 |
| 2,4D (1340) | - | - | 92 a[2] | 51 c | 13 a |
| 2,4D (1675) | - | - | 91 a | 61 c | 12 a |
| 2,4D (1340) | - | 2,4D (670) | 89 a | 96 a | 7 b |
| 2,4D (1675) | - | 2,4D (670) | 94 a | 99 a | 4 b |
| 2,4D (1340) | - | 2,4D (335) + flu (60) | 94 a | 99 a | 2 b |
| 2,4D (1675) | - | 2,4D (335) + flu (60) | 93 a | 98 a | 3 b |
| 2,4D (1340) | - | 2,4D (670) + flu (60) | 94 a | 100 a | 0 b |
| 2,4D (1675) | - | 2,4D (670) + flu (60) | 93 a | 99 a | 6 b |
| 2,4D (1340) | - | flu (60) | 92 a | 86 b | 11 a |
| 2,4D (1675) | - | flu (60) | 91 a | 77 b | 9 a |
| 2,4D (1340) | - | 2,4D (670) + ima (106) | 91 a | 99 a | 4 b |
| - | 2,4D (670) | - | 0 b | 74 b | 9 a |
| - | 2,4D (1005) | - | 0 b | 85 b | 11 a |
| - | 2,4D (1340) | - | 0 b | 95 a | 9 a |
| - | 2,4D (670) + flu (60) | - | 0 b | 79 b | 10 a |
| - | 2,4D (1005) + flu (60) | - | 0 b | 81 b | 10 a |
| - | 2,4D (670) + ima (106) | - | 0 b | 82 b | 10 a |
| - | flu (60) | - | 0 b | 38 d | 11 a |
| Control without herbicide | | | 0 b | 0 e | 13 a |

(1) Abbreviations: DAM, days after mowing; SL, stub lengths; 2,4D, 2,4-D amine; flu, flumiclorac; ima, imazethapyr. (2) Means followed by different letters differ from one another according to the Scott-Knott test ($p \leq 0.05$).

***Table 5*** **-** Control and stub lengths of glyphosate-resistant cotton stalks as a function of the application of herbicide treatments. Nova Ponte (E2), 2014

| Treatment (g a.i. or a.e. $ha^{-1}$) | | | Evaluations (DAM[1]) | | |
|---|---|---|---|---|---|
| Application A (After mowing) | Application B (Single application) | Application C (Sequential application) | % control | | SL (cm) |
| | | | 20 | 90 | 90 |
| 2,4D (1340) | - | - | 100 | 50 f[2] | 9 b |
| 2,4D (1675) | - | - | 100 | 63 e | 7 b |
| 2,4D (1340) | - | 2,4D (670) | 100 | 98 a | 3 c |
| 2,4D (1675) | - | 2,4D (670) | 100 | 98 a | 3 c |
| 2,4D (1340) | - | 2,4D (335) + flu (60) | 100 | 95 a | 3 c |
| 2,4D (1675) | - | 2,4D (335) + flu (60) | 100 | 98 a | 3 c |
| 2,4D (1340) | - | 2,4D (670) + flu (60) | 100 | 98 a | 3 c |
| 2,4D (1675) | - | 2,4D (670) + flu (60) | 100 | 98 a | 3 c |
| 2,4D (1340) | - | flu (60) | 100 | 90 b | 4 c |
| 2,4D (1675) | - | flu (60) | 100 | 90 b | 5 c |
| 2,4D (1340) | - | 2,4D (670) + ima (106) | 100 | 95 a | 3 c |
| - | 2,4D (670) | - | 0 | 35 g | 11 b |
| - | 2,4D (1005) | - | 0 | 71 d | 6 c |
| - | 2,4D (1340) | - | 0 | 78 c | 6 c |
| - | 2,4D (670) + flu (60) | - | 0 | 70 d | 7 b |
| - | 2,4D (1005) + flu (60) | - | 0 | 85 b | 7 b |
| - | 2,4D (670) + ima (106) | - | 0 | 85 b | 7 b |
| - | flu (60) | - | 0 | 60 e | 9 b |
| Control without herbicide | | | 0 | 0 h | 19 a |

(1) Abbreviations: DAM, days after mowing; SL, stub lengths; 2,4D, 2,4-D amine; flu, flumiclorac; ima, imazethapyr. (2) Means followed by different letters differ from each other according to the Scott-Knott test ($p \leq 0.05$).

