



How intercropping systems with corn (*Zea mays*) and *Urochloa ruziziensis* can affect the abundance of *Rhopalosiphum maidis*

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Abstract The cropping systems commonly used in Brazil provide an abundance of hosts for *Rhopalosiphum maidis*. This aphid is an abundant pest in corn and its polyphagous habit allows it to infest many species of Poaceae. This study aimed to examine the effect of cropping systems on the population abundance and dynamics of *R. maidis*. The cropping systems evaluated were Fallow, Hybrid corn SYN 7205 TG, SYN 7205 TLTG Viptera, event MIR162 + Bt11, *Urochloa ruziziensis* grown as monocultures, while intercropping systems included SYN 7205 TG + *U. ruziziensis* and SYN 7205 TLTG Viptera + *U. ruziziensis*. Treatments consisted of five repetitions arranged in randomized blocks. The trial was carried out with two harvests in summer and one in fall. The *R. maidis* population in the three seasons was best described by the negative binomial generalized linear model, and the means were compared by overlapping the confidence intervals predicted by the adjusted

model. When differences occurred, monoculture corn positively affected the abundance of *R. maidis*, while its reproductive performance in *U. ruziziensis* and fallow was lower. Thus, the intercropping with *U. ruziziensis* contributed to aphid management by reducing its population *R. maidis*.

Keywords Santa Fé System · Crop-livestock Integration · ILP · Intercropping System · Vip3Aa20

Introduction

Corn (*Zea mays* L.) and *Urochloa* spp., (sin. *Brachiaria* spp.) intercropping is widely used in the Brazilian agricultural system. It is aimed at grain production and biomass for animal pasture and/or plant residues for direct planting to improve the physical and chemical qualities of the soil and carbon balance, but it also provides a diversity of hosts for *Rhopalosiphum maidis* (Fit.) (Hemiptera: Aphidini).

Assuming that *R. maidis* has the ability to use several species of Poaceae as hosts (Hesler & Dagel, 2010; Robinson & Hsu, 1963), which in Brazil includes corn, sugarcane (*Saccharum officinarum* L.), wheat (*Triticum aestivum* L.), and some forage grasses (eg, *Urochloa* spp.) (Carena & Glogoza, 2004; Foott, 1977; Parchen & Auad, 2016), a direct effect of plant species in intercropping systems on the biology of this pest would be expected.

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In corn, *R. maidis* is the most abundant insect (Resende et al., 2016) in both genetically modified (GM) plants for the expression of endotoxins of the bacterium *Bacillus thuringiensis* Ber. (*Bt*) or non-*Bt* varieties (Shu et al., 2019). Its vertical distribution in this plant occurs initially in the whorl, a structure that provides shelter from biotic (Gonzales et al., 2001) and abiotic factors, but with the development of the plant, this aphid is also found in the leaf sheath, stem, tassel, and leaves covering the ear (Foott, 1977; Resende et al., 2016), most often with individuals grouped in colonies.

A high infestation rate of *R. maidis* in the host is positively associated with lower yields (Al-Eryan & El-Tabbakh, 2004; Foott & Timmins, 1973). Damage caused by this aphid occurs by direct feeding, with the insertion of the stylet into the openings of the stomata of the plant or through the epidermis, intracellular or intercellular, to reach the phloem sap (Bing et al., 1991), thus removing plant nutrients. Moreover, *R. maidis* is a vector of important viruses (Ahmad et al., 2006; Gonçalves et al., 2017; Mar et al., 2013), and honeydew, the liquid residue of carbohydrates, the main component of phloem, is continuously secreted during feeding and accumulates in host structures (Ohshima et al., 1990; Yesbergenova-Cuny et al., 2016).

Given the widespread cultivation of genetically modified corn expressing Bt endotoxins in Brazil, it is essential to include Bt plants in this study. Although Bt toxins are primarily targeted at lepidopteran and coleopteran pests, their potential indirect effects on non-target organisms such as *R. maidis* remain insufficiently understood (Faria et al., 2007). Bt corn may alter plant physiology, nutritional quality, or secondary metabolite profiles, which could in turn influence aphid feeding behavior, population dynamics, and virus transmission. Moreover, the increasing adoption of Bt varieties in intercropping systems with *Urochloa* spp. necessitates

an evaluation of whether these genetically modified plants interact with the host matrix to affect *R. maidis* biology differently than their non-Bt counterparts (Lanzoni et al., 2022). Therefore, including Bt corn in this study is justified to provide a more comprehensive and realistic assessment of *R. maidis* ecology under current Brazilian agricultural conditions. Thus, monocropping and intercropping systems with corn and/or *U. ruziziensis* used in Brazil are excellent models used to examine the behavior of *R. maidis* for the first time, as well as to study the effect that each of them has on the population of this Aphididae.

Materials and methods

The study was carried out at the Experimental Farm of Agricultural Sciences of the Federal University of Grande Dourados (FAECA/UFGD), in Dourados, Mato Grosso do Sul, Brazil, 22°13' S, 54°59' W, and elevation of 458 m. Three different field experiments were conducted during three growing seasons, two as the first season (Summer 2017/2018 and 2018/2019) and one as the second season (Fall 2018). The treatment factors (cropping systems) were (T1) fallow, (T2) hybrid corn SYN 7205 TG (M-S), (T3) SYN 7205 TLTG Viptera, event MIR162+Bt11 (MBt-S), and (T4) *U. ruziziensis* (U-S) as monocultures, while intercropping systems consisted of (T5) SYN 7205 TG (M-I)+*U. ruziziensis* (U-IBt) and (T6) SYN 7205 TLTG Viptera (MBt-I)+*U. ruziziensis* (U-IBt) (Table 1).

Experimental design, cropping system and assessments

Each experimental unit (plot) consisted of 120 m² (10 m×12 m) randomly distributed in five blocks

Table 1 Field trial treatments

treatment	description
t1	cleared soil of vegetation
t2	supremo viptera 3 (nk supremo viptera 3- syngenta®)
t3	status viptera 3 (s1 syn 7205 status tltg vip tc—syngenta®)
t4	sole ruzigrass (<i>U. ruziziensis</i> —brs integra- embrapa)
t5	ruzigrass intercropped with non-bt corn (status tg - syngenta®)
t6	ruzigrass intercropped with bt corn (status vip3 tg tl—syngenta®)

(repetitions), covering 3600 m² of the total area of each experiment (season). Fallow (treatment 1) consisted of cleared soil of vegetation, which promoted the spontaneous growth of plants in the study area, resulting in different species, densities, and distributions in the plots and seasons, as there was no interference in their development. Sowing in the remaining treatments was carried out mechanically. In the case of hybrid corn, spacing was 0.9 m between rows with six plants every 1 m, and for *U. ruziziensis*, spacing was 0.2 m between rows with nine plants every 1 m.

Prior to sowing, the soil in the treatment plots was plowed, harrowed (conventional planting). Fertilization was carried out at planting, with application of 48 kg ha⁻¹ of K₂O in the form of potassium chloride (60% K₂O), incorporated into the soil through the seedling furrow. For nitrogen, topdressing fertilization was performed at the V4 phenological stage of the maize crop, using a rate of 69 kg ha⁻¹ of N in the form of urea (45% N). The nitrogen fertilizer was broadcast onto the soil surface without subsequent mechanical incorporation, evenly covering the inter-row spaces as well. Both fertilizations were carried out manually and uniformly.

Irrigation was homogeneously carried out with sprinklers when needed, as well as weed control in mechanically sown plots and surrounding areas. The latter consisted of an initial use of the herbicide's atrazine and mesotrione (800 and 48 g of active ingredient per hectare, respectively) and then manual weeding. No pest control method was used in the area during the experiments.

