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Full Length Research Paper

Evaluation of stem borer resistance management strategies for Bt maize in Kenya based on alternative host refugia

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Stem borers are the major insect pests of maize in Kenya. The use of *Bacillus thuringiensis* (Bt) technology is an effective way of controlling lepidopteran pests. However, the likelihood of development of resistance to the Bt toxins by the target stem borer species is a concern. Forages, sorghum and maize varieties were evaluated for stem borer preference and survivorship in the laboratory and field in four locations in Kenya to identify suitable species and varieties for refugia. The economics of using the different kinds of refugia was also investigated. Vegetation surveys were conducted in 15 districts of Kenya to quantify the area covered by natural refugia. The field and laboratory trials indicated highest egg production, survivorship and more exit holes in all sorghum and maize varieties and some forages. Sorghum, non-Bt Maize, and improved Napier grass varieties Kakamega 1 and Kakamega 2) should be promoted as refugia species in Kenya. Some species and cultivars were identified as cost-effective, flexible, easily adoptable and compatible with farmers' common production practices. Refugia cultivar with multiple uses is expected to give higher pay-offs than one with single use. However, for successful management of a refugia strategy, strict stewardship is required from appropriate government or community institutions.

Key words: Refugia, cost-benefit analysis, Bt-maize, insect pest resistance management.

INTRODUCTION

Maize is the leading staple food in the world with two-thirds of the global proportion of area grown in sub Saharan Africa developing countries. The maize per capital consumption is 125 kg only third to Mexico and Malawi. The annual demand of maize is 3.2 million tons, while production is only 2.8 million tons, creating a deficit of about 0.4 million tons annually (Pingali, 2001). Farmers view stem borer damage as the major insect pest problem reducing maize yields (Mugo et al., 2001; Mulaa, 1995). The estimated maize stem borer yield losses in Kenya are 13.5% (DeGroote, 2002). Therefore, reducing stem borer damage would improve maize yields, increase individual farmers' on-farm income, and improve Kenya's food security, thus reducing cases of hunger and malnutrition. Farmers in Kenya use pesticides such as Bulldock™ (Beta-cyfluthrin), when they can afford the high cost, or natural products such as ash for stem borer

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Abbreviations: Bt, *Bacillus thuringiensis*; **IRM,** insect resistance management; **IPM,** integrated pest management.

control (Mulaa, 1995). Cultivation of transgenic crops has increased steadily since the commercial introduction of the first genetically modified crops in 1996 reaching 140 million hectares in 2009 (James, 2004). Kenya is considering introduction of *Bacillus thuringiensis* (Bt) maize as evaluated by researchers in the biosafety greenhouse and confined field trials in an open quarantine site to generate appropriate data required by the regulatory authorities (Mugo et al., 2005). Insects are capable of developing resistance to almost any toxin if its usage is continued for sufficiently long time (Mc Kenzie, 1996).

Transgenic insecticidal crops are more likely to expose a larger proportion of the insect populations to selection pressure than foliar insecticides because foliar applications do not get to all individuals in the population (Expert Report, 1998). Gould (1998) has discussed at length some of the theoretical aspects of genetically engineered crops for durable resistance. Major factors considered in the model are perception of risk and larval movement.

Resistance to Bt crops has, however, not been observed in the field since its commercial use for more than 20 years (Tabashnik et al., 2003). However, sub-lethal effects of Bt toxins on insect performance, particularly reduced feeding and delayed larval development have been reported (Eizaguirre et al., 2006). Large-scale cultivation of Bt crops will exert high selection pressure on target pest species. Consequently, these pests may evolve resistance with repeated exposure (Gould, 1998), thereby eliminating the benefit of these crops. Nevertheless, the perceived risk of target pests becoming resistant to Bt crops has led to the development of insect resistance management (IRM) strategies to delay the evolution of resistance (Mugo et al., 2004). The most widely accepted strategy for management of insect resistance is the high-dose/refuge strategy (Alstad and Andow, 1995). The rate of evolution of resistance can be slowed or stopped through the use of appropriate resistance management strategies.

