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Fusarium oxysporum f. sp. *strigae* strain Foxy 2 did not achieve biological control of *Striga hermonthica* parasitizing maize in Western Kenya

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HIGHLIGHTS

- *Striga hermonthica* is a serious parasitic weed of maize in Western Kenya.
- *Fusarium oxysporum* (Foxy 2) is imported into Kenya for biological control.
- Efficacy of Foxy 2 is tested under post-entry quarantine (PEQ) conditions in Kenya.
- Results show that *Fusarium oxysporum* (Foxy 2) is ineffective in Kenya.

GRAPHICAL ABSTRACT

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ABSTRACT

The production of maize, a major staple food crop in sub-Saharan Africa is being constrained by the parasitic weed *Striga hermonthica*. The fungus *Fusarium oxysporum* f. sp. *strigae* (Foxy 2) that causes fusarium wilt of *Striga* in Ghana, West Africa, is being considered for biological control of the weed in Western Kenya. The present study investigated the efficacy of *F. oxysporum* f. sp. *strigae* (Foxy 2) for *S. hermonthica* management in Western Kenya. Research was conducted in post-entry quarantine (PEQ) facilities at Alupe, Busia, Homabay, Kibos and Siaya field stations for two seasons. Each PEQ was a split-plot, with 4 main blocks each having 6 treatment subplots. The treatments included seeds of two *S. hermonthica*-susceptible maize varieties, either coated with Foxy 2 using gum Arabic, gum Arabic alone, or left untreated. Data was collected over seven sampling periods on *S. hermonthica* population per plant, percentage of those that were wilting, and the severity of wilting. Maize plant growth parameters assessed included duration to 50% anthesis and 50% silking, plant height, number of leaves, stover and cob weights, and maize yield per hectare. Statistical analysis was done using SAS 9.1 software. Data on *S. hermonthica* population were analyzed by χ^2-test using Proc Genmod (Poisson); while the other parameters were analyzed by Proc Mixed using study location, season and blocks as random effects, and the sampling periods as repeated effects. All the assessed parameters were similar between plants grown from seeds inoculated with *F. oxysporum* f. sp. *strigae* (Foxy 2), those coated with gum Arabic, and the ones without any coating. These parameters were also not different between the maize varieties. There

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are varying reasons for the disparities between results on *F. oxysporum* f. sp. *strigae* (Foxy 2) obtained in this Kenyan study, and those from researches outside this country. In conclusion, *F. oxysporum* f. sp. *strigae* strain Foxy 2 is predominantly safe on maize growth, but its efficacy in controlling *S. hermonthica* was not evident on the tested Kenyan soils.

1. Introduction

Striga hermonthica (Del) Benth (Scrophulariaceae) is an endemic parasitic weed of maize and other gramineous plants including sorghum, millet, rice, sugarcane, pasture and wild grasses in sub-Saharan Africa (Parker and Riches, 1993; Berner et al., 2003; Beed et al., 2007). *S. hermonthica* is the dominant parasitic weed in Western Kenya, especially in areas such as Busia, Homabay, Siaya and Vihiga counties (Khan et al., 2008; Kilonzi, 2011; Jamil et al., 2012; Avedi, 2013). This parasitic weed is a major threat to cereal crop production, and can cause crop losses as high as 70% (Khan et al., 2008), especially under low soil fertility and drought conditions (Stringer et al., 2009; Kamara et al., 2012). *S. hermonthica* has been rapidly spreading mainly due to anthropogenic activities, through means such as contaminated agricultural produce and animal movement (Berner et al., 1994), with severe effects being instigated by farming practices like monocropping (Berner et al., 2003). Despite efforts to control *S. hermonthica*, the threat due this parasitic weed on cereal production is likely to increase and be exacerbated under the influence of predicted climate changes (Stringer et al., 2009; Rodenburg et al., 2011; Jamil, 2012).

