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Editorial management

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Preface

The African Phytosanitary Journal is emerging as one of the most authoritative journals covering phytosanitary issues. The journal continues to serve as a crucial platform for disseminating significant findings in sanitary and phytosanitary issues. Its uniqueness is attributable to the scope of its coverage which is exclusively focused on matters which need to be addressed if Africa is to realize significant growth in agriculture and trade. The purpose of this journal is to provide a comprehensive view of the latest research and advancements in sanitary and phytosanitary issues that are crucial in upholding standards set by International Plant Protection Convention (IPPC). These standards are aimed at protecting the world's plants, agricultural products and natural resources from plant pests. In APJ volume 4, we present six articles; (i) Prospects of indigenous fungi as novel biological control agents of thrips (*Frankliniella occidentalis* (Pergande, 1895) on tomato (*Solanum lycopersicum* L.) in vivo (ii) Occurrence and distribution of Papaya Mealybug (*Paracoccus marginatus* Williams and Granara de Willink) (Hemiptera: Pseudococcidae) in the coastal area of Kenya (iii) Prospecting for fine scale establishment of exotic stem borer pupal parasitoid (*Xanthopimpla stemmator* Thunberg) in Kenya (iv) Rice husk biochar for carbon sequestration, soil fertility and plant health improvement: A review (v) Integrated Pest Management Decision Support System (IPM-DSS) a tool to support management of tree diseases in Kenya (vi) Effect of climate change on the quality of citrus fruit produced in South Africa.

We extend our gratitude to all contributing authors for their innovative work and to our reviewers for their critical evaluations. We hope you find this journal insightful and inspiring.

Prof. Theophilus M. Mutui, PhD
Managing Editor

Foreword

The African Phytosanitary Journal stands as a beacon in the realm of agricultural trade, offering a vital platform for disseminating crucial information on phytosanitary matters. In a world witnessing heightened globalization and increased trade in agricultural commodities, ensuring the integrity of these exchanges becomes paramount. The journal serves as a channel for bridging the gap between research advancements and practical implementation, thereby safeguarding plant health and facilitating trade.

As we navigate the complexities of global trade, it becomes evident that staying up-to-date with phytosanitary requirements becomes crucially important. Through its extensive peer-review process and wide-ranging scope, the African Phytosanitary Journal strives to keep stakeholders informed of the latest developments and emerging issues in the field. From pest management strategies to cutting-edge technologies, the issue offers invaluable insights aimed at fostering a deeper understanding of phytosanitary challenges and their effective management.

This issue of APJ focusses on invasive species affecting important agricultural products, their management through biological control products, measures for overall plant health improvement and effects of climate change on select fruits. This content is also available online at www.africanphytosanitaryjournal.org.

None of this would be possible without the dedicated efforts of the journal's team, whose commitment and expertise are truly commendable. From the editorial board, reviewers and authors, each individual's contributions are integral to the success of this endeavor. I would like to thank all for their efforts and dedication towards the publication of this issue as the journal continues to serve as a motivation for innovation, knowledge sharing and sustainable development in the years to come.

Dr. Isaac Macharia

Editor in Chief

Scope of the journal

This journal has been developed to enrich knowledge and information in the following thematic areas:

- Pest surveillance
- Pest reporting
- Phytosanitary measures
- Pest Risk Analysis
- Pest identification and analysis
- Food safety
- Quarantine and Biosecurity
- Phytosanitary policy and regulation
- Phytosanitary treatment
- Emerging technologies
- Biological agents
- Pest Management
- Agricultural Chemistry
- Emerging phytosanitary issues
- Biosafety
- Phytosanitary issues in trade
- Other relevant phytosanitary issues

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Prospects of indigenous fungi as novel biological control agents of thrips (*Frankliniella occidentalis* Pergande, 1895) on tomato (*Solanum lycopersicum* L.) in vivo

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Abstract

Tomato (*Solanum lycopersicum* L.) is an important horticultural crop in Kenya. Its production is constrained by many factors, among them arthropod pests and diseases. In response, farmers rely on synthetic pesticides, which lead to contamination of the produce, pest resistance and pollution of the environment hence there is need to identify safer, affordable alternatives. Biological control is considered safe, self-sustaining and cost effective. This study was aimed at determining the effectiveness of indigenous fungi in managing Western flower thrips *Frankliniella occidentalis* on tomato. Efficacy trials were conducted in farmer's fields in Bungoma County, Kenya between March and November 2018. Treatments included fungal isolates *Trichoderma harzianum*, *Gliocladium virens*, *Verticillium* spp., *Paeciliomyces victoriae* and *Fusarium oxysporum* selected after *in vitro* screening. These were compared to commercial fungus *Beauveria basssiana*, a synthetic pesticide imidacloprid and untreated control. Treatments were replicated four times, arranged in a randomized complete block design. Data collected on population of thrips and the yield of tomatoes were subjected to Analysis of Variance (ANOVA). Means were separated using Student Newman-Keuls (SNK) test at $p \leq 0.05$. In the first season at Bukonoi, *F. oxysporum* significantly ($p<0.05$) recorded the least (38.1) mean number of thrips compared to the untreated control (89.2). At Cheptais, *F. oxysporum* and *T. harzianum* treated plots significantly ($p<0.05$) recorded the least mean number of thrips of 48.1 and 20.5 in the first and second season, respectively. Higher yields of 4.9 t ha^{-1} and 29.5 t ha^{-1} were obtained from plots treated with *T. harzianum* in the first and second season, respectively. The findings of this study demonstrated that *F. oxysporum* and *T. harzianum* have the potential to be developed as fungal biopesticides for management of thrips on tomato crop. However, large scale field trials are warranted to validate the effectiveness of these fungal isolates.

Key words: Biopesticides, *Frankliniella occidentalis, Fusarium oxysporum*, *Solanum lycopersicum, Trichoderma harzianum.*

Introduction

The Western flower thrip, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), is an important quarantine arthropod pest of horticultural crops in the world (Infonet-Biovision, 2022). Thrips cause abscission of buds, flowers and deformation of fruits. Thrips are also potential vectors of viral diseases such as Tomato Spotted Wilt Virus and the Tomato Chlorotic Spot Virus (Infonet-biovision, 2022). Despite their negative impacts on living organisms and the environment, synthetic pesticides have been extensively used to manage thrips (Ndakidemi *et al.*, 2016). Frequent application of such pesticides has led to development of resistance (Wagnitz, 2014). The numerous negative effects associated with chemical pesticides have led to increased interest in developing environmentally safer and sustainable strategies to manage arthropod pests. In particular, focus has been on the use of biopesticides as an alternative to synthetic pesticides in integrated pest management strategies (Srijita, 2015).

Biopesticides have several advantages including less toxic residues, safety to non-target organisms, varied modes of action on pests, host specificity, compatibility with other pest management strategies, sustainability and affordability to farmers if produced locally (Ouma *et al.*, 2014). This study investigated the effectiveness of local antagonistic fungi against *F. occidentalis* on tomato under field conditions as alternatives to synthetic pesticides for reduced chemical residues in the produce.

Materials and methods

Description of study sites

Field trials were carried out for two tomato growing seasons in farmers' fields at Bukonoi and Cheptais in Bungoma County, Kenya. The first season was carried out between March and July 2018 while the second season was carried out between August and November 2018. Bukonoi is located at 0°48´36´´N and 34°28´12´´E, 1,635m above sea level (masl) with volcanic soils while Cheptais

is located at 0°48´0´´N, 34°27´36´´E, 1,593 masl with sandy clay loam soils. The County receives bimodal rainfall ranging from 950 to 1500 mm per annum with the long rains being experienced between March to July and short rains between August to November (Jaetzold *et al.*, 2012). The average annual temperatures range from 15 to 23°C (NAFIS, 2018; Bungoma CIDP, 2013-2018).

Source of fungal isolates

The fungal antagonists evaluated were *Gliocladium virens*, *Verticillium* spp., *Trichoderma harzianum, Paeciliomyces victoriae* and *Fusarium oxysporum.* The antagonists were originally isolated from soil samples collected from Bungoma County, Kenya in rhizosphere of tomato plants. These were selected based on their virulence against *Frankliniella occidentalis in vitro* experiments (Barasa *et al.*, 2021). They were mass produced on sorghum (*Sorghum bicolor* L.) grains since it is locally available and has shown good performance (Kumar *et al.*, 2014). Two hundred grams of sorghum were weighed and washed properly three times using fresh tap water. The sorghum grains were pre-cooked by soaking in boiled water for 20 minutes. The substrate (sorghum) was placed into Milner bags (30 x 65cm) and autoclaved for 15 minutes at 121°C then cooled to about 40-45°C. The aerated sorghum bags were inoculated with 3-day old fungal broth and incubated at room temperature. During the incubation period, contents of the polythene bags were manually shaken vigorously every two days to prevent clumping and improve aeration as described by Sivakalai and Ramanathan (2015). After 14 days, the substrate was transferred into sterile plastic trays (25cm x 20cm) covered with a serviette on top and tied with a rubber band. They were allowed to air dry for 10 days at room temperature and conidia were harvested using a sieve (295µm pore mesh size) (Gathage *et al.*, 2016).

One-gram sample of each fungal antagonist was weighed and suspended in 9ml distilled water in separate

universal bottles. The suspension was shaken in a mechanical shaker (Unimax 1010) for 5 minutes and filtered through double layered muslin cloth. The concentration of fungal antagonists was standardized through serial dilution to 1×10^8 conidia g^{-1}. Harvested conidia were packed in sealed polythene bags (30cm x 20cm), labeled and stored at 4°C ready for use in the field.

Crop establishment and trial design

Seeds of Rio-Grande tomato variety were established in a nursery bed. The experimental field (39m by 15m) was manually prepared using a hoe. The field was divided into 32 plots, each measuring 4m by 3m with 1m buffer zones between the plots. The experiment was laid out in a randomized complete block design (RCBD) with eight treatments replicated four times. Four-week-old healthy tomato seedlings from the nursery were transplanted at a spacing of 60cm x30 cm (Infonet-biovision, 2022), making a total of 67 plants per plot. Planting holes were dug per plot and 10g Diammonium phosphate fertilizer was thoroughly mixed with the soil. The seedlings were placed and watered immediately to enhance establishment. Gapping of dead seedlings was done one week after transplanting. Calcium Ammonium Nitrate (CAN) was applied as top dressing at a rate of 10g per plant at fourth week after transplanting. Weeding was done at 3, 6 and 9 weeks after transplanting.

Application of treatments

Treatments application commenced at the sixth week after transplanting of tomatoes. The tomato plants were at flowering stage (BBCH 61). Subsequent treatments were applied every 7 days as foliar sprays. The test fungal isolates *Gliocladium virens*, *Verticillium* spp., *Trichoderma harzianum, Paecilomyces victoriae, Fusarium oxysporum* were applied at concentration of $1x10^8$ conidia g^{-1}. These were compared with registered commercial fungus Bio-power (*Beauveria bassiana*) at recommended dose rate of 100g/20 litres of water, synthetic insecticide Confidor 70 WG®

(Imidacloprid 700g/Kg) at 5g/20 litres of water and a negative control (water).

Each concentration ($1x10^8$ conidia g^{-1}) of *Gliocladium virens*, *Verticillium* spp., *Trichoderma harzianum, Paecilomyces victoriae, Fusarium oxysporum* was mixed with water and then sprayed using a calibrated knapsack sprayer CP 15s (Cooper Pegler and Co. Ltd, Sussex, England) with a flat cone nozzle. Application was done starting with the negative control (water) followed by the test fungal isolates, the standard bio-pesticide and the standard synthetic pesticide imidacloprid, respectively. Spraying was done in the evening between 16:00h and 18:30h to lessen the adverse effects of ultraviolet radiation (Mustafa & Kaur, 2010). During treatment applications, polythene sheets were used to avoid drift of mist to neighboring plots. The knapsack sprayer was thoroughly washed with water and soap, rinsed three times before use in spraying each of the treatments. The treatments were applied in their respective plots five times during the trial period.

Data collection

Assessment of pest population

The assessment of thrips population was conducted at early hours of the day between 7.00-10.00am as described by El-Shafie and Abdelraheem (2012). This was done five times at flowering from 6th to 10th week after transplanting of tomatoes Twenty well developed flowers from 20 randomly tagged tomatoes in the inner rows per plot were cut and placed in high density plastic poly pots (35ml) containing 70% ethanol. Each flower was placed in a petri dish, dissected and rinsed with water making sure that no thrip was washed off. The number of thrips were counted using a tally counter under the dissecting microscope (NTB-3A) at x10 magnification and recorded.

Assessment of tomato yield

At maturity (12th week after transplanting) tomato fruits at pink stage were harvested in whole plots. The produce was graded into marketable and

non-marketable categories. The weight of tomatoes in kilograms was determined using a digital hand-held electronic scale and extrapolated into tons ha^{-1} as follows: Y= (W x 10,000) ÷ A, where, Y is the yield in tons ha^{-1}; W is the total weight in tons of harvested tomatoes and A is the plot size in m^2 (Ashenafi *et al*., 2017).

Statistical analysis

Data on number of thrips was checked for normality using Shapiro-Wilk test and were normalized using square root transformation [SQRT(x+1)] before analysis. The transformed data on thrips and yield of tomatoes were subjected to one-way ANOVA using SAS version 9.1 (SAS Institute, 2013). Post-hoc test was conducted using the Student–Newman–Keuls test (SNK) and means were separated at $p<0.05$ (Sokal & Rohlf, 1995).

Results

In Bukonoi, thrip population in plots treated with fungal isolates were significantly lower ($p<0.05$) compared to populations observed in control plots. over the two trial seasons. In the first season (March-July 2018), plots treated with imidacloprid recorded the least population density of thrips (27.2) and its effect was not significantly different from that recorded in the fungal isolates *G. virens*, *T. harzianum*, *P. victoriae* and *F. oxysporum*. Of the evaluated isolates, plots treated with *F. oxysporum* recorded the least population density of thrips (38.1) and its effect was not significantly different from plots treated with the rest of the fungal isolates and the commercial fungal biopesticide (*B. bassiana*). Control plots recorded the highest population density of thrips (89.2) which was significantly ($p<0.05$) different from the rest of the treatments (Table 1).

In the second cropping season (August-November 2018), a similar trend was observed. Plots treated with imidacloprid recorded the least population density of thrips (17.4) and its effect was not significantly different from plots treated with *Verticillium* spp., *T. harzianum*, *F. oxysporum* and the standard commercial fungus (*B. bassiana*). Of the evaluated isolates, *Verticillium* spp. treated plots

recorded the least population of thrips (17.9) followed by *F. oxysporum* and *T. harzianum* with 18.2 and 18.3 thrips, respectively. Control plots recorded the highest population density of thrips (32.3) which was significantly (p<0.05) different from the rest of the treatments (Table 1).

Table 1: Number of thrips on tomatoes sprayed with different treatments during the two cropping seasons at Bukonoi.

		Mean no. thrips/20 flowers±S.E	
Treatment	**Rate/concentration**	**Season 1 (March-July 2018)**	**Season 2 (August-November 2018)**
G. virens	1x10^8 conidia g^{-1}	43.8bc	22.3b
*Verticillium s*pp.	1x10^8 conidia g^{-1}	46.7b	17.9cd
T. harzianum	1x10^8 conidia g^{-1}	44.1bc	18.3cd
P. victoriae	1x10^8 conidia g^{-1}	44.4bc	21.2bc
F. oxysporum	1x10^8 conidia g^{-1}	38.1bc	18.2cd
B. bassiana	100g/20l of water	54.7b	16.7d
Imidacloprid 700g/Kg	5g/20l of water	27.2c	17.4d
Control (water)	-	89.2a	32.3a
p-value		0.0015	<0.0001
F-value		8.6	18.6

Means followed by the same letter (s) in each column are not significantly different according to Student Newman-Keuls (SNK) test at p<0.05.

At Cheptais, the evaluated fungal isolates significantly (p<0.05) reduced the population of thrips compared to the control for the two trial seasons. In the first cropping season (March-July 2018), plots treated with the standard insecticide (imidacloprid) recorded the

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lowest population density of thrips (28.5) followed by *F. oxysporum* and *T. harzianum* treated plots with 48.1 and 48.8 thrips, respectively. The effect of the evaluated fungal isolates *Verticillium spp.*, *T. harzianum*, *P. victoriae* and *F. oxysporum* in reducing thrips population

was not significantly different from *B. bassiana*. The control plots recorded the highest population density of thrips (90.5) which was significantly different (p<0.05) from the rest of the treatments (Table 2).

During the second cropping season (August-November 2018), plots treated *T. harzianum* recorded the least population density of thrips (19.1) and its effect was not significantly different from the fungal isolates *Verticillium* Spp., *P. victoriae*, *F. oxysporum* and imidacloprid. The control treated plots recorded the highest population density of thrips (35.3) which was significantly (P<0.05) different from the rest of the treatments (Table 2).

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Table 2: Number of thrips on tomatoes sprayed with different treatments during the two cropping seasons at Cheptais

		Mean no. thrips/20 flowers±S.E	
Treatment	**Rate/concentration**	**Season 1 (March-July 2018)**	**Season 2 (August-November 2018)**
G. virens	$1x10^8$ conidia g^{-1}	65.9b	27.1b
Verticillium spp.	$1x10^8$ conidia g^{-1}	50.9c	20.0bc
T. harzianum	$1x10^8$ conidia g^{-1}	48.8c	19.1c
P. victoriae	$1x10^8$ conidia g^{-1}	51.9c	21.5bc
F. oxysporum	$1x10^8$ conidia g^{-1}	48.1c	20.5bc
B. bassiana	100g/20l of water	55.4c	27.3b
Imidacloprid 700g/Kg	5g/20l of water	28.5d	26.1bc
Control (water)	-	90.5a	35.3a
p-value		0.0088	0.0007
F-value		5.3	10.0

Means followed by the same letter (s) in each column are not significantly different according to Student Newman-Keuls (SNK) test at $p \leq 0.05$.

During the first season at Bukonoi, the evaluated fungal isolates significantly ($p<0.05$) improved the yield of tomatoes compared to the control. The standard synthetic insecticide imidacloprid 700g/Kg -treated plots achieved the highest total (4.9t/ha) and marketable (3.7t/ha) yield of tomatoes followed by plots treated with *T. harzianum* and *B. bassiana*. The lowest yield was recorded from the negative control plots (Table 3). In the second season, except for *T. harzianum*-treated plots, the evaluated fungal isolates showed no significant effect on the yield of tomatoes compared to the control plots. Plots treated with *T. harzianum* achieved the highest total (29.5t/ha) and marketable yield (27.4 t/ha) of tomatoes which was significantly ($p<0.05$) different from that achieved in the control plots. The control treated plots recorded the lowest yield (Table 3).

Table 3: Mean yield (t/ha) ± SE of tomatoes harvested for the two seasons at Bukonoi

		Season 1 (March-July 2018)		Season 2 (Aug-Nov 2018)	
Treatment	**Rate/concentration**	**Total**	**Marketable**	**Total**	**Marketable**
G. virens	$1x10^8$ conidia g^{-1}	2.3±0.2bc	1.9±0.2b	24.1±3.1ab	21.8±2.8ab
*Verticillium s*pp.	$1x10^8$ conidia g^{-1}	3.7±1.1b	3.0±1.0ab	26.8±4.3ab	23.9±4.1ab
T. harzianum	$1x10^8$ conidia g^{-1}	4.9±0.8ab	3.7±0.8ab	29.5±2.3a	27.4±2.3a
P. victoriae	$1x10^8$ conidia g^{-1}	3.5±0.3bc	2.8±0.3ab	25.7±2.6ab	23.2±2.5ab
F. oxysporum	$1x10^8$ conidia g^{-1}	2.1±0.3bc	1.6±0.2b	26.9±2.9ab	24.5±2.7ab
B. bassiana	100g/20l of water	4.5±1.8ab	3.4±1.6ab	27.0±2.6ab	24.0±3.8ab
Imidacloprid 700g/Kg	5g/20l of water	6.8±0.4a	4.9±0.4a	28.3±4.3a	25.0±4.2ab
Control (water)	-	0.0±0.0c	0.0±0.0c	18.2±1.8b	16.4±1.8b
p-value		0.0020	0.0150	0.0362	0.0429
F-value		5.1	3.2	1.1	1.0

Means followed by the same letter (s) in each column are not significantly different according to Student Newman-Keuls (SNK) test at $p \leq 0.05$.

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During the first season at Cheptais, the evaluated fungal isolates significantly (p<0.05) improved the yield of tomatoes compared to the control. The plots treated with imidacloprid 700g/Kg achieved the highest total (1.9 t/ha) and marketable (1.2 t/ha) yield of tomatoes followed by plots treated with *G. virens* and *P. victoriae* with marketable yield of 0. 6 t/ha and 0.5 t/ha, respectively. The lowest yield was recorded from the negative control plots (Table 4). In the second season, the evaluated treatments showed no significant effect on the yield of tomatoes compared to control plots. However, plots treated with *Verticillium spp*. recorded the higher total (18.3t/ha) and marketable (14.9t/ha) yields of tomatoes followed by the *T. harzianum* and *F. oxysporum*-treated plots. The lowest yield total (9.5t/ha) and marketable yield (7.0t/ha) was recorded from control plots (Table 4).

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Table 4: Mean yield (t/ha) ± S.E of tomatoes harvested for the two seasons at Cheptais.

Means followed by the same letter (s) in each column are not significantly different according to Student Newman-Keuls (SNK) test at $p \leq 0.05$.

		Season 1 (March-July 2018)		Season 2 (Aug-Nov 2018)	
Treatment	Rate/concentration	Total	Marketable	Total	Marketable
G. virens	1x10^8 conidia g^{-1}	0.9±0.1b	0.6±0.0b	13.8±5.1a	11.7±4.4a
*Verticillium s*pp.	1x10^8 conidia g^{-1}	0.8±0.2b	0.4±0.2b	18.3±3.9a	14.9±3.4a
T. harzianum	1x10^8 conidia g^{-1}	0.7±0.3b	0.4±0.2b	17.9±1.4a	12.9±1.9a
P. victoriae	1x10^8 conidia g^{-1}	0.8±0.3b	0.5±0.2b	14.7±2.4a	11.4±1.9a
F. oxysporum	1x10^8 conidia g^{-1}	0.7±0.3b	0.5±0.2b	15.9±4.0a	12.7±3.2a
B. bassiana	100g/20 L water	1.0±0.1b	0.6±0.2b	13.1±2.7a	10.6±2.0a
Imidacloprid 700g/Kg	5g/20L water	1.9±0.4a	1.2±0.4a	15.7±2.9a	12.0±2.2a
Control (water)	-	0.0±0.0c	0.0±0.0c	9.5±1.3b	7.0±0.7b
p-value		<0.0001	0.0006	0.0659	0.0685
F-value		7.4	5.5	0.7	0.6

Discussion

The evaluated fungal isolates reduced the population of thrips with *F. oxysporum* and *T. harzianum* being most effective. The efficacy of *F. oxysporum* and *T. harzianum* was comparable to that of the commercial fungus (*B. bassiana*) and the synthetic insecticide (Imidacloprid 700g/Kg) demonstrating that these isolates have similar ability as that of the commercial products in suppressing thrips population in tomatoes. These findings compare with those of other researchers who reported insecticidal effects of *F. oxysporum* and *T. harzianum* in reducing infestation of arthropod pests infesting tomato crop (Lakhdari *et al*., 2016; Lengai, 2016; Caccavo *et al*., 2022). *Fusarium. oxysporum* and *T. harzianum* are thus good candidates for biopesticides that can be used in *F. occidentalis* management.

The low tomato yields recorded during first season compared to the second season could be attributed to higher thrips infestation of recorded during the first season. High infestation of tomato plants by thrips has been known to lead to flower abortion resulting in low fruit development and consequently low number of fruits harvested (Infonet-biovision, 2022). These findings corroborate previous studies that have reported reduced populations of arthropod pests by application of fungal antagonists with remarkable increase in tomato yield (El-Shafie & Abdelraheem, 2012; Lengai, 2016).

Among the tested fungal antagonists, *T. harzianum* was more efficacious in reducing the population of thrips with a resultant increase in the yield of tomatoes in both study sites for the two cropping seasons. These findings agree with Caccavo *et al*. (2022) who reported significantly higher fruit yield of tomatoes following application of *T. harzianum* in management of arthropod pests in the field. The effect of *T. harzianum* on the yield of tomatoes can also be attributed to its ability to promote growth of plants as well as inducing resistance to pathogens (Mwangi *et al*., 2009; Sawant, 2014).

Conclusions and recommendations

The findings of this study demonstrated that *F. oxysporum* and *T. harzianum* were most effective in reducing the population of *F. occidentalis* on tomato and also increased marketable yield of tomatoes. Therefore, *F. oxysporum* and *T. harzianum* are good candidates for development as fungal-based bio-pesticides for *F. occidentalis* management on tomato. More studies should be conducted to determine bioactive compounds of these antagonistic fungi. This will be useful in the formulation and consequent commercialization as biopesticides. The synergistic effects between these antagonistic fungi should also be investigated.

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References

Ashenafi, M.Y., Thangavel, S., Alemu, L., & Bekele, K. (2017). Evaluation of tomato cultivars and fungicides for the management of late blight (*Phytophthora infestans* (Mont) de bary) in Holleta, West Showa, Ethiopia. *International Journal of Life Sciences, 5*(2), 161-179.

Barasa, M.W., Kahuthia-Gathu, R., Mwangi, M., & Waceke, J.W. (2021). *In vitro* efficacy of native entomopathogenic fungi against Western flower thrips *Frankliniella occidentalis* (Pergande) of tomato in Kenya. *International Journal of Innovative Approaches in Agricultural Research, 5*(2), 194-202.

Bungoma County Integrated Development Plan. (2013). County Integrated Development Plan 2013-2018 County Government of Bungoma.

Caccavo, V., Forlano, P., Mang, S.M., Fanti, P., Nuzzaci, M., Battaglia, D., & Trotta, V. (2022). Effects of *Trichoderma harzianum* Strain T22 on the Arthropod Community Associated with Tomato Plants and on the Crop

Performance in an Experimental Field. *Insects*, *13*, 418. https://doi.org/10.3390/insects13050418.

El-Shafie, H.A.F., & Abdelraheem, B.A. (2012). Field evaluation of three biopesticides for integrated management of major pests of tomato, *Solanum lycopersicum* L. in Sudan. *Agriculture and Biology Journal of North America, 3*(9), 340-344.

Gathage, J.W., Lagat, Z.O., Fiaboe, K.K.M., Akutse, K.S., Ekesi, S., & Maniania, N.K. (2016). Prospects of fungal endophytes in the control of *Liriomyza* leafminer flies in common bean *Phaseolus vulgaris* under field conditions. *Biocontrol, 61*, 741–753.

Infonet-biovision (2022). Tomatoes, http://www.infonetbiovision.org/default/ct/80/pests.Accessed 20/04/2022.

Jaetzold, R., Hornetz, B., & Schmidt, H. (2012). *Farm Management Handbook of Kenya*. Volume. I-IV (Western, Central, Eastern, Nyanza, Southern Rift Valley, Northern Rift Valley, Coast), Nairobi.

Kumar, S., Thakur, M., & Rani, A. (2014). *Trichoderma*: Mass production, formulation, quality control, delivery and its scope in commercialization in India for the management of plant diseases. *African Journal of Agricultural Research, 9* (53): 3838-3852.

Lakhdari, W., Dehliz A., Acheuk, F., Mlik, R., Hammi1, H., & Matallah, S. (2016). Biocontrol test against the leaf miner of tomato *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) by using entomopathogenic fungi in the Algerian Sahara. *Journal Algerien des Regions Arides (JARA), 13*, 85-89.

Lengai, W.M.G. (2016). *Efficacy of plant extracts and antagonistic fungi as alternatives to synthetic pesticides in management of tomato pests and disease*. Msc. Thesis. University of Nairobi, Kenya.

Mwangi, M. W., Ethel, O. M., Sheila, A. O., & Joyce, M. J. (2009). Effect of *Trichoderma harzianum* and arbuscular mycorrhizal fungi on growth in tomato (*Lycopersicum esculentum* Mill) Seedlings, napier (*Pennisetum purpureum* L.) and tea (C*amellia sinensis* L.) cuttings. *Tropical and Subtropical Agroecosystems, 11*, 423–429.

Mustafa, U., & Kaur, G. (2010). Extracellular enzyme production in *Metarhizium anisopliae* isolates. *Folia Microbiologica, 54* (6), 499-504.

National Farmers Information Service (NAFIS). (2018). Ecological requirements, http://www.nafis.go.ke/vegetables/tomatoes/ecological-requirements/accessed 2/02/2019.

Ndakidemi, H., Kilinçer, N., & Ozkan, C. (2016). Toxicity and repellent effects of some botanical insecticides on the egg larval parasitoid *Chelonus oculator* (Hymenoptera:Braconidae). *Scientific Research and Essays, 9*, 106-113.