The unique maize growing systems in Kenya calls for IRM strategies different from other countries. The most suitable IRM strategy for Kenya could still be the refugia/high dose strategy as part of an integrated pest management (IPM) program. Refugia can be defined as a food source in time or space that does not impose a selection pressure so as to maintain a susceptible population base to mate with resistant individuals in order to delay the appearance of homozygous resistant individuals. Refugia areas can be provided in two possible ways: 1) Only part of the field is planted with the transgenic crop and another part as close as possible is maintained as a conventionally treated area, and 2) only part of the field is planted with transgenic crop and another part (relatively smaller) as close as possible is maintained as untreated maize or other alternative host of stem borers. It is very important to select alternative hosts with economic value, for example high yielding livestock feeds or food crops, which fit in the farming systems as refugia. In Kenya, livestock contributes about 26% of the total agricultural production (Amudavi et al., 2009). Most forage have been found to be economically viable options as compared to growing food and cash crops using scarce farm resources, therefore such forages could be potential refugia species. Studies on development rates, survival rates and fecundity of the common stem borer species in various agro-ecological zones on various alternate hosts are necessary to be able to synchronize the mating between susceptible insects from the refugia with the resistant insects emerging from Bt. maize.

The most important alternative hosts which could also serve as refugia for the four major stem borers (*Busseola fusca* Fuller, *Chilo partellus* Swinhoe, *Sesamia calamistis* Hampson, and *Eldana saccharina* Walker) are reported to be cultivated sorghum, *Sorghum versicolor* Anderson, S*orghum arundinaceum* Stapf, Napier grass (*Pennisetum purpureum* Schumach) and *Hyperrhenia rufa* Nees (Khan et al., 1997). Although stem borers oviposit heavily on some grasses, only few species are favourable for them to complete their life cycles (Huttler, 1996). The IPM could include: early planting, use of pest and disease tolerant varieties, use of environmentally friendly methodologies which preserve natural enemies such as selective pesticides, natural plant products, and use of push-pull strategies (Khan et al., 1997). To be accepted by farmers, IRM strategies must be compatible with the existing cropping systems and normal farming practices, and the refugia crops must be economically viable and socially acceptable to those making the management decisions at the farm level. In addition, it should be easy to implement, or farmers may either ignore or modify it, thus reducing its effectiveness. The objectives of this research were to: (1) Characterize the maize cropping systems in different Kenyan agro-ecologies in order to estimate the potential of natural refugia; (2) characterize and determine the suitability of alternate hosts as refugia for the four major species of maize stem borers (Ahmad and Javed, 2007); (3) assess farmers' preference of different refugia; and (4) assess the economic viability of the potential of adopting planting external refugia in IRM.

MATERIALS AND METHODS

Characterization of maize cropping systems in different agro-ecologies in Kenya to estimate the potential of natural refugia

A household survey was carried out in 2004 and 2005 to characterize the farming systems and estimate the area planted to suitable alternate hosts. A multistage sampling approach was used to randomly select districts, divisions, sub-location, village and farmers. A total of 15 districts were selected in the major maize growing areas and agro-ecologies in Kenya. Random in each district, a division was randomly selected, as was a location chosen from each division, and from each selected location a sub location was selected, and from each sub location, a village was selected. A sample frame was established by listing all the farming households in each selected village, stratified in commercial (>20 acres) and small-scale farmers (<20 acres). A sample of 20-40 households was randomly selected from each village, corresponding to its size, and spread of the strata depending on the number of households in each stratum. In total, 850 farmers were interviewed. Data were collected using a structured questionnaire, which covered the type and area of alternative insect hosts, area under the different farm enterprises, farm size, and personal characteristics of the head of the household (age, sex, education and employment).The percentage area covered by different natural refugia was quantified to estimate the availability of refugia in the existing maize cropping systems.

Evaluation of the effect of hosts plants on stem borer survival, larval development and fecundity

Thirty refugia crops and crop varieties, including varieties of improved Napier grasses, giant panicum, sorghum, coloured guinea, Columbus grass, Guatemala, giant setaria, and maize were tested in the laboratory and in the field. Insect bioassays were conducted to measure larval development rates and fecundity of four stem borer species (*C. partellus, B. fusca*, *S. calamistis* and *E. saccharina*). 30 treatments were arranged in randomized complete block design with three replications. The assays took place at the KARI laboratory in Kitale. Fresh stem cuttings of approximately 0.5 kg of each of the 30 host plants were placed into a 1 clean plastic jar, and 20 neonate larvae from the KARI-Katumani stem borer rearing facility were released in each jar, under ambient laboratory conditions (22-23°C and 65-70 RH). The cuttings were replaced every week, the jars cleaned and the larval weight recorded. Days required for neonate larvae to reach pupation were recorded. At emergence, adult moths emerging from each assay were collected and transferred to a separate jar with paper wax to facilitate oviposition. The number of eggs laid was recorded daily until the moths died.