Assessment of *R. maidis*

Specimens of *R. maidis* in the field were systematically quantified in the field through visual assessments. Assessments were carried out every 7 ± 3 days and consisted of sampling four whole corn plants and/or six tillers of *U. ruziziensis* or six weeds, depending on the plot, starting on November 2017 (n = 14), May 2018 (n = 16) and December 2018 (n = 13) for the first, second, and third seasons, respectively, between the phenological corn stage V4-V5 (fourth—fifth fully expanded leaf) and the end of R6 (physiological maturity), according to Ritchie et al. (1993).

Statistical analysis

All statistical analyses were performed with R software (R Core Team, 2019). Poisson, quasi-Poisson

and negative binomial models were tested. The simulated normal envelope (Moral et al., 2017) revealed that the generalized linear negative binomial model was the best fit for the *R. maidis* population dynamic data for the three seasons. The means were contrasted by overlapping confidence intervals predicted by the negative binomial model, which are presented in the figures, while in the tables, only the original means are shown. The figures were created using the ggplot2 package (Wickham, 2016).

Results

The *R. maidis* population was compared among treatments and during the development of each crop, individualized per plant, independent of the cropping system (Tables 2, 3, 4).

2017–2018 summer season

Among crops (rows), differences were observed starting at day 14 (Fallow 1.67; U-IBt 0.03) until day 77, R6 (M-S 6.00; U-S 0.20) (Fig. 1A) (LRT = 200.30; $P < 0.0001$). When only maize plants were compared in the different cropping systems, at day 28, R1, (M-S 12.50; MBt-I 0.75) and at day 42, R2, (M-S 16.10; M-I 1.10), significant differences were observed (Table 2) (LRT = 31.40; $P < 0.05$). In addition, Fallow after day 14 differed from *U. ruziziensis* at day 42 (Fallow 2.40; U-S 0.10, and I-U 0.13) and at day 63 (Fallow 2.17; I-U 0.03) (LRT = 29.10; $P < 0.05$).

When comparing the infestation *R. maidis* only in the development of corn (columns), higher means were found between days 21 and 77, V9 and R6 (Table 2) (LRT = 30.01; $P < 0.05$), a period that coincides with population increase (Fig. 2). However, within this range, means differed in M-S at day 35, R1 (Fig. 2A), MBt-S at days 21, 35, 42 and 77, V9, R1, R2 and R6 (Fig. 2B), M-I and MBt-I between days 28 to 42, R1 to R2 (Fig. 2C), and at day 77, R6 to MBt-I (Fig. 2D).

In the case of *U. ruziziensis*, days with no variability (0.00) were interspersed with the means. For U-S, a significant difference was observed between days 1 and 56 (0.07 and 1.40) (Fig. 1B) (LRT = 25.05; $P < 0.05$), and for U-Ibt, the highest and similar means occurred between days 42 and 84 and excluded values without variability (Table 2).

Table 2 Summer Season 2017–2018. Mean $\pm$ se of the *R. maidis* population in different cultures and systems

Days	(T1) Fallow	(T2) Maize n Bt [Single]	(T3) Maize Bt [Single]	(T4) <i>U. ruziziensis</i> [Single]	(T5) Maize n Bt [Intercropping]	(T6) Maize Bt [Intercropping]	(T5) <i>U. ruziziensis</i> [Intercropping – n Bt]	(T6) <i>U. ruziziensis</i> [Intercropping – Bt]
1	1,000 $\pm$ 0,844 ABC a	0,000 $\pm$ 0,000 **	0,000 $\pm$ 0,000 **	0,067 $\pm$ 0,046 B a	0,050 $\pm$ 0,050 E a	0,000 $\pm$ 0,000 **	0,233 $\pm$ 0,141 A a	0,000 $\pm$ 0,000 **
7	0,133 $\pm$ 0,093 C a	0,200 $\pm$ 0,156 D a	0,050 $\pm$ 0,050 D a	0,133 $\pm$ 0,104 AB a	0,150 $\pm$ 0,109 DE a	0,000 $\pm$ 0,000 **	0,033 $\pm$ 0,033 A a	0,000 $\pm$ 0,000 **
14	1,667 $\pm$ 1,138 ABC a	0,900 $\pm$ 0,429 CD ab	0,100 $\pm$ 0,069 D ab	0,667 $\pm$ 0,483 AB ab	0,300 $\pm$ 0,300 DE ab	0,200 $\pm$ 0,138 D ab	0,500 $\pm$ 0,467 A ab	0,033 $\pm$ 0,033 B b
21	0,267 $\pm$ 0,209 BC bc	5,200 $\pm$ 3,248 AB a	4,850 $\pm$ 3,311 BC a	0,000 $\pm$ 0,000 **	2,800 $\pm$ 2,800 ABCD ab	9,900 $\pm$ 6,535 ABC a	0,133 $\pm$ 0,133 A c	0,000 $\pm$ 0,000 **
28	0,500 $\pm$ 0,291 BC cd	12,500 $\pm$ 6,697 AB a	7,650 $\pm$ 5,461 ABC ab	0,000 $\pm$ 0,000 **	1,500 $\pm$ 0,686 BCDE abc	0,750 $\pm$ 0,260 CD bcd	0,033 $\pm$ 0,033 A d	0,033 $\pm$ 0,033 B d
35	5,333 $\pm$ 3,586 A a	2,350 $\pm$ 1,286 BCD ab	5,000 $\pm$ 1,642 BC ab	0,000 $\pm$ 0,000 **	0,350 $\pm$ 0,302 DE b	2,000 $\pm$ 1,235 BCD ab	0,000 $\pm$ 0,000 **	0,000 $\pm$ 0,000 **
42	2,400 $\pm$ 2,234 AB ab	16,100 $\pm$ 4,786 AB a	4,450 $\pm$ 1,598 BC ab	0,100 $\pm$ 0,056 AB c	1,100 $\pm$ 0,518 CDE bc	3,450 $\pm$ 1,123 BC ab	0,133 $\pm$ 0,104 A c	1,000 $\pm$ 0,575 A bc
49	0,333 $\pm$ 0,268 BC c	64,300 $\pm$ 13,849 A a	46,900 $\pm$ 11,220 AB a	0,533 $\pm$ 0,287 AB c	6,900 $\pm$ 5,392 ABC ab	24,700 $\pm$ 8,927 AB a	0,167 $\pm$ 0,167 A c	0,700 $\pm$ 0,326 AB bc
56	0,300 $\pm$ 0,268 BC b	48,450 $\pm$ 15,559 A a	74,250 $\pm$ 22,435 A a	1,400 $\pm$ 1,130 A b	16,500 $\pm$ 8,588 AB a	26,100 $\pm$ 10,695 AB a	0,333 $\pm$ 0,188 A b	0,833 $\pm$ 0,732 AB b
63	2,167 $\pm$ 1,148 AB bc	54,150 $\pm$ 14,779 A a	31,450 $\pm$ 6,730 AB a	0,000 $\pm$ 0,000 **	11,300 $\pm$ 8,223 ABC ab	49,950 $\pm$ 14,687 A a	0,033 $\pm$ 0,033 A d	0,333 $\pm$ 0,175 AB cd
70	1,733 $\pm$ 1,502 ABC b	61,450 $\pm$ 15,778 A a	74,050 $\pm$ 23,094 A a	0,467 $\pm$ 0,403 AB b	32,700 $\pm$ 11,769 A a	76,800 $\pm$ 16,291 A a	0,600 $\pm$ 0,409 A b	0,000 $\pm$ 0,000 **
77	1,200 $\pm$ 0,903 ABC ab	6,000 $\pm$ 3,296 AB a	1,700 $\pm$ 1,310 CD ab	0,200 $\pm$ 0,121 AB b	2,600 $\pm$ 1,959 ABCD ab	3,350 $\pm$ 2,267 BC a	0,733 $\pm$ 0,249 A ab	0,867 $\pm$ 0,518 AB ab
84	0,133 $\pm$ 0,079 C a	1,800 $\pm$ 1,550 BCD a	0,650 $\pm$ 0,449 CD a	0,133 $\pm$ 0,079 AB a	0,150 $\pm$ 0,150 DE a	1,300 $\pm$ 1,300 CD a	0,367 $\pm$ 0,200 A a	0,433 $\pm$ 0,213 AB a
91	0,000 $\pm$ 0,000 **	0,000 $\pm$ 0,000 **	0,150 $\pm$ 0,150 D a	0,000 $\pm$ 0,000 **	0,000 $\pm$ 0,000 **	0,000 $\pm$ 0,000 **	0,200 $\pm$ 0,169 A a	0,033 $\pm$ 0,033 B a