Ouma, B., Muthomi, J., & Toroitich, F. (2014). Management of thrips in French beans by integrating biological and synthetic pesticides in conventional spray regimes. *Journal of Renewable Agriculture, 2*(2), 27-37.

SAS Institute. (2013). Base SAS 9.1 procedures guide: Statistical procedures, 40.

Sawant, I.S. (2014). Trichoderma- foliar pathogen interactions. *Mycology Journal, 8*, 58-70.

Sivakalai, S., & Ramanathan, N. (2015). Simple and cost-effective method for mass production of entomopathogenic fungi by using naturally available substrate. *International Journal of Frontiers in Science and Technology, 2*(4), 67-77.

Sokal, R.R., & Rohlf, F.J. (1995). *Biometry*. The Principles and Practice of Statistics in Biological Research, W.H. Freeman and Company, New York.

Srijita, D. (2015). Biopesticides: an eco-friendly approach for pest control. *World Journal of Pharmacy and Pharmaceutical Sciences, 4*(6), 250-265.

Wagnitz, J. (2014). *Biopesticides use in IPM for low desert vegetable and fruit production*. PhD. Thesis. College of Agricultural Sciences and Natural Resources, University of Nebraska, Lincoln.

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Occurrence and distribution of Papaya Mealybug (*Paracoccus marginatus* Williams and Granara de Willink) (Hemiptera: Pseudococcidae) in the coastal area of Kenya

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Abstract

Papaya mealybug, *Paracoccus marginatus* Williams and Granara de Willink (Hemiptera: Pseudococcidae) was first reported in Kenya in 2016. Kenya Plant Health Inspectorate Service (KEPHIS) together with other collaborators has since continuously carried out surveillance and management initiatives to contain the pest. In November and December 2020, a delimiting survey of the papaya mealybug (PMB) was conducted in six coastal counties. The survey was aimed at determining the incidence and intensity of infestations in the farms, host range in the region and to assess the farmers' awareness on management options. Sixty-seven (67) farms were randomly sampled across the six counties. An open data kit (ODK) mobile tool generated questionnaires were administered to collect data on PMB incidence, infestation intensity and management practices applied and their effectiveness based on responses from farmers. Papaya mealybug was confirmed to occur in the six counties surveyed with incidences which ranged from 10-100%. The intensity of infestation in the counties varied from very low to medium based on the applied scale and was higher on fruits compared to the leaves, stems and flowers. The survey further revealed that PMB infested citrus, sugarcane, okra and custard apple that were initially not reported as hosts. Majority (65%) of the farmers interviewed were aware about the occurrence of PMB on their crops and could positively identify and describe it. Some farmers had tried to manage the pest and the lowest incidence (3%) was recorded from fields where farmers combined chemical and cultural practices for management. In order to contain the impact and spread PMB, authorities and research institutions in Kenya may need to consider deploying classical biological control management which has successfully been deployed in other countries.

Key words: Delimiting survey, incidence, infestation intensity, Kenya, papaya mealybug.

Introduction

Papaya mealybug (PMB) *(Paracoccus marginatus)* is a devastating pest of papaya and other crops in Kenya. It is classified in the Order Hemiptera and Family Pseudococcidae. It is native to Mexico and Central America and was first reported in Kenya in 2016 (Macharia *et al*., 2017). Papaya mealybug has been found on more than 200 host plants ranging from vegetables, fruit trees and ornamental plants many of which are of great economic value (Finch *et al*., 2021). The insect can cause great devastation to economies that depend on agriculture (Krishnan *et al*., 2016). The serious invasive pest status of PMB is enhanced by its fast growth, short life span, polyphagous feeding behavior and ease of dispersion. Papaya mealybug completes its life cycle in an average of 15-32 days (Laneesha, Suroshe, Babasaheb, & Shankarganesh, 2020). Reproduction in PMB occurs sexually and each female lays 100-600 eggs in a white waxy ovisac with several generations per year (Muniappan *et al*., 2008). Female PMB undergoes three immature larval stages before moulting into adult stage. Male PMB undergoes two immature larval stages that moult into a non-feeding pre-pupal stage and later into a short-winged adult. First instar crawlers are best suited for dispersal because they can survive for a day or even more without feeding as they locate a suitable feeding site (CABI, 2024). In favourable tropical conditions, PMB can produce as many as 15 generations in a year (CABI, 2024). The estimated optimum and maximum temperature thresholds for full development of PMB is 28.4°C and 32.1°C respectively (Amarasekare, Chong, Epsky, & Mannion, 2008).

Infestations on papaya appears as a cluster of cotton like masses on above ground plant parts. The adult is the most destructive stage of PMB which acts by sucking the sap of the plant and weakening it further. Adult colonies usually establish along the veins and midribs of older leaves and all areas of tender leaves and fruits (Walker *et al*., 2003). In severe attack, leaves turn yellow and necrotic, a characteristic

feature of PMB attack (Krishnan *et al.*, 2016). Infested tender leaves get bunched up and distorted. Heavy infestations and feeding on the phloem sap produces honey dew, which cause formation of the black sooty moulds on the infested fruits and vegetation (Meyerdirk *et al.*, 2004). The honey dew excreted attract ants that form mutual associations with the PMB. Sooty mould formation on the surface of leaves impairs photosynthetic efficiency which further affects the yield of the host crop (Schneider & LaPolla, 2010). Papaya mealybug also attack fruits causing discoloration and shriveling (Sarma, 2013). It is projected that PMB has the potential to cause much damage in the future (Laneesha *et al.*, 2020).

Spread of PMB to new areas is largely aided by animals, ants and human activity. Animals and humans accidentally pick up crawlers of PMB as they brush past infested plants thus transferring them to new host plants (Sarma, 2013). Farm machinery and vehicles passing through crops and fields during pruning and harvesting activities also aid in spreading crawlers to new hosts. Crawlers move from one plant to another and are also dispersed by wind, rain and irrigation water. In trade, transport of infested fresh fruits and plants for planting can transmit PMB over long distances and potentially between countries (Krishnan *et al.*, 2016).

Management of PMB has posed a great challenge for various reasons. Effectiveness of chemical products is limited due to the waxy and cotton coverings on the body of PMB (Tanwar, Jeyakumar, & Vennila, 2010). However, application of profenophos, chlorpyriphos, buprofezin, dimethoate, imidacloprid, thiametoxam, acetampride in appropriate concentrations has been observed to be effective (Krishnan *et al.*, 2016). Biological control is gaining popularity as the most effective management tool against PMB. Classical biological control has been applied successfully in some countries in the Caribbean, Pacific Islands, the state of Florida and Hawaii in the USA and India

(Muniappan *et al*., 2008; Myrick, Norton, Selvaraj, Natarajan, & Muniappan, 2014). Eight host specific parasitoids have so far been reported to give effective control of PMB (Laneesha *et al*., 2020). The parasitoids *Anagyrus loecki* Noyes, *Acerophagus papayae* Noyes and Schauff and *Pseudleptomastrix mexicana* Noyes and Schauff (Hymenoptera: Encyrtidae) have been deployed against PMB in classical biological control in various parts of the world. *Acerophagus papayae* is so far rated the most effective having shown 75-81% suppression of PMB (Laneesha *et al*., 2020). Other natural enemies exploited in biological control include, the mealybug destroyer (*Cryptolaemus montrouzieri*), ladybird beetles, lacewings, hover flies and beetles in the family Coccinellidae (*Scymnus sp*.) (Krishnan e*t al*., 2016).

In Kenya, the first report of PMB was in the coastal region; in Kwale, Mombasa and Kilifi counties (Macharia *et al*., 2017). The pest was detected on papaya (*Carica papaya*), cassava (*Manihot esculenta*), chili pepper (*Capsicum annuum*), guava (*Psidium guajava*), mango (*Mangifera indica*) and eggplant (*Solanum melongena*) with losses of up to 91% on papaya (Macharia *et al*., 2017). The survey underscored the threat posed by PMB on food security and loss of livelihoods in the region. In recommendation, Macharia *et al,* (2017) pointed out the need for further delimiting surveys covering a wider area including examination of potential hosts and natural enemies. It is against this background that this delimiting survey was carried out to determine the incidence and intensity of PMB infestations, the host range and to create awareness among farmers on management options of PMB.

Materials and Methods

This survey was carried out between November and December 2020 in six counties in the coastal region of Kenya; Mombasa, Kilifi, Kwale, Taita Taveta, Lamu and Tana River. A total of 67 small and large farms were randomly sampled across the six counties. The sample size was limited as a precautionary measure

against spreading the pest during surveillance. An open data kit (ODK) mobile tool generated questionnaires that were administered to collect data on name of farm, location, GPS coordinates, farm acreage, host crop, age of the crop, symptoms of PMB expressed, pest incidence, pest infestation intensity, management method(s) applied in control of PMB and their effectiveness based on responses from farmers interviewed. The percentage incidence was determined based on a formula developed and applied by Kennedy *et al*. (2017) while the intensity of infestation was estimated based on a grade chart adopted by Regupathy and Ayyasamy (2010) on tapioca plant. To determine the incidences, 5 spots were selected in each field sampled and, in each spot, 20 plants were selected at random. A total of 100 plants per field were examined. The percentage incidence of infested plants was computed from the number of plants affected and total number of plants observed: Percentage incidence (%) = Number of plants affected / Total number of plants observed X 100.

The intensity of infestation on the whole plant and specific plant parts was estimated using visual parameters based on grades provided (table 1). Besides papaya, other crops infested by PMB were recorded. Destructive sampling was done where necessary for PMB extraction in the laboratory and further identification of the host plants. Farmers were also interviewed and responses recorded on checklist embedded in ODK questionnaire on their knowledge of PMB, management options applied and their efficacy. Chi-square test of independence was carried out to determine whether there was a relationship between the following parameters: presence of PMB and the cropping system, farmers' knowledge and PMB infestations in the farms, frequency of scouting and presence of PMB in the fields, and the management practice and average incidences of PMB.

Table 1: Grade chart for estimating the intensity of infestation of papaya mealy bug

Intensity	Infestation levels
Very Low (1)	i. Few individuals of PMB found casually
Low (2)	i. PMB found in low numbers
	ii. No adverse symptoms e.g. deformation of leaves observed on affected plants
Medium (3)	i. Almost 75-100% coverage of leaves /fruits/ inflorescence
	ii. Yellowing of leaves
	iii. Shedding of infested leaves and fruits
High (4)	i. Almost all plant parts (stem, leaves, flowers and fruits) covered with PMB showing white appearance
	ii. Leaves, fruits and inflorescences are covered with honey dew excretion and sooty mould
Very High (5)	i. All plant parts (stem, leaves, flowers and fruits) are covered with PMB showing white appearance
	ii. Honey dew rain under the tree
	iii. Crinkling of leaves
	iv. Drying and death of plants

Source: © Regupathy and Ayyasamy (2010)

Results and Discussion

Incidence and intensity of infestations of PMB on papaya

A total of 67 farms were surveyed in the 6 counties (figure 1). More farms were sampled in Lamu due to the vastness of the county while Mombasa was least

sampled because it is largely urban with limited farming activities.

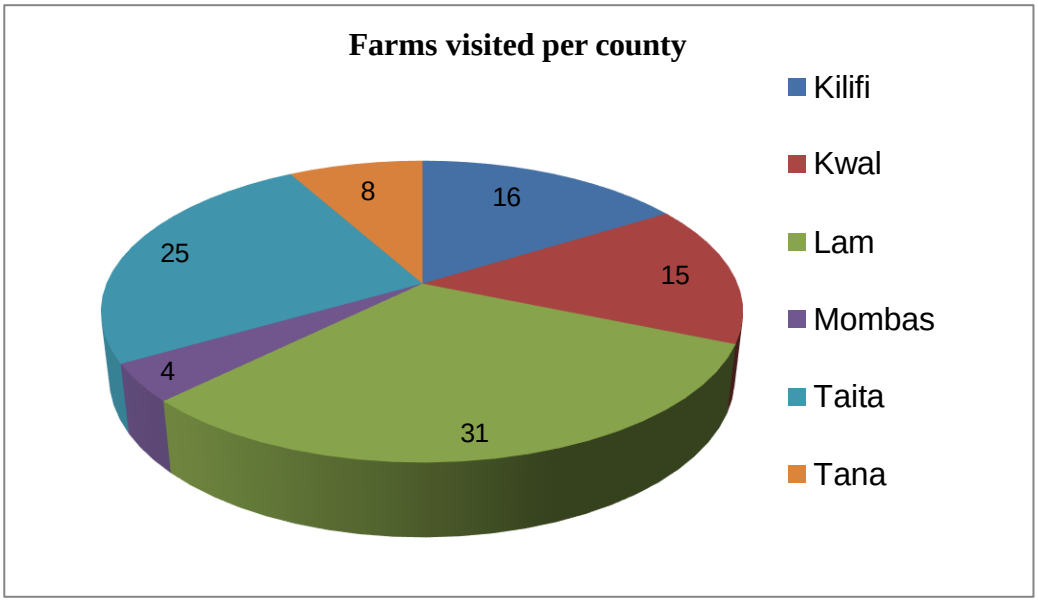

Figure 1: Distribution of farms as sampled across the counties

The findings confirmed that PMB occurred in all the six counties surveyed: Kilifi, Kwale, Lamu, Mombasa, Taita Taveta and Tana River. In the first report which only covered four counties, PMB was detected to occur in Kwale, Kilifi and Mombasa but absent in Taita Taveta county (Macharia *et al.*, 2017). The survey demonstrated that PMB had spread to the entire coastal region in less than three years. Papaya mealybug is physiologically at its optimum in temperature range of 25±5 ºC (Krishnan *et al.*, 2016). Further, in temperatures above 25ºC, females exhibit highest fecundity producing an average of 300 eggs per cycle. Papaya mealybugs have the ability to develop and establish successfully in areas with temperature range of between 18 ºC and 30 ºC (Amarasekare *et al.*, 2008). Coastal Kenya is generally warm with

temperatures mostly above 20ºC throughout the year. This is considered suitable for reproduction of PMB and with increased reproduction, came spread in order to explore food sources.

The survey also revealed varying levels of infestations in the counties (Table 2). The intensity of infestation ranged from very low to medium based on the scale applied on tapioca (Regupathy & Ayyasamy, 2010). Tana River County showed very low infestation while Kwale, Lamu and Taita Taveta showed low infestation. Kilifi and Mombasa showed medium infestations. The varying infestation intensities could be attributable to varying PMB management practices applied across the counties.

Table 2: Overall infestation across the six counties

County	Intensity of infestation
Kilifi	3
Mombasa	3
Kwale	2
Lamu	2
Taita Taveta	2
Tana river	1

Where; 1- Very low, 2- Low, 3- Medium, 4- High, 5- Very high

Incidences of PMB across the surveyed sub-counties ranged from 10% to 100% (Table 3). Kaloleni Sub-County in Kilifi County and Chewani Sub-County in Tana River County recorded the lowest incidences of 10% and 20% respectively. Mwatate and Taveta Sub-Counties in Taita Taveta recorded the highest incidences of 100% (table 3). Macharia *et al* (2017) observed that about 7.2% of farmers in the region applied various management options ranging from traditional, cultural to chemical methods to manage PMB. The various management practices applied together with the varying weather conditions across the sub counties could explain the PMB incidences observed.

Table 3: Incidence and infestation intensity of PMB on papaya in the different coastal sub counties.

County	Sub-County	PMB Incidence (%)	PMB Intensity
Kilifi	Kilifi North	80%	3
	Magarini	75%	3
	Kilifi South	67.50%	3
	Malindi	50%	3
	Ganze	64%	2
	Kaloleni	10%	2
Kwale	Msambweni	90%	3
	Kinango	95%	2
	Kwale	95%	2
	Lungalunga	68%	2
	Matuga	55%	2
	Kubo	40%	2
Lamu	Lamu East	70%	2
	Lamu West	41%	2
	Mpeketoni	32.50%	2
Mombasa	Changamwe	92%	3
Tana river	Tana River Delta	60%	2
	Chewani	20%	1
Taita Taveta	Mwatate	100%	2
	Taveta	100%	2
	Voi	26%	2

Where; 1- Very low, 2- Low, 3- Medium, 4- High, 5- Very high

The intensity of infestation was high on fruits (14%) compared to other parts of papaya plant (Table 4). Stems were the second highly infested plant parts (3%) followed by leaves and flowers (2%). Papaya mealybug like other mealybugs has a piercing-sucking mouth parts. They feed by inserting their mouthparts into plant tissues to suck the sugary sap from the phloem and other cells. The high preference for fruits compared to other papaya plant parts can be attributed to the softness of fruits and high concentration of sugars as the fruit ripens.

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Table 4: Intensity levels of infestation on plant parts

Part of the plant	Intensity infestation by PMB	No. of counts	Percentage
Leaves	Low	45	68%
	Medium	20	30%
	High	1	2%
Stem	Low	58	89%
	Medium	5	8%
	High	2	3%
Flowers	Low	53	85%
	Medium	8	13%
	High	1	2%
Fruits	Low	28	43%
	Medium	28	43%
	High	9	14%

Host range of Papaya Mealy Bug

From the survey, papaya emerged as the most preferred host of PMB at 65% incidence followed by cassava (18%), mango and sugarcane (5%), citrus (3%) with castor plant, guava and okra at 2% (figure 2). In Kenya, PMB had previously been detected on papaya (*Carica papaya*), cassava (*Manihot esculenta*), chili pepper (*Capsicum annuum*), guava (*Psidium guajava*), mango (*Mangifera indica*), and eggplant (*Solanum melongena*) by Macharia *et al.* (2017). This survey revealed an expansion in the host range to include citrus, sugarcane, okra and custard apple. This may be because of the polyphagous nature of PMB. PMB has been reported to infest plants from 22 families of economic importance including weeds (Finch *et al.*, 2021; Muniappan *et al.*, 2008). It is therefore important to continue monitoring surveys in order to detect any further expansion in host range.

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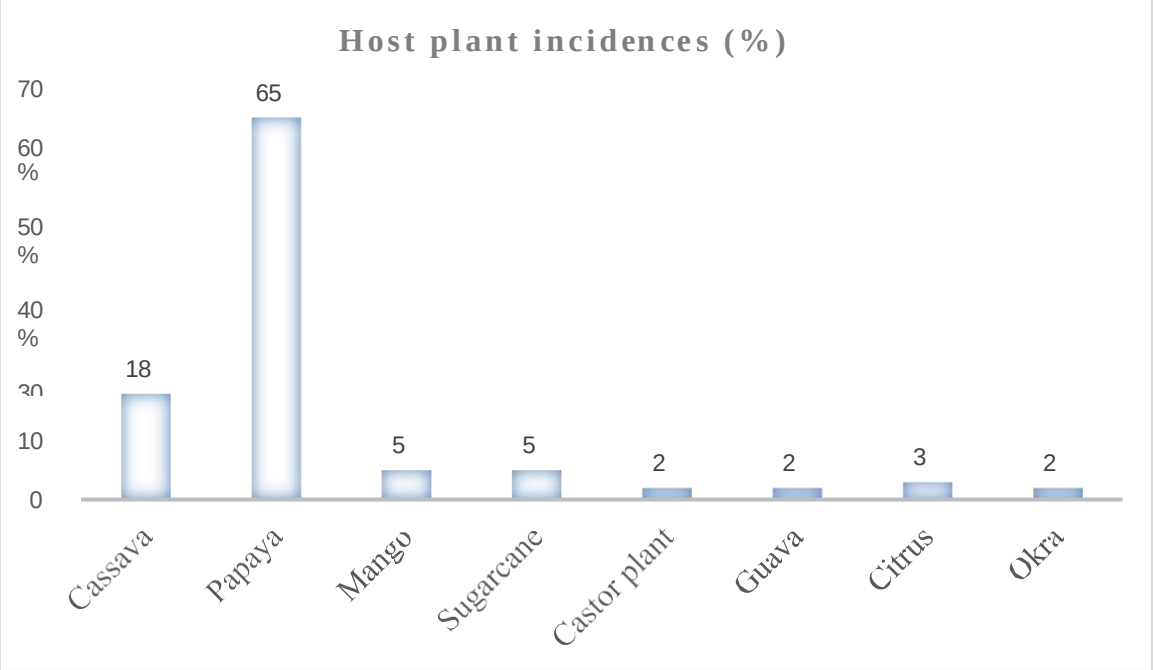

Figure 2: Infestation incidences of PMB on various hosts plant

During the survey, it was also observed that farmers intercropped papaya with other crops. The analysis revealed that there was a statistically significant relationship between cropping system and PMB infestations in the farms (X(2) = 7.487, p=0.024). Papaya mealybug was observed to be more dominant in intercropped farms than in monocrops. Famers in the surveyed area mostly intercropped fruit trees (papaya, mango, citrus, guava and castor plant) with cassava, sugarcane and vegetables like okra. Being a polyphagous pest, PMB may have preferred the intercrops as alternative hosts. Undefined farms were generally poorly managed, weed infested and neglected therefore could not be clearly defined as monocrop or intercrop system.

Farmer awareness and management of Papaya Mealy Bug

During the survey, farmers were interviewed to assess their level of knowledge of PMB. Majority (65%) of the farmers were aware about the occurrence of PMB on their crops and

could positively identify and describe it while 35% were not aware about PMB neither could they positively identify the pest. A section (2%) of the interviewed farmers did not respond to the question.

Further analysis revealed that there was a significant relationship between farmer's knowledge on PMB and the infestations in the farms (X (1) = 13.367 p<0.000). Knowledgeable farmers applied some management measures on PMB in the farms and this led to the reduced infestations in such farms. Farmers were also interviewed on the frequency of scouting for pests and diseases, particularly for PMB in their farms. The results showed that PMB was more dominant in farms where no scouting was undertaken. Scouting for pests and diseases results in early detection and initiation of intervention measures.

On whether there occurred a relationship between frequency of scouting and presence of PMB in the fields, a chi-square test of association was conducted. A significant relationship between the frequency of scouting and the presence of PMB in the fields was detected (X (3) = 51.330, p<0.05). This could imply that farmers who scouted their farms consequently applied control measures more as compared to those who never carried out any scouting and that may have led to the low incidences of infestation.

Average incidences of PMB in the farmers' fields was evaluated in relation to the management practices that farmers used. A significant relationship between the pest management practice and PMB incidences was detected in the farmer fields (X (3) = 61.916, p<0.05). The highest average incidence was recorded in farms where no management practice was applied (figure 3). This finding could be supported by the biology of PMB which has shown that in favourable environmental conditions and plenty of food, PMB can reproduce up to 15 generations in a year (CABI, 2024). The lowest average incidence (3%) was recorded in fields where farmers combined chemical and cultural practices

in the control of PMB. Therefore, a single approach may not effectively work in managing PMB. The combination is a partial integrated approach which may have contributed to increased susceptibility of PMB life stages therefore a better approach as compared to a single management approach. It is important therefore to increase the awareness of farmers on various management options and the best combinations to achieve an effective integrated management.

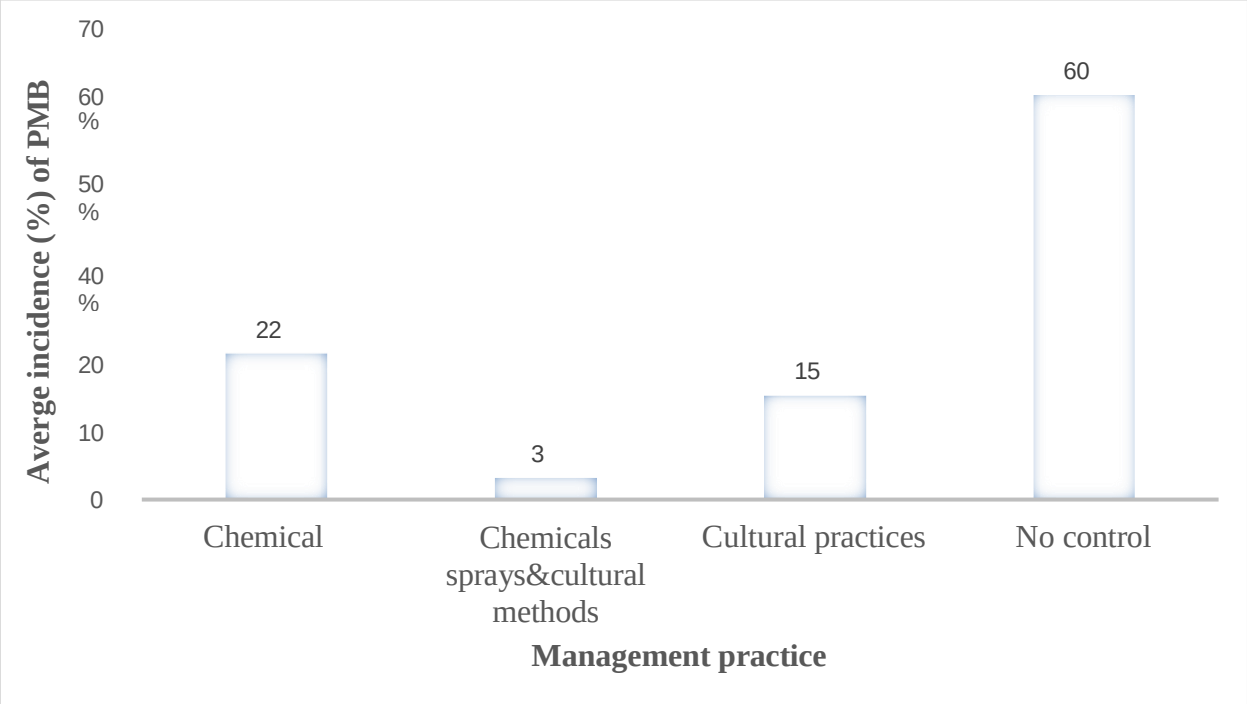

Figure 3: Percentage Incidences of PMB in different management practices

Conclusion and recommendations

During this survey, PMB was confirmed to occur in Taita Taveta, Mombasa, Kwale, Kilifi, Tana River and Lamu counties. In the first report, PMB had only been detected in Kwale, Kilifi and Mombasa Counties. This survey showed that PMB had spread to all the coastal counties in less than three years. The intensity of infestations ranged from very low to medium as per the applied scale and was higher on fruits compared to other plant parts. The survey also revealed that PMB had expanded its host range to include citrus, sugarcane, okra and castor that were not initially reported. The quick spread to other hosts demands effective management, regular scouting, monitoring and control. Increased awareness amongst farmers, agricultural extension workers and other stakeholders needs to be sustained to support effective management efforts in the region. To contain the spread, authorities and research institutions in Kenya should consider classical biological control which has successfully been deployed in other countries.

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References

Amarasekare, K. G., Chong, J.-H., Epsky, N. D., & Mannion, C. M. J. J. o. E. E. (2008). Effect of temperature on the life history of the mealybug *Paracoccus marginatus* (Hemiptera: Pseudococcidae). *Economic Entomology, 101*(6), 1798-1804.

CABI, (2024). Crop Protection Compendium, 2019 Edition. CABI International Publishing Wallingford, UK.www.cabi.org. Retrieved on 17th January 2024.

Finch, E. A., Beale, T., Chellappan, M., Goergen, G., Gadratagi, B. G., Khan, M. A. M., Wyckhuys, K. A. J. P. M. S. (2021). The potential global distribution of the papaya mealybug, *Paracoccus marginatus,* a polyphagous pest. *Pest Management Science, 77(3)*, 1361- 1370.

Kennedy, John & Devi, Mani. (2017). Survey of Papaya Mealybug (*Paracoccus marginatus*) on Tapioca Crop in Different Districts of Tamil Nadu. *International Journal of Current Microbiology and Applied Sciences*, *6:* 503-510. 10.20546/ijcmas.2017.602.057.

Krishnan, J. U., George, M., Ajesh, G., Jithine, J., Lekshmi, N., Deepasree, M. J. J. o. E., & Studies, Z. (2016). A review on *Paracoccus marginatus* Williams, papaya mealybug (Hemiptera: Pseudococcidae). *Journal of Entomology and Zoology Studies 4*(1), 528-533.

Laneesha, M., Suroshe, S. S., Babasaheb, B., & Shankarganesh, K. J. T. I. J. O. A. S. (2020). Papaya mealybug (*Paracoccus marginatus*) (Hemiptera: Pseudococcidae): A new threat to agri-horticulture ecosystem. *The Indian Journal of Agricultural Sciences.* 90(3), 455- 462.

Macharia, I., Kimani, E., Koome, F., Kosiom, T., Heya, H., Otipa, M., Oronje, M. (2017). First report and distribution of the papaya mealybug, *Paracoccus marginatus*, in Kenya. *Journal of Agricultural and Urban Entomology*, *33(1)*, 142-150.

Meyerdirk, D. E., Muniappan, R., Warkentin, R., Bemba J., & Reddy, G. V. P. (2004). Biological control of the papaya mealybug, Paracoccus marginatus (Hemiptera: Pseudococcidae) in Guam. *Plant Protection Quarterly*, 19: 110-114.