Field trials of recommended forages and maize for stem borer preference and suitability as refugia

The same 25 refugia crops were evaluated during four seasons during the 2001/2005 period at five sites. Four of the sites were on KARI centers located at different maize growing ecologies in Kenya. KARI Kitale, situated at latitude 1°01' N, longitude 35°7.5'E, at an elevation of 1,890 masl, receives on average 1,143 mm annual rainfall and the soils are loamy. The KARI Embu Center, located in an area with nitisol soils, is on latitude 0°449'S, longitude 37°42'E, elevation 1,510 masl, and receives an average of 1,693 mm rainfall annually. KARI Kakamega (latitude 0° 16'S, longitude 34°45'E) is at an elevation of 1,585 masl, on nitisol, and receives about 1,250 mm annual rainfall. KARI Mtwapa (latitude 3° 50'S, longitude 39° 44'E), has an elevation of 15 masl, receives on average 1,200 mm annual rainfall and the soils are sandy.

The fifth site was on-farm, but researcher managed, in Lurambi division of Kakamega district (latitude 3° 50'S, longitude 39° 44'E). Lurambi is situated at an elevation of 1,585 masl, receives on average1, 916 mm annual rainfall and the soils are sandy loam. Each refugia was planted on a plot of 5 m length with 5 rows per plot. Maize and sorghum seeds were planted at 75 cm between rows and 30 cm between plants. The grasses were planted according to the local recommendation, using seed or cuttings. Four weeks after seedling emergence for maize and sorghum and 6 weeks after planting the grasses, 20 stems borer pupae, kept on moist filter paper, were placed in each plot, so the emerging moths would lay eggs on the seedlings. At physiological maturity, 10 plants were randomly sampled per plot and assessed for leaf damage, number of larvae per pupae and exit and entry holes, stem diameter and dry matter production. Grain yield was also measured for maize and sorghum. Leaf damage was assessed based on a 0-9 (where by 0 was no damage and 9 very serious damage causing dead heart) scale.

Stakeholder evaluation of the refugia

To increase farmers' understanding of the importance of refugia, workshops were organized in the three KARI stations with field trials. Farmers, agricultural extension officers and researchers were invited to visit the trials. Group discussions were conducted, separately for each gender with each of the categories (Farmers, agricultural extension officers and researchers). Participants were explained the objectives of the exercise first. Then they were asked to rank the different refugia using an agreed criteria based on their observations in the experimental plots.

Assessment of economic viability of refugia crops and varieties

To assess the economic viability of refugia, an economic analysis of the refugia field experiments was conducted. For each treatment, data were collected on the amount of labour used for planting, weeding, and harvesting. This was measured in work-days of actual work done in the fields during each operation carried out. The quantities of inputs used, in particular seed, basal and top-dress fertilizers, were recorded, and the maize yields measured. Local input and output prices were also recorded.

The data were collected by researchers and extension officers during each activity. Some data were collected during routine monitoring of the experiments and cross-checked at the community level through focus group discussions and key informant interviews in the respective study sites. For the on-farm research managed trial in Kakamega, the researchers and extension workers guided farmers as to how to list inputs required for each treatment. Where there was great variability in prices over time, average farm gate prices were computed. Average wage rates from different sites were used to estimate the cost of labor. Production costs and revenue from each refugia option were computed and extrapolated from plot level to per hectare basis for comparison.

Data analysis

The number of eggs produced, percent survival, number of days to complete the life cycle, larval weight, damaged plants, exit holes, stem diameter, dry matter production and grain yield, were analyzed using a two-way analysis of variance. Correlation analysis was conducted to determine the relationships among phenotypic traits. Fisher's least significant difference was used to separate differences in treatment means at $P < 0.05$. In order to evaluate the economic viability of the IRM strategies which was the farmers' derived utility from each option, partial budgeting technique was used. This was done by comparing production costs and revenue from each refugia strategy. It was assumed that farmers will maximize the net benefits π as shown in equation 1 subject to:

$$\text{Maximize } \pi_k = Y_i P_y - X_i P_x \quad (1)$$

Table 1. Life cycle (egg to adult emergence), egg production and survival of *Busseola fusca* and *Sesamia calamistis* reared on different hosts under Laboratory conditions, Kitale, 2002-2005.