*Values without variability. Uppercase letters compare values between columns and lowercase lines

Table 3 Fall Season 2018. Mean $\pm$ se of the *R. maidis* population in different cultures and systems

Days	(T1) Fallow	(T2) Maize n Bt [Single]	(T3) Maize Bt [Single]	(T4) <i>U. ruzizien-</i> <i>sis</i> [Single]	(T5) Maize n Bt [Intercropping]	(T6) Maize Bt [Intercropping]	(T5) <i>U. ruzizien-</i> <i>sis</i> [Intercropping - Bt]	(T6) <i>U. ruzizien-</i> <i>sis</i> [Intercropping - Bt]
1	0,00 $\pm$ 0,00 *	6,10 $\pm$ 1,78 A a	6,75 $\pm$ 1,87 A a	1,67 $\pm$ 0,51 A ab	3,60 $\pm$ 1,35 A ab	6,20 $\pm$ 1,82 A a	0,60 $\pm$ 0,35 A b	0,47 $\pm$ 0,25 A b
7	0,23 $\pm$ 0,12 C bc	3,40 $\pm$ 1,27 AB a	4,45 $\pm$ 1,27 A a	1,33 $\pm$ 0,46 AB ab	3,40 $\pm$ 0,92 A a	1,60 $\pm$ 0,63 ABC	0,10 $\pm$ 0,06 AB c	0,23 $\pm$ 0,10 A bc
14	0,40 $\pm$ 0,27 BC bc	5,15 $\pm$ 1,34 A a	2,80 $\pm$ 0,93 A ab	0,50 $\pm$ 0,32 ABC	2,35 $\pm$ 0,67 ABC	5,40 $\pm$ 2,78 A a	0,13 $\pm$ 0,10 AB c	0,00 $\pm$ 0,00 *
21	0,13 $\pm$ 0,13 C c	3,45 $\pm$ 0,91 ABC a	6,60 $\pm$ 2,16 A a	0,23 $\pm$ 0,14 ABC	2,15 $\pm$ 0,83 ABC	3,65 $\pm$ 1,12 A a	0,03 $\pm$ 0,03 B c	0,03 $\pm$ 0,03 A c
28	0,00 $\pm$ 0,00 *	5,15 $\pm$ 1,73 A a	3,80 $\pm$ 1,57 A a	0,20 $\pm$ 0,10 B b	3,25 $\pm$ 1,25 A a	2,75 $\pm$ 0,82 AB	0,03 $\pm$ 0,03 B b	0,07 $\pm$ 0,05 A b
35	0,00 $\pm$ 0,00 *	1,25 $\pm$ 0,76 ABC a	1,15 $\pm$ 0,44 ABC a	0,00 $\pm$ 0,00 *	0,75 $\pm$ 0,44 ABC a	1,20 $\pm$ 0,56 ABCD a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
42	0,50 $\pm$ 0,43 BC a	1,15 $\pm$ 0,7 ABC a	1,05 $\pm$ 0,49 ABC a	0,10 $\pm$ 0,10 C a	0,90 $\pm$ 0,76 ABC a	0,35 $\pm$ 0,24 BCD a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
49	0,10 $\pm$ 0,07 C bc	2,30 $\pm$ 0,98 ABC a	1,45 $\pm$ 0,94 AB ab	0,03 $\pm$ 0,03 C c	1,55 $\pm$ 0,57 ABC a	0,20 $\pm$ 0,16 CD	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
56	2,60 $\pm$ 2,23 AB a	0,30 $\pm$ 0,18 C abc	0,05 $\pm$ 0,05 C c	0,07 $\pm$ 0,05 C c	1,00 $\pm$ 1,00 ABC	1,65 $\pm$ 1,40 ABC	0,00 $\pm$ 0,00 *	0,20 $\pm$ 0,20 A bc
63	3,83 $\pm$ 3,73 A a	0,00 $\pm$ 0,00 *	0,15 $\pm$ 0,11 BC b	0,07 $\pm$ 0,07 C b	0,25 $\pm$ 0,18 C b	0,35 $\pm$ 0,21 BCD b	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
70	0,00 $\pm$ 0,00 *	1,15 $\pm$ 1,10 ABC a	1,80 $\pm$ 1,75 AB a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,05 $\pm$ 0,05 D b	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
77	0,00 $\pm$ 0,00 *	0,45 $\pm$ 0,45 BC a	2,00 $\pm$ 2,00 AB a	0,00 $\pm$ 0,00 *	0,25 $\pm$ 0,20 BC	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
84	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,85 $\pm$ 0,85 ABC a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *

*Values without variability. Uppercase letters compare values between columns and lowercase lines. Data from days 91, 98 and 105 were deleted because they showed no variability

Table 4 Summer Season 2018–2019. Mean $\pm$ se of the *R. maidis* population in different cultures and systems