Most recommended weed control measures have not been successful in addressing the *S. hermonthica* problem, while others are not sustainable (Kanampiu et al., 2002). For instance, practices that were developed for controlling *Striga asiatica* in the United States require chemical inputs and equipments that are not affordable by most farmers in Africa (Berner et al., 1995, 2003). Integrated *Striga* Management (ISM) strategies are being developed for the control of *S. hermonthica* in Africa (Berner et al., 2003; Beed et al., 2007; Vanlauwe et al., 2008; Venne et al., 2009). Biological control is a vital component of ISM (Smith, 1991; Berner et al., 2003; Watson, 2013), which was advanced by the active search for natural enemies of *Striga* species back from the 1960's in East Africa (Davidson, 1963; Milner, 1967; Greathead and Milner, 1971; Spencer, 1973; Greathead, 2003).

Of recent interest in ISM is the potential use of microbial biological control agents (BCA) (Bowers, 1982; Charudattan, 2001), and particularly plant pathogenic fungi that infect *S. hermonthica* and other parasitic weeds including *Orobanche* spp. (Kroschel et al., 1996; Berner et al., 2003; Müller-Stöver et al., 2004; Nemat Alla et al., 2008; Watson, 2013). At least 52 fungal species belonging to 16 genera have been isolated from *Striga* species, with many of them being pathogenic to the parasitic weed (Berner et al., 2003). In West Africa, *Fusarium* species were the most prevalent, while *Fusarium oxysporum* was the dominant species comprising 93% among isolates obtained from a survey on diseased *S. hermonthica* plants (Abbasher et al., 1998; Berner et al., 2003). *F. oxysporum* that infected *S. hermonthica* included isolate Foxy 2 from North Ghana (Abbasher et al., 1995), isolate PSM197 from Samaru in Nigeria (Marley et al., 1999), and isolate M12-4A from Mali (Ciotola et al., 1995, 2000). Through the use of molecular tools on *F. oxysporum* isolate Foxy 2 and PSM197, a new *forma specialis* named *F. oxysporum* f. sp. *strigae* Elzein et Thines, which causes fusarium wilt of *Striga* species was identified by Elzein et al. (2008). This fungal strain offers hope to farmers in Africa whose livelihoods have been constrained by *S. hermonthica* that attacks their cereal crops.

F. oxysporum f. sp. *strigae* (Foxy 2) has been found to be highly potent for biological control of *S. hermonthica* (Schaub et al., 2006; Venne et al., 2009). *F. oxysporum* f. sp. *strigae* (Foxy 2) has specificity towards *Striga* species, and is non-pathogenic to cereal crops (Elzein and Kroschel, 2006; Beed et al., 2007). This strain of *F. oxysporum* exerts pathogenicity on *S. hermonthica* seedlings while still underground by destroying the appressorium, the hyaline tissue, xylem vessels and cortical parenchyma (Elzein et al., 2010; Ndambi et al., 2011). In emerged *S. hermonthica*, the fungal hypha adheres to the root surface, penetrates and enters the apical region of the root, grows through the endodermis and reaches the xylem (Elzein et al., 2010; Ndambi et al., 2011). *F. oxysporum* f. sp. *strigae* (Foxy 2) has already been developed into a commercializable product by the University of Hohenheim in collaboration with the seed company SUET Saat-und Erntetechnik GmbH, Eschwege, Germany (Kroschel et al., 2010; Elzein et al., 2012).

Farmers in Africa are likely to adopt *F. oxysporum* f. sp. *strigae* (Foxy 2) as seed treatment developed in Europe for *S. hermonthica* control. However, regulation of biological control agents within the European Union is expensive and time-consuming, often surpassing eight years, while knowledge on safety is limited mostly resulting in exaggerated registration requirements (Ehlers, 2009). In Ghana west Africa, despite the availability of biopesticides registration guidelines (EPA, 1994), there have been limited biological control agents available for agricultural producers (Pwamang, 2012). 'Research Into Use', a new initiative sponsored by The Department for International Development (DFID) (United Kingdom), has helped develop 'a guide to registration of biological control agents' (Pwamang, 2012; EPA, 2011). Despite *F. oxysporum* f. sp. *strigae* (Foxy 2) having originated in Ghana, biopesticide registration in this country has just started to develop (RIU, 2013). Therefore, Kenya will serve as a pilot country, because of its well established biopesticide registration procedures (Kroschel et al., 2010; Hoeschle-Zeledon et al., 2013). The work in Kenya will be the first example of using a mycoherbicide in African agriculture (Kroschel et al., 2010). Information on the efficacy of exotic strains of *F. oxysporum* for biological control is required (Gullino and Migheli, 1999; Kairo et al., 2003; Beed and Dubois, 2009; Ochieno, 2010). Such necessary information for biopesticide registration is generated under post-entry quarantine (PEQ), which is applied to a consignment after entry (IPPC, 2013). This process is in line with International Standards for Phytosanitary Measures (FAO-ISPM, 2006, 2010; Avedi, 2013). The Government of Kenya maintains these standards through the Kenya Standing Technical Committee on Imports and Exports of live organisms (KSTCIE). KSTCIE is chaired by the Ministry of Agriculture with its secretariat located at the Kenya Plant Health Inspectorate Services (KEPHIS). Some of the key stakeholders of KSTCIE include; Pest Control Products Board (PCPB), Kenya Agricultural Research Institute (KARI), Department of Veterinary Services (DVS), Ministry of Public Health and Sanitation (MPHS), National Environment Management Authority (NEMA), National Museums of Kenya (NMK), private institutions etc.