Muniappan, R., Shepard, B., Watson, G., Carner, G., Sartiami, D., Rauf, A., & Hammig, M. D. (2008). First report of the papaya mealybug, *Paracoccus marginatus* (Hemiptera: Pseudococcidae), in Indonesia and India. *Journal of Agricultural and Urban Entomology*, 25(1), 37- 40.

Myrick, S., Norton, G. W., Selvaraj, K., Natarajan, K., & Muniappan, R. J. C. P. (2014). Economic impact of classical biological control of papaya mealybug in India. *Crop protection, 56*, 82-86.

Regupathy, A., & Ayyasamy, R. J. H. (2010). Infestation of the invasive papaya mealy bug *Paracoccus marginatus* Williams and Granara de Willink in small scale papaya farming system in Tamil Nadu. *Hexapoda, 17(1)*, 12-20.

Sarma, A.K. (2013). Invasion of papaya mealy bug, *Paracoccus marginatus* in Assam. *Indian Journal of Entomology 75(4)*, 355-356.

Schneider, S., & LaPolla, J.J.S.E. (2010). Inn. Phylogeny and

taxonomy of the mealybug tribe Xenococcini (Hemiptera: Coccoideae: Pseudococcidae) with a discussion of trophobiotic associations with *Acropyga roger* ants. *Systematic Entomology, 114(2)*, 162- 180.

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Prospecting for fine scale establishment of exotic stem borer pupal parasitoid (X*anthopimpla stemmator* Thunberg) in Kenya

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Abstract

Lepidopteran stem borers are an important constraint to cereal production in Sub-Saharan Africa. The exotic *Chilo partellus* (Swinhoe) is one of the most economically important stem borer pest causing extensive losses on cereal crops in Kenya. This pest has also displaced indigenous species of stem borers while expanding its range in warm, mid and high altitude areas. In order to exert control on various developmental stages of this pest, both *Cotesia flavipes* Cameron (larval endoparasitoid) and *Xanthopimpla stemmator* Thunberg (pupal endoparasitoid) were imported and released in 2002 in the Eastern region of Kenya. This study was conducted to assess the establishment status, spread and impact of *X. stemmator* on *C. partellus* following its release in Kenya. Stem borer sampling was done on farms where the biocontrol agents had been released and on transects radiating outwards from them every 15km to assess spread. A total of 100 maize plants were inspected for stem borer infestation and destructive sampling done on 10 maize stems per farm to collect immature stem borer stages. Emerging parasitoids and adult moths were identified, counted and recorded. Results of this study showed that *C. partellus* was the most dominant stem borer species (constituted 71.2%) followed by *Sesemia calamistis* and *Busseola fusca* (26.0 and 2.8% respectively). A decrease in overall stem borer infestation (22.47±7.42%) with no significant difference across distances from parasitoid release points (F=0.4; df=3, 51; p>0.05) was also recorded. Seven parasitoid species were recovered, the most abundant being *C. flavipes* and this coupled with a significant increase in parasitism (25.27±3.27%) (V=1213, p<0.05) from pre-release levels. The parasitoid of interest, *X. stemmator* was not recovered. This suggests a failure to establish though there is need to sample alternative hosts before this is declared.

Key words*:* Classical biological control, lepidoptera, pupal parasitoid, post release survey, *Xanthopimpla stemmator*, Eastern Kenya

Introduction

Lepidopteran stem borers constitute important biotic factors that constrain maize and sorghum production in Sub Saharan Africa (SSA) (Brownbridge, 1991; Odindo, 1991; Schulthess *et al.*, 1997; 2007). However, losses associated with stem borer pest infestation varies among regions in SSA depending of stem borer community composition. In East Africa, the economically important lepidopteran stem borers are *Busseola fusca* (Fuller) and *Sesamia calamistis* Hampson (Family: Noctuidae) and *Chilo orichalcociliellus* Strand and *Chilo partellus* (Swinhoe) (Family: Crambidae) (Nye, 1960, Bonhof *et al.*, 1997, Overholt *et al.*, 2001). All the aforementioned pest species are indigenous to African continent except for *C. partellus* (Nye, 1960; Bleszynski, 1970; Van Hamburg, 1979) which was accidentally introduced from Asia in 1930s (Tams, 1932). Since its introduction, *C. partellus* has become one of the most economically important pests with losses associated with its infestation varying between 73 and 100% in maize, and 88 and 100% in sorghum (Seshu Reddy, 1983; 1988; Ampofo, 1986; Seshu Reddy & Walker, 1990).

Due to economic importance of *C. partellus*, different management strategies including chemical, cultural, habitat management and host plant resistance have been utilized to reduce its populations (Seshu Reddy, 1985; Bonhof, 2000; Kfir *et al.*, 2002). Focus shifted towards biological control in order to find ecologically sound, technically and economically feasible techniques (De Bach, 1974; Sanda & Sunusi, 2014). A wide range of indigenous parasitoids including *Cotesia sesamiae* (Cameron), *Dolichogenidea polaszeki* Walker, *Chelonus curvimaculatus* (Cameron), (larval parasitoids), *Pediobius furvus* (Gahan), and *Dentichasmias buseolae* (Heinrich) (gregarious pupal parasitoids) and *Psilochalsis soudanensis* (Steffan) (solitary pupal parasitoid) expanded their range to include this exotic species (Kfir, 1992; Zhou *et al.*, 2003). However, the effect of this native parasitoid assemblage has been recorded at less than 5% and is considered negligible (Mohyuddin &

Greathead, 1970; Oloo & Ogeda, 1990; Bonhof *et al.,* 1997; Zhou *et al*., 2003). *icipe*'s biological control programme thus spearheaded the importation and eventual release of the exotic, koinobiont, larval endoparasitoid *C. flavipes* Cameron from *C. partellus'* native range in 1993 (Overholt *et al*., 1994a).

To further suppress *C. partellus* population and build on stem borer natural enemy complex in Kenya, a solitary, idiobiont, pupal endoparasitoid, *Xanthopimpla stemmator* Thunberg (Hymenoptera: Ichneumonidae) was imported from South Africa in 2001. *Xanthopimpla stemmator* which is Asian in origin, is known to parasitize pupae of various lepidopteran stem borers. Prior to release in 2002, various pre-release studies were carried out regarding host suitability (Gitau *et al*., 2007), interspecific competition with native parasitoid species (Muli *et al*., 2006) and its performance in the field (Muturi *et al*., 2005). After these studies, releases were done in the Eastern region of Kenya, at two locations, Machakos and Kitui. Despite its potential, no post release assessments have been carried out to confirm its establishment. This study was thus undertaken to document fine scale establishment status and spread of *X. stemmator* since its release in Kenya in 2002.

Methodology

Description of study area

This study was carried out in the Eastern region of Kenya where pupal parasitoid, *X. stemmator*, was released in 2002. *Xanthopimpla stemmator* was released on various farms in Machakos and Kitui counties (Figure 1). The Eastern region is located in dry mid-altitude agro-ecological zone, characterized by temperatures ranging from 14 to 33°C. The area lies at an altitude of 700-1,400masl and receives annual rainfall varying between 300 and 550mm (Corbett, 1998).

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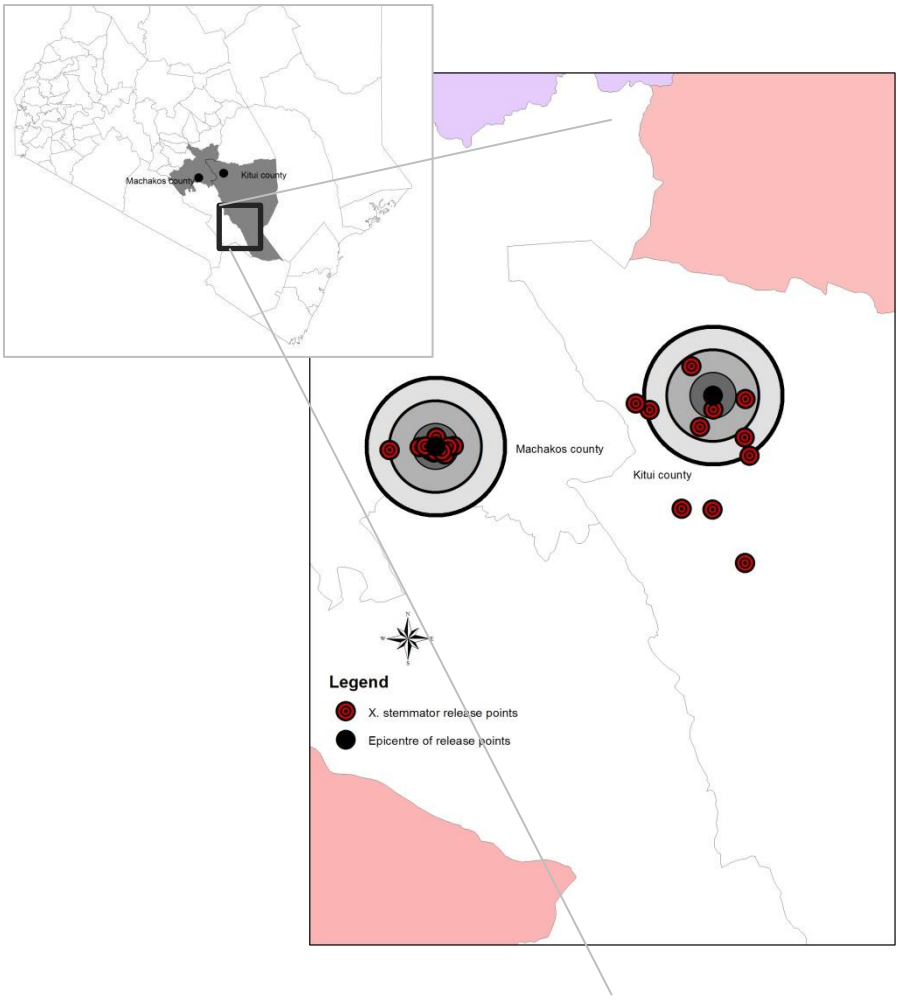

Figure 1: Release and sampled sites for *X. stemmator* in Machakos and Kitui counties, Eastern region of Kenya.

Sampling for stem borers

Maize farms around *X. stemmator* release sites were identified and marked for assessment of stem borer infestation and parasitism. Marked farms radiated outwards along transects in the four cardinal compass directions as the terrain allowed. Stem borer infestation levels were assessed in farms at intervals of 15, 30 and 45 km along transects laid in the cardinal directions from the release points (Figure 1).

In each farm, a total of 100 maize plants were inspected for stem borer infestation during which 10 infested maize stems were destructively

sampled and dissected. Immature stem borer stages were collected, identified and categorized (as small {1st and 2nd instars}, medium, {3rd and 4th instars} and large {5th and 6th instars}). Identified larvae were placed individually in glass vials containing artificial diet (Onyango and Ochieng-Odero, 1994) and transported to the laboratory at *icipe* where they were reared at ambient temperatures of 24-25˚C and a relative humidity of 55-65%, with a 12:12 light: dark photoperiod. Samples were inspected daily for parasitoid cocoons, pupal development, pupal parasitoid and adult moth emergence. Pupae were transferred into plastic jars lined with wet paper towels. Humidity in the jars was maintained by moistening the soft paper towels once every 2 days using a few drops of distilled water. Larval parasitoids and adult stem borer moths were identified and recorded.

Statistical analyses

The number of infested plants was expressed as a percentage of the total plants inspected in respective fields and resulting data was used to compute percentage stem borer infestation. At each sampling distance, inspected farms were treated as replicates and the data pooled before analysis. Parasitoid cocoons that were spun from appropriate larval stages were expressed as a proportion of the respective field densities in order to compute percentage parasitism. Percentage infestation and parasitism were subjected to the normality test and data that failed the normality test were appropriately transformed before further analysis. Normally distributed data was analysed using One-Way ANOVA and significantly different means were separated using Tukey's HSD test. Data which failed the normality test was subjected to Kruskal-Wallis rank sum test and significantly different means were separated using Nemenyi post-hoc test ($p<0.05$). One sample *t*-test and Wilcoxon rank sum tests were used to compare mean infestation and parasitism levels obtained before and after parasitoid release.

Results

Stem borer species composition and diversity

A total of 5,500 maize plants were sampled from 55 farms surveyed during

the study. Three stem borer species, *C. partellus, B. fusca* and *S. calamistis* were identified from the sampled larvae. *Chilo partellus* was the most dominant pest constituting 71.2% of the total stem borer population collected. The other two species, *S. calamistis* and *B. fusca,* were generally low constituting 26.0 and 2.8% of the total stem borer community respectively (Table 1).

Table 1: Stem borer species recovered, their percentage composition and pest density per infested plant in Eastern region

Stem borer species	% composition	Larval density ($\bar{x}$ ±SE)
Chilo partellus	71.2	2.4±0.4[b]
Sesamia calamistis	26	0.8±0.2[a]
Busseola fusca	2.8	0.1±0.0[a]
χ^2 value		74.92
df		2
p value		2.20E-16

Parasitoid and hyperparasitoid species composition and diversity

Seven parasitoid species were recovered during the survey with the ecological congeners, *C. flavipes* and *C. sesamiae* being the most abundant (Table 2). In addition to parasitoids, hyperparasitoid, *Aphagnomus fijiensis* (Ferriére) was also recovered from some larvae. Larval parasitoids dominated the stem borer natural enemy complex in the study area with only one pupal parasitoid, *Dentichasmias busseolae* Heinrich identified from the collection.

Table 2: Parasitoids recovered, their percentage composition, guild and host species in Eastern region.

Parasitoid species	Composition (%)	Guild	Stem borer species parasitized
Cotesia flavipes (Cameron)	76.5	Larval	*C. partellus, S. calamistis, B. fusca*
Cotesia sesamiae (Cameron)	7.6	Larval	*C. partellus, S. calamistis, B. fusca*
Dolichogenidea polaszeki Walker	0.1	Larval	*S. calamistis*
Chelonus curvimaculatus (Cameron)	0.4	Larval	*C. partellus, B. fusca*
Atherigona sp (Rondani)	0.03	Larval	*C. partellus*
Dentichasmias busseolae Heinrich	0.2	Pupal	*C. partellus*
Sturmiopsis parasitica (Curran)	0.0	Larval/pupal	*B. fusca*
Aphanogmus fijiensis (Ferriére)	15.1	Hyperparasitoid	*C. partellus, S. calamistis*

Stem borer infestation and parasitism levels

During the survey, overall stem borer infestation was estimated to be 22.5±7.4% (Table 3). Further analysis revealed no difference in infestation across distances from parasitoid release points ($F_{3,51}$=0.4; p>0.05) (Table 3). Stem borer infestation levels significantly reduced after the release of *C. flavipes* and *X. stemmator* (t_{54}=41.6; p<0.05). Stem borer parasitism levels in this region were recorded at 25.3±3.3%. This was a significant increase from parasitism levels previously recorded following parasitoid release (V=1213; p<0.05). Pupal parasitism was estimated at 0.03±0.02% (Table 4).

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Table 3: Stem borer infestation and parasitism levels ($\bar{x} \pm SE$) across distances from release points.

Distance from release points	No. of farms	Infestation	Parasitism
0KM	10	22.4±6.7[a]	26.6±7.6[a]
15KM	20	24.8±2.1[a]	31.9±6.0[a]
30KM	14	20.6±2.6[a]	23.0±5.8[a]
45KM	11	20.7±3.3[a]	14.9±6.7[a]
df		3, 51	3, 51
F value		0.4	4.34
p-value		0.75	0.23

Table 4: Overall stem borer infestation before and after parasitoid release in Eastern region of Kenya

Period	Infestation (%)	Period	Parasitism (%)
Pre-release (1997)	92[a]	Pre-release (2001)	10[a]
2014	22.5±7.4[b]	2014	25.3±3.3[b]
t value	41.63	*V* value	1213
df	54		
p value	2.20E-16	*p* value	0.0002

Discussion

Suppressing stem borer pest population is considered an important factor in enhancing maize production in tropical Africa. However, stem borer management interventions and their successful implementation varies among regions depending on the dominant/target pest species. During this study, *C. partellus* dominated the pest community in Eastern Kenya followed by *B. fusca* and *S. calamistis*, an observation that corroborated findings of Songa *et al*. (2002a, b; 2007). Except for *C. partellus*, all other stem borer species in the pest community are indigenous to the Africa continent. As an exotic species, *C. partellus* recruited several native natural enemies a characteristic that can explain the high number of natural

enemies found associated with its larvae during the study. Similar observations were made in other studies during which native natural enemies reportedly expanded their host range to include the exotic *C. partellus* (Oloo & Ogedah, 1990; Kfir, 1992). Results obtained also uphold reports that *C. partellus* has a larger number of parasitoids attacking it in comparison to native stem borers (Zhou *et al.*, 2003). Despite the high number of parasitoids associated with stem borers in this area, the list might not be exhaustive as the survey was limited to a certain distance and only on farms radiating from *X. stemmator* release points. Other researchers recovered much more parasitoids from the stem borer population in the same region (Songa *et al.*, 2002a).

Growing dominance of *C. partellus* in the region due to limited success of indigenous natural enemies in suppressing its population informed the decision to introduce additional exotic natural enemies in the region. Larval parasitoid, *C. flavipes*, and pupal parasitoid, *X. stemmator*, were released in Eastern Kenya as part of classical biological control to augment population of indigenous natural enemies in the region. Collective action by the stem borer natural enemy assemblage within the Eastern region resulted in reduction of overall stem borer infestation in comparison to levels observed before release of *C. flavipes* and *X. stemmator*. The observed reduction was consistent across all different sampled radii and similar patterns were observed with respect to parasitism levels. Generally, there was a considerable increase in parasitism compared to lower levels (0.1-5.69%) recorded before release of *X. stemmator* (Songa *et al.*, 2002a). Observations in the present study are consistent with findings of other studies that have shown an existence of positive relationship between the diversity of parasitoids and parasitism (Hawkins & Gagne, 1989; Hawkins & Gross, 1993). Despite the high diversity of parasitoids recovered during this survey, *D. busseolae* was the only pupal parasitoid recovered. It was however present in low numbers with significantly low resultant parasitism, results that are consistent with findings

of previous studies (Mohyuddin & Greathead, 1970; Oloo & Ogedah, 1990). This study was undertaken 15 years after the release of *X. stemmator* in the region and contrary to research expectation, the study did not yield any *X. stemmator* specimen. This observation may or may not imply failure of *X. stemmator* to establish in the region.

Pre-release host suitability studies revealed that *X. stemmator* has a broad host range and could successfully parasitize and develop in *C. partellus*, *S. calamistis* and *B. fusca* (Gitau *et al.*, 2005). A range of reasons (excluding host suitability) could be advanced in an attempt to explain the lack of recovery within the surveyed fine scale. First, the releases were done on ten farms during short rains of 2002 in Kitui. However, no repeat releases were carried out. In Machakos, *X. stemmator* releases were done in the short rains of 2002 and 2003 and during the long rains of 2003 on an average of seven farms each time. CBC proponents agree that multiple releases boost the natural enemy population after the initial introduction in a new environment (Sanda & Sunusi, 2014). This is because the establishment process is marred by both biotic and abiotic factors whose effects can be abated by pumping in more and fresher individuals (Sanda & Sunusi, 2014). Biological control agent releases may need to be repeated sometimes over years to increase chances of establishment. Non-recovery of *X. stemmator* is not unique to this study. In Mozambique, *X. stemmator* was only recovered during the release season and one year after its release but not in subsequent years (Cugala, 2007).

Secondly, the biological control programme's main objective that necessitated *X. stemmator*'s release was to suppress *C. partellus* population. *Chilo partellus* occurrence in wild habitat has been reported by various researchers (Songa *et al.*, 2002a, Ong'amo *et al.* 2006b; Otieno *et al.* 2006; Mohamed *et al.*, 2007). Country-wide surveys on wild host plants in Kenya revealed that more than 95% of *B. fusca* and *C. partellus* were found on wild sorghum species providing a suitable refugia for *X. stemmator*. The wild habitat was however not sampled

during this survey and this study cannot confirm the presence of *X. stemmator* in the wild. However, this gap needs to be explored before further decisions regarding the use of *X. stemmator* in management of *C. partellus* is made as wild host plants play an important role in the stem borer pest and parasitoid perennation (Muturi *et al.*, 2005; Mailafiya *et al.*, 2010).

Thirdly, an aspect of competition within the parasitoid community whose differentiation was demonstrated by the attack method used, was shown to be an important criterion in parasitoid selection (Muli *et al.*, 2006). *Xanthopimpla stemmator* uses the "drill and sting" attack strategy (Smith *et al.*, 1993) whereby the parasitoid pierces the stem to gain access to pupa in pupal chamber. While comparing the different attack strategies employed by pupal parasitoids, the "ingress and sting" attack strategy whereby the parasitoid seeks and attacks the stem borer host within the tunnel was thought to be superior to the "drill and sting" strategy (Muli *et al.*, 2006). *Xanthopimpla stemmator's* ovipositor length is about 0.52cm (Muturi *et al.*, 2005) and thus stem borer pupae in thin stemmed plants such as sorghum, millet and rice would be much readily available than those in large stemmed plants such as maize and sugarcane (Hailemichael *et al.*, 1994). This emphasizes further, the importance of sampling alternative hosts in order make a clear decision on whether *X. stemmator* established in the region or not.

Biological control success and failure reports from various countries inform decision making processes. Though reports of failed establishment of *X. stemmator* were also been made in South Africa where releases were done on maize and sorghum fields (Moore & Kfir, 1996, Kfir, 1997), its non-recovery during this study cannot be regarded as a non-establishment until wild and/or alternative hosts are sampled. This is because it successfully managed *Eldana saccharina* and *Chilo sacchariphagus* in sugarcane in South Africa (Conlong, 1994), Mozambique, Mauritius and Reunion (Moutia & Courtis, 1952; Moore & Kfir 1996; Conlong & Goebel 2002). Though *X. stemmator* was not recovered in maize fields during the study, the hope to use it in

management of *C. partellus* in the area is ignited by the recovery of two specimen in maize fields in Lunga Lunga along Kenya/Tanzania border in a separate study (Abonyo, unpublished data). This result corroborated findings by Bonhof *et al*. (1997) who reported the parasitoid along the Kenyan Coast. Presence of *X. stemmator* along the Kenyan coast is thought to have come from influx of parasitoid populations from Tanzania, Uganda, Ethiopia, Zanzibar and Eritrea (Mailafiya, 2009) where releases had been done. These possible influxes of *X. stemmator* from neighbouring countries indicate that populations may have established in the respective countries. This study is therefore recommending repeated release of *X. stemmator* in selected multiple sites using populations from neighbouring countries.

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References

Ampofo, J.K.O. (1986). Maize stalk borer (Lepidoptera: Pyralidae) damage and plant resistance. *Environmental Entomology 15*, 1124-1129.

Bleszynski, S. (1970) A revision of the world species of *Chilo Zincken* (Lepidoptera: Pyralidae). *Bulletin of the British Museum of natural History (Entomology) 25,* 99-195.

Bonhof, M.J. (2000). *The impact of predators on maize stem borers in coastal Kenya*.

Bonhof, M.J., Overholt,W. A., Van Huis, A. & Polaszek, A. (1997). Natural Enemies of Cereal Stemborers in East Africa: a Review. *International Journal of Tropical Insect Science*, *17*(01), 19–35. doi:10.1017/S1742758400022141.

Brownbridge, M. (1991). Native Bacillus thuringiensis Isolates for the management of lepidopteran cereal pests. *International Journal of Tropical Insect Science*, *12*(1-2-3), 57–61.

doi:10.1017/S1742758400020531.

Conlong, D.E. (1994). A review and perspectives for the biological control of the African sugarcane stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae). *Agriculture, Ecosystems and Environment 48*, 9-17.

Conlong, D.E & Goebel, R. (2002). Biological control of *Chilo sacchariphagus* (Lepidoptera: Crambidae) in Mozambique: The first steps. *Proceedings of the South Africa Sugar Technology Association 76*,310-319.

Corbett, J.D. (1998). Classifying maize production zones in Kenya through multivariate cluster analysis. In: Hassan, R. M. (1998). Maize technology development and transfer: A GIS application for research planning in Kenya.

Cugala, D. (2007). Impact assessment of natural enemies on stem borer populations and maize yield in three agro-ecological zones in Mozambique. PhD thesis, Kenyatta University, Nairobi, Kenya.

De Bach, P. (1974). Biological control by natural enemies. *Cambridge University Press.*

Delobel, A. (1975). Une population hivernante de *Chilo partellus* (Lepidoptera: Pyralidae) sure la cote ouest de Madagascar. *ORSTOM Series Biologie 10,* 17-23.

Ehler, L.E & Hall, R.W. (1982). Evidence for competitive exclusion of introduced natural enemies in biological control. *Environmental Entomology 11*, 1-4.

Gitau, C. W., Ngi-Song, A.J., Overholt, W.A & Otieno, S.A. (2005). Acceptance and suitability of four lepidopteran stemborers for the development of the pupal parasitoid *Xanthopimpla stemmator* (Hymenoptera: Ichneumonidae). *Biocontrol Science and Technology*, *15*(6), 585–600. doi:10.1080/09583150500088603.

Gitau, C.W., Otieno, S.A., Overholt, W.A. & Pierce, F. (2007). Host preference of *Xanthopimpla stemmator* (Hymenoptera : Ichneumonidae) and its

reproductive performance on selected African lepidopteran stem borers. *Biocontrol Science and Technology*, *17*(5), 499–511. doi:10.1080/09583150701311572.

Hailemichael, Y., Smith, J.W., & Wiedenmann, R.N. (1994). Host finding behaviour, host acceptance and host suitability of the parasite, *Xanthopimpla stemmator. Entomologia Experimentalis et Applicata*, *71*, 155–166.

Hawkins, B.A & Gagne, R.J. (1989). Determinants of assemblage size for the parasitoids of Cecidomyiidae. *Oecologia 81,* 75-88.

Hawkins, B.A & Gross, P. (1993). Species richness and population limitation in insect-parasitoid host systems. *American Naturalist 139*, 417-423.

Jalali, S.K., Singh, S.P., Ballal, C.R & Kumar, P. (1988). Competitive interaction between *Cotesia Kazak* and *Hyposoter didymator*, exotic parasitoids of *Heliothis armigera*. *Entomologia Experimentalis et Applicata 46*, 221-225.

Kfir, R. (1992). Seasonal abundance of the stem borer *Chilo partellus* (Lepidoptera: Pyralidae) and its parasites on summer grain crops. *Journal of Ecomonic Entomology 85,* 518-529.

Kfir, R. (1997). Competitive displacement of *Busseola fusca* (Lepidoptera: Noctuidae) by *Chilo partellus* (Lepidoptera: Pyralidae). *Annals of the Entomological Society of America 90,* 619-624.

Kfir, R., Overholt, W.A, Khan, Z.R., & Polaszek, A. (2002). Biology and management of economically important lepidopteran cereal stem borers in Africa. *Annual Review of Entomology*, *47*, 701–31. doi:10.1146/annurev.ento.47.091201.145254.

Khadioli, N., Tonnang, Z.E.H., Muchugu, E., Ong'amo, G., Achia, T., Kipchirchir, I. & Le Ru, B. (2014). Effect of temperature on the phenology of *Chilo partellus* (Swinhoe) (Lepidoptera, Crambidae); simulation and visualization of the potential future distribution of *C. partellus* in Africa under warmer temperatures through the development of life-table param. *Bulletin of*

Entomological Research, *104*(6), 809–22. doi:10.1017/S0007485314000601.

Kioko, E.N., Overholt, W.A & Mueke, J.M. (1995). Larval development in *Chilo orichacociliellus* and *Chilo partellus*: A comparative study in the laboratory. Proc. Meet. Sci. Conf. Afr. Assoc. Insect Sci., 10th, Mombasa, 1993, pp. 191–98. Nairobi: African Association of Insect Science.

Mailafiya, D.M. (2009). Diversity and ecological preference of parasitoids associated with lepidopteran stem borers in Kenya. PhD thesis, Kenyatta University, Nairobi, Kenya.

Mailafiya, D.M., Ru, B.P.Le, Kairu, E.W., Calatayud, P.A & Dupas, S. (2010). Geographic distribution, host range and perennation of *Cotesia sesamiae* and *Cotesia flavipes* Cameron in cultivated and natural habitats in Kenya. *Biological Control*, *54*(1), 1–8. doi:10.1016/j.biocontrol.2009.11.008.

Mohamed, H.M., Khan, Z.R., Overholt, W. A. & Elizabeth, D.K. (2007). Behaviour and biology of *Chilo partellus* (Lepidoptera: Pyralidae) on maize and wild gramineous plants. *International Journal of Tropical Insect Science*, *24*(04), 287–297. doi:10.1079/IJT200440.

Mohyuddin, A.I and Greathead, D.J (1970). An annotated list of the parasites of graminaceous stem borers in East Africa, with a discussion of their potential in biological control. *Entomophaga 15,* 241- 274.

Moutia, L.A and Courtois, C.M. (1952). Parasites of the moth borers of sugarcane in Mauritius. *Bulletin of Entomological Research 43*, 325-359.