Days	(T1) Fallow	(T2) Maize n <i>Bt</i> [Single]	(T3) Maize <i>Bt</i> [Single]	(T4) <i>U.</i> <i>ruziziensis</i> [Single]	(T5) Maize n <i>Bt</i> [Intercop- ping]	(T6) Maize <i>Bt</i> [Intercop- ping]	(T5) <i>U.</i> <i>ruziziensis</i> [Intercropping – n <i>Bt</i>]	(T6) <i>U.</i> <i>ruziziensis</i> [Intercropping – <i>Bt</i>]
1	0,00 $\pm$ 0,00 *	0,10 $\pm$ 0,07 D a	0,20 $\pm$ 0,12 E a	0,07 $\pm$ 0,05 A a	0,10 $\pm$ 0,10 D a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,33 $\pm$ 0,24 A a
7	0,00 $\pm$ 0,00 *	0,20 $\pm$ 0,16 CD a	0,15 $\pm$ 0,15 E a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
14	0,00 $\pm$ 0,00 *	0,30 $\pm$ 0,30 CD a	0,75 $\pm$ 0,75 DE a	0,27 $\pm$ 0,23 A a	0,00 $\pm$ 0,00 *	1,10 $\pm$ 0,64 B a	0,03 $\pm$ 0,03 A a	0,03 $\pm$ 0,03 A a
21	0,00 $\pm$ 0,00 *	1,55 $\pm$ 0,62 BCD ab	10,60 $\pm$ 6,78 ABC a	0,20 $\pm$ 0,14 A b	0,00 $\pm$ 0,00 *	3,65 $\pm$ 2,38 AB a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
28	0,00 $\pm$ 0,00 *	2,50 $\pm$ 1,60 BC a	2,15 $\pm$ 0,92 CDE a	0,00 $\pm$ 0,00 *	0,80 $\pm$ 0,47 CD a	0,85 $\pm$ 0,66 B a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
35	0,00 $\pm$ 0,00 *	0,90 $\pm$ 0,57 CD ab	6,75 $\pm$ 5,10 BCD a	0,13 $\pm$ 0,10 A b	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
42	0,00 $\pm$ 0,00 *	0,85 $\pm$ 0,80 CD ab	7,85 $\pm$ 3,90 ABCD a	0,00 $\pm$ 0,00 *	0,35 $\pm$ 0,30 CD b	0,80 $\pm$ 0,65 B ab	0,00 $\pm$ 0,00 *	0,03 $\pm$ 0,03 A b
49	0,03 $\pm$ 0,03 A b	19,30 $\pm$ 7,16 AB a	12,60 $\pm$ 5,10 ABC a	0,00 $\pm$ 0,00 *	2,60 $\pm$ 2,06 BC a	3,80 $\pm$ 3,20 AB a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
63	0,00 $\pm$ 0,00 *	88,20 $\pm$ 23,46 A a	58,10 $\pm$ 14,05 AB a	0,00 $\pm$ 0,00 *	4,10 $\pm$ 3,60 ABC b	19,75 $\pm$ 10,00 A ab	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
70	0,00 $\pm$ 0,00 *	129,10 $\pm$ 30,93 A a	84,70 $\pm$ 22,06 A a	0,00 $\pm$ 0,00 *	14,85 $\pm$ 11,28 AB a	36,25 $\pm$ 17,15 A a	0,00 $\pm$ 0,00 *	0,00 $\pm$ 0,00 *
77	0,00 $\pm$ 0,00 *	41,15 $\pm$ 21,08 A a	32,00 $\pm$ 7,59 AB a	0,00 $\pm$ 0,00 *	28,80 $\pm$ 21,61 AB a	10,10 $\pm$ 3,60 AB a	0,00 $\pm$ 0,00 *	0,33 $\pm$ 0,19 A b
84	0,00 $\pm$ 0,00 *	93,60 $\pm$ 28,45 A a	44,45 $\pm$ 19,32 AB a	0,00 $\pm$ 0,00 *	40,90 $\pm$ 19,41 A a	42,95 $\pm$ 25,71 A a	0,00 $\pm$ 0,00 *	0,20 $\pm$ 0,17 A b
91	0,00 $\pm$ 0,00 *	1,00 $\pm$ 0,78 CD ab	1,75 $\pm$ 1,60 CDE a	0,00 $\pm$ 0,00 *	0,90 $\pm$ 0,64 CD ab	5,75 $\pm$ 2,17 AB a	0,07 $\pm$ 0,05 A b	0,57 $\pm$ 0,30 A ab

*Values without variability. Uppercase letters compare values between columns and lowercase lines

2018 fall season

The comparisons among crops revealed that at day 1, V4, M-S, MBt-S, U-S, and MBt-I treatments were significantly different from U-I and U-Ibt (LRT=24.00; $P<0.05$), and at day 7, V5, M-S, MBt-S and M-I differed from U-I, U-Ibt and Fallow (LRT=29.00; $P<0.05$) (Table 3). Starting at day 14, V7, the highest values represented by similar means were observed in corn, regardless of the cropping system until day 35, VT (LRT=28.34; $P<0.05$). At day 56, R2, a significant difference was observed (MBt-I 1.65; MBt-S 0.05), and at day 70, R2, M-S and MBt-S had the highest means, differing from MBt-I ($P<0.05$).

Regarding Fallow and *U. ruziziensis*, differences were observed at day 7 (U-S 1.33; U-I 0.10), after day 56 (Fallow 2.60; U-S 0.07 and U-Ibt 0.20) and at day 63 (Fallow

3.83; U-S 0.07) ($P<0.05$). Fallow also differed from the other crops at day 63, R2 (3.83) (Table 3) ($P<0.05$).

Mean differences across columns reflected a higher population density during the early stages of crop development (Figs. 3 and 4), as after day 91 the *R. maidis* population was zero. During the development of *U. ruziziensis*, the highest and statistically equal means occurred in U-S between days 1 and 21 (Fig. 3B) and in U-I between days 1 and 14. Fallow at days 56 and 63 (Fig. 3A) and in the development of corn plants, it occurred in M-S (Fig. 4A) and MBt-S (4B) from days 1 to 49, V4 to R1, and at day 70, R2, the mean of day 77, R3 for Mbt-S was included. In intercropped corn, the highest means were observed in M-I from days 1 to 56 and 84, V4 to R2 and R3 (Fig. 4C), MBt-I 1 at days 35 and 56, and V4 to VT and R2 (Fig. 4D).