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***Table 6*** **-** Percentages of control and stub lengths of glyphosate-resistant cotton stalks as a function of the application of herbicide treatments. Primavera do Leste (E3), 2014

| Treatment (g a.i. or a.e. ha$^{-1}$) | | | Evaluations (DAM[1]) | | |
|---|---|---|---|---|---|
| Application A (After mowing) | Application B (Single application) | Application C (Sequential application) | % control | | SL (cm) |
| | | | 20 | 50 | 50 |
| 2,4D (1340) | - | - | 93 a[2] | 54 c | 10 b |
| 2,4D (1675) | - | - | 93 a | 46 d | 9 b |
| 2,4D (1340) | - | 2,4D (670) | 93 a | 80 b | 4 c |
| 2,4D (1675) | - | 2,4D (670) | 94 a | 79 b | 5 c |
| 2,4D (1340) | - | 2,4D (335) + flu (60) | 94 a | 83 b | 2 c |
| 2,4D (1675) | - | 2,4D (335) + flu (60) | 93 a | 86 a | 2 c |
| 2,4D (1340) | - | 2,4D (670) + flu (60) | 92 a | 91 a | 2 c |
| 2,4D (1675) | - | 2,4D (670) + flu (60) | 94 a | 90 a | 1 c |
| 2,4D (1340) | - | flu (60) | 92 a | 75 b | 4 c |
| 2,4D (1675) | - | flu (60) | 95 a | 78 b | 3 c |
| 2,4D (1340) | - | 2,4D (670) + ima (106) | 93 a | 75 b | 6 b |
| - | 2,4D (670) | - | 0 b | 35 e | 7 b |
| - | 2,4D (1005) | - | 0 b | 40 e | 9 b |
| - | 2,4D (1340) | - | 0 b | 48 d | 8 b |
| - | 2,4D (670) + flu (60) | - | 0 b | 60 c | 7 b |
| - | 2,4D (1005) + flu (60) | - | 0 b | 76 b | 7 b |
| - | 2,4D (670) + ima (106) | - | 0 b | 59 c | 8 b |
| - | flu (60) | - | 0 b | 35 e | 12 b |
| Control without herbicide | | | 0 b | 0 f | 17 a |

[1] Abbreviations: DAM, days after mowing; SL, stub lengths; 2,4D, 2,4-D amine; flu, flumiclorac; ima, imazethapyr. [2] Means followed by different letters differ from each other according to the Scott-Knott test ($p \leq 0.05$).

***Table 7*** **-** Percentages of control and stub length of glyphosate-resistant cotton stalks as a function of the application of herbicide treatments. Sorriso (E4), 2014

| Treatment (g a.i. or a.e. ha$^{-1}$) | | | Evaluations (DAM[1]) | | |
|---|---|---|---|---|---|
| Application A (After mowing) | Application B (Single application) | Application C (Sequential application) | % control | | SL (cm) |
| | | | 20 | 50 | 50 |
| 2,4D (1340) | - | - | 92 a[2] | 39 c | 7 c |
| 2,4D (1675) | - | - | 92 a | 45 c | 7 c |
| 2,4D (1340) | - | 2,4D (670) | 95 a | 69 b | 5 c |
| 2,4D (1675) | - | 2,4D (670) | 92 a | 65 b | 5 c |
| 2,4D (1340) | - | 2,4D (335) + flu (60) | 94 a | 81 a | 6 c |
| 2,4D (1675) | - | 2,4D (335) + flu (60) | 94 a | 76 a | 6 c |
| 2,4D (1340) | - | 2,4D (670) + flu (60) | 93 a | 89 a | 4 c |
| 2,4D (1675) | - | 2,4D (670) + flu (60) | 93 a | 88 a | 5 c |
| 2,4D (1340) | - | flu (60) | 93 a | 64 b | 5 c |
| 2,4D (1675) | - | flu (60) | 92 a | 61 b | 5 c |
| 2,4D (1340) | - | 2,4D (670) + ima (106) | 93 a | 74 b | 5 c |
| - | 2,4D (670) | - | 0 b | 39 c | 9 b |
| - | 2,4D (1005) | - | 0 b | 36 c | 10 b |
| - | 2,4D (1340) | - | 0 b | 43 c | 6 c |
| - | 2,4D (670) + flu (60) | - | 0 b | 51 c | 8 b |
| - | 2,4D (1005) + flu (60) | - | 0 b | 44 c | 9 b |
| - | 2,4D (670) + ima (106) | - | 0 b | 43 c | 8 b |
| - | flu (60) | - | 0 b | 28 c | 10 b |
| Control without herbicide | | | 0 b | 0 d | 14 a |

[1] Abbreviations: DAM, days after mowing; SL, stub lengths; 2,4D, 2,4-D amine; flu, flumiclorac; ima, imazethapyr. [2] Means followed by different letters differ from each other according to the Scott-Knott test ($p \leq 0.05$).