Moore, S.D and Kfir, R. (1996) Biological studies of *Xanthopimpla stemmator* (Thunberg) (Hymenoptera: Ichneumonidae), a parasitoid of lepidopteran stem borers. *African Entomology 4,* 131-136.

Muli, B.K., Schulthess, F., Maranga, R.& Kutima, H.L. (2006). Biological Control Interspecific competition between *Xanthopimpla stemmator* Thunberg and *Dentichasmias busseolae* Heinrich (Hymenoptera : Ichneumonidae), in East Africa. *BioControl 36*, 163–170.

Muturi, J.J., Ngi-Song, A.J., Schulthess, F., Mueke, J.M., & Sétamou, M. (2005). Location of stemborer pupae in various host plants and implications for the performance of natural enemies with emphasis on the pupal parasitoid *Xanthopimpla stemmator* (Hymenoptera: Ichneumonidae). *International Journal of Tropical Insect Science*, *25*(01), 12–18. doi:10.1079/IJT200549.

Mwalusepo, S., Tonnang, H.E.Z., Massawe, E.S., Okuku, G.O., Khadioli, N., Johansson, T.& Le Ru, B. P. (2015). Predicting the impact of temperature change on the future distribution of maize stem borers and their natural enemies along East African mountain gradients using phenology models. *PLoS ONE*, *10*(6), 1–23. doi:10.1371/journal.pone.0130427.

Niyibigira, E.I., Abdallah, Z.S., Overholt, W.A., Lada, V.Y and Van Huis, A. (2001). Distribution and abundance, in maize and sorghum, of lepidopteran stem borers and associated indigenous parasitoids in Zanzibar. *Insect Science and Its Application*, *21*(4), 335–346.

Nye, I.W.B. (1960). The insect pests of graminaceous crops in East Africa. *Colonial Research Studies 31*, 1-4.

Odindo, M.O. (1991). Management of cereal stem borers, especially *Chilo partellus* using Microsporidia. *Insect Science and Its Application*, *12*(1), 51–55.

Ofomata, V.C. (1997). Ecological interactions between *Chilo orichalcociliellus* Strand and *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae) on the Kenya coast. PhD thesis. Nnamdi Azikiwe University, Anambra State, Nigeria. 206 pp.

Ofomata, V.C., Overholt, W.A.; Van Huis, A.; Egwuatu, R.I & Ngi-Song, A.J. (1999). Niche overlap and interspecific association between *Chilo partellus* and *Chilo orichalcociliellus* on the Kenya coast. *Entomologia Experimentalis et Applicata 93*, 141–48.

Ofomata, V.C., Overholt, W.A., Lux, S.A., VanHuis, A & Egwuatu, R.I. (2000). Comparative studies on the fecundity, egg survival, larval feeding and development of *Chilo partellus* (Swinhoe) and *Chilo*

orichalcociliellus Strand (Lepidoptera: Crambidae) on five grasses. *Annals of the Entomological Society of America 93*, 492–99.

Oloo, G.W & Ogeda, K. (1990). The incidence of *Chilo partellus* (Swinh.) (Crambidae) and the contribution of natural enemies to its mortality under intercropping systems in Kenya. *Tropical Pest Management 36,* 244-248.

Onyango, F.O & Ochieng'-Odero J.P.R. (1994). Continuous rearing of the maize stem borer *Busseola fusca* on an artificial diet. *Entomologia experimentalis et Applicata 73*,139-144.

Omwega, C.O., Overholt, W.A., Mbapila, J.C., & Kimani-Njogu, S.W. (1997). Establishment and dispersal of *Cotesia flavipes* (Cameron) (Hymenoptera: Braconidae), an exotic endoparasitoid of *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae) in Northern Tanzania. *African Entomology*, *5*(1), 71–75.

Ongamo, G.O., Rü, B.P. Le, Dupas, S., Moyal, P., Muchugu, E., Calatayud, P. and Silvain, J. (2006). The role of wild host plants in the abundance of lepidopteran stem borers along altitudinal gradient in Kenya. *Annales de La Société Entomologique de France (Nouvelle Série)*, *42*(1), 363–370.

Otieno, N.A., Rü, B.P. Le, Ongamo, G.O., Dupas, S., Calatayud, P., Makobe, M. & Silvain, J. (2006). Diversity and abundance of wild host plants of lepidopteran stem borers in two diff erent agroecological zones of Kenya. *Annales de La Société Entomologique de France (Nouvelle Série)*, *42*(3-4), 371–380.

Overholt, W.A., Ngi-Song, A.J., Omwega, C.O, Kimani-Njogu, S.W., Mbapila, J., Sallam, M. N & Ofomata, V. (1997). A review of the introduction and establishment of Cotesia flavipes Cameron in East Africa for biological control of cereal stem borers. *Insect Science and Its Application*, *17*(1), 79–88.

Overholt, W.A., Kimani, S.K., Mbapila, J., Lammers, P. & Kioko, E. (1994). Ecological considerations of the

introduction of *Cotesia flavipes* Cameron (Hymenoptera : Braconidae) for biological control of *Chilo partellus* (Swinhoe) (Lepidoptera : Pyralidae), in Africa. *Biocontrol News and Information*, *15*(2), 19N–24N.

Overholt. W.A., Songa. J.M., Ofomata, Y. C., Jeske, R. (2000). The spread and ecological consequences of the invasion of *Chilo partellus* (Swinhoe) (Lepidoptera; Crambidae) in Africa. In: Lyons. E.E.. Miller. S.E. (Eds.), Invasive Species in Eastern Africa: Proceedings of a Workshop Held at ICIPE, 5-6 July, 1999. ICIPE Science Press. Nairobi, Kenya. pp. 52- 58.

Overholt, W.A., Maes, K.V.N and Goebel, F.R. (2001). Field guide to the stemborer larvae of maize, sorghum and sugarcane in Eastern and Southern Africa. Nairobi: *ICIPE Science Press*. p 31.

Sallam, M.N., Overholt, W.A. & Kairu, E. (1999). Comparative evaluation of *Cotesia flavipes* and *C. sesamiae* (Hymenoptera: Braconidae) for the management of *Chilo partellus* (Lepidoptera: Pyralidae) in Kenya. *Bulletin of Entomological Research*, *89*, 185–191. doi:10.1017/S0007485399000279.

Sallam, M.N., Overholt, W.A. & Kairu, E. (2001). Dispersal of the exotic parasitoid *Cotesia flavipes* in a new ecosystem. *Entomologia Experimentalis et Applicata*, *98*, 211–217.

Sallam, M.N.S. (2006). A review of sugarcane stem borers and their natural enemies in Asia and Indian Ocean Islands: an Australian perspective. *Annales de La Société Entomologique de France (Nouvelle Série)*, *42*(3-4), 263–283. doi:10.1080/00379271.2006.10697459.

Sanda, N.B., & Sunusi, M. (2014). Fundamentals of biological control of pests. *IJCBS Review*, *1*(6), 1–11.

Schulthess, F., Bosque-Perez, N.A.; Chabi-Olaye, A.; Gounou, S.; Ndemah, R & Goergen, G. (1997). Exchange of natural enemies of lepidopteran cereal stem borers between African regions . *Insect Science and its Applications* 17, 97-

108.

Schulthess, E., Ogwang, J.A., Mueke, J.M., & Omwega, C.O. (2007). Distribution and Relative Importance of Lepidopteran Cereal Stemborers and Their Parasitoids in Uganda. *Phytoparasitica*, *35*(1), 27–36.

Seshu Reddy, K. (1983). Studies on the stem-borer complex of sorghum in Kenya. *Insect Science and Its Application*, *4*(1), 3–10.

Seshu Reddy, K.V. (1985). Relative susceptibility and resistance of some sorghum lines to stem borers in Western Kenya. *Insect Science and its Applications 6,* 401-404.

Smith, J.W.J.R.; Wiedenmann, R.N & Overholt, W.A.(1993). Parasites of Lepidoperan stemborers of tropical gramminaceous plants. *ICIPE Science Press,* Nairobi, Kenya 89pp.

Seshu Reddy, K.V. (1988). Assessment of on-farm yield losses in sorghum due to insect pests. *Insect Science Application 9*, 679–685.

Seshu Reddy, K.V and Walker, P.T. (1990). A review of the yield losses in graminaceous crops caused by *Chilo spp. Insect Science and its Applications 11*, 563-569.

Songa, J.M., Overholt, W.A., Mueke, J.M. and Okello, R.O. (2001). Colonisation of *Cotesia flavipes* (Hymenoptera: Braonidae) in stem borers in the semi-arid Eastern province of Kenya. *Insect Science and Its Application*, *21*(4), 289–295.

Songa, J.M., Overholt, W. A., Okello, R.O., & Mueke, J.M. (2002a). Control of lepidopteran stemborers in maize by indigenous parasitoids in semi-arid areas of Eastern Kenya. *Biological Agriculture & Horticulture*, *20*(1), 77–90. doi:10.1080/01448765.2002.9754949

Songa, J.M, Overholt, W.A., Mueke, J.M & Okello, R.O. (2002b). Regional distribution of lepidopteran stemborers and their parasitoids among wild grasses in the semi-arid eastern Kenya. *African Crop Science Journal*, *100*(2), 183–194.

Songa, J.M., Jiang, N., Schulthess, F. & Omwega, C. (2007). The role of intercropping different cereal species in controlling lepidopteran stemborers on maize in Kenya.

Journal of Applied Entomology, *131*(1), 40–49. doi:10.1111/j.1439-0418.2006.01116.x.

Tams, W.H.T. (1932). New species of African Heterocera. *Entomologist 65*: 1241-1249.

Van Hamburg, H. (1979). The grain-sorghum stalk-borer, *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae): Seasonal changes in adult populations in grain sorghum in the Transvaal. *Journal of the Entomological Society of Southern Africa 42*: 1-9.

Vinson, M.R. (2001). Long-term dynamics of an invertebrate assemblage downstream from a large dam. *Ecological Applications*, *11*(3), 711–730. doi:10.1890/1051-0761(2001)011

Zhou, G, Baumgartner, J & Overholt, W.A. (2001). Impact assessment of an exotic parasitoid on stemborer (Lepidoptera) population dynamics in Kenya. *Ecological Applications*, *11*(5), 1554–1562.

Zhou, G., Overholt, W.A., & Kimaninjogu, S. W. (2003). Species richness and parasitism in an assemblage of parasitoids attacking maize stem borers in coastal Kenya. *Ecological Entomology*, *28*(1), 109–118. doi:10.1046/j.1365-2311.2003.00477.x

Tanwar, R., Jeyakumar, P., & Vennila, S. (2010). *Papaya mealybug and its management strategies*: National Centre for Integrated Pest Management New Delhi.

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Rice husk biochar for carbon sequestration, soil fertility and plant health improvement: A review

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Abstract

Carbon dioxide (CO_2) is considered one of the ozone layer gases that contribute to climate change. As the area under agricultural use expands, the level of CO_2 from soil as an agricultural by-product increases in the atmosphere. Burning rice husks in open air, decomposing plant materials among other activities release CO_2 directly to the atmosphere. Rice husks as a by-product of rice production in Kenya has both the potential to be a source of greenhouse gas (GHG) and production of biochar. Production and deposition of rice husk biochar (RHB) into soil is thought to be one of the viable options for permanent carbon storage with related benefits to soil fertility. This review seeks to consolidate information from various studies that highlight the innovative way of using RHB in combating climate change, improving soil fertility, plant health and crop yields. Studies that have demonstrated beneficial use of RHB were evaluated to prepare this review. When RHB is used as a soil amendment, it has the ability to increase soil carbon storage, mitigate 10% of the current anthropogenic carbon emissions, improve pH and raise Cation Exchange Capacity (CEC), increase available plant nutrients, enhance inherent plant immunity, increase crop yields and improve water quality by increasing retention of nutrients and agrochemicals for plant utilization. A review of the benefits of RHB use in agriculture and climate change mitigation will enhance its adoption. The review further emphasizes the usefulness of pyrolysis in turning organic waste into bioenergy, compost and other beneficial products while protecting the environment.

Key Words: Carbon dioxide, climate change, global warming, innovation, ozone layer, temperature.

Introduction

Biochar use is considered a viable strategy in reducing farm waste, improving soil quality and sequestering carbon to reduce greenhouse gas emissions and mitigate climate change (Mandal & Jeyaraman, 2013). Globally biochar is viewed as a soil management strategy that can increase soil carbon, provide energy and increase crop yield, while mitigating the effects of climate change through carbon sequestration (Griscom *et al.*, 2017; Smith *et al.*, 2020). Recent research has shown that biochar is effective in suppressing plant pathogens such as *Ralstonia solanacearum* in tomatoes, nematodes and insect pests (Lehmann, 2009; Lehmann *et al.*, 2011; Poveda *et al.*, 2021). In a potted plants experiment, Huang *et al.* (2015), found that soil amended with biochar at a concentration of 1.2% increased rice plants resistance against root gall nematodes (*Meloidogyne graminicola*). Rice husk biochar has potential to boost the resistance of rice seedlings against nematodes and improve rice growth parameters and increase rice yields among other crops to boost food security (Liu *et al.*, 2020).

In China, Qian *et al.* (2014), found that biochar as a soil amendment improved nitrogen use efficiency and increased crop productivity leading to reduced nitrogen fertilizer use. In Ghana, biochar was used to improve soil moisture and nutrient retention for vegetable production (Yakubu *et al.*, 2020) while in Nigeria, it was used as a soil amendment to enhance cocoyam productivity and soil sustainability in sandy loam soils (Adekiya *et al.*, 2020). Studies in Kenya have shown the positive effect of biochar application in soil in increased maize and soybean yields (Kimetu *et al.* 2008 ;Kätterer *et al.* 2019).

Kenya's communication to United Nations Framework Convention on Climate Change in 2015 identified charcoal production as a major contributor to Green House Gas emissions and identified a dual approach of promoting improved biochar kilns and supporting alternative fuel sources (Government of Kenya, 2018; Johnson & Johnson, 2018). The same report proposed that more

efficient charcoal production methods be sought while pursuing alternative fuels. Pyrolysis of biomass at high temperatures and low oxygen conditions produce biochar, syngas and bio-oils in a process with low GHG production (Verheijen *et al.,* 2010; Woolf *et al*., 2010; Wuebbles *et al*., 2017). Biochar is considered an affordable negative emission technology for large scale deployment in carbon dioxide removal and sequestration (Tisserant & Cherubini, 2019).

In Kenya, climate change induced droughts, floods and heat have negatively impacted on human health, food security and economic development. Agriculture is among the identified sources of GHG emissions in Kenya (Nin-pratt, 2023) . Rice husk as an agricultural waste, has continued to increase GHGs in the atmosphere in its common disposal methods. It is estimated that 20% of total rice yields is rice husks. When disposed in canals, the husk increases water turbidity and lowers its quality while affecting the health of its users. When used as mulch in the paddy fields, rice husks decompose and release methane and nitrous oxide which are greenhouse gases.

While biochar-derived media has been internationally identified as a viable carbon sequestration medium, growth stimulant and plant health booster when used as a soil amendment or growth medium (Huang *et al*., 2015), its use in Kenya is limited and not popular with farmers in agricultural production.

This review is focused on the potential for inclusion of biochar soil amendment in integrated pest management systems for plants. Its potential use as a sterilized plant media is also significant in production of pest free seedlings.

Biochar production and properties

Biochar is an organic material produced from biomass which has been pyrolyzed at zero or low oxygen conditions (Verheijen *et al*., 2010). It is a solid carbonaceous residue that can be used as fuel, fertilizer or for activated carbon production. Other uses include; smelting of iron as a reductant, water and gas purification, waste water

treatment, poisons adsorbent in the chemical industry and a scrubber in skincare industry (Manya, 2019).Thermochemical conversion of biomass through pyrolysis produce biochar, syngas (H_2, CO, CO_2 and CH_4), heat and liquid (bio-oil) and water (Stewart *et al.*, 2013; (Nanda *et al.*, 2016; Wuebbles *et al.*, 2017). The temperatures, heating rate and time used during pyrolysis determine the quality of biochar produced as well as the by-products. Nanda *et al.* (2016) found that biochar produced at lower temperatures have higher yield, higher CEC and conductivity while production at higher temperature yields less biochar and more volatile liquids and syngas. The biochar produced at higher temperatures is highly adsorptive, high in fixed carbon, pH and porosity. Slow pyrolysis converts at least 50% of biomass into biochar with bio-oils and syngas as the byproducts (IBI, 2018). The bio-oils and syngas can be used as clean energy source. Agricultural by-products have gained attention in recent years as sources of energy due to their advantages of low cost, limited availability of wood and potential to reduce greenhouse gas emission (Dahou *et al.*, 2018).

Rice Husk is one such agricultural by-product that could potentially be utilized in Kenya due to its abundance and lignocellulosic composition. However, rice stalks and husks take a long time to decompose and they pose a disposal challenge for rice millers in Mwea (CGA, 2018). In Kenya there is inefficient biochar production technologies with low conversion ratios such as the traditional earth mound kilns (Ministry of environment, water and natural resources, 2013).

The recently elevated interest on biochar as a soil amendment rose from the discovery that it is source of high amounts of organic carbon and sustained fertility of the Amazonian soils better known as the *terra preta de Indio* (Lehmann & Joseph, 2012).

Biochar classification

Biochar can be classified based on its physiochemical properties such as carbon storage value, fertilizer value, liming value and particle size distribution (Joseph, 2015; IBI, 2018). Classification of biochar based on its properties enables stakeholders to identify the most suitable biochar type

for a particular use (Joseph, 2015). Jindo *et al*. (2014) found that biochar feedstock source and the pyrolysis temperature both affected the physiochemical properties of biochar, with high heat (over 600°C). The high heat pyrolysis degrades functional groups and yield high carbon content while lower temperature pyrolysis yields more biochar. Agricultural waste feed stocks produced more biochar which had unique chemical properties due to higher silica content while biochar from woody materials had higher carbon content and high absorption character. In his study of effect of biochar sources, application rate and placement in soil on soil health and crop growth, Guo, (2020) concluded that biochar from wood debris and crop residues contain low plant nutrients when compared with biochar derived from compost or manure. He also found that biochar types vary considerably in chemical and physical characteristics based on the feedstock used and biochar production conditions. Even when similar feedstock was used, variation in the pyrolysis temperature and duration changed the biochar characteristics significantly with poultry manure yield reducing from 60.1% to 45.7% when the pyrolysis temperature was doubled from 300°C to 600°C. Similarly corn cobs yield reduced from 26.4% to 18.5% when production temperatures were increased from 450°C to 500°C while the pH declined from 10.3 to 7.8. Ash also increased when pyrolysis temperatures were raised for hardwood from 32 to 42 gkg^{-1} while the yield fell from 32.7% to 25.8%. The total nitrogen content for poultry litter reduced from 12.1 to 1.2 gkg^{-1}while total phosphorus and potassium increased from 27.9 and 87.9 gkg^{-1} to 30.5 and 91.5 gkg^{-1} respectively when pyrolysis temperature was raised from 300°C to 600°C. It followed the same trend even when the temperature was raised less drastically from 300°C to 400°C, where total nitrogen reduced from 41.7 to 26.3 gkg−1 and total phosphorus and potassium increased from 22.7 to 69.3 gkg^{-1} to 26.3 and 81.2 gkg^{-1} respectively (Guo, 2020).

In a study conducted in Taiwan, Varela Milla *et al*. (2013), found that RHB had higher EC and higher amount of dissolvable ions than wood biochar

(WB), both had low heavy metals, WB had a higher carbon content and micro porosity, both had high concentration of potassium and Silicon though fresh rice husks was much higher than RHB and WB. In the same analysis, Varela Milla *et al.* (2013) found that when compared to rice husk, RHB had a higher pH. Silica similarly increased from 107 to 171mg/Kg, calcium and magnesium also increased from 108 and 175nmg/Kg to 220 and 182 mg/Kg respectively. This explained the rise in pH after pyrolysis.

Global use of biochar

Globally, biochar is viewed as a better soil management strategy that can increase soil carbon while mitigating effects of climate change through carbon sequestration, providing energy and increasing crop yields (Griscom *et al.*, 2017; Smith *et al.*, 2020). Biochar is considered an affordable negative emission technology for large scale deployment in carbon dioxide removal and sequestration (Tisserant & Cherubini, 2019).

Maikol *et al.* (2021) proposed the use of chicken litter-derived biochar as a soil amendment to increase soil nutrients, reduce soil acidity and exchangeable aluminium in Malaysia in order to increase rice yields. India has a huge problem in disposal of agricultural by products due to the age-old practice of burning crop residues (Sandip *et al.*, 2013). Biochar use is considered a viable strategy in reducing farm waste, improving soil quality and sequestering carbon to reduce greenhouse gas emissions and mitigate climate change (Sandip *et al.*, 2013). Biochar is used in south east Asian countries as renewable energy source, to improve soil fertility, control greenhouse gas emission and water filter in waste water treatment (Khawkomol *et al.*, 2021).

In Ghana, biochar was used to improve soil moisture and nutrient retention for vegetables production (Yakubu *et al.*, 2020). In Nigeria, it was used as a soil amendment to enhance cocoyam productivity and soil sustainability in sandy loam soils (Adekiya *et al.*, 2020).

Biochar production and use in Kenya

According to the Kenya National Bureau of Statistics (KNBS), (2019), 11.7% of Kenyans use charcoal as their primary source of fuel with 55.1 using firewood. In urban areas, charcoal use has increased to 17.7%. An estimated 22 million cubic meters of wood are used annually to meet Kenya's charcoal demand (MEWNR, 2013). In Kenya over 90% biochar production is through traditional earth mound kilns which use wood as the primary feedstock and has an approximate conversion efficiency of 14% MEWNR, 2013; Njenga *et al*., 2017). Second generation earth mound kilns have improved the conversion efficiency to 30% but its adoption is still low in Kenya. Other kilns used in Kenya include the drum kilns with a conversion rate of 20-30%, Mekko biochar kiln with a conversion rate of 50-75% and the large scale use retort kiln with a conversion rate 0f 70-80% MEWNR, 2013). Gasification jikos have also been used as an energy source while at the same time gasifying rice husks to biochar (Ismail *et al*., 2016). Gitau *et al.* (2019), found that use of gasifier jiko converts 16.6% wood biomass into biochar while reducing household firewood use by 40% and carbon monoxide, carbon dioxide and particulate matter by 57%, 41%, and 79% respectively.

A study in Vihiga, Western Kenya demonstrated that pyrolytic stoves can be used to utilize farm waste to cook and produce biochar which can be used as a soil conditioner to improve crop production (Torres, 2011). Studies in Central, Eastern and Western regions of Kenya showed that small amounts of biochar from farm feedstock when used along with inorganic fertilizers increased maize yields (Kätterer *et al*., 2022). Increasing soil organic carbon using biochar and sawdust was able to restore soil quality and crop productivity of degraded soils in Western Kenya (Kimetu *et al*., 2008). Use of biochar in Njoro and Mau Narok as a soil amendment can increase soil fertility and increase potato yields (Mbabazize *et al.,* 2023).

Effects of biochar-derived media on plant immunity

Plant immunity is defined as the inherent or induced capacity of plants to resist biological attack by pathogens. Molecules released by pathogens are recognized by the plant's surface

receptors which triggers the plant's defense mechanism. The plants defense mechanism is two pronged, relying on Pathogen-Associated Molecular System (PAMP), which is the first line of defense and the effector triggered immunity which is the second layer of defense (Bürger & Chory, 2019). The PAMP system triggers the first defense which may be overcome by some pathogen using effector proteins that interferes with the immune signaling system, this in turn triggers the plant to deploy the second line of defense - the effector triggered immunity (Bürger & Chory, 2019). Plant cells have gene transcription programs that regulate their response to their environment including stress due to pathogens (Moore *et al.*, 2011). Encounter with pathogens leads to gene reprogramming to prioritize response to the pathogen over normal growth (Moore *et al.*, 2011). The programming and reprogramming regulators are ordered by a blend of signaling hormones including salicylic acid, jasmonic acid and ethylene (Van Der Ent *et al.*, 2009, Nahar *et al.*, 2011).

Effect of biochar media on soil organisms

In Jiangxi, China biochar was found to have positive effects on soil microbes such as rhizobacteria but detrimental effects on some soil fauna including nematodes (Liu *et al.*, 2020). The effect of biochar on soil biota was direct and included effect on soil pH and increasing pore size (Liu *et al.*, 2020). In Egypt, the application of biochar in combination with furfural inhibited root knot nematodes in tomatoes more than untreated controls or individual applications of furfural or biochar (Abdelnabby *et al.*, 2018). In Ghana, RHB decreased nematode population but had an insignificant effect on flying insect pests Huang *et al.* (2015). Biochar did not have a direct nematicidal effect on *Meloidogyne graminicola* nematodes but acted to suppress the nematodes by enhancing hydrogen peroxide (H_2O_2) accumulation in plants and activation of the ethylene signaling pathway. Adding 1.2% concentration of biochar to the potting mix reduced nematode effect on rice roots due to enhanced ethylene signaling pathway. Huang *et al.* (2015)

described this phenomenon as priming of the plant defense mechanism for rapid activation against plant pathogen. Biochar was found to be a priming agent for induced plant resistance against the negative effects of parasitic nematodes (Huang *et al.*, 2015). In a related research, biochar was demonstrated to have a priming effect on genes associated with plant growth and defense such as jasmonic acid, brassionosteroids and cytokins (Jaiswal *et al.*, 2020).

In Netherlands, priming of innate plant defence in *Arabidopsis thaliana* (L.) Heynh. accession Col-0 against downy mildew using a rhizobacteria (*Pseudomonas fluorens*) and β-aminobutyric acid induced plant resistance to the disease (Van Der Ent *et al.*, 2009). Jaiswal *et al.* (2020), explored the ability of biochar to induce systemic resistance in tomatoes against crown rot disease caused by *Fusarium oxysporium* f.sp. *radicis lycopersici*. The study used transcriptomic analysis to demonstrate that biochar had a priming effect on gene expression and up-regulated the pathways of plant defense genes such as jasmonic acid to significantly suppress the disease and improve plant performance by 63%.

Biochar was found to induce plant resistance to pests and diseases such as *Fusarium oxysporum* on asparagus, *Ralstonia solanacearum*, *Botrytis cinerea* and *Clavibacter michiganensis* subsp. *michiganensis* on tomato by boosting plant defense mechanisms (Frenkel *et al.*, 2017). According to the study conducted by Frenkel *et al.* (2017) use of biochar as a growth medium for seedlings suppressed plant diseases at lower concentrations (≤1%) while higher concentrations (≥3%) were ineffective or induced some diseases such as vascular wilt disease in tomato caused by *Fusarium oxysporum* f.sp *radicis lycopersici*. The same study found that biochar had positive influence on plant growth when in concentrations higher than 25%. In a similar study, Jaiswal *et al.*, (2020), found that biochar induced resistance in tomato plants against crown rot caused by a soil borne pathogen - *Fusarium oxysporum* f.sp *radicis lycopersici* by up to 63%. Various studies on effect of biochar on plant diseases proved that

low concentrations of 0.5 to 5% had positive effect on disease suppression against *Botrytis cinera*, *Phytophthora cinnanomi*, *Plasmodiophora brassica*, *Ralstocia solanacearum* and *Rhizoctonia solani* (Frenkel *et al*., 2017)

Effect of biochar-derived media on nematodes

Plant parasitic nematodes are a major constraint in crop production due to their intricate relationship with host plants, wide host range and high level of damage caused (Bernard *et al*., 2017). Root knot nematodes (*Meloidogyne spp*), cyst nematodes (*Heterodera* and *Globodera spp*), and lesion nematodes (*Pratylenchus spp*) are the most economically important species due to their wide host range and level of damage caused by infestation (Bernard *et al*., 2017), (Gnamkoulamba *et al*., 2018). Nematodes penetrate the root elongation zone and enter the vascular bundles where they induce a permanent feeding site by injecting secretions from their pharyngeal glands into the plant cell. Management of nematodes includes use of nematicides, treatment of seed with carbofuran, dipping seedling roots in systemic insecticides and use of resistant varieties (Bernard *et al*., 2017). Over 100 nematode species affect rice production globally. In Mwea, Namu *et al*. (2019), found 22 genera of nematodes causing huge losses in rice production. Namu *et al.* (2018) found 11 of these nematode species in irrigated paddy fields in Mwea including the root knot nematodes (*Meloidogyne graminincola*) which was found across all sampled sites.

Desmedt *et al*., (2020), studied the mechanism of plant defense against nematodes and found the plant immunity against nematodes relies on production of metabolites with anti-nematode activity which they called anti nematode phytochemicals. Resistance to root knot nematodes in rice plants was largely attributed to jasmonic acid and ethylene signaling with salicylic acid playing a minor role (Nahar *et al*., 2011).