The present study was conducted in Kenya to evaluate the effects of *F. oxysporum* f. sp. *strigae* (Foxy 2) on *S. hermonthica* infestation and consequences on maize crop yield. It is hypothesized that *F. oxysporum* f. sp. *strigae* strain Foxy 2 will achieve biological

control of *S. hermonthica* parasitizing maize in Western Kenya, through pathogenic mechanisms that suppress the weed, thereby enhancing the growth and yields of maize crop.

2. Materials and methods

2.1. Post-entry quarantine (PEQ) facilities

Studies were carried out in post-entry quarantine (PEQ) facilities, which are structures designed for official confinement of imported living organisms, in this case *F. oxysporum* f. sp. *strigae* (Foxy 2), which are undergoing further investigation after entry into new territories or environments (Kairo et al., 2003; IPPC, 2013). A post-entry quarantine facility was a field (57.4 m × 34 m) surrounded by a trench 0.5 m wide and 1 m deep to prevent escape of *F. oxysporum* f. sp. *strigae* (Foxy 2) to the environment through means such as run-off and soil colonization. A barbed wire fence surrounded the field, and a steel gate (2 m × 2.5 m) installed to restrict access into the facility. A footbath (45 cm × 70 cm) containing Kerol® disinfectant (HighChem East Africa Ltd, Nairobi, Kenya) was placed at the entrance to decontaminate any person upon entry and exit from the PEQ facility. A weather-proof guardhouse was constructed outside the gate for security personnel and storage.

Training of personnel was carried out on handling and sanitation procedures hence preventing anthropogenic spread of the fungus (Anderson et al., 2004; Suffert et al., 2009; Stack et al., 2010; Ochieno, 2010). Protective clothing including gumboots and dust coats were provided for use by personnel. In addition, records of the site plan, all activities, staff and visitors of the PEQ were kept at the guardhouse. The PEQ was regularly audited by the Kenya Plant Health Inspectorate Services (KEPHIS), to ensure that it met the outlined ISPM 34 standards (FAO-ISPM, 2010).

2.2. Experimental locations

Post-entry quarantine facilities were constructed for the confinement of *F. oxysporum* f. sp. *strigae* (Foxy 2) within five locations where *S. hermonthica* is endemic i.e., KARI-CIMMYT collaborative research facilities at Kibos in Kisumu (0° 02'S–34° 48'E), Busia Agricultural Training Centre (0° 26'S–34° 15'E), Kenya Agricultural Research Institute at Alupe in Busia county (0°1′–0°46′S, 33° 54′–34°26′ E), Homabay Agricultural Training Centre (0°40′–0° S and 0°–34° 50′E), and Siaya Agricultural Training Centre (0° 26′–0° 18′S, 33° 58′–34° 33′ E). Some details of climatic and edaphic characteristics of these locations have been described by Osumba et al. (2011).