Host plant	*Busseola fusca*			*Sesamia calamistis*		
	Life Cycle (days)	Survival (%)	No. of eggs Produced	Life Cycle (days)	Survival (%)	No. of eggs Produced
Napier Grass	64.5 [a]	2.8 [c]	5.0 [c]	60.9 [a]	3.3 [c]	93.0 [b]
Local Sorghum	60.3 [a]	37.8 [a]	184.8 [b]	56.5 [b]	13.3 [b]	67.0 [c]
Maize	53.2 [b]	18.5 [b]	246.6 [a]	51.7 [b]	27.5 [a]	629.3 [a]

Means with the same letter in a column are not significantly different from each other at $P < 0.05$.

Table 2. Average larval weight of four species of stem borer reared on four groups of hosts under controlled conditions, Kitale, 2002-2005.

Host plant	*Chilo partellus*	*Busseola fusca*	*Sesamia calamistis*	*Eldana sacharina*
Wild Grasses	0.018 [c]	0.038 [a]	0.035 [a]	0.015 [a]
Maize	0.023 [a]	0.025 [b]	0.020 [b]	0.015 [a]
Napier	0.017 [c]	0.026 [b]	0.014 [c]	0.012 [b]
Sorghum	0.024 [a]	0.025 [b]	0.021 [b]	0.015 [a]
Overall Mean	0.02	0.026	0.02	0.013

Subject to acreage of refugia = 20% of maize area and Bt maize = 80%

Where, π = Net benefit of production of refugia 'k'; Y= output in kg of maize and refugia; X_{ik} = quantity of inputs to produce product 'i' in IRM 'k'; P_y= output price for refugia 'i'; P_{xi} =input price I for product 'i'.

The net profit from practicing proposed IRM strategy k was computed assuming 80% of net profit from B_t maize and 20% from refugia. The net benefit from the IRM was computation as given in equation 2:

$$\pi_{IRM} = ((0.8\pi_{Bt} + 0.2\pi_{ref}) - \pi_{Bt}) \quad (2)$$

Assumptions of the model for the computation of the profits were that the price of output were: Bt maize (KES 16/kg), Sorghum and Napier (KES 8/kg), Coloured guinea (KES 3/kg), Sudan grass (KES 3/kg), Guatemala (KES 3/kg), Giant setaria (KES 3/kg), Columbus grass (KES 3 per kg), and Giant panicum (KES 3 per kg).

RESULTS

Laboratory evaluation of the refugia

The laboratory studies revealed that there were significant differences (P=0.001) between the host plants in life cycle, percent survival and number of eggs produced by *B. fusca* and *S. calamists* (Table 1). Larvae reared on maize had the shortest life cycle, with those reared on Napier grasses showing the longest development time. Egg production per female was highest for larvae reared on maize and lowest for Napier grass. *B. fusca*, the species for which resistance development is a major concern, showed the highest survivorship on sorghums and maize and lowest on Napier grass. Larval weight gain was generally greatest for the two preferred hosts, sorghum and maize for *B. fusca* and *S. calamistis* (Table 2).

Field evaluation of the refugia

There were significant differences among the refugia crops and varieties (p=0.001) in all trait measured. Results from field trials indicated higher borer damage rating and exit holes in all sorghum and maize varieties (Table 3). The highest number of damaged plant was among Napier and sorghum varieties. The highest number of stem borer exit holes on stems was among Napier, sorghum and maize varieties. However, it was notable that all the sorghum and some maize varieties showed the highest leaf damage scores. The highest numbers of larvae recovered per plant were from Napier Kakamega 1 three sorghum varieties and maize hybrid H622.

There was a significant correlation between number of stem borer larvae and exit holes and between stem diameter and number of exit holes indi-cating borer preference of crop species with thick stems (Table 5) Napier Kakamega 1, and Napier Kakamega 2, Columbus grass, Sudan grass, sorghums Sorghum 1 white, sorghum 2 brown, sorghum 3 red, and sorghum Seredo, and maize H622, H614D, maize Mugindo and maize muzihana showed traits that are desirable as refugia species.