In Ghana, increased concentrations of sea shell biochar of 1 part to 1 part soil reduced root galling due to root knot nematodes in tomato (Ibrahim *et al.*

2019). In Egypt a study on the effect of rice straw biochar on root knot nematodes (*M. incognita*) by Ahmed, (2021), found that an application of 21g/pot reduced egg masses and root galls due to *M. incognita* in eggplants by 80 and 93%. A study in Western Kenya by Munyua, *et al*. (2015), found that galling due to root knot nematodes infection in beans reduced while bean yields increased when biochar and vermicompost soil amendments were added. Frenkel, (2017) urged further research to determine whether biochar addition in potting mixes can reduce nematode damage to plants.

Biochar as a soil amendment

Nanda *et al*. (2016) concluded that biochar improves the soil and enhances plant growth by increasing bioavailability of water and essential plant nutrients while providing good micro-environment for proliferation of essential micro-organisms. Li *et al*. (2018) found that application of 2% biochar in silty clay soil significantly reduced nitrate leaching and increased potassium availability to plants in China. Application of 6-9 tha^{-1} rice husk biochar as lime increased maize yield more than 23% in acidic soils in East Java, Indonesia (Nurhidayati & Mariati, 2014). This was due to the effect of rice husk charcoal on increasing available plant nutrients. Martinsen *et al.* (2015) found that an application of 1% RHB equivalent to 30 tha^{-1} raised the pH of acidic Indonesian soil by 0.04. Soils amended with biochar in Nigeria were found to have neutralized pH, increased total nitrogen and phosphorous, improved CEC and higher count of soil beneficial fungi and bacteria (Nanda *et al*., 2016; Adekiya *et al*., 2020).

A trial in Nandi, Kenya found that soils in former charcoal earth mound kiln locations was rich in carbon, phosphorous and potassium whereas soil micro fauna were found to decrease except for centipedes when compared to non-kiln areas (Kamau *et al*., 2017). This observation was explored in further research where it was confirmed that biochar application over $60tha^{1}$ exerted negative effects on soil fauna (Liu *et al*., 2020).

Biochar as a plant growth media

Important plant growth media characteristics includes the pH, CEC, C:N ratio, electrical conductivity (EC) which is a measure of total soluble salts in a media, porosity-which should range between 50-70%, Bulk density, water holding capacity which typically ranges from 45-65% by volume and sterility which is especially important in green house media (Robbins & Evans, 2011).

A study to compare the agronomic properties of rice and wood biochar found that RHB improves biomass production in water spinach by increasing the stem and leaf size (Varela *et al.*, 2013). According to Carter *et al.*, 2013, RHB application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*), at rates of 25, 50 and 150 gkg^{-1} increased the pH of the media in comparison to control and contained elevated levels of some trace metals and exchangeable cations (K, Ca and Mg). The final biomass, root biomass, plant height and number of leaves in all the cropping cycles also increased in comparison to no biochar treatments (Carter *et al.*, 2013). A long term experiment in Sumatra, Indonesia found that cacao biochar applied at a rate of 15 tha^{1} increased PH, CEC and potassium resulting to significantly higher maize yields for three consecutive seasons as seen in the figure below (Cornelissen *et al.*, 2018).

Peat based plant growth media are expensive in Kenya and coco peat production from peat bogs have been found to contribute to the increased release of GHG to the atmosphere (Steiner & Harttung, 2014). Rice husk biochar has been found to have good plant growth media characteristics including sterility, neutral to high pH and high water-holding capacity (Frenkel *et al.*, 2017). Matt (2015), in her studies on nursery media for tree seedlings propagation in Missouri, USA, found that biochar can replace 45% peat, perlite and vermiculite mix without any decrease in plant biomass growth. In a study on horticultural rooting media improvement in the Netherlands, Blok *et al.* (2017), found that wood based biochar could replace other potting soil constituents by up to

20-50% without negative growth effects. A study of alternative tree seedlings growth media in Ghana, identified RHB and groundnut husk biochar as suitable growth mediums for African mahogany (*Khaya senegalensis*) (Bernard *et al.*, 2020). Soils amended with biochar in Nigeria were found to have neutralized pH, increased total nitrogen and phosphorous, improved CEC and higher count of soil beneficial fungi and bacteria (Adekiya *et al.*, 2020). Soil amendment with biochar was found to enhance cocoyam productivity and soil sustainability in sandy loam soils (Adekiya *et al.*, 2020). In Kenya, Abubakari *et al.* (2018) conducted a trial of various soil less media and found that soil less plant growth media composed of RHB and composted sawdust in a 2:1 ratio gave the highest yields. These studies demonstrate the potential of biochar effect as a growth media in increasing crop yields.

Biochar and carbon sequestration

The Paris agreement on climate change requires that greenhouse gas emissions and sinks be balanced by the second half of this century (Anderson & Peters, 2016). Technologies of carbon dioxide removal from the atmosphere are required in order to limit global warming to less than 2°C based on pre-industrial levels (Hoad, 2016; Rogelj *et al.*, 2016). Integrated assessment models which inform policy makers assume massive deployment of negative emissions technologies (NET) to divert society from the high-temperature pathway (Anderson & Peters, 2016). Available NET include direct air capture of CO_2, enhanced weathering, bioenergy production with carbon capture and storage, afforestation and soil carbon sequestration (Smith, 2016; Tisserant & Cherubini, 2019). Soil carbon sequestration through biochar is one of the more affordable negative emission technologies for carbon dioxide removal with a net reduction of 1.67 tCO2eq per tonne of feedstock (Tisserant & Cherubini, 2019).

The Carbon cycle and carbon sequestration

Plants convert atmospheric CO_2 naturally through photosynthesis. Plant decomposition releases CO_2 back to the atmosphere. In contrast, transforming

this biomass into biochar that decomposes much more slowly diverts carbon from the rapid biological cycle into a much slower biochar cycle (Lehmann, 2007b; Lehman & Joseph, 2015). As the area under agricultural use expands, CO_2 from soil as an agricultural by-product has been added to the atmosphere (Schlesinger & Amundson, 2019). Rice production is associated with release of two GHG; methane (CH_4) and nitrous oxide (N_2O) under anaerobic production system (Chirinda *et al.*, 2018). Global rice production accounts for 2.5 of all human induced GHG mainly due to methane gas release estimated at 36 million MT (Aller *et al.*, 2017). According to Lehman & Joseph (2015), diverting merely 1% of annual net plant uptake into biochar would mitigate almost 10% current anthropogenic carbon emissions. In 2013, Mwea rice mills alone produced 10,095 tons of rice husks from 50,476 tons of rice milled. The husks were used as cooking fuel or burnt in open air with the attendant release of over 1000 tons of CO_2 emission to the atmosphere using a greenhouse gas emission factor of 0.1Kg CO_{2eq}/Kg rice. Other disposal methods for the rice husks such as disposal in canals, livestock bedding and mulch also contribute to production of other GHG such as methane and nitrous oxide.

Terra preta- black earth in Portuguese, found in the Amazonian jungle has served as an inspiration to many scientists researching ways of using biochar carbon to improve agricultural production while at the same time storing carbon in the soil and avoiding its use as charcoal hence reducing addition of CO_2 to the atmosphere (Clarke, 2013). Amazonian Indians in the Amazon basin used to produce the *terra preta* soils 1000 years ago and they are still more fertile than other surrounding soils (Lehmann & Joseph, 2015). Biomass consists of roughly 50% carbon, however when converted to biochar, the amount of carbon is reduced by 50% and the release is slowed down by one or two orders of magnitude (Scholz *et al.*, 2014). The normal carbon cycle is carbon neutral while the biochar carbon cycle withdraws 20% carbon from the atmosphere by sequestration (IBI, 2018)(Figure 1). Production and

deposition of biochar into soil is thought to be a viable option in permanent

carbon storage with related benefits to soil fertility (Matovic, 2011).

In their work to test ability of RHB in promoting carbon sequestration, Carter *et al*. (2013), found a positive linear correlation between carbon storage in the top 10cm of soil and RHB application rate. Similarly, Koyama *et al*. (2015), found a positive linear correlation between carbon storage in the soil and RHB application with a corresponding increase of 98-149% of the added carbon. However, Schlesinger & Amundson, (2019) urge more experimental research on the extent of carbon sequestration through better soil management while averring that it contributes very little to stabilization of CO_2 concentration in the atmosphere.

Biochar has also attracted the attention of climate change mitigation experts since as a stable carbon store, it can be used for carbon sequestration in the soil when used as a soil amendment (Nanda *et al*., 2016). Besides sequestering carbon in the soil, biochar contains reductive and oxidative

function groups which play a significant role in degrading wastewater pollutants. A trial by Amen *et al*., 2020, demonstrated that RHB has a lead adsorption capacity of 96.41% and a cadmium uptake capacity of 96.73%. Biochar adsorbent qualities have also been found to be effective in removal of microplastic pollutants from water (Abuwatfa *et al*., 2021).

Conclusions

Biochar enhances plant growth and activates plants natural defenses. Its use has variously been demonstrated to suppress pathogens and improve soil conditions for the proliferation of beneficial microorganisms. Incorporation of biochar in the soil improves the soil's physical and bio-chemical properties. This tends to improve soil fertility and enhance plants productivity. This was found to be enhanced in sandy and acidic soils. Being a stable carbon store, biochar application to the soil diverts carbon found in biomass to a much slower carbon cycle and thus its use lowers carbon emissions to the atmosphere

and sequesters carbon in the soil for long durations.

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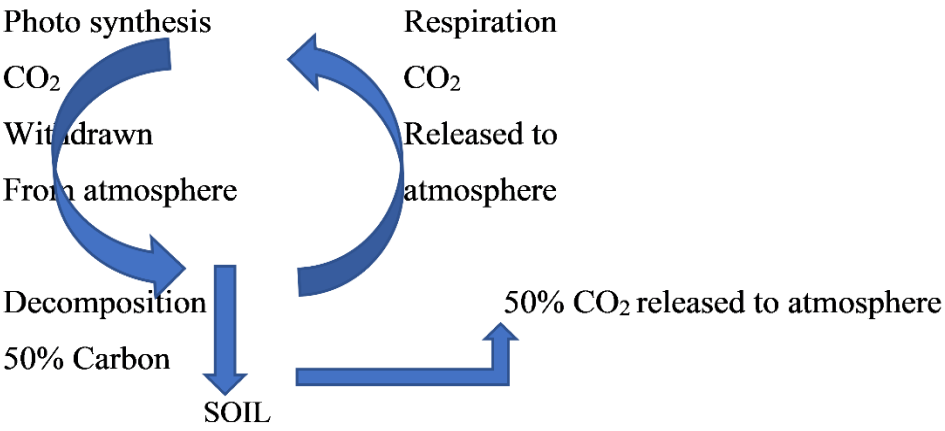
Normal Carbon Cycle - 0% Net CO_2 withdrawal from atmosphere



Biochar Carbon Cycle - 20% Net Carbon withdrawal from the atmosphere.

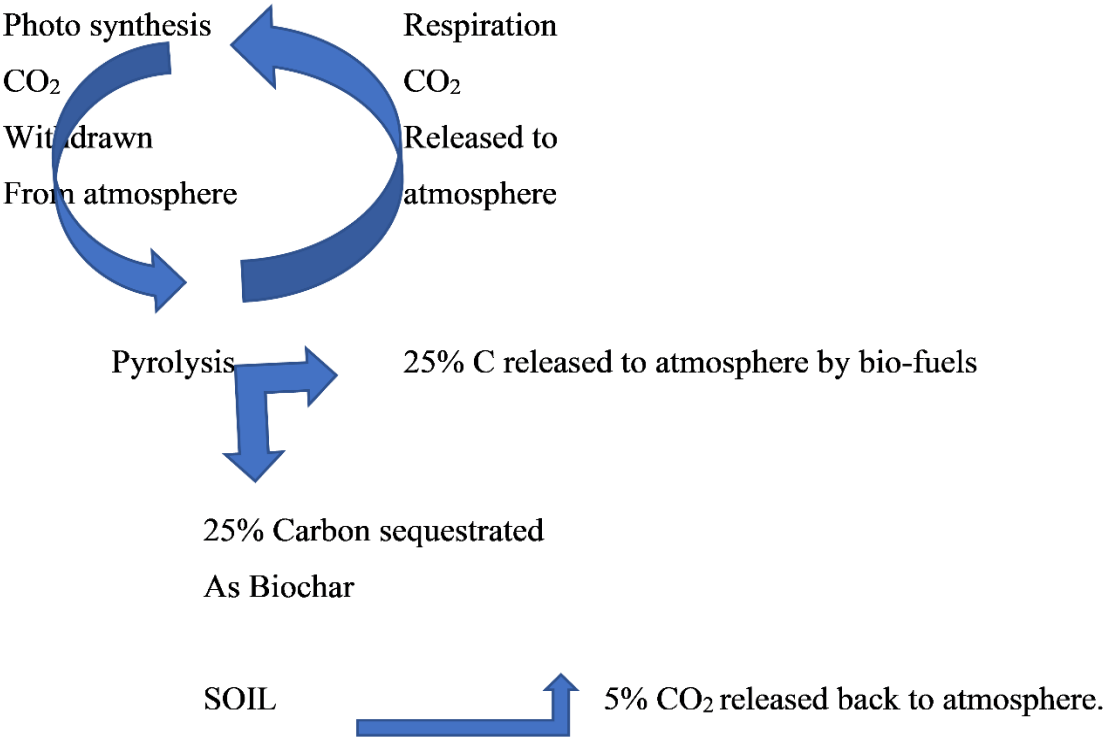


Figure 1: Normal Carbon cycle versus Biochar Carbon cycle.

Recommendations

Biochar use should be adopted especially in dry or acidic soils in Kenya as a soil amendment to improve soil fertility and plant yield. It should also be considered as a cultural plant protection method in integrated plant protection systems. Biochar as a soil amendment should also be considered as a climate change mitigation strategy due to its carbon sequestration potential. Further research on use of biochar as a drought mitigation measure in ASALS due to its water retention characteristic and in its utility as potting media for plantlets and other potted seedlings that require sterile media should be conducted. Further research should be conducted on the applicability of biochar as a climate change mitigation measure in Kenya. It is also proposed to study further on use of energy produced from pyrolysis of biochar especially from sustainable feedstock such as agricultural, industrial and even urban waste. Applications for biochar as an affordable natural adsorbent of heavy metals and other soil and other contaminants should be further explored in purification of water and rehabilitation of soils.

References

Abdelnabby, H., Hu, Z., Wang, H., & Zhang, X. (2018). Furfural–biochar-based formulations show synergistic and potentiating effects against *Meloidogyne incognita* in tomato. *Journal of Pest Science*, *91*(1), 203–218. https://doi.org/10.1007/s10340-017-0872-x.

Abubakari, A.H., Atuah, L., & Banful, B.K. (2018). Growth and yield response of lettuce to irrigation and growth media from composted sawdust and rice husk. *Journal of Plant Nutrition*, *41*(2), 221–232. https://doi.org/10.1080/01904167.2017.1384013.

Abuwatfa, W.H., Al-muqbel, D., Al-othman, A., Halalsheh, N., & Tawalbeh, M. (2021). Case Studies in Chemical and Environmental Engineering Insights into the removal of microplastics from water using biochar in the era of COVID-19: A mini review. *Case Studies in Chemical and Environmental Engineering*, *4*, 100151. https://doi.org/10.1016/j.cscee.2021.100151

Adekiya, A.O., Agbede, T.M., Olayanju, A., Ejue, W.S., Adekanye, T.A., Adenusi, T.T., & Ayeni, J.F. (2020). Effect of Biochar on Soil Properties, Soil Loss, and Cocoyam Yield on a Tropical Sandy Loam Alfisol. *Scientific World Journal*, *2020*. https://doi.org/10.1155/2020/9391630.

Ahmed, N. (2021). Rice Straw and Peanut Residues Biochars as Eco- Friendly Approaches for Controlling Root-Knot Nematode, *Meloidogyne incognita* Infecting Eggplant. *Egyptian Academic Journal of Biological Sciences, F. Toxicology & Pest Control*, *13*(2), 91–102. https://doi.org/10.21608/eajbsf.2021.189667.

Akoko, G., Kato, T., & Tu, L.H. (2020). Evaluation of irrigation water resources availability and climate change impacts-a case study of Mwea irrigation scheme, Kenya. *Water (Switzerland)*, *12*(9). https://doi.org/10.3390/W12092330.

Aller, D., Rathke, S., Laird, D., Cruse, R.,

& Hatfield, J. (2017). Impacts of fresh and aged biochars on plant available water and water use efficiency. *Geoderma*, *307*(August), 114–121. https://doi.org/10.1016/j.geoderma.2017.08.007.

Amen, R., Yaseen, M., Mukhtar, A., Ullah, S., Al-sehemi, A.G., Ra, S., Babar, M., Lai, C., Ibrahim, M., Asif, S., Shehzad, K., Majeed, M., & Bokhari, A. (2020). Lead and cadmium removal from waste water using eco-friendly biochar adsorbent derived from rice husk , wheat straw and corncob. *Cleaner Engineering and Technology*, *1*(May). https://doi.org/10.1016/j.clet.2020.100006.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182–183. https://doi.org/10.1126/science.aah4567.

Arouna, A., Fatognon, I.A., Saito, K., & Futakuchi, K. (2021). Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: Lessons learned from 10 years of the Coalition for African Rice Development. *World Development Perspectives*, *21*(January). https://doi.org/10.1016/j.wdp.2021.100291.

Axelsson, L., Franzén, M., Ostwald, M., Berndes, G., Lakshmi, G., & Ravindranath, N.H. (2012). Perspective: Jatropha cultivation in southern India: Assessing farmers' experiences. *Biofuels, Bioproducts and Biorefining*, *6*(3), 246–256. https://doi.org/10.1002/bbb

Bernard, G.C., Egnin, M., & Bonsi, C. (2017). The Impact of Plant-Parasitic Nematodes on Agriculture and Methods of Control. In *Nematology - Concepts, Diagnosis and Control*. https://doi.org/10.5772/intechopen.

Bernard, N.B., Latif, I.N., & Edmond, G. T. (2020). Biochar as an alternative growth medium for tree seedlings in the Guinea Savanna Zone of Ghana. *African Journal of Plant Science*, *14*(7), 248–253. https://doi.org/10.5897/ajps2019.1796

Blok, C., Van Der Salm, C., Hofland-

Zijlstra, J., Streminska, M., Eveleens, B., Regelink, I., Fryda, L., & Visser, R. (2017). Biochar for horticultural rooting media improvement: Evaluation of Biochar from gasification and slow pyrolysis. *Agronomy*, *7*(1). https://doi.org/10.3390/agronomy7010006.

Bürger, M. & Chory, J. (2019). Stressed Out About Hormones: How Plants Orchestrate Immunity. *Cell Host and Microbe*, *26*(2), 163–172. https://doi.org/10.1016/j.chom.2019.07.006.

Carter, S., Shackley, S., Sohi, S., Suy, T., & Haefele, S. (2013). The Impact of Biochar Application on Soil Properties and Plant Growth of Pot Grown Lettuce (*Lactuca sativa*) and Cabbage (*Brassica chinensis*). *Agronomy*, *3*(2), 404–418. https://doi.org/10.3390/agronomy3020404.

Chirinda, N., Arenas, L., Katto, M., Loaiza, S., Correa, F., Isthitani, M., Loboguerrero, A.M., Martínez-Barón, D., Graterol, E., Jaramillo, S., Torres, C.F., Arango, M., Guzmán, M., Avila, I., Hube, S., Kurtz, D.B., Zorrilla, G., Terra, J., Irisarri, P., … Bayer, C. (2018). Sustainable and low greenhouse gas emitting rice production in Latin America and the Caribbean: A review on the transition from ideality to reality. *Sustainability (Switzerland)*, *10*(3). https://doi.org/10.3390/su10030671

Cho, M.S., Meng, L., Song, J.H., Han, S.H., Bae, K., & Park, B.B. (2017). The effects of biochars on the growth of Zelkova serrata seedlings in a containerized seedling production system. *Forest Science and Technology*, *13*(1), 25–30. https://doi.org/10.1080/21580103.2017.1287778.

Clarke, S. (2013). From the ground up. *The Canadian Nurse*, *109*(5), 20–24.

Cornelissen, G., Jubaedah, Nurida, N.L., Hale, S.E., Martinsen, V., Silvani, L., & Mulder, J. (2018). Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. *Science of the Total Environment*, *634*(0806), 561–568. https://doi.org/10.1016/j.scitotenv.

2018.03.380.

Dahou, T., Defoort, F., Thiéry, S., Grateau, M., Campargue, M., Bennici, S., Jeguirim, M., & Dupont, C. (2018). The influence of char preparation and biomass type on char steam gasification kinetics. *Energies*, *11*(8), 1–15. https://doi.org/10.3390/en11082126

Desmedt, W., Mangelinckx, S., Kyndt, T., & Vanholme, B. (2020). A Phytochemical Perspective on Plant Defense Against Nematodes. *Frontiers in Plant Science*, *11*(November). https://doi.org/10.3389/fpls.2020.602079

FAOSTAT. (2019). *FAOSTAT Data-Underrnourishment in Kenya*. http://www.fao.org/faostat/en/#data/FS

Frenkel, O., Jaiswal, A.K., Elad, Y., Lew, B., Kammann, C., & Graber, E.R. (2017). The effect of biochar on plant diseases: what should we learn while designing biochar substrates? *Journal of Environmental Engineering and Landscape Management*, *25*(2), 105–113. https://doi.org/10.3846/16486897.2017.1307202.

Gnamkoulamba, A., Tounou, A.K., Tchabi, A., Kolombia, Y.A., Agboka, K., Tchao, M., Adjevi, A.K.M., & Batawila, K. (2018). Occurrence, abundance and distribution of plant-parasitic nematodes associated with rice (*Oryza* spp.) in different rice agroecosystems in Togo. *International Journal of Biological and Chemical Sciences*, *12*(2), 618. https://doi.org/10.4314/ijbcs.v12i2.1

Government of Kenya. (2018). *National Climate Change Action Plan (Kenya): 2018-2022. Nairobi: Ministry of Environment and Forestry. I*. www.environment.go.ke

Government of Kenya. (2019). *Agricultural Sector Transformation and Growth Strategy*. 1–221. http://www.kilimo.go.ke/wp-content/uploads/2019/01/ASTGS-Full-Version.pdf

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P.,

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024

Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R.& Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114.

Guo, M. (2020). The 3R Principles for Applying Biochar to Improve Soil Health. *Soil Systems*, *4*(1), 9. https://doi.org/10.3390/soilsystems4010009.

Hoad, D. (2016). The 2015 Paris Climate Agreement: Outcomes and their impacts on small island states. *Island Studies Journal*, *11*(1), 315–320.

Huang, W. kun, Ji, H. li, Gheysen, G., Debode, J., & Kyndt, T. (2015). Biochar-amended potting medium reduces the susceptibility of rice to root-knot nematode infections. *BMC Plant Biology*, *15*(1), 1–15. https://doi.org/10.1186/s12870-015-0654-7.

Ibrahim, F., Quainoo, A.K., & Kankam, F. (2019). Effect of Shea Nut Shell Biochar on Root Knot Nematodes (*Meloidogyne spp.*) of Tomato (*Solanum lycopersicum L.*). *Annual Research & Review in Biology*, *30*(2), 1–7. https://doi.org/10.9734/arrb/2018/45187.

International Biochar Initiative. (2018). *Biochar - biochar-international*. https://www.biochar-international.org/biochar/

Jaetzold, R. & Schmidt, H. (1983). Farm management handbook of Kenya. *Natural Conditions and Farm Information*, *II*, 319.

Jaiswal, A.K., Alkan, N., Elad, Y., Sela, N., Philosoph, A.M., Graber, E.R., & Frenkel, O. (2020). Molecular insights into biochar-mediated plant growth promotion and systemic resistance in tomato against Fusarium crown and root rot disease. *Scientific Reports*, *10*(1), 1–16. https://doi.org/10.1038/s41598-020-70882-6.

Jindo, K., Mizumoto, H., Sawada, Y., Sanchez-Monedero, M.A., & Sonoki,

T. (2014). Physical and chemical characterization of biochars derived from different agricultural residues. *Biogeosciences*, *11*(23), 6613–6621. https://doi.org/10.5194/bg-11-6613-2014.

Johnson, O.W. & Johnson, F.X. (2018). *Overcoming barriers to sustainable charcoal in Kenya October 2018*. *October*, 1–6.

Joseph, J. L. and S. this is not complete(2015). Biochar for Environmental Management. In J. L. and S. Joseph (Ed.), *Biochar for Environmental Management*. https://doi.org/10.4324/9780203762264.

Joseph, S., Taylor, P., & Cowie, A. (2020). *Choosing a biochar reactor to meet your needs - Biochar for Sustainable Soils*. https://biochar.international/guides/biochar-reactor-to-meet-needs/

Kamau, S., Barrios, E., Karanja, N.K., Ayuke, F.O., & Lehmann, J. (2017). Spatial variation of soil macrofauna and nutrients in tropical agricultural systems influenced by historical charcoal production in South Nandi, Kenya. *Applied Soil Ecology*, *119*(June), 286–293. https://doi.org/10.1016/j.apsoil.2017.07.007.

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., Nyberg, G., Vanlauwe, B., & Röing de Nowina, K. (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. *Field Crops Research*, *235*(March), 18–26. https://doi.org/10.1016/j.fcr.2019.02.015.

Kätterer, T., Roobroeck, D., Kimutai, G., Karltun, E., Nyberg, G., Sundberg, C., & de Nowina, K. R. (2022). Maize grain yield responses to realistic biochar application rates on smallholder farms in Kenya. *Agronomy for Sustainable Development*, *42*(4). https://doi.org/10.1007/s13593-022-00793-5

Kenya National Bureau of Statistics (KNBS). (2019). *2019 Kenya Population and Housing Census Volume I : Population By County and*

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024

Sub-County: Vol. I (Issue November). http://www.knbs.or.ke

Khan, Z., Zhang, K., Khan, M.N., Fahad, S., Xu, Z., & Hu, L. (2020). Coupling of biochar with nitrogen supplements improve soil fertility, nitrogen utilization efficiency and rapeseed growth. *Agronomy*, *10*(11). https://doi.org/10.3390/agronomy10111661

Khawkomol, S., Neamchan, R., Thongsamer, T., Vinitnantharat, S., Panpradit, B., Sohsalam, P., Werner, D., & Mrozik, W. (2021). Potential of biochar derived from agricultural residues for sustainable management. *Sustainability (Switzerland)*, *13*(15). https://doi.org/10.3390/su13158147

Kimetu, J.M., Lehmann, J., Ngoze, S.O., Mugendi, D.N., Kinyangi, J.M., Riha, S., Verchot, L., Recha, J.W., & Pell, A.N. (2008). Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems*, *11*(5), 726–739. https://doi.org/10.1007/s10021-008-9154-z.

Koyama, S., Inazaki, F., Minamikawa, K., Kato, M., & Hayashi, H. (2015). Increase in soil carbon sequestration using rice husk charcoal without stimulating CH_4 and N_2O emissions in an Andosol paddy field in Japan. *Soil Science and Plant Nutrition*, *61*(5), 873–884. https://doi.org/10.1080/00380768.2015.1065511

Lehmann, J., Joseph, S. (2009). Biochar for Environmental Management: Science, Technology and Implementation - Google Books. In *Biochar for Environmental Management* (pp. 251–270.). https://books.google.com.pk/books?hl=en&lr=&id=gWDABgAAQBAJ&oi=fnd&pg=PA421&dq=Biochar+effects+on+soil+nutrient+transformations.+In:+Lehmann,+J.,+Joseph,+S.+(Eds.),+Biochar+for+Environmental+Management:+Science+and+Technology.+Earthscan,+London,+UK,+pp.+2.

Lehmann, J., & Joseph, S. (2012). Biochar for environmental management: An introduction.

Biochar for Environmental Management: Science and Technology, *1*, 1–12. https://doi.org/10.4324/9781849770552.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., & Crowley, D. (2011). Biochar effects on soil biota - A review. *Soil Biology and Biochemistry*, *43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022.

Li, S., Zhang, Y., Yan, W., & Shangguan, Z. (2018). Effect of biochar application method on nitrogen leaching and hydraulic conductivity in a silty clay soil. *Soil and Tillage Research*, *183*(June), 100–108. https://doi.org/10.1016/j.still.2018.06.006.

Liu, T., Yang, L., Hu, Z., Xue, J., Lu, Y., Chen, X., Griffiths, B. S., Whalen, J.K., & Liu, M. (2020). Biochar exerts negative effects on soil fauna across multiple trophic levels in a cultivated acidic soil. *Biology and Fertility of Soils*, *56*(5), 597–606. https://doi.org/10.1007/s00374-020-01436-1.

Maikol, N., Haruna, A.O., Maru, A., Asap, A., & Medin, S. (2021). Utilization of urea and chicken litter biochar to improve rice production. *Scientific Reports*, *11*(1), 1–20. https://doi.org/10.1038/s41598-021-89332-y.