2.3. Experimental design

The experiment comprised of six treatments that included two commercial maize varieties susceptible to *S. hermonthica*; either inoculated with *F. oxysporum* f. sp. *strigae* (Foxy 2) using gum arabic as a seed adhesive, or coated with gum arabic only, or untreated control. These were laid out in a split-plot design on a field (57.4 m × 34 m) modified into the previously described PEQ facility having four main blocks (20.7 m × 9 m), each with six treatment subplots (4.9 m × 3 m) spaced at 3 m. Each subplot had 6 rows of 9 planting holes spaced at 70 cm × 30 cm (i.e. $N = 1296$), excluding border rows. A buffer strip 5 m wide was left between and around the four blocks. The two commercial maize varieties utilized in this study i.e. WH 403 and WH 507 (Western Seed Company, Kenya Ltd), are susceptible to *S. hermonthica* (Odhiambo et al., 2011; Omondi, 2013). All plants were inoculated with *S. hermonthica* seeds and supplied with diammonium phosphate (DAP) fertilizer. The trials were conducted during the long rain season (April 2012–August 2012) and repeated in the short rain season (September 2012–January 2013).

2.4. Fusarium oxysporum f. sp. strigae (Foxy 2) inoculum, maize germplasm and Striga seeds

The experiments utilized *F. oxysporum* f. sp. *strigae* (Foxy 2) inoculum that had been obtained from severely diseased *S. hermonthica* in North Ghana by Abbasher et al. (1995), and preserved on Synthetic Nutrient-poor Agar (SNA) – medium with 5% (v/v) glycerol at −40 °C at the University of Hohenheim, Stuttgart, Germany (Nirenberg, 1976; Zahran, 2008; Ndambi, 2011). The inoculum had been formulated into 10^6 CFUs of homogenized dried chlamydospores. Maize seeds of WH403 and WH507 varieties were obtained from Western Seed Company Ltd and shipped to the University of Hohenheim, Stuttgart, Germany, for seed coating with *F. oxysporum* f. sp. *strigae* (Foxy 2). *S. hermonthica* seeds were obtained from the KARI-CIMMYT collaborative facilities at Kibos, already formulated into a *S. hermonthica*: sand mixture of 1:4 as described by Berner et al. (1997).

2.5. Planting and agronomic practices

Land on the PEQ facilities was prepared by hand digging, and two maize seeds/hole planted at 70 cm × 30 cm, in a depth of ~3 cm. One table spoonful of *S. hermonthica* seed-sand mixture (~1000 *S. hermonthica* seeds) was placed in every planting hole. Fertilizer (DAP granules) was applied at the rate of 1 tea spoonful per planting hole. Two weeks after germination, the seedlings were thinned to one per hole. Hand weeding was done after every two weeks for all weeds except *S. hermonthica*.

2.6. Data collection

Growth and yields of maize plants were recorded based on procedures used at KARI. These involved collecting data on 5 alternating plants from each of the 6 inner rows, and hence 30 plants per plot. These plants had been marked using red ribbons. Plant height (stem base to youngest leaf apex) was measured using a ruler, and the number of open leaves per plant counted every 14 days till tasselling. Number of days to 50% anthesis and 50% silking (ear emergence) per plot were recorded. At maturity (senescence), the number of maize cobs on the sampled plants per plot were counted. The total weight of maize cobs per plot were measured using a portable electronic scale (Constant 14192-7, South Korea). Grain moisture content was determined by randomly picking 3 cobs per plot, then extracting a grain from each cob, and placing the three in a grain moisture meter (GMK-303A, G-won Hitech Co., Ltd, Seoul, South Korea). This was done in triplicate. The weight of the grains per plot and the moisture content (MC) were used to determine yields in tonnes per hectare using the formula described by De Groote et al. (2004) and Khalil et al. (2011);

$$\text{Yield (ton ha}^{-1}) = \frac{\text{FW}(100 - \text{MC}_1) \times S \times 10000\ \text{m}^2}{(100 - \text{MC}_2) \times P\ \text{m}^2 \times 1000\text{Kg}}$$

whereby; FW = weight of harvested cobs (Kg); moisture content (%) in grains at harvest (MC_1) and required in maize grain at storage (MC_2 i.e. 13%); S = shelling percentage (85%); P = plot size.

Striga hermonthica growth and wilt symptoms were assessed. The number of emerged *S. hermonthica* plants within 15 cm radius of each maize stem was recorded. The proportion of *S. hermonthica* plants expressing wilt symptoms was used to calculate percentage wilting. Severity of wilting in *S. hermonthica* was estimated using a

visual rating scale of 1–5 whereby, 1 = healthy, 2 = slightly infected, 3 = moderately infected, 4 = highly infected almost dead, and 5 = dead plant.