Different results were found for E1 and E2 regarding the single application of 2,4-D for the chemical management of cotton stalk. 2,4-D showed limited efficacy when applied alone immediately after cotton mowing (Application A) in the experiment conducted in Santa Helena de Goiás. However, single-application treatments with 2,4-D applied at stub length ranging from 5 to 10 cm (Application B) demonstrated improved control proportional to the doses of 2,4-D applied (Table 4). In the experiment conducted in Nova Ponte (Table 5), the maximum control provided by 2,4-D applied alone was 78%, which was insufficient to prevent the cotton stalk from resprouting.

Under the situation of restricted availability of time faced by many farmers, when only one application could be used for cotton stalk destruction (simulating Application B), the results from E1 and E2 demonstrate that, in this case, the best alternatives are the use of a high dose of 2,4-D alone (1,340 g a.e. $ha^{-1}$) or combinations of this active ingredient with other herbicides with different mechanisms of action (flumiclorac or imazethapyr). Nevertheless, these treatments alone failed to meet the host-free period required by law that is 60 days after cotton harvest.

The stub lengths of the cotton plants were inversely related to the control evaluations, because the final stub length was shortest in the treatments with the highest efficacy in the chemical destruction of cotton stalk (Tables 4 and 5). Data from E2 showed the importance of combining mowing with herbicide application for cotton stalk control, since the stub lengths were shorter than the stub lengths of the control plants without herbicide, where only mowing was used, even in treatments without high control levels (Table 5). Similar to the visual control evaluation, the treatments with the highest efficacy in decreasing cotton stub resprouting consisted of sequential herbicide applications.

Similar to E1 and E2, the treatments consisting of sequential herbicide applications in both experiments conducted in Mato Grosso (E3 and E4) provided higher efficacy in cotton stalk control than the treatments with a single application (Tables 6 and 7). Accordingly, the best alternatives were the treatments consisting of 2,4-D application immediately after cotton mowing (regardless of the dose), followed by sequential application of 2,4-D + flumiclorac.

Flumiclorac is a protoporphyrinogen oxidase inhibitor, with typical contact effect (Ramires et al., 2010; Nandula et al., 2012). Although fast plant defoliation was found in treatments with flumiclorac application alone (60 g a.i. $ha^{-1}$), no further injury symptoms were observed, which accounted for the relatively low control levels provided by this herbicide.

The results clearly indicate that the chemical destruction of cotton stalk with flumiclorac should be performed only in combination with other herbicides or in management systems that include sequential applications. The combination of herbicides with different mechanisms of action allows an expanded spectrum of weed control in a single application, which not only improves weed control, but also work as an important measure to delay selection of resistant populations (Craigmyle et al., 2013).

Treatments consisting of sequential herbicide applications also provided the greatest reductions in cotton stub lengths in E3 and E4, with a 72% mean reduction in this variable observed in this group of treatments compared with the mowed control without herbicides (Tables 6 and 7). A smaller cotton stub length enables the use of lower doses or even fewer applications for the chemical control of cotton stalk, because the plants are more sensitive to herbicide activity with a decreased recovery potential.

Table 8 outlines the results of the assessment of stub plant percentages in Experiments 1 and 2. In treatments with mowing and no herbicide application, the percentages of plants that did not resprout (averaging 59 and 9% at 90 DAM in E1 and E2, respectively) demonstrate the contribution of the mowing practice to cotton stalk destruction. This result also indicates that mowing when performed only once is unable to ensure acceptable levels of elimination of cotton stalk to meet the requirements of host-free period.

The benefits of herbicide application immediately after cotton mowing may be observed in the evaluations performed at 20 DAM. In both experiments (E1 and E2) fewer stub plants were found in those treatments when compared to treatments with mechanical control only. This is probably related to the associated effect of physical damage caused by cotton shoot mowing and the intoxication caused by the herbicides, creating adverse conditions for the morphophysiological recovery of the cotton plants.