Mandal, H.R., Katel, S., Subedi, S., & Shrestha, J. (2021). Plant Parasitic Nematodes and their management in crop production: a review. *Journal of Agriculture and Natural Resources*, *4*(2), 327–338. https://doi.org/10.3126/janr.v4i2.33950

Manya, J.J. (Universidad de Z. (Ed.). (2019). *Advanced Carbon Materials from Biomass:an overview* (Issue May). Green Carbon Project and Consortium.

Martinsen, V., Alling, V., Nurida, N.L., Mulder, J., Hale, S.E., Ritz, C., Rutherford, D. W., Heikens, A., Breedveld, G. D., & Cornelissen, G. (2015). pH effects of the addition of three biochars to acidic Indonesian mineral soils. *Soil Science and Plant Nutrition*, *61*(5), 821–834.

https://doi.org/10.1080/00380768.2015.1052985.

Matovic, D. (2011). Biochar as a viable carbon sequestration option: Global and Canadian perspective. *Energy*, *36*(4), 2011–2016. https://doi.org/10.1016/j.energy.2010.09.031..

Mbabazize, D., Mungai, N. W., & Ouma, J. P. (2023). Effect of Biochar and Inorganic Fertilizer on Soil Biochemical Properties in Njoro Sub-County, Nakuru County, Kenya. *Open Journal of Soil Science*, *13*(07), 275–294. https://doi.org/10.4236/ojss.2023.137012.

Ministry of Agriculture. (2008). Republic of Kenya Ministry of Agriculture National Rice Development Strategy (2008 – 2018). *Strategy*, 1–25. https://www.jica.go.jp/english/our_work/thematic_issues/agricultural/pdf/kenya_en.pdf

Ministry of Environment, Water and Natural Resources, Kenya. (2013). *Analysis of the Charcoal Value Chain in Kenya Final Report. August2013*. Kenya Forest Service.

Moore, J.W., Loake, G.J., & Spoel, S.H. (2011). Transcription dynamics in plant immunity. *Plant Cell*, *23*(8), 2809–2820. https://doi.org/10.1105/tpc.111.087346.

Mutiga, S.,& Rotich, F. (UoEm); Correll, J. C. (UARK) and Talbot, N. J. (TSL). (2019). *Factsheets for Rice Production , East Africa Rice Sheath Rot*. 2019.

Nahar, K., Kyndt, T., de Vleesschauwer, D., Höfte, M., & Gheysen, G. (2011). The jasmonate pathway is a key player in systemically induced defense against root knot nematodes in rice. *Plant Physiology*, *157*(1), 305–316. https://doi.org/10.1104/pp.111.177576.

Namu, J., Karuri, H., Alakonya, A., Nyaga, J., & Njeri, E. (2018). Distribution of parasitic nematodes in Kenyan rice fields and their relation to edaphic factors, rainfall and temperature. *Tropical Plant Pathology*, *43*(2), 128–137. https://doi.org/10.1007/s40858-017-0194-9.

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024
Namu, J., Alakonya, A., Karuri, H., Nyaga, J., Masanga, J., & Njeri, E. (2019). Response of Selected Kenyan Rice Cultivars to Infection by Root Knot Nematode (*Meloidogyne incognita*). *Journal of Crop Science and Biotechnology*, *22*(1), 47–54. https://doi.org/10.1007/s12892-017-0101-0

Nanda, S., Dalai, A.K., Berruti, F., & Kozinski, J.A. (2016). Biochar as an Exceptional Bioresource for Energy, Agronomy, Carbon Sequestration, Activated Carbon and Specialty Materials. *Waste and Biomass Valorization*, *7*(2), 201–235. https://doi.org/10.1007/s12649-015-9459-z

Nin-pratt, A. (2023). Mitigating Greenhouse Gas Emissions in Kenya ' s Food System Economic Interdependencies and Policy Opportunities. August.

Nurhidayati, N. & Mariati, M. (2014). Utilization of maize cob biochar and rice husk charcoal as soil amendment for improving acid soil fertility and productivity. *Journal of Degraded and Mining Lands Management*, *2*(1), 223–230. https://doi.org/10.15243/jdmlm.2014.021.223

FAO, O. P. (2020). OECD-FAO Agricultural Outlook 2020-2029. In *OECD Publishing Paris, /Food and Agriculture Organization of the United Nations, Rome*. https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2020-2029_1112c23b-en

Poveda, J., Martínez Gómez, Á., Fenoll, C., & Escobar, C. (2021). The use of biochar for plant-pathogen control. *Phytopathology*, 1–26. https://doi.org/10.1094/phyto-06-20-0248-rvw.

Qian, L., Chen, L., Joseph, S., Pan, G., Li, L., Zheng, J., Zhang, X., Zheng, J., Yu, X., & Wang, J. (2014). Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. *Carbon Management*, *5*(2), 145–154. https://doi.org/10.1080/17583004.2014.912866

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024

Robbins, J.A., & Evans, M.R. (2011). *Growing Media for Container Production in a Greenhouse or Nursery: Part II – Physical and Chemical Properties*. 4. https://www.uaex.edu/publications/PDF/FSA-6098.pdf.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, *534*(7609), 631–639. https://doi.org/10.1038/nature18307.

Sandip Mandal, S. Jeyaraman, B.V. and A.K.S., Srinivasarao, K.A. Gopinath, G. Venkatesh, A.K. Dubey, H.W., & T.J. Purakayastha, H. Pathak, Pramod Jha, B.L. Lakaria, D.J.R. (2013). *Use of Biochar for soil Health enhancement and greenhouse gas mitigation in India*. *1*, 62.

Schlesinger, W.H., & Amundson, R. (2019). Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology*, *25*(2), 386–389. https://doi.org/10.1111/gcb.14478.

Scholz, S.B., Sembres, T., Roberts, K., Whitman, T., Wilson, K., Lehmann, J., Ahmed, S., Hammond, J., Ibarrola, R., Shackley, S., & Haszeldine, S. (2014). Biochar Systems for Smallholders. In *The World Bank*. https://doi.org/10.1596/978-0-8213-9525-7.

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, *22*(3), 1315–1324. https://doi.org/10.1111/gcb.13178

Smith, P., Soussana, J.F., Angers, D., Schipper, L., Chenu, C., Rasse, D.P., Batjes, N H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J.E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena,

A., & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. In *Global Change Biology* 26(1), 219–241.

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024

https://doi.org/10.1111/gcb.14815

Steiner, C. & Harttung, T. (2014). Biochar as a growing media additive and peat substitute. *Solid Earth*, *5*(2), 995–999. https://doi.org/10.5194/se-5-995-2014.

Stewart, C.E., Zheng, J., Botte, J., & Cotrufo, M.F. (2013). Co-generated fast pyrolysis biochar mitigates green-house gas emissions and increases carbon sequestration in temperate soils. *GCB Bioenergy*, *5*(2), 153–164. https://doi.org/10.1111/gcbb.12001

Tisserant, A. & Cherubini, F. (2019). Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation. *Land*, *8*(12). https://doi.org/10.3390/LAND8120179.

Torres, D. (2011). *Biochar Production With Cook Stoves and Use As a Soil*. *January*.

Van Der Ent, S., Van Hulten, M., Pozo, M.J., Czechowski, T., Udvardi, M.K., Pieterse, C. M.J., & Ton, J. (2009). Priming of plant innate immunity by rhizobacteria and β-aminobutyric acid: Differences and similarities in regulation. *New Phytologist*, *183*(2), 419–431. https://doi.org/10.1111/j.1469-8137.2009.02851.x.

Varela Milla, O., Rivera, E.B., Huang, W.J., Chien, C.C., & Wang, Y.M. (2013). Agronomic properties and characterization of rice husk and wood biochars and their effect on the growth of water spinach in a field test. *Journal of Soil Science and Plant Nutrition*, *13*(2), 251–266. https://doi.org/10.4067/S0718-95162013005000022

Verheijen, F., Jeffery, S., Bastos, A.C., Van Der Velde, M., & Diafas, I. (2010). Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. In *Environment* 8(4). https://doi.org/10.2788/472.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(5). https://doi.org/10.1038/ncomms1053

Wuebbles, D.J., Fahey, D.W., Hibbard,

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024

K.A., Dokken, D.J., Stewart, B.C., & Maycock, T. K. (2017). Climate science special report: fourth National Climate Assessment. *U.S. Global Change Research Program*, *1*, 470.
https://doi.org/10.7930/J0J964J6

Yakubu, A., Danso, E.O., Arthur, E., Kugblenu-Darrah, Y.O., Sabi, E.B., Abenney-Mickson, S., Ofori, K., & Andersen, M.N. (2020). Rice straw biochar and irrigation effect on yield and water productivity of okra. Agronomy Journal, 112(4), 3012–3023.
https://doi.org/10.1002/agj2.20230.

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ISSN 2617-1856 (Paper) DOI: 10.52855/YKJO1175
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Integrated Pest Management Decision Support System (IPM-DSS) a tool to support management of tree diseases in Kenya

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Abstract

Tree diseases have been noted as one of the major causes of abnormalities and malformations on perennial plants. Tree disease research in Kenya has resulted in a list of diseases identified to cause significant losses on forest plantations. The need for management of such diseases have been on the increase. The Decision Support System (DSS) was envisioned to help stakeholders make decisions to manage tree diseases on farm and in tree plantations. Information was collected across Kenya on diseases affecting seed, seedlings, plantations, natural forests and post-harvest products in sawmills. The data was entered into excel sheets and organized for database administration on MySQL software. Over 20 major fungal species were identified and their biology, distribution and management determined. This information was further fed into a query system to allow different groups of stakeholders to access the information for diagnosis and control of tree diseases. Results showed that major tree diseases in Kenya were caused by fungi belonging to the families; Botryosphaeriaceae, Nectriaceae, and Amphisphaeriaceae. The data and information availed through this query system is being used in trend analysis for proactive control and management of tree diseases in Kenya. It will also be used for farmer advisory services through closest match selection of symptom appearance based on the tree species. The query system is an innovation that will also be used for Citizen Science Data Capture to aid Kenya Forestry Research Institute in detecting emerging diseases in real-time for phytosanitary measures. The identification of commonly occurring pathogens in commercial forestry species in the country has led to research towards their control and tree improvement for resistance to tree diseases. Future plantation establishment should be based on resistant species and high-quality germplasm for maximum survival and improved yields.

Key words: Advisory services, Botryosphaeriaceae, citizen science, Decision Support System, Integrated Pest Management, tree diseases.

Introduction

The first disease identified in the Kenya Forestry Research Institute (KEFRI) pathology section was a seedling disease on *Pinus pinea* in 1953 (Njuguna & Machua, 2021). The pathogen responsible was identified as *Fusarium* fungal species. Incidences of introduced species of pest and disease outbreaks have been on the increase over time. Among the diseases, *Botryosphaeria* canker is prevalent on Eucalyptus trees. The other notable diseases include *Dothistroma* needle blight (*Mycosphaerella spp.*) and *Diplodia pinea* (*Sphaeropsis sapinea*) on pines, cypress canker (*Lepteutypa cupressi*), armillaria root rot (*Armillaria mellea*). Common disease symptoms recorded in Kenya include; stem canker that appears as a sunken area with discoloration on a tree stem or twig, damping off (death of seedlings on the nursery bed before or after germination), twig and branch dieback (death of shoots from the leader progressing toward the stem). Other symptoms recorded on foliage include; leaf blight (brown turning of foliage from green to yellow and finally to brown indicating death of the leaves or needles), leaf rust (brown appears on the leaf margin causing the leaf to curl and die) (Agrios, 2005).

These pathogens have global distribution with many being exotic having used different pathways to infect both exotic and native tree species (Slippers *et al.*, 2007). The different pathogens are spread through wind, water and root to root contact (Njuguna *et al.*, 2011). Control measures include proper sanitation, use of fungicides, removal of infected plant parts, surface sterilization and use of clean certified seed when sowing (Njuguna & Machua, 2021). For post-harvest diseases, wood can be treated with preservatives to prevent infection by various stain fungi commonly recorded on timber.

A Decision Support System (DSS) is an information-based system used to help in determining best course of action and their best sequence. It is built upon a model management system, user interface and knowledge base. It is an interactive tool combining software, human interaction, models and hardware

(Tripathi, 2011). It supports the user's decision-making process as an extra help in the management of tree diseases and pests. The model management system which stores the model developedto help in decision making e.g. presence of insect will direct you to insect pest data. It also requires a user interface which is the homepage where a user keys in the ideas for processing to get possible solutions. KEFRI holds data that spans from 1950s to 2020 on pests and diseases in Kenya. The software makes suggestions based on data contained in the knowledge base which is the data uploaded onto the software application. It may include information from internal and external sources which can be in the form of backend data or publications. Decision Support Systems are a machine learning tool and form compendia for access to information. The system brings together human judgement and computer-based solutions for solution finders to choose a course of action, which in this case is management of tree diseases.

This is the basis upon which the KEFRI Integrated Pest Management (IPM) DSS was envisioned. The tool will be an interactive web-based application for management of tree pests and diseases and will offer advisory services to tree growers on timings of the control and management of tree diseases across different agro-ecological zones in the country. The application is expected to provide stakeholders with valuable information on best methodologies for prediction, diagnosis and management of forest pests and diseases.

Methodology

Information used in this study was collated from records in the forest pathology laboratory, postgraduate research studies as well as advisory service visits to stakeholders within the country. Other records used came from forest plantations and tree nurseries in the region. The pathology team responds to foresters, nursery foremen and farmers' calls to visit a site and collect samples when symptoms of physiological interruption or malformation appear. In some cases, a correctly sampled and carefully preserved tree part was sent to the pathology lab for analysis. The samples collected or received were brought to the lab, recorded and

processed to identify the causal organism of the plant distress. From the results of the lab analysis the information was entered in Microsoft Excel files and later exported into a MYSQL database for web hosting and control of access to the different target user groups i.e. university students, foresters, extension officers, scientists and farmers. The information files were then used to create the knowledge base of the KEFRI IPM DSS. Upon typing a query in the system, a user will be able to access certain information pertaining to symptoms, control and management of a disease.

For the pilot phase the database development team focussed on diseases affecting the common plantation species namely Eucalyptus, pines, cypress, *Grevillea robusta* for the high potential areas and *Melia volkensii* which is best suited for dry areas. Pathogens of trees from the review were described, records of their occurrence highlighted as well as management and control measures provided where known.

In the development of the KEFRI IPM DSS, the following modules were used:

1. Online Public Access Catalog (OPAC): This is the front page that all the users have access to. On this page one can traverse the application to any other page and module. The page also contains the query criterion which allows users to use the symptoms, tree species name and the location from which the data was collected to build a query. This helps a stakeholder scan through the database and view the disease details. The details can also be viewed as a PDF document and are downloadable as well.
2. Pests and Diseases Module: This module allows authorized system users to manage pests and diseases data. Under this module authorized users are able to enter, edit or delete pests and diseases data.
3. System Module: This module allows authorized users to change the application settings and set other control information that affects the flow of data and links

to various pages that make up the application.

4. GIS Module: This module controls the location of data collection points. It gives the user the exact locations of places where the disease data was collected on the Google Map.

Results and discussion

The review revealed that the KEFRI Pathology section had 3000 records of diseases from nurseries, plantations, wood lots, sawmills and natural forests. All the records were entered into Microsoft Excel sheets from the existing incident report cards and were being progressively uploaded onto the database. From the data entered, there were recurring pathogens across the tree species reported (Appendix 1). Key tree species affected were isolated and their range of diseases are listed and discussed below.

Key diseases of pine

Pines are exotic trees from Mexico introduced in Kenya for timber production. Before mid-1970s *Pinus radiata* was widely planted due to its superior wood quality. However, an epidemic of *Dothistroma* blight caused by the fungi *Dothistroma pini* caused a replacement of the species by *Pinus patula,* a more resistant species but of poorer wood quality (Senalik & Farber, 2021). At the nursery, seedlings can be infected by *Pythium sp.* which causes rotting of seeds in the seed bed before or shortly after germination, a condition known as damping off. The disease causes poor or no germination of seeds on the bed hence great losses in the nursery and in glasshouses. Control of the disease is through proper nursery hygiene with well aerated and optimal watering in the seed bed.

Another fungus which causes disease on pines is *Phytophthora sp.* The fungus causes slow growth of seedlings with chlorosis and wilting on foliage (Bose *et al*., 2019). In severe cases the pathogen causes root rot, dieback and death of seedlings. In plantations, *Phytophthora sp.* kills feeder roots and causes girdling lesions on larger roots or the root crown and collar rots and can also cause stem cankers in some tree species. However, it has been found that forest conditions do not favour this fungus' growth.

Botrytis cinerea causes blight on flowers, leaves and shoots of infected plants. It also causes fruit rots and sometimes cankers in succulent stems. Brown lesions are formed on leaves. This fungus reproduces indefinitely by colonizing dead and dying plant materials. It enters plants by direct penetration of leaves and succulent stems. It is dispersed by air and water in high humidity seasons and is also spread by insect vectors e. g fruit flies. It kills plant tissues by a combination of enzymatic and toxic actions, causes death of plants in green houses and in the field especially young plants.

Armillaria mellea causes rotting of roots that causes die back and wilting leading to death of trees. It forms white felty mycelium under bark of tree. Wood decay is confined to sapwood of killed roots and butt seen after the tree dies. It causes decomposition of roots and butts of dead trees and stumps. This fungus grows much more rapidly towards the tips of disease-girdled roots than butts of living trees (Coetzee *et al*., 2005). It always works with insects and secondary pathogens to successfully colonize new plants. Due to its root-to-root contact mode of infection the fungus can cause death of trees and other plants in the infested area.

Dothistroma pini (Mycosphaerella pini) is a yellow turning reddish brown blight on pine needles affected by the disease. It causes stunted growth followed by shoot die back and eventual death of infected trees (Barnes et al., 2004). Needles turn brown as lesions start as spots and enlarge as bands and cause death of distal parts. Reddish colour is due to dothistromin, a toxin that kills the needles in advance of the fungus. Disease is dispersed by wind driven rain or mist. The fungus causes death of trees within five years of infection effectively killing young plantations and led to the stopping of *P. radiata* planting in Kenya in the late 1970s (Gibson, 1975).

Botryosphaeria ribis is an endophyte whose effect is mostly seen when the plant is stressed and kills rapidly by causing leaf blight, die-back and cankers on plants. Wood beneath cankers is brown and extends several centimeters below and above the canker (Chungu *et*

al., 2010). Diseased stems in gum producing plants have gummosis. The fungus has been reported to kill drought stressed pines. The pathogen belongs to a *B. dothidea* - *B. ribis* disease complex that causes severe problems to trees stressed by drought, freezing, wounds or insect attack. Infection is initiated by conidia dispersed by dripping or splashed water and can also be transmitted by pruning tools. The fungus causes fruit rots and death of plants and spreads very easily through plantations.

Diplodia pinea causes tip blight, resinous cankers on main stems and branches, dieback and misshapen tops, death of cones, seedling blight, gray to black stain on sapwood, stunted growth of young plantations and sometimes death of entire trees. When severe shoots are blighted, branches are deformed. Damage is usually severe to pines that are stressed by water shortage, heat, soil compaction or frost (Ivory, 1994). Damage to non-pine conifers occurs when there is environmental stress and a large supply of spores from pines. Pathogen overwinters in dead needles, stems, and cones dispersed when temperature and moisture permit. It enters needles through stomata and their spread occurs during warm wet weather.

Fusarium circinatum causes pitch canker-resin-soaked lesions on twigs and small branches. Eventual girdling occurs. Dieback is prominent on some species. When in seeds, the diseased seedlings wilt and die. This fungus is dispersed by air, water and insects. It is also transported with pine seeds. Lesion formation starts soon as the infection occurs and kills highly susceptible species by causing death of branches and deformation of trees, suppression of growth and death of seed crops (Sinclair & Lyon,2005).

Key diseases of *Eucalyptus* species in Kenya

Eucalyptus tree species are exotic species from Australia. Different species are suited to different agro-ecological zones in Kenya. *E. camaldulensis* is suited to semi-arid zones, *E. globulus* to high altitude areas (can tolerate frost), *E. saligna* to highlands and is prone to termite damage. Propagation of *Eucalyptus* species is by seedlings or

clones and direct sowing at site. Seeds do not require any pre-treatment. The species coppices well and has a wide range of uses including heavy and light construction (as timber), poles, posts, veneer, fuel wood and wind break.

Pythium sp. causes rotting of seeds before germination (pre-emergence damping off) leading to poor or no germination of seeds on the seed bed and watery stems and death of seedlings after germination (post emergence damping off). Soil borne fungi which favour high soil moisture content, high humidity, high seedling density and high organic content in the soil (Moorman, 2016).

Rhizoctonia solani causes leaf and shoot blight on seedlings. Seedlings develop water-soaked lesions, wilt and then die. The fungus grows as a saprophyte on soil and compost. It is also present in non-sterile soil and its growth is favoured by over watering and shade causing excessive moisture (Mutitu *et al*., 2008).

Erysiphe cichoracearum usually recorded as *Oidium* spp. is detected as powdery mildew on leaves of seedlings formed by a wide mat of mycelium on the leaves (Old *et al*., 2003) The fungus is dispersed by wind or water and germinates on the surfaces of leaves creating germ tubes and haustoria that help them get nutrients from the host. They survive as cleistothecia and start new infections when conditions are favorable, causes poor growth, necrosis and leaf fall thereby photosynthesis.

Botryosphaeria cankers causes shoot die back and stem cankers on trees in the field. It also causes kino exudation, forms lesions that can lead to bark cracking, eventual rot of sapwood and death of the tree (Slippers *et al.*, 2009). This fungus has been classified as an opportunistic fungus that attacks the tree on the onset of stress and can be preceded by insect attack or poor pruning that exposes cambium to infection (Slippers & Wingfield, 2007). Clones are more susceptible to the pathogen.

Cryphonectria cankers cause basal cankers, branch stubs, girdling of stems and sudden death during hot weather. Wood decay below cankers is yellow-orange. Infection is mostly through wounds, natural growth cracks and branch stubs or exposed roots but can

also be infected into new coppices from the old stump. Development of shallow network of cracks on bottom bark of the tree can lead to secondary infection by other fungi. Fungus growth is favoured by high rainfall, humidity and high temperatures and available susceptible hosts and grows more rapidly during dry seasons (Roux *et al*., 2005).

Mycosphaerella blight causes leaf spots, leaf blotch and leaf crinkles, necrosis around leaf margins, premature defoliation and stunting of trees (Carniege *et al*., 2007). Fungus growth is favoured by prolonged rainfall periods and abundant moisture during which the spores are released from fruiting bodies and spread to neighbouring susceptible hosts. Pseudothecia also form in cankers (Crous, 2002).

Stereum hirsutum is a wood decaying fungus that causes loss in mechanical strength of the wood. It causes white mottled rot of sapwood and heartwood (Gezahgne *et al*., 2003). Basidiocarps have smooth undersurface and bleed red fluids when injured. It forms sporophores on dead stumps and branches. Basidiospores from sporophores disseminate to form mycelium. Once inside, rhizomorphs spread intercellularly causing dry heart rot. It enters through wounds and branch stubs (Gibson, 1966).

Cylindrocladium spp. cause severe foliar and shoot blight by merging of tiny necrotic spores on leaf surface seen as leaf spots. Other symptoms of infection include; cutting, root and collar rots, damping off in very humid regions, twig dieback, wilting and death (Jimu *et al*., 2015). Fungi are resistant to bio-degradation hence they survive in soil as microsclerotia which germinate when stimulated by root exudates. Fungus growth is favored by high rainfall and high humidity as conidia are dispersed by water (Sharma & Mohanan, 1992). Attack is most notable in saplings and pole-sized trees as these are in a stage of growing rapidly. The fungus causes crown dieback and defoliation and leads to secondary infection by canker fungi which causes death of trees (Rodas *et al.,* 2005).

Botrytis cinerea causes blight on flowers leaves and shoots of infected plants. It also causes fruit rots and sometimes

cankers in succulent stems. Brown lesions are formed on leaves. This fungus reproduces indefinitely by colonizing dead and dying plant materials (Mwangi, 2014). It enters plants by direct penetration of leaves and succulent stems. It is dispersed by air and water in high humidity seasons and is also spread by insect vectors e.g fruit flies. It kills plant tissues by a combination of enzymatic and toxic actions and causes death of plants (especially young plants) in green houses and in the field.

Armillaria root rot causes growth reduction, yellowish leaves, branch die-back, rapid browning and death of the plant resin or gum production. Wood decay is confined to sapwood of killed roots and butt seen after the tree dies (Mwangi *et al*., 1994). The fungus causes decomposition of roots and butts of dead trees and stumps. Species of this fungus grows much more rapidly towards the tips of disease-girdled roots than butts of living trees and always works with insects and secondary pathogens to successfully colonize new plants. It causes death of trees and other plants around it.

Phytophthora root rot causes stunted leaves, bark cracks, necrotic lesions, basal cankers, collar and root rots, girdling of stems and gummosis (Bose *et al*., 2019). The fungus grows during high temperature seasons and germination occurs during wet seasons. It attacks from tiny roots followed by the large ones causing girdling and eventually death of large trees but its effects are more rapid on seedlings. It causes death of seedlings in the nursery and glass house and death of large trees in the field.

Key diseases of Cypress in Kenya

Cypress canker

A canker is a localized necrosis of the bark and cambium on stems, branches or twigs. They are often sunken because the stem continues to get bigger on the fringes of the infected parts. Also, callus may be produced around the canker that makes it more sunken. It is caused by several species of fungi. In Kenya, the disease was first observed in 1942 on *C. macrocarpa* and research found that *C. macrocarpa* was the most susceptible of the species he tested. The disease was later reported on *C. lusitanica* at Chehe in

1947 and the pathology, spread and possible origin of the disease was studied by Rudd Jones (Rudd, 1953). By 1969 studies showed that the incidence of canker caused by *Lepteutypa cupressi* (*Monochaetia unicornis* Cooke & Ellis) had declined. In Kenya, plantations of *Cupressus macrocarpa* another exotic species were severely damaged by *Lepteutypa cupressi* (*Syn Seiridium unicorne* Cooke & Ellis; B. Sutton) a stem canker fungus (Odera & Arap Sang, 1980). The pathogen survives in infected bark tissue. During wet weather, spores are released and spread to nearby hosts or healthy branches. These spores are spread by splashing and water runoff. They can also be carried longer distances by contaminated pruning tools and movement of infected plants. Since the fruiting bodies needed for identification are found near oozing cankers, it is important to include the entire branch when sampling.

The disease causes cankers, branch deformation, branch and twig dieback. The first symptom of the disease is the production of resin. As the pathogen progresses it interferes with the sap-conducting system, eventually causing death of the branch or main trunk above the wound. Branches die rapidly, yellowing almost overnight as the foliage is starved of sap. Sunken cankers, with a reddish tinge, form at the entry point of the fungus, and resin often exudes from the edges of the cankers or through cracks in the bark. Individual cankers are long and thin and may be numerous along a branch. Spore-producing structures of the fungus can be seen on the bark surface as small, circular, black dots. They can also be transferred from plant to plant on pruning tools, or through the transport of infected cuttings or plants (Olembo, 1969).

Pestalotiopsis funerea causes damping off, root and collar rot of seedlings, needle blight, shoot or tip blight, twig die-back and stem cankers on affected plants. The fungus is both endophytic and pathogenic to pines which means that it attacks on the onset of stress and kills living tissue rapidly. The spores of the fungus are dispersed by splashing or running water and produce fruiting bodies under the epidermis of leaves,

stems, fruit and other flower parts. The conidia push up when the plant part is moistened. It causes many plant diseases which eventually kill the plant. It can be managed by avoidance of stress on the trees by planting the right species in the correct sites (Sinclair & Lyon, 2015).

Armillaria root rot

In tropical Africa, Armillaria root rot is prevalent in Central and Eastern Africa. Armillaria root rot has been reported on *Cupressus lusitanica* in the highlands of eastern Africa specifically in high-altitude areas of Kenya. The disease attacks the roots forming whitish area between the bark and the wood. It can also spread upwards to the stem. Armillaria root rot is caused by several species of the fungus *Armillaria*. However, *A. heimii* is by far the major causal species on *Cupressus lusitanica*. This can easily be grown on artificial media (Mwangi *et al*., 1994).

The production of resin at the collar is a common response of Abietaceae, especially pines, attacked by *A. ostoyae* or *A. heimii*. Infection of a root system does not immediately result in the appearance of symptoms on the aerial part. These only begin to show when the collar is attacked or when several large roots are destroyed (Coetzee *et al*., 2005). Attacked trees appear brownish which progress until the tree dies. The main symptom is the presence at the level of the cambium of white, thick, mycelial fans, sometimes constituting a continuous mycelial tube. Clusters of mushrooms form at the base of the infected tree, indicating attack. Fruit bodies though rare occur in clusters at the base of infected stumps and dead trees especially on *C. lusitanica*. Most of the fruit bodies that were found seem to correspond to the species *A. heimii* although they vary in size and some are often larger than those described by for *A. heimii*. Trees can die in patches as the fungus spreads through root-to-root contact.