2.7. Statistical analysis

Data were analyzed using SAS software (version 9.1) at $p \leqslant 0.05$ significance level (SAS Institute, 2004). Means and standard errors were generated by Proc Means. Prior to statistical analysis, the raw data sets were checked for normality using graphs generated by Proc Univariate; while appropriate Box-Cox power transformations for plant height, number of leaves, stover weight, cob weight and yield (ton ha^{-1}) were generated using Proc Transreg. Data on percentage wilting *S. hermonthica* was arcsine square root transformed, while severity of wilting was transformed into ranks using Proc Means. Untransformed data was used for *S. hermonthica* population, days to 50% silking and 50% anthesis. Populations of *S. hermonthica* between coating treatments and maize varieties were analyzed by Proc Genmod for Poisson distributions (χ^2-test), using the seven sampling periods as repeated effects. Analysis of variance (*F*-test) between coating treatments and maize varieties was performed by Proc Mixed for split-plot designs, using location, season and blocks as random effects, and the seven sampling periods as repeated effects. Mean separation was done using *t*-test in the least-squares means (LSmeans) procedure whenever there was significant difference between treatments ($p < 0.05$).

3. Results and discussion

In the present PEQ study done in Western Kenya, maize plants from seeds inoculated with *F. oxysporum* f. sp. *strigae* (Foxy 2) and the non-inoculated ones had similar populations of *S. hermonthica*, which did not differ in levels wilting (Table 1). Such results of no difference in *S. hermonthica* population and wilting between maize inoculated with *F. oxysporum* f. sp. *strigae* (Foxy 2) and non-inoculated maize were first reported by Avedi (2013). In Nigeria, Zarafi et al. (2014) found that *F. oxysporum* f. sp. *strigae* isolate Foxy 2 and PSM197 had no negative effect on *S. hermonthica* in terms of plant height, biomass and vigour; with isolate PSM197 even having stimulatory effect on *S. hermonthica* biomass. Our observations vary from those done outside Kenya, which recorded low *S. hermonthica* population on cereals, attributed to destruction of its seeds and wilting plantlets by *F. oxysporum* f. sp. *strigae* and other *Fusarium* species (e.g. Abbasher and Sauerborn, 1992; Kroschel et al., 1996; Ciotola et al., 2000; Marley and Shebayan, 2005; Schaub et al., 2006; Ibrahim et al., 2009; Venne et al., 2009; Elzein et al., 2010).

Maize plants grown from seeds inoculated with *F. oxysporum* f. sp. *strigae* (Foxy 2) had similar levels of growth and yields as the non-inoculated ones (Table 1). This implies that *F. oxysporum* f. sp. *strigae* (Foxy 2) did not negatively affect the maize plants, and hence was non-pathogenic and safe on the crop as already established (Ciotola et al., 1995; Elzein and Kroschel, 2006; Ndambi et al., 2012; Zarafi et al., 2014). Furthermore, *F. oxysporum* f. sp. *strigae* (Foxy 2) has been found to have stimulatory effects on beneficial rhizosphere microbes (Musyoki et al., 2014). However, host range studies have found solanaceous plants (Irish potato, tomato and eggplant) to be susceptible to *F. oxysporum* f. sp. *strigae* strain Foxy 2 and PSM197, hence discouraged as intercrops of inoculated cereals (Zarafi et al., 2014). *F. oxysporum* f. sp. *strigae* (Foxy 2) is therefore not highly specific to *S. hermonthica* as thought before (Ref. Elzein and Kroschel, 2006), which justifies the use of post-entry quarantine (PEQ) facilities to evaluate such exotic fungi. These host range results for *F. oxysporum* f. sp. *strigae* (Foxy 2) published by Zarafi et al. (2014), which even contradict those reported earlier by Elzein and Kroschel (2006) in relation to susceptibility of solanaceous plants, should have been declared to the Government of Kenya prior to importation of the microbe. Besides, the negative effects of *F. oxysporum* f. sp. *strigae* (Foxy 2) towards solanaceous plants justifies the stringent regulatory requirements and extended registration periods for biological control agents within the European Union (Ehlers, 2009). Furthermore, the lack of host specificity in *F. oxysporum* f. sp. *strigae* (Foxy 2) also raises questions on the actual identity of this plant pathogen, despite having been found to be a distinct *forma specialis* (see Elzein and Kroschel, 2006; Elzein et al., 2008). Identification of *F. oxysporum* variants has been a challenge (Jacobsen and Gordon, 1991; Leslie and Summerell, 2006; Ochieno, 2010, 2013), even when molecular techniques are applied (Dita et al., 2010; Fourie et al., 2011). Therefore, there may be need for elaborate comparisons between *F. oxysporum* f. sp. *strigae* and other *Fusarium* spp., especially those that colonize *S. hermonthica*, cereal crops and solanaceous plants (see Correll, 1991; Nemat Alla et al., 2008; Michielse and Rep, 2009). This should also include further histological studies to find out why *F. oxysporum* f. sp. *strigae* would infect the xylem of *S. hermonthica* (Ndambi et al., 2011), but not the xylem of host plants (Elzein et al., 2010), yet the xylem vessels are connected (Ndambi et al., 2011, 2012), with the nutrient source being the crops (Musselman, 1980; Pageau et al., 2003).