Table 3. Plant traits measured after infesting refugia species and varieties with *C. partellus* larvae.

Entry	Host plant	Number of stem borer damaged plants (No.)	Stem borer exit holes (No.)	Leaf damage (score 1-5)	Larvae per plant (No.)	Stem diameter (Cm)	Dry matter yield (t/ha)	Grain yield (t/ha)
1	Napier Bana	17.90^{ab}	0.45^{b}	1.67^{b}	0.01^{b}	6.48^{b}	12.85^{b}	…
2	Napier Clone 13	15.20^{ab}	0.47^{b}	1.81^{a}	0.02^{b}	6.54^{b}	11.43^{b}	…
3	Napier French Cameroon	18.39^{ab}	0.33^{c}	1.72a	0.01^{b}	5.27^{b}	12.95^{b}	…
4	Napier Kakamega 1	22.16^{a}	0.50^{ab}	1.88^{a}	0.16^{a}	10.16^{a}	18.65^{a}	…
5	Napier Kakamega 2	20.10^{a}	0.51^{ab}	1.87^{a}	0.01^{b}	10.42^{a}	13.78^{b}	…
6	Napier Kakamega 3	15.89^{ab}	0.69^{a}	1.75^{a}	0.02^{b}	10.61^{a}	14.36^{b}	…
7	Napier Mariakani	14.81^{ab}	0.73^{a}	1.70^{a}	0.00b	11.87^{a}	12.76^{b}	…
8	Napier 16798	12.43^{b}	0.52^{ab}	1.77^{a}	0.06^{ab}	9.55^{ab}	9.89^{c}	…
9	Columbus Grass	24.35^{a}	0.56^{a}	1.70^{a}	0.14^{a}	1.78^{b}	4.80^{b}	…
10	Giant Panicum Grass	11.72^{b}	0.34^{b}	1.33^{b}	0.01^{b}	1.22^{c}	1.67^{d}	…
11	Giant Setaria Grass	11.27^{b}	0.36^{b}	1.36^{b}	0.01^{b}	4.19^{a}	1.82^{d}	…
12	Sudan Grass	24.05^{a}	0.52^{a}	1.79^{a}	0.04^{a}	1.25^{c}	7.78^{a}	…
13	Sorghum 1 White	16.74^{b}	1.66^{b}	2.36^{a}	0.19^{a}	2.14^{b}	6.94^{a}	1.21^{b}
14	Sorghum 2 Brown	23.81^{a}	1.69^{b}	2.39^{a}	0.28^{a}	3.12^{a}	5.05^{a}	2.50^{a}
15	Sorghum 3 Red	20.43^{a}	2.34^{a}	2.22^{a}	0.10^{b}	2.87^{a}	3.57^{b}	1.71^{b}
16	Sorghum 4 Brown	18.78^{a}	2.34^{a}	2.25^{a}	0.10^{b}	3.00^{a}	3.35^{b}	1.51^{b}
17	Sorghum Seredo	14.84^{b}	1.57^{b}	2.21^{a}	0.16a	2.27^{b}	3.26^{b}	1.17^{b}
18	Pearl Millet	17.47^{a}	1.38^{c}	1.79^{b}	0.00^{b}	1.96^{b}	7.68^{a}	0.45^{c}
19	Maize Coast Comp.	17.57^{a}	1.04^{a}	1.61^{b}	0.11^{b}	6.17^{a}	5.00^{ab}	3.13^{c}
20	Maize - H 614D	16.76^{ab}	1.64^{a}	1.86^{b}	0.14^{b}	5.16^{a}	6.16^{a}	5.42^{a}
21	Maize - H622	16.02^{ab}	1.32^{b}	1.86^{b}	0.37^{a}	5.24a	4.20^{c}	3.01^{b}
22	Maize - Mungindo	9.19^{c}	0.47^{c}	2.08^{a}	0.01^{c}	6.17a	6.96^{a}	3.09^{b}
23	Maize - PH3253	16.73^{ab}	1.27^{b}	1.84^{b}	0.07^{c}	5.14ab	4.67^{c}	4.48^{a}
24	Maize-PH4	16.91^{ab}	1.16^{b}	1.88^{b}	0.04^{c}	5.85b	6.27^{a}	3.80^{b}
25	Maize - Muzihana	16.58^{ab}	1.78^{a}	2.32^{a}	0.09^{b}	6.19a	6.99^{a}	3.84^{b}

Characterization of maize cropping systems in different agro-ecologies in Kenya to estimate the potential of natural refugia

Results from the survey showed that Kwale district at the coastal region of Kenya had maize equivalent refugia of 19% during the short rains and 5% during the long rains (Table 6). Makueni, Mt. Elgon, TransNzoia and Vihiga Districts had less than 20% refugia during the long rains (Table 6), due largely to an almost exclusive planting of maize, with very little area planted to alternate hosts, including sorghum.