Conclusion

Disease diagnosis is the first step in efficient control and management of pathogen spread to prevent outbreaks that cause yield losses. The work summarized here will be packaged in a software application that will help students, researchers and farmers to identify diseases affecting trees easily. It

has been deemed cost effective and with the right user education, has a huge potential to help curb tree diseases on species of commercial importance in Kenya. Several steps are yet to be taken to complete the KEFRI IPM DSS before it is ready for use and all suggestions will help improve the application.

Recommendations

All researchers are called upon to help improve the information in the database by reviewing the records in the query system. Use of compendia and decision support systems can help in faster disease identification which will in turn help reduce spread of the pests. It will also be an important tool for promotion of citizen science for data collection in forest pathology in Kenya and its neighboring countries.

References

Agrios, G.N. (2005). *Plant Pathology* (5th ed.). Burlington, Massachusetts. Elsevier Academic Press.

Barnes, I., Crous, P.W., Wingfield, B.D. & Wingfield, M.J. (2004). Multigene phylogenies reveal that red band needle blight of *Pinus* is caused by two distinct species of *Dothistroma, D. septosporum* and *D. pini*. *Studies in Mycology 50*, 551–65.

Bose, T., Roux, J., Burgess, T.I., Shaw, C. & Wingfield, M.J. (2019). Susceptibility of *Eucalyptus grandis* and *Acacia mearnsii* seedlings to five *Phytophthora* species common in South African plantations. *Forest Pathology 49*, e12560.

Carniege, A.J., Burgess, T.I., Beilharz, V. & Wingfield, M.J. (2007). New species of *Mycosphaerella* from Myrtaceae in plantations and native forests in eastern Australia. *Mycologia 99*, 461–474.

Chungu, D., Muimba-Kankolongo, A., Wingfield, M.J & Roux, J. (2010): Plantation forestry diseases in Zambia: contributing

factors and management options. *Annals of Forest Science 67*, 1–9.

Coetzee, M.P.A., Wingfield, B.D., Bloomer, P. & Wingfield, M.J. (2005). Phylogenetic analyses of DNA sequences reveal species partitions amongst isolates

Gezahgne, A., Roux, J. & Wingfield, M.J. (2003). Diseases of exotic Eucalyptus and Pinus species in Ethiopian plantations. *South African Journal of Science 99*, 29-33.

Gibson, I.A.S. (1966). A note on *Stereum sanguinolentum* (Alb. and Schw.) Fr. A new record for Kenyan forests. *East African Agricultural and Forestry Journal 33*, 38-40.

Gibson, I.A.S. (1975). Diseases of forest trees widely planted as exotics in the tropics and Southern Hemisphere. Part 1. Important members of the Myrtaceae, Leguminosae, and Meliace, Commonwealth Forestry Institute. University of Oxford, UK, pp. 21–34.

of *Armillaria* from Africa. *Mycological Research 109*, 1223–1234.

Crous, PW. (2002). Taxonomy and pathology of Cylindrocladium (Calonectria) and allied genera. APS Press, St. Paul, Minnesota, USA.

Ivory, M.H. (1994). Records of foliage pathogens of *Pinus* species in tropical countries. *Plant Pathology 43*, 511–518.

Jimu, L., Wingfield, M.J., Mwenje, E., Roux, J. (2015). Diseases of Eucalyptus species in Zimbabwean plantations and woodlots. *Southern Forests 77*, 221–230.

Jones, D. R. (1954). Studies on a canker disease of cypresses in East Africa, caused by *Monochaetia unicornis* (cooke & ellis) sacc: II. Variation in the morphology and physiology of the pathogen. *Transactions of the British Mycological Society 37*(3), 286-305.

Moorman, G. (2016). Pythium Extension pamphlet, Pennsylvania State

University, College of Agricultural Sciences.

Mutitu, K.E., Mwangi, L., Otieno, B. & Minjire, M. (2008) Pests and diseases associated with Eucalyptus in Kenya. KEFRI Research Note No. 7.

Mwangi, L., Mwenje, E., Makambila, C., Chanakira-Nyahwa, F., Guillaumin, J.J., Mohammed, C. (1994). Ecology and pathogenicity of Armillaria in Kenya, Zimbabwe and the Congo. In: Johansson M, Stenlid J, eds Proceedings of the 8th International Conference on Root and Butt Rots. Uppsala, Sweden: IUFRO, 34–44.

Mwangi, L. (2014). Pests and diseases of Eucalyptus and their management. KEFRI Brochure.

Njuguna, J., Barklund, P., Ihrmark, K. and Stenlid, J. (2011). A canker and dieback disease threatening the cultivation of *Grevillea robusta* on small scale farms in Kenya. *African Journal of Agricultural Research 6*(3), 748-756.

Njuguna, J. & Machua, J. (2021). *Commercial Forestry in Kenya*. Muguga, Kenya. Kenya Forestry Research Institute, KEFRI publication.

Odera, J.A. & Arap Sang, F.K. (1980). Quarantine as a tool of pest and disease control with reference to the Kenya situation. Paper presented at the Commonwealth Forestry Congress, Trinidad and Tobago.

Old, K.M., Wingfield, M.J. & Yuan, Z.Q. (2003) A manual on the diseases of Eucalypts in south-East Asia, Center for International Forestry Research, CIFOR, Indonesia.

Olembo, T.W. (1969). The incidence of cypress canker in East Africa. *East African Agricultural and Forestry Journal XXXV* (2), 166-173.

Rodas, C.A., Lombard, L., Gryzenhout, M., Slippers, B., Wingfield, M.J. (2005). Cylindrocladium blight of Eucalyptus grandis in Colombia. *Australasian Plant Pathology 34*, 143–149.

Roux, J., Meke, G., Kanyi, B., Mwangi, L., Mbaga, A., Hunter, G.C.,

Nakabonge, G., & Wingfield M.J. (2005). Diseases of plantation forestry trees in Eastern and Southern Africa. *South African Journal of Science 101*, 409 – 413.

Senalik, C.A. & Farber, B. (2021). Chapter 5: Mechanical properties of wood. In: Wood handbook—wood as an engineering material. General Technical Report FPL-GTR-282. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 46 pp.

Sharma, J.K. & Mohanan, C. 1992. Relative susceptibility of Eucalyptus provenances to Cylindrocladium leaf blight in Kerala, India. *European Journal of Forest Pathology 22*, 257–265.

Sinclair, W.A. & Lyon, H.H. (2005) *Diseases of Trees and shrubs* (2nd ed.). London, England. Cornell University Press.

Slippers, B. & Wingfield, M.J. (2007): Botryosphaeriaceae as endophytes and latent pathogens of woody plants: Diversity, ecology and impact. *Fungal Biology Reviews 21*, 90–106.

Slippers, B., Burgess, T., Pavlic, D., Ahumada, R., Maleme, H., Mohali, S., Rodas C. & Wingfirld, M.J. (2009). A diverse assemblage of Botryosphaeriaceae infect Eucalyptus in native and non-native environments. *Southern Forests 71*(2),101-110.

Tripathi, K. (2011). Decision Support System is a tool for making better decisions in the organization. *Indian Journal of Computer Science and Engineering 2*(1), 112-117.

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Appendix I: Summary table of key diseases of tree species in Kenya as per KEFRI pathology records

HOST NAME	***DISEASE NAME***	***SYMPTOMS***
Acacia mearnsii	*Armillaria mellea, Lenzites sp.*	No symptoms
Acacia melanoxylon	*Armillaria mellea Trametes hirsuta*	Rot
Acacia mollissima	*Lygia sp.*	Witches broom
Acacia podalyriifolia	*Sclerotium rolfsii*	Root rot
Acacia polycantha	*Armillaria mellea*	Root rot
Acrocarpus fraxinifolius	*Psathyrella disseminata*	Fungus fructification
Alnus nepalensis	*Alternaria tenuis*	Death of seedlings
Araucaria angustifolia	*Armillaria mellea*	Swollen with lots of resin, cracks and white mycelium
Arundinaria alpina	*Engleromyces geotzii*	Fructification
Cassia siamea	*Fusarium sp.*	Canker and extended Dieback
Cassipourea elliottii	*Hormodendron*	Superficial and internal stain
Cherry tree (culture)	*Armillaria mellea*	Diseased cherry tree
Chlorophora excelsa	*Cercospora sp., Helicobasidium purpureum, Oidium sp.*	Leaf infection, root rot, mildew infection

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Cupressus benthamii	*Polystictus versicolor*	white rot
Cupressus lusitanica	*Monochaetia unicornis*	Browning and death of branchlets, cankers
Cupressus lusitanica	*Polyporus balsameus*	specimen of butt rot and heart rot
Cupressus macrocarpa	*Coniophora cerebella*	Brown cubical rot
Cupressus macrocarpa	*Polystictus coriolus*	Sporophores on rotted wood
Cupressus macrocarpa	*Polystictus versicolor*	Butt rot
Cupressus macrocarpa	*Tyromyces albidus*	Heart rot
Cupressus sp.	*Armillaria mellea*	No symptoms
Cupressus sp.	*Biatorella resinae*	No symptoms
Cupressus sp.	*Ganoderma applantum*	Bracket of fomes
Cupressus sp.	*Polyporus balsamus*	Heart rot
Cupressus sp.	*Polytictus versicolor*	Heart rot
Eucalyptus citriodora	*Fusarium sp.*	Damping off
Eucalyptus maculata	*Fusarium sp.*	Damping off
Eucalyptus maidenii	*Mycosphaerella moelleriana*	Leaf spot
Eucalyptus paniculata	*Stereum hirsutum*	No symptoms
Eucalyptus resinifera	*Armillaria mellea*	Root rot, Trees dying singly
Eucalyptus saligna	*Stereum hirstum*	Gummous canker

Euclaea laurifolia	*Cronartium gilgianum*	Leaf spot with prominent fungus growth
Fallen trunk	*Polystictus sp.*	White stringy rot
Ficoloha laurifolia	*Fomes fastuosus*	Rot in living tree
Fungus fructification	*Urneola sp.*	Fungus fructification
Grevillea grassland	*Lepiota procera*	No symptoms
Grevillea robusta	*Polyporus gilvus*	Rot and sporophore from old stump
Grevillea robusta	*Polystictus versicolor*	white rot
Gymnospora luteola	*Lenzites palisotii*	white rot
Hagenia abyssinica	*Polystictus versicolor*	Pieces of brackets
Juglans sp.	*Gleosporium sp.*	Dieback
Juniperus procera	*Fomes demidoffii*	Fructification from standing trees
Juniperus procera	*Ceratostoma juniperae*	A common gall of native cedar
Juniperus procera	*Daedalea juniperina*	Brown cubical rot
Juniperus procera	*Tyromyces albidus*	Tree rotted and invaded by borers
Juniperus sp	*Daedalea juniperina*	Brown cubical rot
Lenzites trabea	*Bracket fungus*	dark coloured bracketsof a polypolous fungus
Malus pumila	*Bacterium tumefasciens*	Root gall

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Mwitundu	*Stereum hirsutum*	Brackets on wood
Ocotea usambarensis	*Armillaria mellea*	Radial cracks, root rot
Ocotea usambarensis	*Fomes senex*	Butt rot and bracket
Olea capensis	*Polystictus cumeabarium*	Rotten timber
Olea capensis	*Stereum hirsutum*	Fallen timber
Olea chrysophylla	*Panus fulvus*	Fructification on stump
Olea welwitschii	*Polytictus versicolor*	Rot associated with fruit bodies
Parinari sp.	*Stereum sp.*	White rot with fruit body
Pines and cypress	*Armillaria mellea*	Butt rot
Pinus canariensis	*Armillaria mellea*	Rot
Pinus caribaea	*Diplodia pinea*	Needle cast
Pinus caribaea	*Cylindrocarpon radicicola*	Root disease
Pinus clausa	*Armillaria mellea*	Root rot
Pinus halepensis	*Thelephora sp.*	No symptoms
Pinus Leiophylla	*Armillaria mellea*	Root rot
Pinus occidentalis	*Armillaria mellea*	Root rot
Pinus occidentalis	*Arthrinium sp.*	Minute button like objects on the needles
Pinus patula	*Armillaria mellea*	Root rot

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Pinus patula	*Pestalotiopsis sp.*	Tip Dieback
Pinus patula	*Botrytis blight*	Fungus growth at collar
Pinus patula	*Fusarium species*	Dying off
Pinus patula	*Phoma sp.*	Death of seedlings
Pinus patula	*Suillus luteus*	Fructification
Pinus pinaster	*Armillaria mellea, Lycoperdon sp.*	No symptoms
Pinus pinea	*Fusarium sp.*	Damping off of seedlings.
Pinus radiata	*Alternaria sp., Armillaria mellea, Cladosporium sp., Fusarium sp., Diplodia pinea, Dothistroma pini,*	Tip Dieback
Pinus radiata	*Hypholoma fasciculare, Naemacyclus niveus Pestalotiopsis virgatula, Polyporus acularius, Pythium sp.*	Fungus fructification, damping off
Pinus radiata	*Rhizoctonia solani, Thelephora terrestris*	No symptoms
Pinus radiata & Cupressus macrocarpa	*Armillaria mellea*	Trees dying off
Pinus radiata & P. patula	*Armillaria mellea*	Root rot
Pinus radiata, patula & caribaea	*Armillaria mellea*	All dead wood had a black zone lines in the butt. Upper wood was stained

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		yellow and had insect larvae in tunnels under bark.
Pinus sp.	*Fusarium sp.*	Needle fall on leading shoots particularly buds
Pinus taeda	*Armillaria mellea*	Root rot
Piptadenia sp.	*Polyporaceae*	No symptoms
Podocarpus sp.	*Coniophora cerebella*	Rot
Podocarpus sp.	*Corynelia uberata*	Leaves covered with black sooty sport
Prunus serotina	*Armillaria mellea*	White mycelium under the bark
Pygeum africanum	*Armillaria mellea*	Butt rot
Pygeum africanum	*Oidium sp.*	Powdery mildew
Schinus molle	*Armillaria mellea*	Root rot
Tectona grandis	*Cephaleuros sp.*	Rusty brown spotting of leaves
Unidentified stump	*Armillaria mellea*	Root rot
Unidentified stump	*Ganoderma alvondii*	Fructification
Widdringtonia whyteii	*Armillaria mellea*	No symptoms
Widdringtonia whyteii	*Botrytis blight*	Tip Dieback

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Effect of climate change of the quality of Citrus fruit produced in South Africa

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Abstract

Climate change is an observed reality with a significant impact globally. South Africa is not immune to this phenomenon. Like the rest of the world, South Africa experiences rise in mean air temperature and changes in rainfall trends. Since plant systems are influenced by weather, it is expected that climate change will have an effect on the production and quality of fruit. The objective of this study was to determine the impact of climate change on the quality of citrus fruit produced in South Africa. In conducting the study, historical fruit quality data was collected from packhouses in the Eastern and Western Cape provinces of South Africa over a period of 12 and 8 years respectively. Trend analysis was done on the data to determine whether there is a trend that can be observed over the period of data collection. The total soluble solids of fruit showed a marginal increase over the period of observation. Titratable acidity showed a marginal decrease. The incidence of sunburn on fruit seemed to increase over time. Other disorders like decay, creasing and oleocellosis did not show a definite trend of increasing or decreasing over time. Rind disorders seemed to decrease during the period of observation. This report discusses how the observed trends were influenced by changes in rainfall and temperature over the period of observation. It is then concluded that in this case study, the impact of climate change was not very profound and it had both negative and positive effects. The current results point toward a bleak future for citrus producers. To remain profitable, it may be necessary for producers to invest in climate change adaptation technologies.

Key words: Climate change, citrus fruit, fruit quality, oleocellosis, titratable acidity

Introduction

Climate change has been identified as a serious threat to food security, human livelihood, and sustainable development in many parts of the world (Midgley *et al*., 2005; Ziervogel *et al*., 2014; Verschuur *et al*., 2021). The Intergovernmental Panel on Climate Change (IPCC) 6th summary for policy makers report of 2021 pointed out that overwhelming scientific evidence exists, showing that the earth's atmosphere is warming, and there are changes in the earth's rainfall patterns. Climate change and its deleterious effects is a global phenomenon and South Africa is not immune to this vulnerability. Zeirgovel *et al*. (2014) reported that the mean annual air temperature in South Africa has increased about 1.5 times the global average, in the past five decades. This study further reported weak and non-significant rainfall trends, in both magnitude and direction, but pointing towards a decreasing trend. Climate change projection models show that, inland areas will experience higher temperature increase than coastal areas. Rainfall trends will also vary, with the Eastern parts of the country receiving higher rainfall than the Western parts (DFFE, 2013, Engelbrecht, 2019). Since Plant systems, and by extension yield and fruit quality, are influenced by environmental factors, it is expected that climate change will influence the production and quality of fruits (Adams 1988).

Commercial fruit production in South Africa occurs on 203, 989 hectares of land, spread over the nine provinces of the country (Fruits South Africa, 2023). To the land planted with different fruit types, citrus covers about 49% of this land, making it the most planted fruit type in South Africa. By virtue of being widely planted, citrus also has the highest production and export volumes of all fruits produced in the country (Fruits South Africa, 2023). Admittedly, the extent of climate change in the production regions will influence citrus production and fruit quality. It has been shown that climate change may influence the phenology of citrus fruit, leading to early flowering in some areas but also delayed flowering was reported in other regions (Fitchett *et al*., 2014;

Abobatta, 2019). Colour change on lemons was found to be delayed, by one week to two months due to the rise in air temperature (Erena *et al*., 2019). Internal fruit quality in most cases was found to improve with climate change, but there were also cases where the soluble solids were worse off due to this phenomenon (Abobatta, 2019, Nawaz *et al*., 2020; Wang *et al*., 2022).

Undoubtedly there is a wealth of information on the impact of climate change on the quality of citrus fruits. However, there is an opportunity to examine this effect at different stages of the value chain, starting on the farm, through to the packhouse and ending in the market. The objective of this study was to examine the effect of climate change on the quality of citrus fruits at different stages of the value chain.

Materials and methods

In the Western Cape, data was obtained from fruit quality records of a packhouse in Simondium area of the Western Cape (33°49´57´´S 18°57´09´´E). The selected growers and as standard procedure, they check quality of fruit delivered to the packhouse. The data used in this study is historical quality data collected by the packhouse, from 2013 to 2021 (8 years).

In the Eastern Cape, citrus fruit quality data was obtained from a packhouse in the Sunday's River Valley. This data was collected from retention samples, which are fruit samples that the packhouse keeps back after a day's pack to monitor for any defects that may develop in the exported fruit. These are fruit samples from standard packhouse which are then kept in a room at ambient temperature and evaluated weekly. The data obtained from the Sunday's River Valley was for historical fruit quality data from 2010 to 2021 (12 years).

Quality parameters evaluated on citrus fruit

Total Soluble Solids measured as Brix – the TSS was measured by juicing a sample of 10 fruit, using a fruit juicer and filtering the juice on a wash. One

mil lilitre of the juice was placed on an packhouse, packs fruit from several Atago refractometer and brix reading

recorded. Titratable acidity was measured by sampling 25 ml of citrus juice and titrating with 0.1N Sodium hydroxide to an end point pH of 8.2. The titratable acidity was calculated using the formula (ml NaOH/25 ml) x (0.1 N NaOH/0.1562).

Fruit classification - the sample of 100 fruit was classified based on presentation, clean blemish free fruit was classified as super select, clean fruit with a few small blemishes was classified as Class 1, fruit with some blemishes but still of export quality was classified as Class 2, fruit with a lot of blemishes and not suitable for export, was classified as Class 3 also known as out of grade fruit, considered unsuitable for export.

The incidence of Oleocellosis was measured as a percentage of fruits with the disorder irrespective of size and severity. The incidence of sunburn was measured as a percentage of fruits with the disorder irrespective of size and severity. The incidence of creasing was determined by counting the number of fruits with the disorder irrespective of size and severity.

Decay was separated by type:

- Alternaria rot (*Alternaria citri*) – the incidence of Alternaria rot was determined by counting the fruits with this type of decay irrespective of the size of the lesion.
- Anthracnose (*Colletotrichum gloeosporioides*) - the incidence of anthracnose was determined by counting the fruits with this type of decay irrespective of the size of the lesion.
- Brown rot (*Phytophthora citrophthora)* - the incidence of brown rot was determined by counting the fruits with this type of decay irrespective of the size of the lesion.
- Stem end rot (*Lasiodiplodia theobromae*) - the incidence of stem end rot was determined by counting the fruits with this type of decay irrespective of the size of the lesion.
- Blue mould (*Penicillium italicum*) - the incidence of Blue mould was determined by counting the fruits with this type of decay

irrespective of the size of the lesion.

- Green mould (*Penicillium digitatum*) - the incidence of green mould was determined by counting the fruits with this type of decay irrespective of the size of the lesion.
- Sour rot *Geotrichum citri-aurantii*) - the incidence of sour rot was determined by counting the fruits with this type of decay irrespective of the size of the lesion.

Rind disorders were separated by type:

- Rind pitting – the incidence of rind pitting was determined by counting the number of fruits with the disorder irrespective of severity.
- Rind breakdown - the incidence of rind breakdown was determined by counting the number of fruits with the disorder irrespective of the severity

Results

The total soluble solids of different citrus varieties showed a slight increasing trend over the period of observation (Figure 1). Between 2013 and 2021 the total soluble solids increased by 4.6%. The average titratable acid of different citrus varieties did not show a major change over time (Figure 2). In 2013 the average acidity of fruit was 1.1% and in 2021 the acidity was slightly lower at 1.0%. Oleocellosis, decay, red scale and sunburn on fruit did not show a trend of increasing or decreasing over the period of monitoring (Figure 3).

When citrus fruit quality was monitored on arrival in the market, some varieties, Satsuma and Clementine, stood out with poor quality in the market (Figure 4). The Satsuma in some years recorded up to 45% out of grade fruit. However, the loss in quality did not show a definite trend that could be linked to climate change. The main reasons for poor quality in the market was decay and rind disorders. In isolated cases it was cubing, which occurred because of soft fruit.

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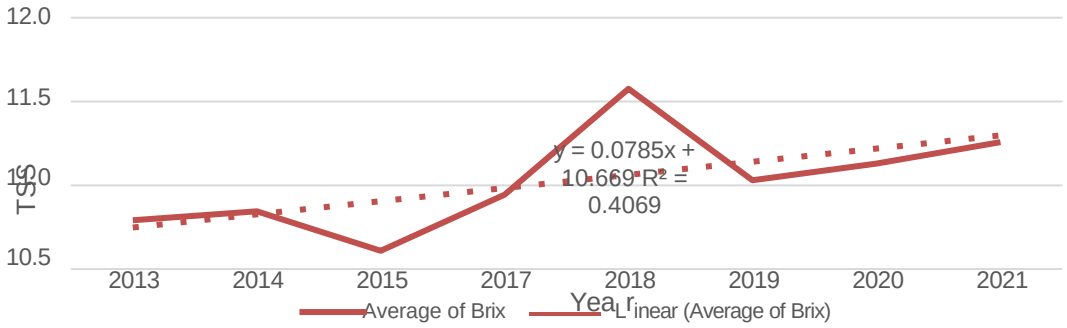

Figure 4: Average total soluble solids of different citrus varieties in the Western Cape monitored between 2013 and 2021.

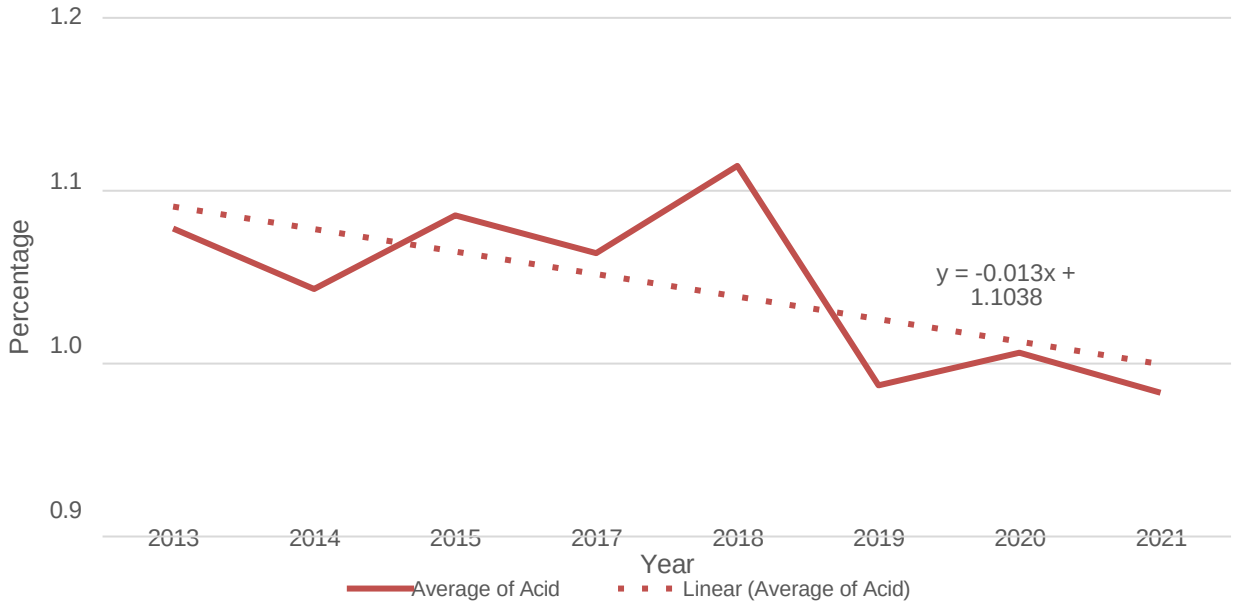

Figure 5: Average titratable acidity of different citrus varieties in the Western Cape.

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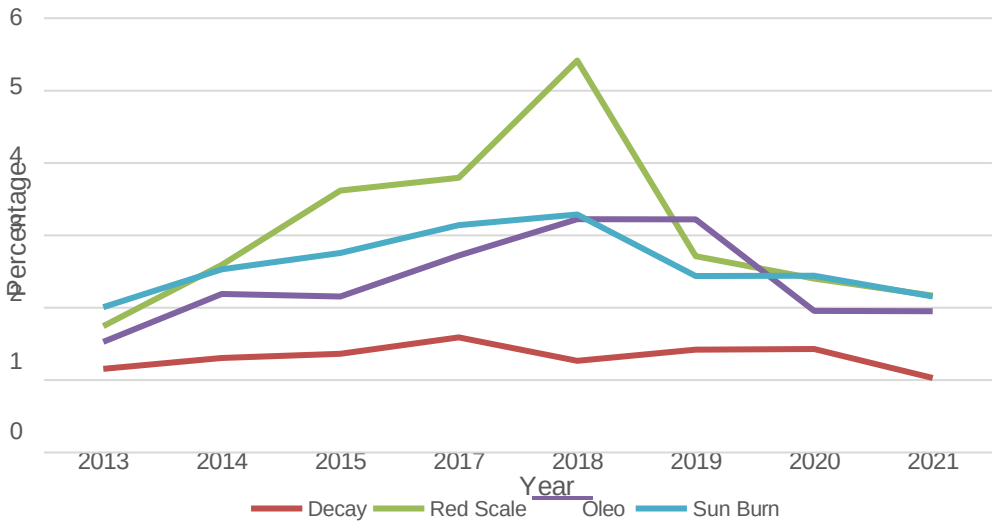

Figure 6: Development of selected disorders on different citrus varieties in the Western Cape monitored between 2013 and 2021.

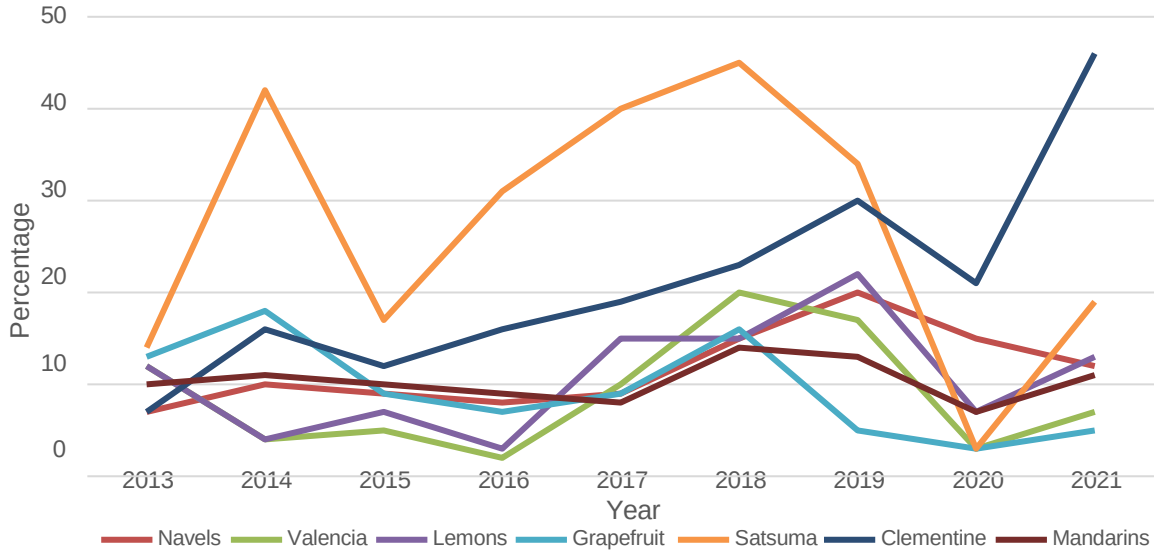

Figure 7: Out of grade fruit on arrival in the market, monitored between 2013 and 2021**.**

Creasing on retention samples showed an increasing trend from 2010 to 2016 (Figure 5). However, after 2016, the levels dropped, and fluctuations thereafter did not show a definite trend of increasing or decreasing.