Studies outside Kenya have reported improvement in plant growth and yields in cereal crops inoculated with *F. oxysporum* f. sp. *strigae* (Foxy 2) among other pathogens of *S. hermonthica* (Kroschel et al., 1996; Marley and Shebayan, 2005; Zahran, 2008; Zahran et al., 2008; Venne et al., 2009). The relevance of *F. oxysporum* f. sp. *strigae* (Foxy 2) in improving maize growth and yields is not evident in the present Kenyan trial (Table 1), which was also the case in the Nigerian study by Zarafi et al. (2014). Therefore, *F. oxysporum* f. sp. *strigae* (Foxy 2) showed poor performance and did not provide effective biological control of *S. hermonthica* under the Kenyan conditions (Beed et al., 2013).

The puzzle that needs to be resolved is why *F. oxysporum* f. sp. *strigae* isolates such as Foxy 2 and PSM197 had good performance outside Kenya in the earlier researches. Yet, in the present work done in Kenya, as well as a recent report from Nigeria by Zarafi et al. (2014), there is no evidence that *F. oxysporum* f. sp. *strigae* isolate Foxy 2 and PSM197 suppressed *S. hermonthica* and enhanced plant growth. A similar question has also remained unresolved in Kenya and Uganda, which concerns endophytic *Fusarium oxysporum* V5w2, between findings that do not indicate its efficacy as a biological control agent but pathogenicity to the crop (Ochieno, 2010), and those supporting good performance of the fungus (e.g. Dubois et al., 2006, 2011; Athman et al., 2007; Sikora et al., 2008; zum Felde, 2011; Paparu et al., 2008, 2009, 2013; Waweru et al., 2013, 2014). Issues concerning *F. oxysporum* V5w2 are still of public interest (Gatonye, 2011a,b; Masiga, 2011a,b; Opiyo, 2011a,b).

Variations in the biological control activity of *F. oxysporum* f. sp. *strigae* (Foxy 2) may be due to differences in biotic and abiotic factors (Beed et al., 2013). Inhibitive endophytic and rhizosphere microbes are among biotic factors that have been linked to reduced performance of *F. oxysporum* and other microbial biological control agents (Berner et al., 2003; Mackinaite, 2004; Beed et al., 2007; Ochieno, 2010). *Striga hermonthica* is more virulent in susceptible germplasm than in relatively tolerant ones (Berner et al., 2003), which can make *F. oxysporum* (Foxy 2) to appear more effective in the tolerant varieties (Schaub et al., 2006; Watson, 2013). It is not clear whether strains of *S. hermonthica* in Western Kenya are different from those of Ghana in terms of virulence towards maize cultivars, and how they could impact on *F. oxysporum* f. sp. *strigae* (Foxy 2). This issue is further complicated by the fact that strains of *S. hermonthica* vary in different regions of Africa (Berner et al., 2003; Estep et al., 2011; Welsh and Mohamed, 2011; Atera et al.,

Table 1
Effect of the exotic biological control agent *Fusarium oxysporum* f. sp. *strigae* (Foxy 2) on the hemi-parasitic weed *Striga hermonthica* and maize plants (*Zea mays*) (mean ± SE) under post-entry quarantine field conditions in Western Kenya.