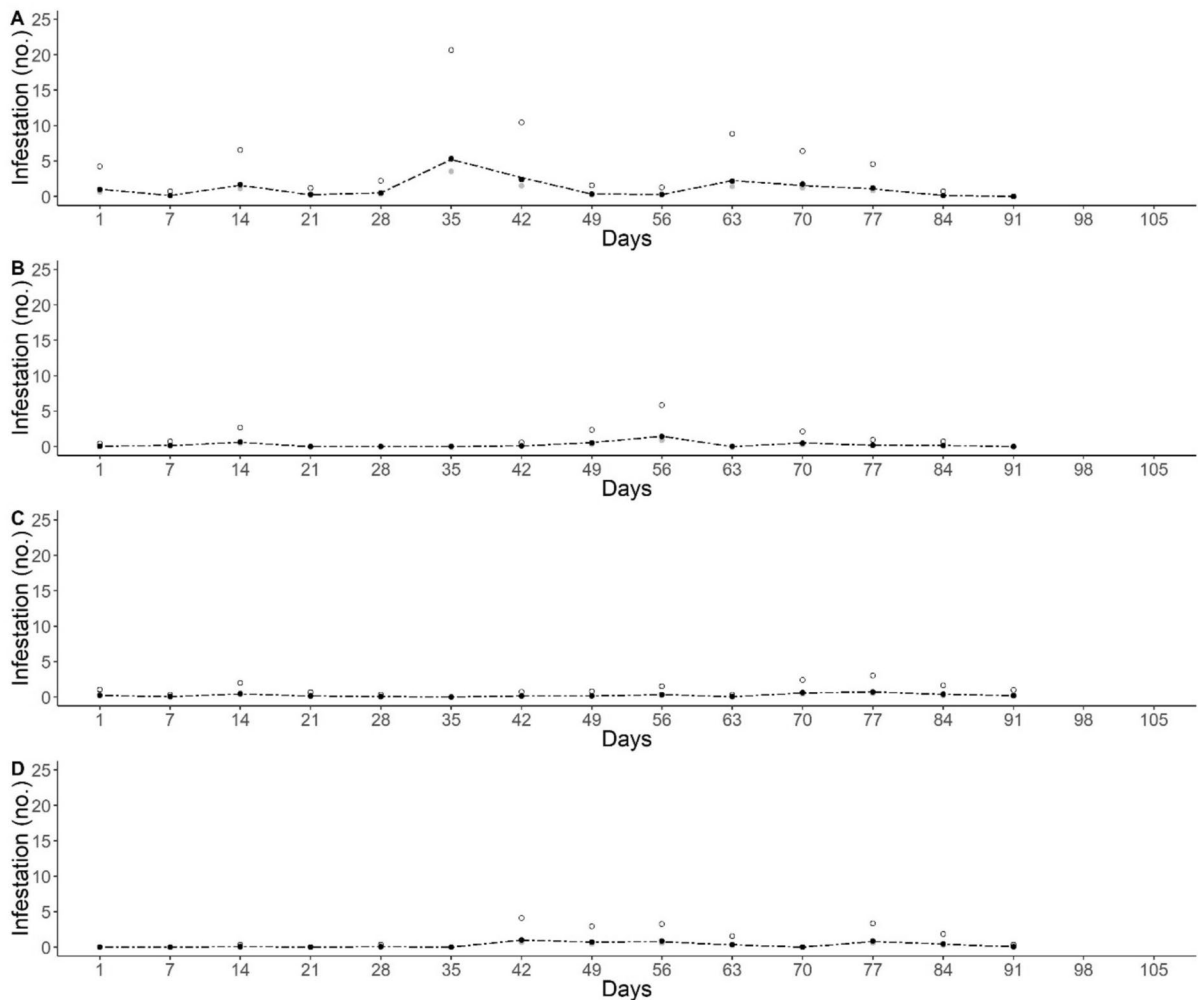


Fig. 1 Summer Season 2017–2018. Population dynamics of *R. maidis* during the development of **A**) Fallow (T1), **B**) *U. ruziziensis* (single) (T4), **C**) *U. ruziziensis* (intercropping with maize n-Bt) (T5) and **D**) *U. ruziziensis* (intercropping with maize Bt) (T6)

2018–2019 Summer season

The population of *R. maidis* differed among crops from day 21, V9 (MBt-S 10.60; U-S 0.20) (Table 4) (LRT=55.01; $P < 0.05$), but when only corn plants were compared, differences were observed at day 42, R2, (MBt-S 7.85; M-I 0.35) and at day 63, R4, since M-S (0.85) and MBt-S (7.85) differed from M-C (4.10), not including the values without variability found in the intercropped corn at days 1, 7, 14, 21 and 35 ($P < 0.05$). Due to the constant variability of the data in *U. ruziziensis* and fallow, no differences were observed (Fig. 5).

The contrast of means of the predicted model during crop development revealed that the *R. maidis* population differed only in corn, and it was higher in the monoculture system (Table 4) ($P < 0.05$). In M-S, a significant increase was observed at day 49, R3 (19.30) extended to day 84, R5 (93.60) (Fig. 6A), and in MBt-S at day 21, V9 (10.60) and after day 42, R2 (7.85) until day 84, R5 (44.45) (Fig. 6B). Similar population dynamics were observed in intercropped corn, starting at day 63, R4 in M-I, (4.10) until day 84 (40.90) (Fig. 6C) and for MBt-I at day 21, V9, (3.65) and from day 49, R3, (3.80) to 91, R6, (5.75) (Fig. 6D).

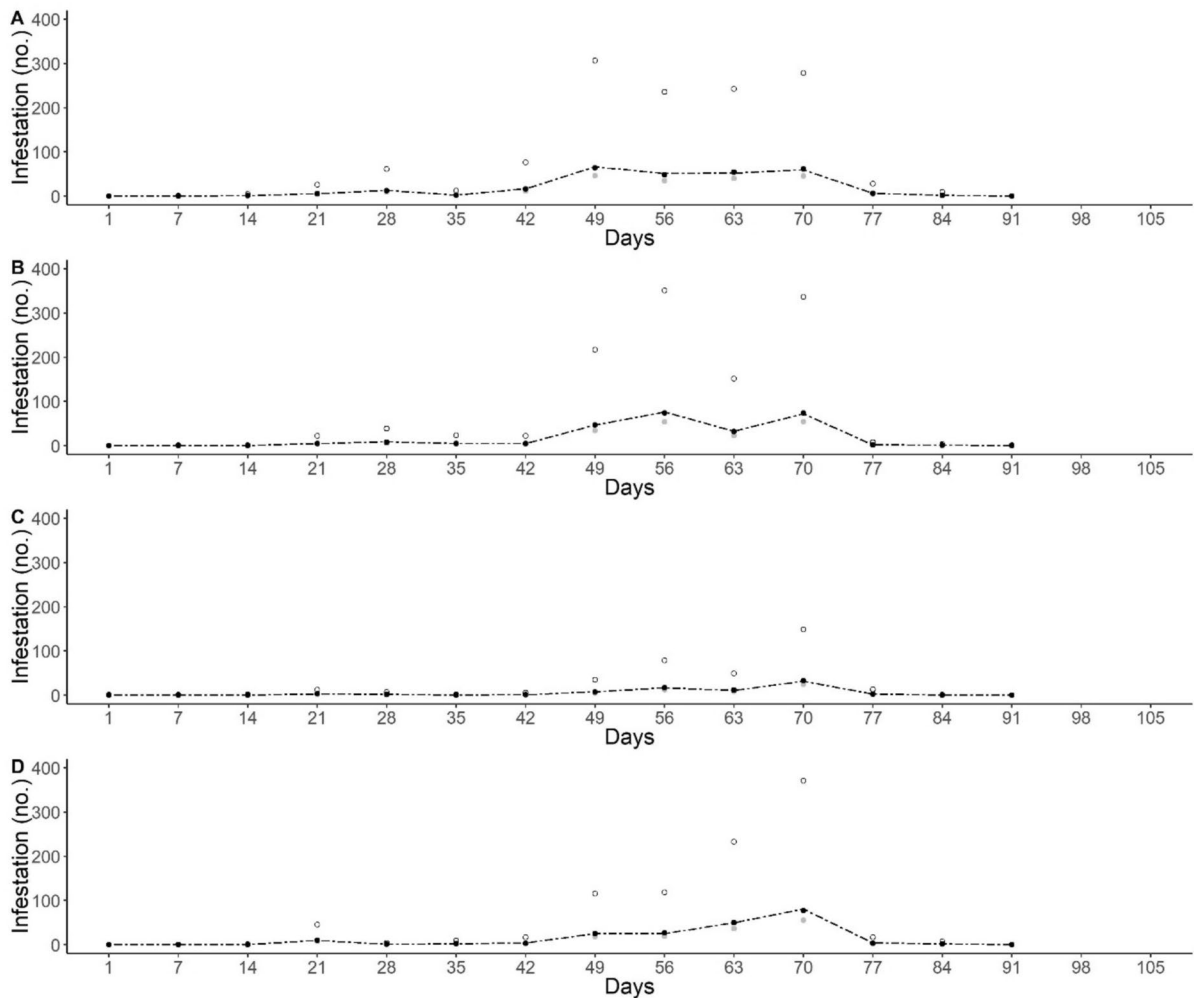


Fig. 2 Summer Season 2017–2018. Population dynamics of *R. maidis* during the development of **A)** (T2) maize n-Bt (single), **B)** (T3) maize Bt (single), **C)** (T5) maize n-Bt (intercropping) and **D)** (T6) maize Bt (intercropping)

Discussion

Our results demonstrated that intercropping with *U. ruziziensis* significantly reduced *R. maidis* abundance on corn plants compared to monoculture systems, particularly during the summer season. Furthermore, higher aphid infestations were consistently observed in monoculture corn, regardless of Bt or non-Bt genotype, while *U. ruziziensis* hosted low aphid populations and likely acted as a diluting or trap host.