***Table 8*** **-** Percentages of stub regrowth cotton plants as a function of the application of herbicide treatments. Santa Helena de Goiás (E1) and Nova Ponte (E2), 2014

| Treatment (g a.i. or a.e. $ha^{-1}$) | | | Evaluations (DAM[1]) | | | |
|---|---|---|---|---|---|---|
| Application A (After mowing) | Application B (Single application) | Application C (Sequential application) | E1 | | E2 | |
| | | | 20 | 90 | 20 | 90 |
| 2,4D (1340) | - | - | 21 b[2] | 18 b | 0 c | 57 c |
| 2,4D (1675) | - | - | 31 b | 21 b | 0 c | 48 c |
| 2,4D (1340) | - | 2,4D (670) | 31 b | 5 c | 0 c | 11 d |
| 2,4D (1675) | - | 2,4D (670) | 18 b | 1 d | 0 c | 13 d |
| 2,4D (1340) | - | 2,4D (335) + flu (60) | 19 b | 1 d | 0 c | 14 d |
| 2,4D (1675) | - | 2,4D (335) + flu (60) | 25 b | 1 d | 0 c | 11 d |
| 2,4D (1340) | - | 2,4D (670) + flu (60) | 22 b | 0 d | 0 c | 10 d |
| 2,4D (1675) | - | 2,4D (670) + flu (60) | 25 b | 1 d | 0 c | 11 d |
| 2,4D (1340) | - | flu (60) | 23 b | 9 c | 0 c | 15 d |
| 2,4D (1675) | - | flu (60) | 26 b | 11 c | 0 c | 15 d |
| 2,4D (1340) | - | 2,4D (670) + ima (106) | 20 b | 1 d | 0 c | 11 d |
| - | 2,4D (670) | - | 72 a | 16 b | 90 a | 66 b |
| - | 2,4D (1005) | - | 50 a | 7 c | 95 a | 39 c |
| - | 2,4D (1340) | - | 50 a | 2 d | 93 a | 39 c |
| - | 2,4D (670) + flu (60) | - | 55 a | 11 c | 94 a | 41 c |
| - | 2,4D (1005) + flu (60) | - | 54 a | 6 c | 90 a | 33 c |
| - | 2,4D (670) + ima (106) | - | 60 a | 10 c | 81 b | 35 c |
| - | flu (60) | - | 59 a | 25 b | 89 a | 43 c |
| Control without herbicide | | | 59 a | 41 a | 97 a | 91 a |

(1) Abbreviations: DAM, days after mowing; 2,4D, 2,4-D amine; flu, flumiclorac; ima, imazethapyr. (2) Means followed by different letters differ from each other according to the Scott-Knott test ($p \leq 0.05$).

Generally, the plots treated with more than one herbicide application had fewer stub plants at 90 DAM. Thus, like the results from the visual control evaluations, the best alternatives to reduce the number of resprouted plants for single-application treatments (Application B) consisted of using herbicide combinations or 2,4-D at high doses (Table 8).

The percentage of stub cotton plants decreased in both experiments conducted in Mato Grosso (E3 and E4) when 2,4-D was applied immediately after cotton mowing (Table 9). The differences in the percentages of stub plants between treatments with single or sequential applications decreased at 50 DAM when Applications B and C had already been performed. However, the percentages of stub plants remained lower in the plots treated with more than one herbicide application. The performance observed following treatment with a single herbicide application (Application B) in E3 and E4 differed. High percentages of stub cotton plants were observed in this group of treatments in the experiment conducted in Primavera do Leste, whereas these values remained high but differed from the control without herbicides in the experiment conducted in Sorriso.

To better understand the practical implications of the results of the different experiments on glyphosate-resistant cotton stalk destruction, a contrast analysis was performed for the stub length response variable between treatments with two sequential herbicide applications (Applications A and C) and treatments with one single application (Application B; Table 10). Significant differences between the groups of treatments were observed at all sites, demonstrating that herbicide application immediately after mowing followed by a second application at the start of plant resprouting had a higher potential to destroy cotton stalk than a single application.

In the contrast analysis, the smallest differences in stub cotton lengths were observed in the experiment conducted in Sorriso, because the plants treated with sequential herbicide applications had stubs that were on average 3 cm shorter than the stubs of the plants treated with a single application (Table 10). The analysis of this performance together with the data on the percentages of control and stub cotton plants clearly showed that these variables were related, because the experiment conducted in Sorriso had the lowest treatment efficacy of all experiments.