Treatments	*n*	*Striga hermonthica*			Maize (*Zea mays*)						
		Population (count)	Wilting (percent)	Wilt severity (score)	Anthesis (days)	Silking (days)	Plant height (cm)	Leaves (count)	Stover weight (g)	Cob weight (g)	Yield (t/ha)
Overall	24	3.8 ± 0.2	39.7 ± 0.9	1.5 ± 0.0	71.0 ± 0.2	70.9 ± 0.2	83.4 ± 0.8	14.0 ± 0.1	227.0 ± 17.8 a	163.5 ± 7.7	1.3 ± 0.1
Control	8	3.8 ± 0.2 a	41.2 ± 1.1 a	1.5 ± 0.0 a	70.9 ± 0.3 a	70.8 ± 0.2 a	84.3 ± 1.5 a	14.0 ± 0.1 a	240.9 ± 18.6 a	162.1 ± 11.0 a	1.4 ± 0.1 a
Gum Arabic	8	4.1 ± 0.3 a	38.7 ± 1.8 a	1.4 ± 0.1 a	70.9 ± 0.3 a	71.1 ± 0.1 a	82.9 ± 1.8 a	14.0 ± 0.1 a	217.7 ± 36.8 a	170.5 ± 18.4 a	1.2 ± 0.1 a
Foxy2	8	3.5 ± 0.2 a	39.2 ± 1.7 a	1.6 ± 0.1 a	71.2 ± 0.4 a	71.0 ± 0.4 a	82.8 ± 1.0 a	14.1 ± 0.0 a	222.5 ± 37.2 a	157.8 ± 10.7 a	1.2 ± 0.1 a
Variety A	12	3.9 ± 0.2 a	39.6 ± 1.4 a	1.5 ± 0.0 a	71.0 ± 0.3 a	71.0 ± 0.2 a	82.8 ± 1.3 a	14.0 ± 0.1 a	221.3 ± 26.7 a	150.8 ± 10.5 a	1.2 ± 0.1 a
Variety B	12	3.7 ± 0.2 a	39.8 ± 1.2 a	1.5 ± 0.0 a	71.1 ± 0.3 a	71.0 ± 0.3 a	84.0 ± 1.0 a	14.0 ± 0.1 a	232.8 ± 24.6 a	176.1 ± 10.5 a	1.4 ± 0.1 a
Variety A	4	3.9 ± 0.4 a	42.5 ± 1.6 a	1.5 ± 0.0 a	71.0 ± 0.6 a	70.9 ± 0.3 a	84.0 ± 3.1 a	14.1 ± 0.1 a	230.0 ± 28.5 a	141.2 ± 13.8 a	1.2 ± 0.1 a
Variety A + Gum Arabic	4	4.2 ± 0.4 a	37.0 ± 1.7 a	1.5 ± 0.1 a	70.8 ± 0.5 a	71.2 ± 0.1 a	82.2 ± 2.8 a	14.0 ± 0.2 a	181.6 ± 18.5 a	155.7 ± 27.1 a	1.1 ± 0.0 a
Variety A + Foxy2	4	3.5 ± 0.4 a	39.4 ± 3.1 a	1.6 ± 0.1 a	71.0 ± 0.4 a	70.8 ± 0.4 a	82.1 ± 1.0 a	14.0 ± 0.0 a	252.1 ± 76.2 a	155.5 ± 15.5 a	1.1 ± 0.2 a
Variety B	4	3.7 ± 0.3 a	39.9 ± 1.2 a	1.4 ± 0.0 a	70.8 ± 0.2 a	70.6 ± 0.3 a	84.6 ± 1.1 a	14.0 ± 0.1 a	251.7 ± 26.9 a	182.9 ± 9.4 a	1.5 ± 0.2 a
Variety B + Gum Arabic	4	4.0 ± 0.5 a	40.3 ± 3.2 a	1.4 ± 0.1 a	71.0 ± 0.5 a	70.9 ± 0.2 a	83.7 ± 2.7 a	14.0 ± 0.2 a	253.9 ± 71.3 a	185.2 ± 26.5 a	1.3 ± 0.1 a
Variety B + Foxy2	4	3.5 ± 0.3 a	39.0 ± 1.7 a	1.6 ± 0.1 a	71.4 ± 0.6 a	71.2 ± 0.7 a	83.6 ± 1.7 a	14.1 ± 0.1 a	192.8 ± 7.1 a	160.2 ± 17.1 a	1.4 ± 0.1 a
Coating (2, 6)*	*F*-value	3.3**	0.1	0.6	0.1	0.2	0.01	0.02	0.01	0.1	0.1
	p-value	0.2	0.99	0.76	0.91	0.78	0.89	0.99	0.93	0.34	0.59
Variety (1, 6)*	*F*-value	3.4**	0.0	0.1	0.01	0.1	0.02	0.00	0.01	1.1	0.3
	p-value	0.1	0.90	0.60	0.92	0.85	0.99	0.97	0.99	0.89	0.95
Coat × Var (2, 6)*	*F*-value	0.5**	0.01	0.1	0.1	0.3	0.00	0.04	0.1	0.3	0.01
	p-value	0.8	0.99	0.94	0.95	0.78	0.99	0.96	0.88	0.78	0.99