Seasonal effects on population dynamics

Specimens of *R. maidis* were present on corn plants since the first evaluation in the Fall V4 and Summer V4-V5 seasons, but population dynamics differed markedly between seasons. The richness and composition of arthropods were lower in the fall season than in the summer season (Fernandes et al., 2019), which we attribute to lower temperatures recorded during fall. Temperatures below 21 °C decrease the reproductive and survival rates of *R. maidis* (Kuo et al., 2006; Maia

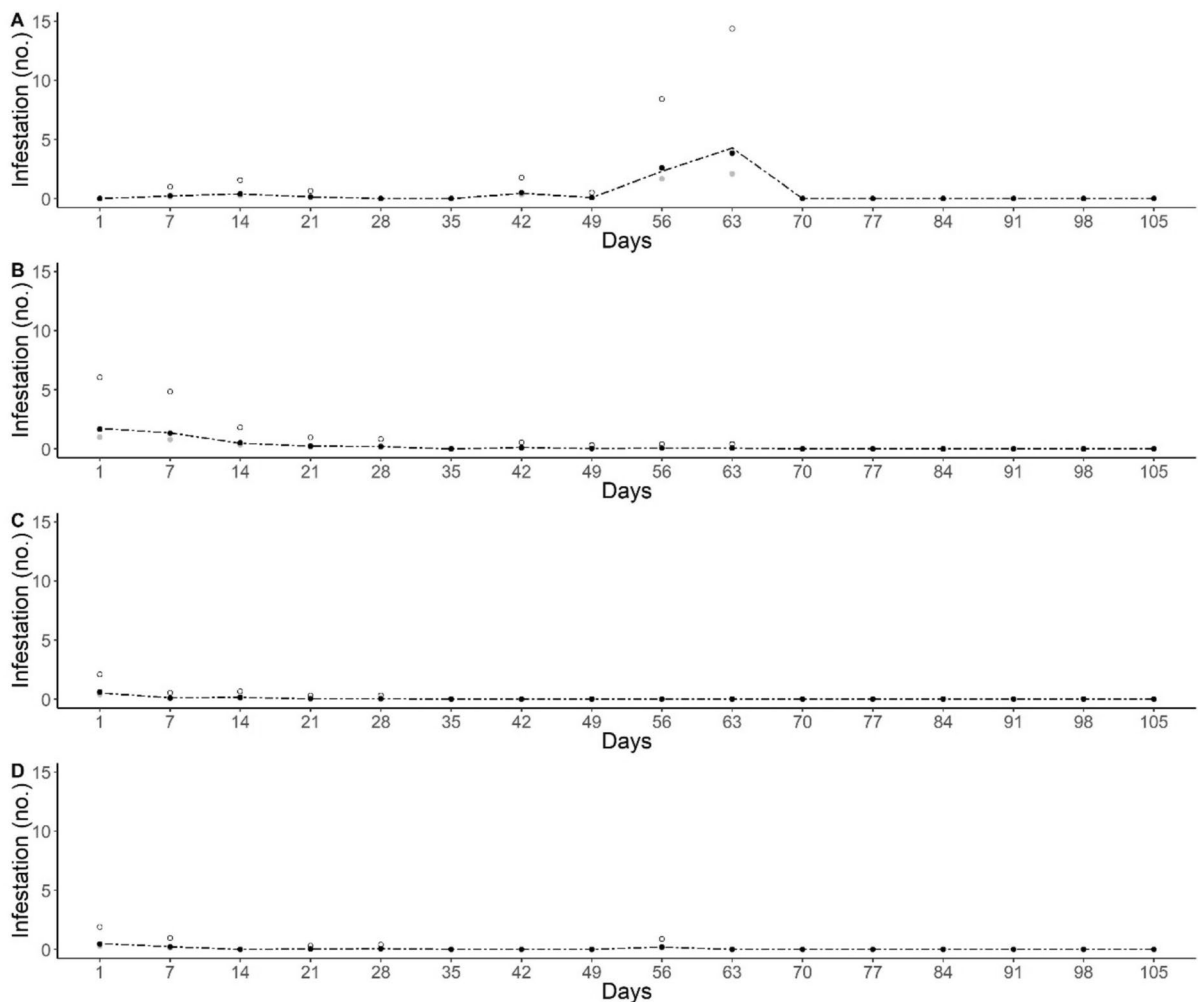


Fig. 3 Fall Season 2018. Population dynamics of *R. maidis* during the development of **A**) (T1) Fallow, **B**) (T4) *U. ruziziensis* (single), **C**) (T5) *U. ruziziensis* (intercropping with maize n-Bt) and **D**) (T6) *U. ruziziensis* (intercropping with maize Bt)

et al., 2004), as well as the production of winged forms (Chen et al., 2019). Consequently, the low population variability observed in the fall season in our study is consistent with temperature being a limiting factor for aphid development.

In the summer season, a gradual increase in infestation was observed along with corn development. The first significant population increase was recorded at stage V9, peaking during R3 and R5. This relationship has been well documented (Foott, 1977; Guo et al., 2017; Kieckhefer & Gellner, 1988; Maia et al., 2005; Robinson & Hsu, 1963), and the interactions that most affect the intrinsic population rate will be discussed below.

Plant defense compounds and aphid establishment

The establishment and performance of aphid pests are influenced, among other factors, by the translocation of exudates and defense compounds present in the phloem. Corn seedlings produce high concentrations of toxic compounds responsible for antibiosis and antixenosis against *R. maidis* (Louis et al., 2015; Meihs et al., 2013; Varsani et al., 2019). However, these concentrations tend to decrease with seedling development (Bosak et al., 2013; Cambier et al., 2000; Eleftherianos et al., 2006; Gonzales et al., 2001). The lower accumulation of defense compounds as plants mature allows an increase