Rind breakdown spiked in 2011, then decreased drastically in 2012 (Figure 6). From 2012 to 2020, the occurrence and fluctuation of all rind breakdown did not show a definite trend except for a spike in rind breakdown in the 2020 season. Rind pitting showed little fluctuation, hovering between 8 and 10%, for the period of observation.

Sunburn on fruit showed a general upward trend over the twelve-year period of observation (Figure 7). The 2016 season had uncharacteristically high levels of sunburn, which were about three to six times higher than the other season where the disorder was measured. The incidence of Alternaria rot (*Alternaria citri*) fluctuated over the years but did not show a definite trend (Figure 8). Anthracnose (*Colletotrichum gloeosporioides*) reached a peak in the early years, 2013, thereafter it decreased and remained low, especially from 2016 where it has remained close to 0%. The incidence of brown rot (*Phytophthora citrophthora)* also had an early peak, 2011, thereafter decreased and remained relatively low for most of the seasons under observation. Stem end rot (*Lasiodiplodia theobromae*) showed an erratic trend through the observation period that wasn't definite.

Blue mould (*Penicillium italicum*) incidence on fruit showed an upward trend for a few seasons, peaking in 2016, then began decreasing thereafter (Figure 9). Green mould (*Penicillium digitatum*) infection on fruits showed seasonal variation but no definite trend of increasing or decreasing over the years. The incidence of sour rot (*Geotrichum citri-aurantii*) showed seasonal fluctuation until 2015, thereafter decreasing for the rest of the observation period.

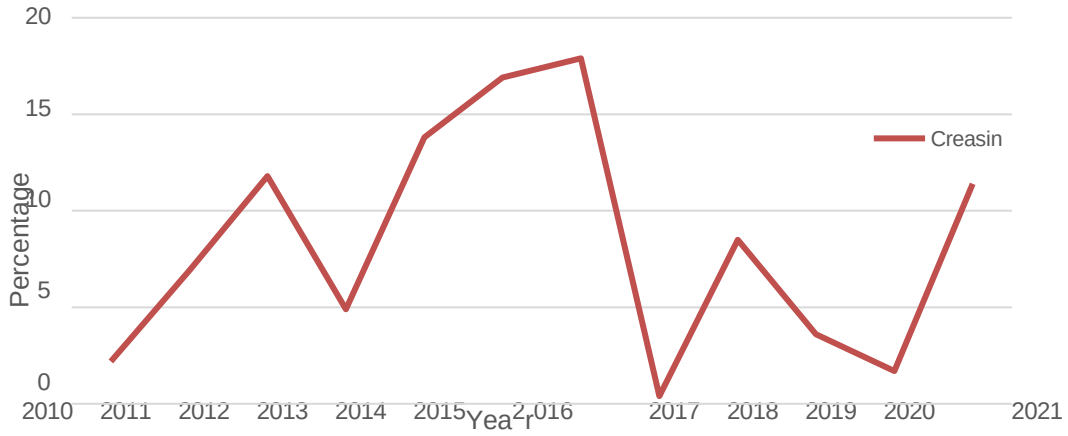

Figure 8: Development of creasing on different citrus varieties in the Eastern Cape monitored between 2010 and 2021.

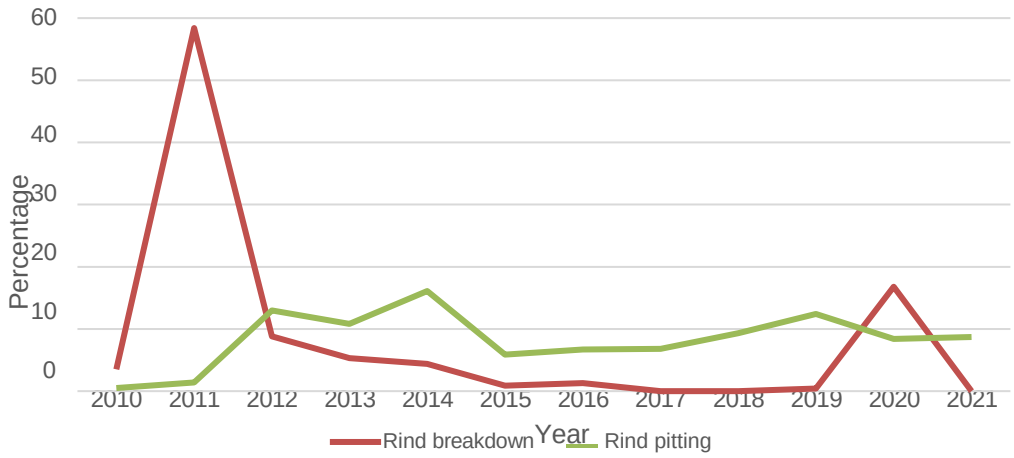

Figure 9: Development of rind breakdown and rind pitting on different citrus varieties in the Eastern Cape monitored between 2010 and 2021.

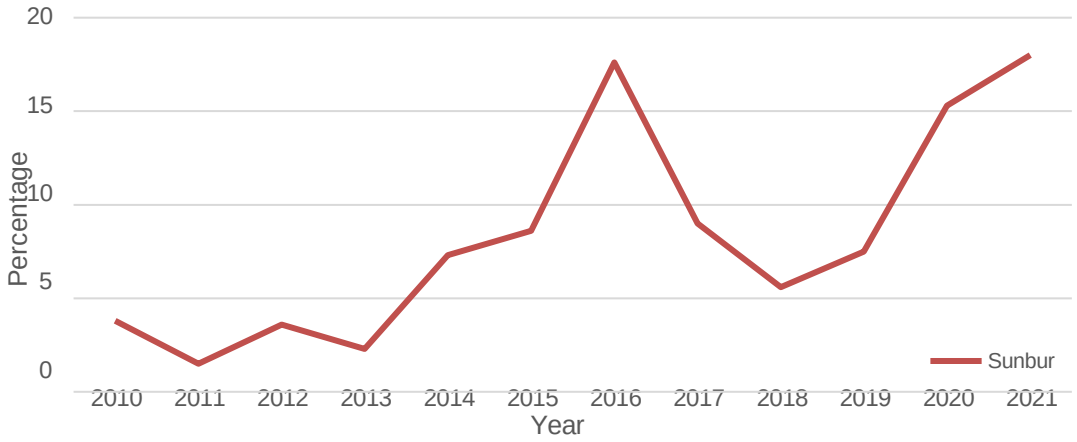

Figure 10: Development of Sunburn on different citrus varieties in the Eastern Cape monitored between 2010 and 2021.

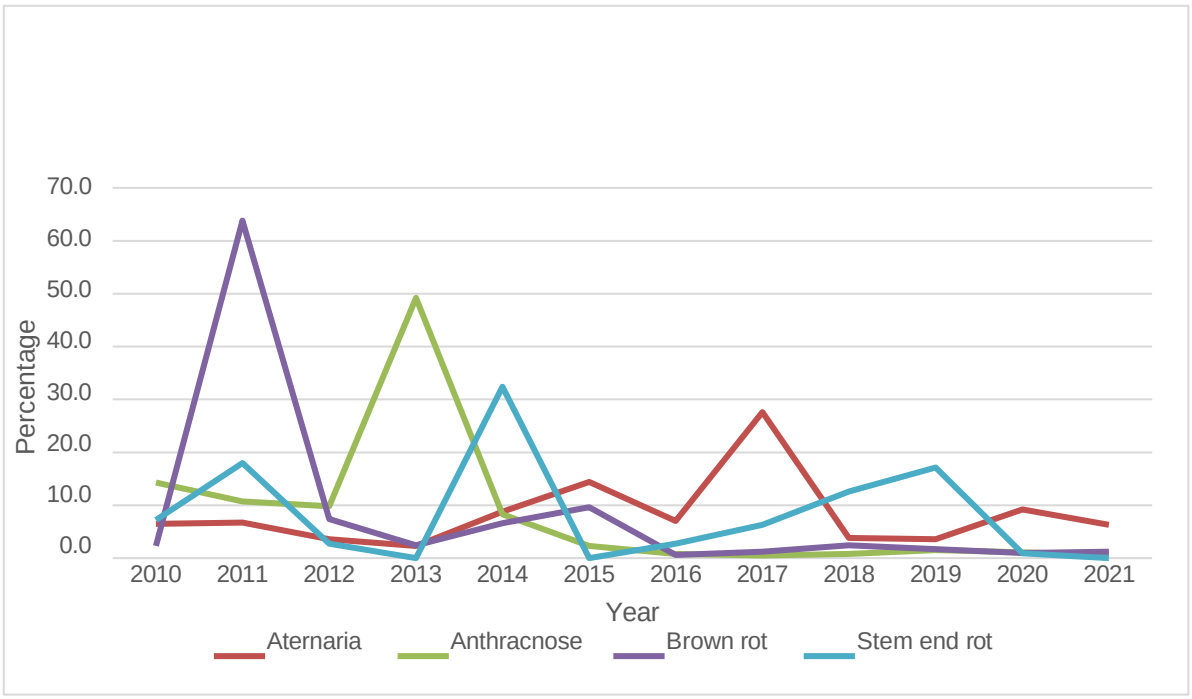

Figure 11: Development of different types of decay on citrus fruit in the Eastern Cape monitored between 2010 and 2021.

Figure 12: Development of decay, caused by wound pathogens in the, on different citrus varieties in the Eastern Cape monitored between 2010 and 2021.

Discussion

With rising air temperatures and reduced precipitation in the regions, the fruit response observed was higher brix and marginal decline in acidity. This trend is not necessarily unexpected because, it has been shown in numerous studies that reduced water supply to citrus trees during the fruit maturation phase increases soluble solids and acidity in fruit (Verreynne *et al*., 2001; Valiante and Albrigo, 2004; Treeby *et al*., 2007; Perez-Perez *et al*., 2009). The reduction in rainfall allows for better control and management irrigation, where farmers can implement deficit irrigation, uninterrupted by rainfall. The difference with the current result was on acidity which did not increase but showed a marginal decline. Valiante and Albrigo (2004) explained a decrease in acidity of citrus fruit with rising temperatures as the result of increased respiration which may lead to faster turnover of acidity. It is therefore suggested that the decrease in titratable acidity observed in citrus fruit from the Western Cape of South Africa could be in response to rising air temperature resulting in higher respiration and acid turnover. Although, it must be stated that the change in acidity is very small.

Other quality parameters on citrus fruit, including sunburn, decay, oleocellosis and red scale infection, did not show a response to climate change. While there are peaks and troughs in the occurrence of these quality issues, a direct association with temperature or rainfall could not be ascertained. On sunburn in particular, some farms may already be employing some climate change mitigation approaches such as netting or the use of kaoline-based spray products which are known to reduce sunburn (El-Tanany *et al*., 2019).

The Eastern Cape, experienced drought from 2016 to 2021, therefore the creasing was expected to increase on susceptible citrus varieties. However, this was not the case in the data collected. There are two plausible reasons for this observation. The first reason has been mentioned previously which is the fact

that fruit sorting may have removed most of the creasing that had developed in the field. Furthermore, since creasing does not increase in storage, the figures reported in the report are not a true reflection of the creasing levels, that may have developed on fruit in the field (Saleem *et al*., 2014; Juan and Jiezhong, 2017). Secondly, since commercial citrus plantings are irrigated, in South Africa, this could have partially negated the negative effects of the drought, resulting in creasing levels not increasing due to the drought as would be expected.

The seasonality in the occurrence of rind disorders suggests that environmental factors play a role in their development. However, the exact environmental or climatic factors exacerbating rind disorders have not been defined (Lado *et al*., 2018). Several factors, including late rains just before harvest, fruit shading, vitamin C content of fruit, have been associated with the development of rind disorders (Bassal and El-Hamahmy, 2011; Cronjé *et al*., 2011; Cronjé *et al*. 2013 Magwaza *et al*. 2019). Clearly rind disorders are influenced by multiple factors, from environmental to postharvest handling of fruit. The rind pitting trend reported on fruit from the Eastern Cape was variable but generally low during the drought years. This supports the findings by Cronjé *et al*., (2011) that late rains a few weeks before the start of the season can exacerbate the occurrence of the disorder. In this case the drought was beneficial and could have led to less rind disorders.

Sunburn is generally removed during sorting and grading of fruit, so the sunburn reported in this report is that which was missed by the sorting and grading in the packhouse. Since sunburn is photodamage on fruit, occurring in the field, and caused by excessive heat or light irradiance, it cannot develop further after harvest (Munne-Bosch and Vincent, 2019). The observed trend was for Sunburn to increase over the years of fruit quality observation. It is accepted that climate change in the Eastern Cape is associated with increasing temperatures and drier conditions as well

as an increase in the number of very hot days (DEDEA, 2011; Munne-Bosch and Vincent, 2019; Ndlovu *et al.,* 2021). Therefore, the sunburn trends are in line with the trends seen in climate change.

Alternaria rot (also known as black rot of citrus) is caused by *Alternaria citri* and is a widespread postharvest disease across all citrus producing areas, particularly humid environments where it causes significant economic losses (Umer *et al*., 2021, Sardar *et al*., 2022). The pathogen affects most above ground organs of citrus trees including leaves, branches, twigs, as well as fruits (Umer *et al*., 2021). Alternaria rot can infect plant parts for a wide range of temperatures, from 15^{o}C to 35^{o}C, with the ideal being 25^{o}C. However, fruits are susceptible for much longer in cooler climates (Umer *et al*., 2021). In the period under study, no objective trend wasnoted with regards to the development of Alternaria rot on citrus fruit, except for the spike in prevalence in the 2017 season.

Anthracnose rot is a citrus disease caused by multiple species within the *Colletotrichum* genus of fungi, causing serious losses on production globally (Wang *et al.,* 2021). Anthracnose infection before harvest reduces yield, while postharvest anthracnose reduces fruit quality, negatively affecting fruit export and marketability (Phoulivong *et al*., 2012). The fungus requires humid conditions as well as a temperature range of 25 to 28^{o}C for infection to occur (Majune *et al*., 2018). The disease is more prevalent during springs of prolonged wet periods and seasons of most rainfall occurring late in the season than normal (Eskalen and Adaskaveg, 2019). Anthracnose has remained very low in the Eastern Cape over the last few seasons, and this was possibly due the low rainfall received in the province (Mahlalela *et al*., 2020).

Brown rot (*Phytophtora* spp.) has remained relatively low in the area, with a low number of fruits with the decay intercepted from retention samples. *Phytophtora* is a soilborne fungal disease, requiring water or rain drop splash to move from the soil to low hanging fruit

(Savage *et al.*, 2021). Furthermore, fruits need to be wet for at least three hours with a temperature range of 27 to 30°C, for spores to infect (Timmer *et al.,* 2000). With climate change causing drought conditions in the Eastern Cape, the low cases of brown rot during this period are in line with the prevailing conditions in the province.

Diplodia stem-end rot is another economically important postharvest decay caused by the pathogen *Lasiodiplodia theobromae* (synonyms: *Botryodiplodia theobromae* and *Diplodia natalensis*) (Zhang and Bautista-Baños, 2014). The disease affects all kinds of citrus fruits, and very prevalent in hot and humid climates of tropical and subtropical regions (Forehand, 2021). Infection on immature fruits in-field requires high temperature as well as high and frequent rainfall, whilst degreening as well as excess delay in processing fruits at the packhouse are ideal conditions for the development of symptoms post harvesting (Zhang and Bautista-Baños, 2014). The occurrence of stem-end rot has been low in the Eastern Cape which can be attributed to the low rainfall received in the region.

Green mould and blue mould of citrus fruit are caused by the same genus of pathogen and are considered as the most economically important postharvest diseases of citrus fruit in all production areas (Palou, 2014). Green mould did not show a definite trend with rising temperature and reduced rainfall. Sour Rot caused by *Geotrichum citri-aurantii* is the third most economically important wound pathogens of citrus (Wang *et al.*, 2020). The prevalence of sour rot has been low since the province was affected by drought from 2016, which is expected as the pathogen is most active under high rainfall conditions (François *et al.*, 2022). The result on wound pathogen could also be confounded by good post-harvest fungicide treatments, in the packhouse and good cold chain management all which can reduce the incidence of decay on citrus fruit (Njombolwana *et al.*, 2013).

There is indication that some rind disorders may be reduced in hot and dry weather conditions, as less rind disorders developed, in storage, during the drought years compared to the period before the drought. Disorders like creasing and sunburn, clearly do not develop any further in storage and are mainly determined by pre harvest conditions. The development of most types of decay seemed to reduce during the drought years. Therefore, climate change had both negative and positive effect on fruit quality. Most of the positive effects may have been due to climate change adaptation, like shade netting of orchards, use of precession farming and high-tech post-harvest handling in the packhouse.

Conclusions and recommendations

The study showed the vulnerability of citrus fruit to climate change, particularly rising temperatures and reduced precipitation. It was further shown that the effect of climate change is not only negative but can be positive in some cases. While sunburn poses a great risk, by increasing out of grade fruit, which can lead to low profitability on the farm. The positive results of climate change included improved internal quality, in terms of total soluble solids and lower incidence of decay and rind disorders under warm and dry conditions.

To remain resilient and profitable, farms have implemented and need to continue to invest in climate change adaptation measures, which significantly lessens the impact of climate change. Shade netting, climate smart precision farming, state of the art degreening chambers and packhouses with high tech equipment are some of the adaptations seen on farms. The results of the study suggest that the negative impact of climate change on citrus fruit quality is not very pronounced at this stage.

There is room for further research on this topic, where farms with climate adaptation will be separated from farms without any adaptations. Furthermore, the investigation should start on the farm and continue to the packhouse and finally to arrival in the market, to assess the

effect at different levels of the value chain.

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References

Abobatta, W.F. (2019). Potential impacts of global climate change on citrus cultivation. *MOJ Ecology and Environmental Sciences*, 4(6): 308–312.

Adams, R.M., Hurd, B.H., Lenhart, S., & Leary N. (1998). Effect of global climate change on agriculture: an interpretative review. *Climate Research*, 11: 19-30.

Bassal, M., & El-Hamahmy, M. (2011). Hot water dip and preconditioning treatments to reduce chilling injury and maintain postharvest quality of Navel and Valencia oranges during cold quarantine. *Postharvest Biology and* Affected by Rootstock in Addition to Postharvest Treatments. In: K. Hannweg and M. Penter (Eds.) "*II Technology*, 60: 186-191.

Cronjé, P.J.R. (2013). Postharvest Rind Disorders of 'Nadorcott' Mandarin Are *All Africa Horticulture Congress 1007"*. ISHS Acta Horticulturae, Korbeek-Lo, Belgium .Pp. 111-117.

Cronjé, P.J.R., Barry, G.H., & Huysamer, M. (2011). Postharvest rind breakdown of 'Nules Clementine' mandarin is influenced by ethylene application, storage temperature and storage duration. *Postharvest Biology and Technology*, 60: 192-201.

Department of Economic Development and Environmental Affairs (DEDEA). (2011). Eastern Cape climate response strategy.

Retrieved on July 24, 2022 from http://projects.gibb.co.za/Portals/3/projects/200911%20Eastern%20Cape%20Environmental/State%20of%20Environment%20Report%20%20Work%20in%20progress%20draft.pdf

Department of Fisheries, Forestry and the Environment. (2013). Full technical report on the implications of climate change for the agricultural sector in South Africa. Retrieved on July 24, 2022 from www.dffe.gov.za/sites/default/files/docs/implications_climatechange_foragriculture.pdf

El-Tanany, M.M., Kheder, A.M.A. & Abdalla, H.R. (2019). Effcet of some treatments in reducing sunburn in 'Balady' Mandarin fruit trees (*Citrus reticulata*, Blanco). *Middle East Journal of Agriculture Research,* 8 (3): 889-897.

Engelbrecht, F. (2019). Green Book – Detailed projections of future climate change over South Africa. Technical report, Pretoria: CSIR.

Erena, M., Brotons, J.M., Manera, F.J., & Castaner, J.P. (2019). Influence of climate change on natural degreening of lemons (*Citrus limon* L. Burm. f). *Journal of Agriculture and Technology*, 21 (1): 169-179.

Eskalen, A., and Adaskaveg, J.E. (2019). Anthracnose - *Colletotrichum gloeosporioides*. UC IPM Pest Management Guidelines: Citrus. UC ANR Publication 3441. Retrieved on August 10, 2022 from https://www2.ipm.ucanr.edu/agriculture/citrus/Anthracnose/

Fitchett J.M., Grab S.W., Thompson D.I. & Roshon G. (2014). Spatio-temporal variation in phenological response of citrus to climate change in Iran: 1960-2010. *Agricultural and Forest Meteorology* 198: 285-293.

Forehand, B. (2021). Diplodia Citrus Rot – What Is Diplodia Stem-End Rot of Citrus Trees. Retrieved on August 11, 2022 from https://www.gardeningknowhow.com/edible/fruits/citrus/diplodia-citrus-rot.htm.

François, G.A., de Moraes Pontes, J.G., Pereira, A.K., and Fill, T.P. (2022). Exploring the Citrus Sour Rot pathogen: biochemical aspects, virulence factors, and strategies for disease management-a review. *Fungal Biology Reviews,* 41: 70-83.

IPCC, (2021): Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V.,P. Zhai, A., Pirani, S.L., Connors, C., Péan, S., Berger, N., Caud, Y., Chen, L., Goldfarb, M.I., Gomis, M., Huang, K., Leitzell, E., Lonnoy, J.B.R., Matthews, T.K., Maycock, T., Waterfield, O., Yelekçi, R., and Zhou, B. (eds.)]. Cambridge University Press. In Press.

Juan, L.I., and Jiezhong, C.H.E.N. (2017). Citrus Fruit-Cracking: Causes and Occurrence. *Horticultural Plant Journal*, 3(6): 255-260.

Lado, J., Gambetta, G., and Zacarias, L. (2018). Key determinants of citrus fruit quality:Metabolites and main changes during maturation. *Scientia Horticulturae*, 233: 238-248.

Magwaza, L.S., Carmen Alamar, M., Tesfay, S.Z., Mditshwa, A. Opara, U.L., and Terry, L.A. (2019). Investigating the involvement of ABA, ABA catabolites and cytokinins in the susceptibility of 'Nules Clementine' mandarin to rind breakdown disorder. *Journal of*

the Science of Food and Agriculture, 99:4142–4149.

Mahlalela, P.T., Blamey, R.C., Hart, N.C.G., and Reason, C.J.C. (2020). Drought in the Eastern Cape region of South Africa and trends in rainfall characteristics. *Climate Dynamics*, 55: 2743–2759.

Majune, D.J., Masawe, P.A., and Mbega, E.R. 2018. Status and Management of cashew disease in Tanzania. *International Journal of Environment, Agriculture and Biotechnology*, *3*(5): p.264441.

Midgley, G.F., Chapman, R.A., Hewitson, B., Johnston, P., de Wit, M., Ziervogel, G., Mukheibir, P., van Niekerk, L., Tadross, M., van Wilgen, B.W., Kgope, B., Morant, P.D., Theron, A., Scholes, R.J., and Forsyth, G.G. (2005). A Status Quo, Vulnerability and Adaptation Assessment of the Physical and Socio-economic Effects of Climate Change in the Western Cape. *Report to the Western Cape Government*, Cape Town, South Africa.

Munné-Bosch, S., and Vincent, C. 2019. Physiological Mechanisms Underlying Fruit Sunburn. *Critical Reviews in Plant Sciences*, 38 (2): 140-157.

Nawaz, R., Abbasi, N.A., Hafiz, I.A., Khalid, A. (2020). Impact of climate variable on fruit internal quality of Kinnow Mandarin (*Citrus nobilisi* Lour x *Citrus nobilisi* Tenor) in the ripening phase grown under varying environmental conditions. *Scientia Hoticulturea, 265*: 109235.

Ndlovu, M., Clulow, A.D., Savage, M.J., Nhamo, L., Magidi, J., & Mabhaudhi, T. (2021). An Assessment of the Impacts of Climate Variability and Change in KwaZulu-Natal

Province, South Africa. *Atmosphere, 12:* 427-449.

Njombolwana, N.S., Erasmus, A., Van Zyl, G., du Plooy, W., Cronjé, P.J.R., & Fourie, P.H. (2013). Effects of citrus wax coating and brush type on imazalil residue loading, green mould control and fruit quality retention of sweet oranges. *Postharvest Biology and Technology, 86*: 362 – 371.

Palou, L. (2014). *Penicillium digitatum*, *Penicillium italicum* (Green Mold, Blue Mold). In: Bautista- Baños, S. (Ed.) *Postharvest Decay Control Strategies*. pp. 45-102.

Perez-Perez, J.G., Robles, J.M., & Botia, P. (2009). Influence of deficit irrigation in phase III of fruit growth in fruit quality of 'lane late' sweet orange. *Agricultural Water Management, 96* (6): 969-974.

Saleem, B.A., Hassan, I., Singh, Z., Malik, A.U., & Pervez, M.A. (2014). Comparative changes in the rheological properties and cell wall metabolism in rind of healthy and creased fruit of 'Washington' navel and 'Navelina' sweet orange (*'Citrus sinensis* [L.] Osbeck). *Australian Journal of Crop Science, 8* (1): 62-70.

Sardar, M., Ahmed, W., Al Ayoubi, S., Nisa, S., Bibi, Y., Sabir, M., Khan, M.M., Ahmed, W., & Qayyum, A. (2022). Fungicidal synergistic effect of biogenically synthesized zinc oxide and copper oxide nanoparticles against *Alternaria citri* causing citrus black rot disease. *Saudi Journal of Biological Sciences, 29*(1): 88-95.

Savage, C., Mamba, L., and Du Plooy, W. (2021). Brown rot. South African Fruit Journal. https://www.safj.co.za/brown-rot/. Last accessed: 8 July 2022.

Timmer, L.W., Zitko, S.E., Gottwald, T.R., & Graham, J.H. (2000). *Phytophthora* Brown Rot

of Citrus: Temperature and Moisture Effects on Infection, Sporangium Production, and Dispersal. *Plant Disease*, *84* (2): 157-163.

Treeby, M.T., Henroid, K.B., Bevington, D.J., & Storey, M.R. (2007). Irrigation management and rootstock effect on navel orange [*Citrus senensis* (L.) *Agricultural Water Management, 91* (1-3): 24-32.

Umer, M., Mubeen, M., Ateeq, M., Shad, M.A., Atiq, M.N., Kaleem, M.M., Iqbal, S., Shaikh, A.A., Ullah, I., Khan, M., Kalhoro, A. A., & Abbas, A. (2021). Etiology, epidemiology and management of Citrus Black Rot caused by *Alternaria citri*- An outlook. *Plant Protection*, *5* (2): 105-115.

Valiante, J.I., and Albrigo, L.G. (2004). Flower bud induction of sweet orange tree [*Citrus sinesis* (L) Osbeck]: Effect of low temperature, crop load and bud age. *Journal of the American Society for Horticultural Science, 129* (2): 158-164.

Verreynne, J.S., Rabe, E., & Theron, K.I. (2001). Effect of combined deficit irrigation and summer trunk girdling on internal fruit quality of 'Marison" Clementines. *Scientia Hort*. *91* (1-2): 25-37.

Verschuur, J., Li, S., Wolski, P. & Otto, F.E.L. (2021). Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. *Sci Rep, 11*: 3852.

Wang, S., Xie, W., Yan, X. (2022). Effect of future climate change on citrus quality and yield in China. *Sustainability,* 14: 9366.

Wang, S., Ruan, C., Yi, L., Deng, L., Yao, S. & Zeng, K., (2020). Biocontrol ability and action mechanism of *Metschnikowia citriensis* against *Geotrichum citri-aurantii* causing sour rot of postharvest citrus fruit. *Food microbiology*, *87*: 103375.

Wang, W., de Silva, D.D., Moslemi, A., Edwards, J., Ades, P.K., Crous,

P.W. & Taylor, P.W. (2021). Colletotrichum species causing anthracnose of citrus in Australia. *Journal of Fungi*, *7*(1), p.47.

Ziervogel, G., New, M., van Garderen, E.A., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Meyer, J. & Michele, W. (2014). Climate change impacts and adaptation in South Africa*. WIREs Climate Change*, *5*: 605-620.

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