*Degrees of freedom for *F*-test (denominator, numerator) for all parameters (except *Striga hermonthica* population **χ^2-Value; coating df = 2, variety df = 1, coating × variety df = 2) Means with the same letter are not significantly different (*t*-test, $p > 0.05$).

2013). Defensive factors in *S. hermonthica* and maize plants towards microbes may inhibit the colonization of their tissues by *F. oxysporum*, thereby limiting its biological control potential (Watson, 2013). Crops modify soil microbial communities through rhizodeposition (Bais et al., 2006; Beed et al., 2007), which affects the pathogenicity and virulence of biological control agents (Berg, 2009; Raaijmakers et al., 2009). Abiotic factors such as the form of nitrogen in soil, pH, moisture and temperature affect the infection of plants by *Fusarium* species (Doohan et al., 2003; Nasir et al., 2003). However, these explanations are not convincing in addressing the lack of efficacy towards *S. hermonthica* and pathogenicity in solanaceous crops, when *F. oxysporum* f. sp. *strigae* is applied for biological control.

Research on the biological control of *S. hermonthica* is shifting focus towards the use of native strains of *F. oxysporum* and other biological control agents. In Kenya, the local isolate *F. oxysporum* f. sp. *strigae* (Foxy FK3) has been undergoing on-station and on-farm evaluation in the Western region (Okalebo et al., 2012; Sunda et al., 2012). Research on *F. oxysporum* f. sp. *strigae* (Foxy FK3) in Kenya has yielded promising results (Beed et al., 2013). In all cases, a bioherbicide will only be adopted if field efficacy is proven to farmers and policy makers, and will only provide significant value if integrated with other technologies for the control of *S. hermonthica* (Beed et al., 2007; Watson, 2013).

Results from this PEQ study have shown that *F. oxysporum* f. sp. *strigae* (Foxy 2) is predominantly safe on maize growth, but its efficacy in controlling *S. hermonthica* was not evident on the tested Kenyan soils. Therefore, *F. oxysporum* f. sp. *strigae* (Foxy 2) is not suitable for release to Kenyan farmers as it will not benefit them in the management of *S. hermonthica* (Ajanga and Avedi, 2013). Future studies need to bio-prospect for native strains of *F. oxysporum* and other microbial isolates that are well adapted for *S. hermonthica* control under the Kenyan conditions. These will require accurate microbial identification. The contribution of endophytic and rhizosphere microbes in the function of *S. hermonthica* biological control process amidst the influence of abiotic factors requires in-depth investigation. Policies related to the use of microbial endophytes need to be developed and strengthened (Ochieno, 2010), so as to address perceived hindrances in the regulation of biological control agents (Ehlers, 2009). Stringent research protocols need to be applied in the assessment of *Fusarium* species as biological control agents, to verify their performance within their area of origin, and through post-entry quarantine facilities when imported. In conclusion, *F. oxysporum* f. sp. *strigae* strain Foxy 2 did not achieve biological control of *Striga hermonthica* parasitizing maize in Western Kenya.

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