***Table 9*** **-** Percentages of stub regrowth cotton plants as a function of the application of herbicide treatments. Primavera do Leste (E3) and Sorriso (E4), 2014

| Treatment (g a.i. or a.e. ha$^{-1}$) | | | Evaluations (DAM[1]) | | | |
|---|---|---|---|---|---|---|
| | | | E3 | | E4 | |
| Application A (After mowing) | Application B (Single application) | Application C (Sequential application) | 20 | 50 | 20 | 50 |
| 2,4D (1340) | - | - | 43 b[2] | 64 b | 41 b | 59 b |
| 2,4D (1675) | - | - | 49 b | 62 b | 43 b | 57 b |
| 2,4D (1340) | - | 2,4D (670) | 45 b | 37 c | 46 b | 32 d |
| 2,4D (1675) | - | 2,4D (670) | 48 b | 43 c | 46 b | 33 d |
| 2,4D (1340) | - | 2,4D (335) + flu (60) | 51 b | 16 d | 46 b | 20 e |
| 2,4D (1675) | - | 2,4D (335) + flu (60) | 46 b | 14 d | 43 b | 18 e |
| 2,4D (1340) | - | 2,4D (670) + flu (60) | 48 b | 7 d | 44 b | 6 f |
| 2,4D (1675) | - | 2,4D (670) + flu (60) | 40 b | 8 d | 43 b | 9 f |
| 2,4D (1340) | - | flu (60) | 50 b | 39 c | 46 b | 43 c |
| 2,4D (1675) | - | flu (60) | 33 b | 24 d | 45 b | 39 d |
| 2,4D (1340) | - | 2,4D (670) + ima (106) | 37 b | 33 c | 43 b | 33 d |
| - | 2,4D (670) | - | 93 a | 88 a | 75 a | 61 b |
| - | 2,4D (1005) | - | 96 a | 93 a | 71 a | 65 b |
| - | 2,4D (1340) | - | 97 a | 77 b | 67 a | 49 c |
| - | 2,4D (670) + flu (60) | - | 93 a | 79 b | 77 a | 62 b |
| - | 2,4D (1005) + flu (60) | - | 91 a | 48 c | 76 a | 54 c |
| - | 2,4D (670) + ima (106) | - | 99 a | 78 b | 78 a | 64 b |
| - | flu (60) | - | 97 a | 74 b | 83 a | 66 b |
| Control without herbicide | | | 97 a | 98 a | 76 a | 89 a |

[1] Abbreviations: DAM, days after mowing; 2,4D, 2,4-D amine; flu, flumiclorac; ima, imazethapyr. [2] Means followed by different letters differ from each other according to the Scott-Knott test ($p \leq 0.05$).

***Table 10*** **-** Estimated contrasts for cotton stub length

| Site | $\hat{C}$ = Applications A + C *versus* Application B |
|---|---|
| | Estimate |
| Santa Helena de Goiás (E1) | -5[1] |
| Nova Ponte (E2) | -4 |
| Primavera do Leste (E3) | -5 |
| Sorriso (E4) | -3 |

[1] Means differ significantly according to the method of orthogonal contrasts at 1% probability.

One possible explanation for the decreased efficacy of the treatments in cotton stalk destruction in Sorriso may be related to the total volume of rainfall between mowing and completing the last evaluation in this experiment. The daily rainfall rate during the period was 0.07 mm in this area, whereas the values were 1.36, 2.4, and 0.84 mm in E1, E2, and E3 (Figure 1).

Drought has a negative impact on cotton stalk destruction because the soil water deficit limits herbicide redistribution inside plants due to the reduced water absorption and evapotranspiration capacity. Reduced herbicide efficacy under drought conditions has been reported for weeds, and increased wax deposition in the leaf epidermis and therefore decreased absorption have been described as the main reasons for this decreased performance (Hatterman-Valenti et al., 2006; Zhou et al., 2007).

The chemical method provided high control levels with an efficacy level conditioned by the number of applications and the active ingredient used. The application of flumiclorac alone was unable to satisfactorily control cotton stalk. Single 2,4-D application (regardless of the dose) either immediately after mowing or on stub cotton plants also failed to effectively control cotton stalk. Conversely, the best results were observed when 2,4-D was combined with other herbicides in sequential applications, with the additional benefit of broadening the weed control spectrum resulting from the use of these combinations of active ingredients. Furthermore, the possibility of reducing the 2,4-D dose in the second application through combination with other active ingredients decreases the risk of the occurrence of carryover to crops sown in succession, including soybean.