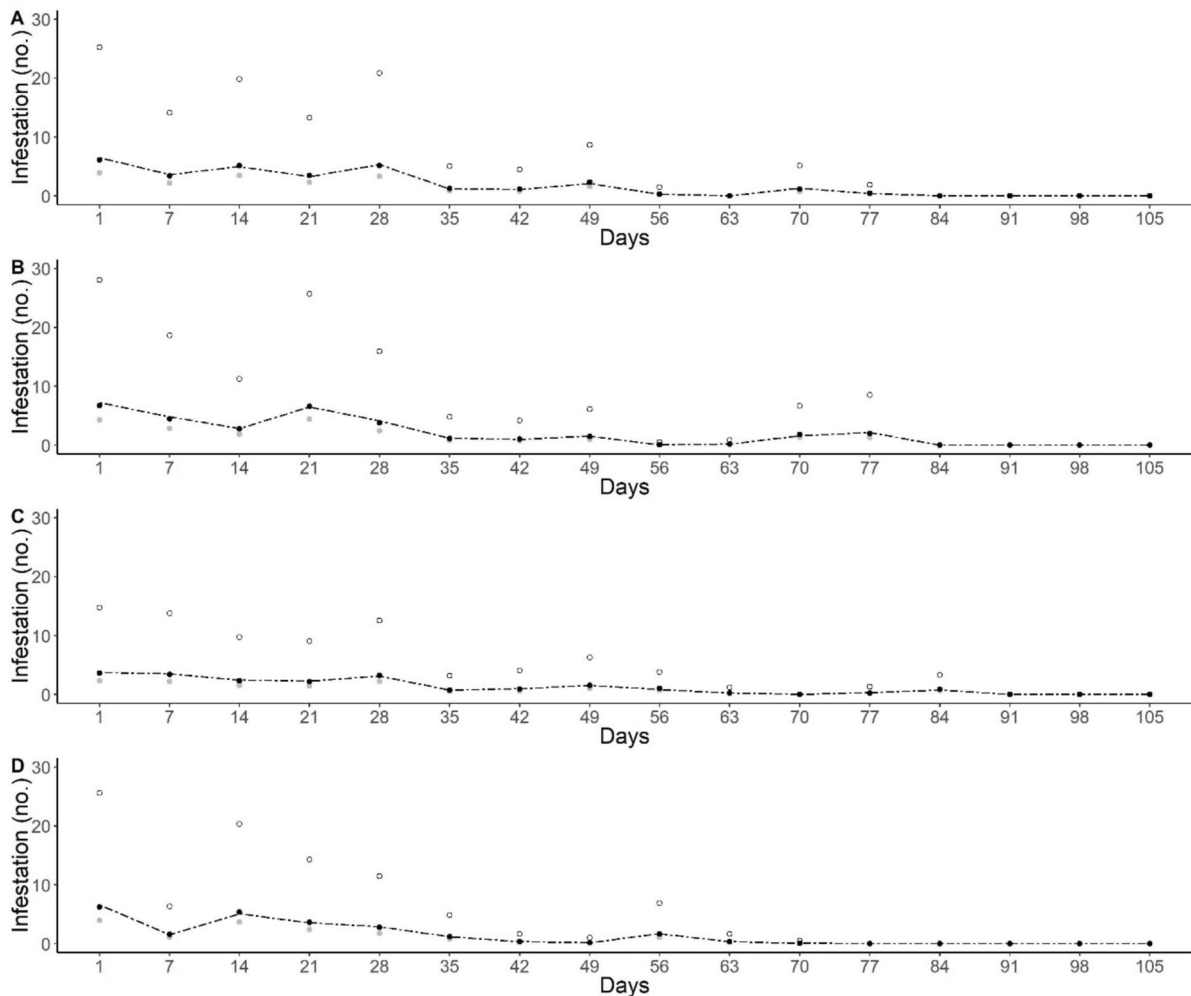


Fig. 4 Fall Season 2018. Population dynamics of *R. maidis* during the development of **A**) (T2) maize n-Bt (single), **B**) (T3) maize Bt (single), **C**) (T5) maize n-Bt (intercropping) and **D**) (T6) maize Bt (intercropping)

in the intrinsic rate of the aphid population, which is also positively influenced by higher concentrations of amino acids in the phloem (Ponder et al., 2003). We acknowledge that comparisons among different studies on phloem sap exudate concentrations are complex due to methodological variability (Karley et al., 2002; Plett et al., 2016; Yesbergenova-Cuny et al., 2016).

The composition of phloem exudates in leaves of different ages differs significantly (Jakobs et al., 2018; Karley et al., 2002), and leaf senescence precedes assimilate photoremobilization to non-photosynthetic organs, especially during the reproductive stage (Kumar et al., 2019; Seebauer et al., 2004). This provides *R. maidis* with new suitable structures for infestation

and is reflected in the aphid's preference for sites near reproductive organs (Resende et al., 2016) that accumulate metabolites, resulting in an increase in colony size.

Winged morph production and host migration

The higher density of *R. maidis* directly influences the metamorphosis of 1st and 2nd instars into winged nymphs (Chen et al., 2019). In our study, this phenomenon occurred during the summer season at stages R3 and R5, coinciding with the approach of physiological maturity of the corn plant. Similar results on population dynamics have been found in wheat fields (Akhtar & Khaliq, 2004). The

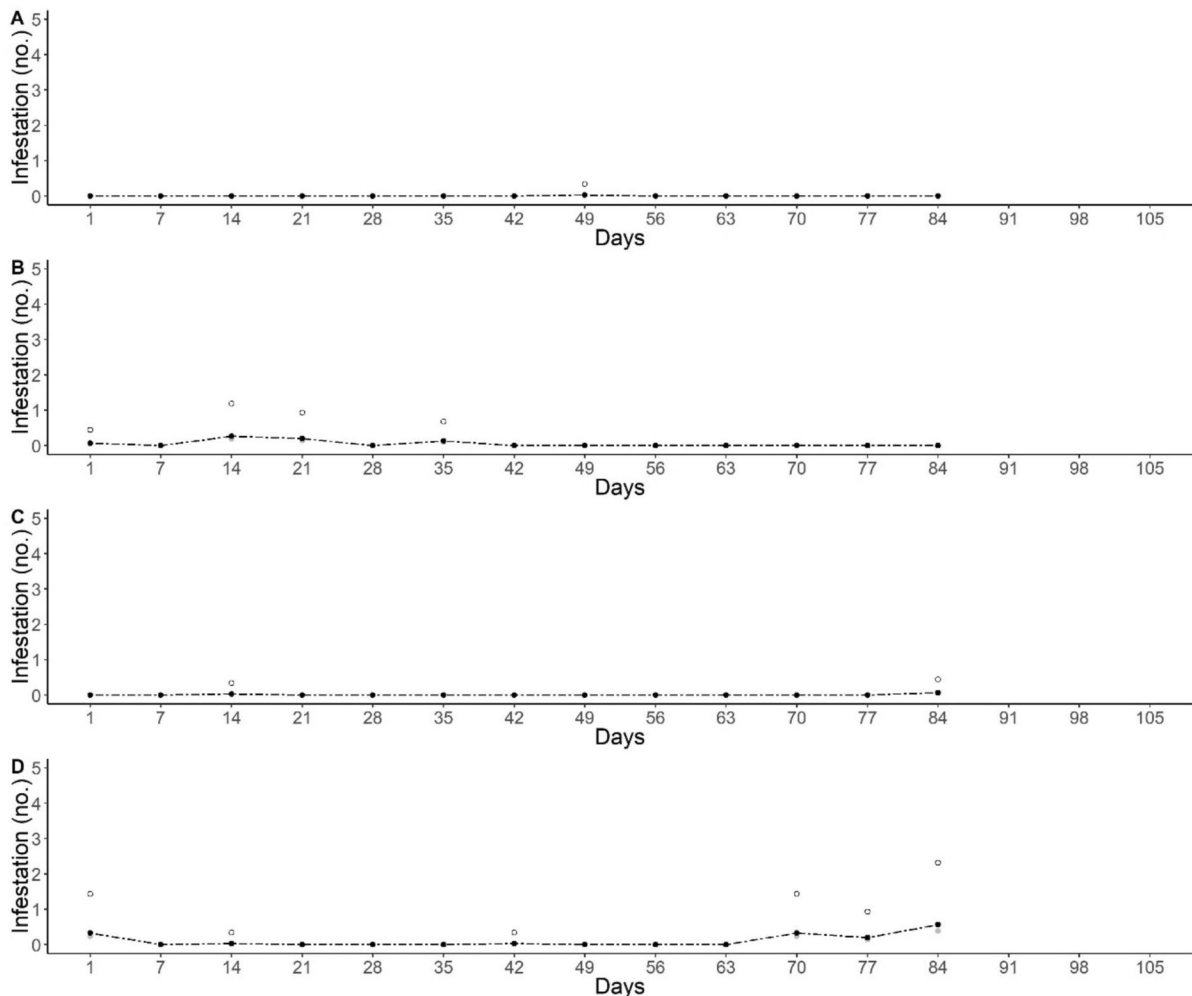


Fig. 5 Summer Season 2018–2019. Population dynamics of *R. maidis* during the development of **A**) (T1) Fallow, **B**) (T4) *U. ruziziensis* (single), **C**) (T5) *U. ruziziensis* (intercropping with maize n-Bt) and **D**) (T6) *U. ruziziensis* (intercropping with maize Bt)

ability to migrate to new hosts, including non-cultivated Poaceae (Hesler & Dagel, 2010; Robinson & Hsu, 1963), has allowed *R. maidis* to infest plants in fallow areas, which may serve as reservoirs for viruses present in Brazil that have *R. maidis* as a vector (Ahmad et al., 2006; Bekele et al., 2018; Gonçalves et al., 2017; Mar et al., 2013).