## Experiments conducted in 2015

At 20 DAM, the application of 2,4-D at 1340 g a.e. $ha^{-1}$ immediately after mowing decreased the percentage of regrowth cotton plants in relation to the control without herbicide application (Table 11). In Primavera do Leste and Campo Verde, the reduction in the percentage of regrowth promoted by the combined effect of mowing and 2,4-D application as compared to mowing was only, in average, 28 and 65%, respectively. Such results corroborate with what was found in the 2014 experiments, demonstrating the importance of combining mechanical and chemical practices to improve cotton stalk destruction.

***Table 11 -*** Percentages of stub regrowth cotton plants as a function of the application of herbicide treatments. Primavera do Leste (E5) and Campo Verde (E6), 2015

| Treatment (g a.i. or a.e. $ha^{-1}$) | | Evaluations (DAM[1]) | | | | | |
|---|---|---|---|---|---|---|---|
| Application A (After mowing) | Application B (Sequential application) | E5 | | | E6 | | |
| | | 20 | 35 | 50 | 20 | 35 | 50 |
| 2,4D (1340) | 2,4D (670) | 45 b | 9 c | 11 d | 31 b | 6 b | 7 b |
| 2,4D (1340) | 2,4D (670) + par (400) | 42 b | 14 b | 23 b | 37 b | 5 b | 6 b |
| 2,4D (1340) | 2,4D (670) + gly (1440) | 46 b | 12 b | 12 d | 34 b | 5 b | 7 b |
| 2,4D (1340) | 2,4D (1340) + gly (1440) | 42 b | 14 b | 17 c | 34 b | 3 b | 7 b |
| 2,4D (1340) | 2,4D (670) + glu (400) | 43 b | 5 d | 7 e | 38 b | 6 b | 10 b |
| 2,4D (1340) | 2,4D (670) + car (28) | 47 b | 1 e | 3 f | 32 b | 2 b | 3 b |
| 2,4D (1340) | 2,4D (670) + flu (60) | 43 b | 1 e | 3 f | 36 b | 1 b | 3 b |
| 2,4D (1340) | 2,4D (1005) + flu (60) | 44 b | 1 e | 2 f | 39 b | 0 b | 2 b |
| 2,4D (1340) | 2,4D (1340) + flu (60) | 48 b | 0 e | 1 f | 31 b | 0 b | 2 b |
| 2,4D (1340) | 2,4D (670) + saf (49) | 49 b | 6 d | 8 e | 34 b | 2 b | 5 b |
| Control without herbicide | | 73 a | 84 a | 91 a | 62 a | 68 a | 69 a |

[1] Abbreviations: 2,4D, 2,4-D amine; par, paraquat; gly, glyphosate; glu, glufosinate; car, carfentrazone; flu, flumiclorac; saf, saflufenacil; DAM, days after mowing. [2] Means followed by different letters differ from each other according to the Scott-Knott test ($p \leq 0.05$).

At 35 DAM, the lower percentage of regrowth plants was verified in treatments where the association of 2,4-D with carfentrazone or flumiclorac was used in Application B in Primavera do Leste (E5) (Table 11). The increase of 2,4-D dose at application B, when applied in association with flumiclorac, did not show any positive effect to reduce regrowth of cotton plants. For the Campo Verde experiment, no differences among the herbicides used in application B were found, and performance was similar for all herbicidal treatments until 50 DAM.

Despite glufosinate and saflufenacil caused a slightly lower control when compared to carfentrazone and flumiclorac, their application in association with 2,4-D provided a significant reduction in cotton regrowth. These results indicate that glufosinate and saflufenacil could be evaluated in upcoming experiments, so alternatives from other mechanisms of action can be available for cotton stalk destruction.

The efficacy of chemical destruction of glyphosate-resistant cotton stalk varies according to the weather conditions that occur after herbicide application. The application of 2,4-D immediately after cotton mowing is essential for cotton stalk destruction; however, this treatment alone does not provide acceptable efficacy. Also, a single application to regrowth plants shows no acceptable efficacy in cotton stalk destruction. The best options for glyphosate-resistant cotton stalk control are 2,4-D application immediately after mowing, followed by application of combinations of 2,4-D and herbicides such as flumiclorac, carfentrazone or imazethapyr to stub cotton plants.

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