Host plant species and cropping system effects

The abundance of *R. maidis* differed depending on the crop, as population performance is influenced by phloem composition (Apablaza & Robinson, 1967; Caballero et al., 2001) and the physical characteristics

of the hosts, which vary among plant species (Jakobs et al., 2018). The better performance of *R. maidis* on corn plants compared to forage or weeds is evident (Branson, 1972; Hesler & Dagel, 2010; Robinson & Hsu, 1963). Studies conducted under similar climatic conditions have shown that corn plants promote greater increases in the population's intrinsic and reproductive rates (Kuo et al., 2006; Razmjou & Golizadeh, 2010) than *Urochloa* sp. (sin. *Brachiaria*) (Parchen & Auad, 2016).

In our study, the lower infestation observed in *U. ruziziensis*, regardless of the cropping system, reduces the probability of metamorphosis into winged nymphs (Chen et al., 2019). Consequently, this grass

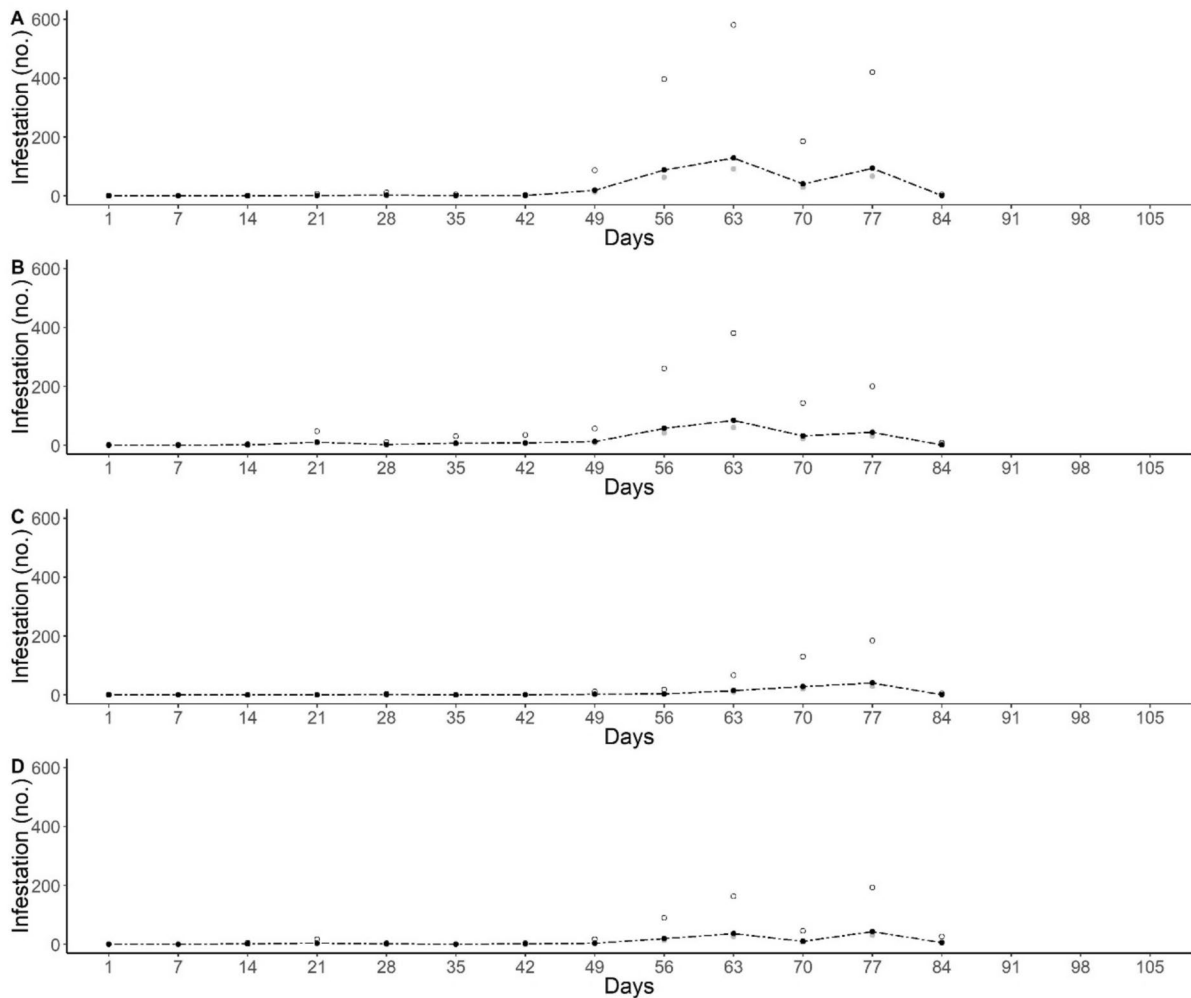


Fig. 6 Summer Season 2018–2019. Population dynamics of *R. maidis* during the development of **A**) (T2) maize n-Bt (single), **B**) (T3) maize Bt (single), **C**) (T5) maize n-Bt (intercropping) and **D**) (T6) maize Bt (intercropping)

contributes to the system as a less favorable host for *R. maidis* migrating between areas or plants, thus reducing aphid populations on corn. Significant differences between cropping systems were found in the 2017–2018 summer season at stages R1 (M-S; MBt-I) and R2 (M-S; M-I), and in the 2018–2019 summer season at R2 (MBt-S; M-I) and R4 (M-S and MBt-S; M-I), with the highest means consistently observed in monoculture corn. The negative effects of *Urochloa* spp. on pest arthropod populations suggest their potential use as a trap crop intercropped with corn (Cheruiyot et al., 2018). However, we emphasize that this hypothesis remains to be specifically evaluated for *R. maidis*, as does the variability of existing

karyotypes (Jauset et al., 2000; Potan & Gautam, 2019).

Effects of Bt corn and lepidopteran damage on *R. maidis*

A central finding of our study is that *R. maidis* abundance differed between Bt and non-Bt corn under field conditions. Although previous studies have reported that the biological cycle and predominance of *Rhopalosiphum* spp. are not directly affected by *Bacillus thuringiensis* proteins in genetically modified plants (Guo et al., 2016; Shu et al., 2018, 2019),

we observed clear variability between Bt and non-Bt plants in the field, consistent with reports by Lumbierres et al. (2004, 2011).

We propose the following hypotheses to explain this difference, none of which were directly tested in our study. First, plants damaged by *Spodoptera* spp.—which are predominant in non-Bt corn (unpublished data)—may have reduced attractiveness to *R. maidis* under controlled conditions (Bernasconi et al., 1998). However, due to the high intrinsic growth rate of *R. maidis*, this behavior is difficult to observe in the field. Second, the impact that damage by *Spodoptera* spp. may have on the reproduction of this Aphididae remains uncertain (Tzin et al., 2015). It is possible that Bt plants, experiencing reduced lepidopteran herbivory, allocate fewer resources to induced defenses (e.g., jasmonate-mediated pathways), indirectly benefiting phloem-feeding aphids. This hypothesis, while supported by literature from other plant–herbivore systems, requires direct experimental validation in our study system.

Conclusions and implications

Thus, the peculiarities of each crop, cropping system, host plant species, and biological factors all impact *R. maidis* population dynamics, and the existing interactions are complex and essential for understanding the behavior of this Aphididae. Although *R. maidis* infests *U. ruziziensis*, its reproductive performance on this grass is low. Simultaneously growing corn (whether Bt or non-Bt) with *U. ruziziensis* results in lower abundance of *R. maidis* on corn plants, as indicated by higher means in monoculture corn during the summer season. The performance of *R. maidis* is strongly influenced by temperature; thus, population variability was low in the fall season. Our findings support intercropping with *U. ruziziensis* as a promising integrated pest management strategy to suppress *R. maidis* populations in Brazilian corn systems, while also highlighting that Bt corn may inadvertently favor aphid outbreaks under certain seasonal conditions, warranting continued monitoring.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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