Stakeholder evaluation of the refugia

Surveys conducted with workshop participants in the various maize growing ecologies, showed that criteria used to rank different refugia differed among researchers, extensionists and farmers. The common criteria used by all groups were tolerance to stem borer attack; alternative uses of refugia including food, pasture, refugia, and hay; and the ability to attract and support stem borers (Table 4). The farmers also mentioned availability of seed as an important criterion. The major crite-

Table 4. Ranking of refugia by male farmers, extension staff and researchers in 2006 field day.

Rank	Farmers refugia selection	Farmers criteria	Extension refugia selection	Extension criteria	Researchers refugia selection	Researchers criteria
1	Napier Kakamega 2	Attractive to stem borers but tolerant to damage	Local sorghum 9 Red	Attractiveness to stem borer but tolerant to damage	Maize H516	Cob size and Yield
2	Maize H614D	High yielding	Local sorghum 4 Brown	Growth vigor	Maize H623	Disease tolerance
3	Local sorghum 2 Brown	Multiple uses food and livestock feed	Maize H614	High yielding	Columbus Grass	Tolerance to lodging
4	Maize Hybrid 623	Availability of planting material	Napier Gold Coast	Multiple uses food and livestock feed	Giant setaria	Good husk cover
5	Maize PH4	Market price	Local Sorghum 2 Brown	Easy to establish	Napier Ex-Matuga	Early maturity

Table 5. Correlation between yield and insect resistance traits.

Trait	Average number of stem borer damaged plants	Average number of stem borer exit holes	Leaf damage score Scale (1-9)	Average number of larvae per plant	Stem diameter Cm	Dry matter yield t/ha	Grain yield t/ha
Number of stem borer damaged plants	1						
Number of stem borer exit holes	0.21	1					
Leaf damage score	0.26	0.75 ***	1				
Number of larvae per plant	0.33	0.48 **	0.49 **	1			
Stem diameter	-0.18	-0.40 *	-0.17	-0.24	1		
Dry matter yield	0.18	-0.47	-0.08	-0.29	0.75 ***	1	
Grain yield	-0.16	-0.33	-0.37	-0.01	0.80 ***	0.15	1

ria used by male and female participants were yield for food and fodder, early maturity, tolerance to pests and diseases, plant height (shorter varieties being preferred for lodging resistance) and tolerance to bird damage. Other criteria used by female farmers were seed color (the brown ones being preferred), grain size, panicle size, ratoonability, drought tolerance and ability to continuously produce fresh leaves. The researchers added criteria such as fodder biomass, stem size, colour of leaves, plant uniformity (in size and grain colour) and growth vigour. The best ranked refugia options were conventional maize, sorghum and Napier grass. The eight options that were common to all top-10 ranked options were Napier Kakamega 2, maize Hybrid 614 and Local Sorghum brown.

Economic evaluations of the refugia

The results of total cost, total revenue and net benefits of eight selected refugia as ranked by stakeholders showed that the three food crops (Bt maize, conventional maize and sorghums) produce large benefits, but the fodder crops only produce small benefits (Figure 1). Bt maize had the highest net benefit (KShs 130,000/ha), followed by conventional maize (115,000/ha) and sorghum (Kshs 105,000/ha).The top fodder crop was Napier grass which has a net benefit (first year) of KES 19733/ha. The net benefits of Napier will be higher in later years, since it does not need to be replanted, but still lower than the revenue from food crops.

The other refugia that gave positive returns were coloured guinea, Guatemala, and Sudan grass, in that order. Columbus grass and giant setaria gave a negative return, that is, the revenue did not cover the costs (Table 7). Since refugia with negative net returns are not likely to be acceptable by farmers, the likely options for structuring the refugia are conventional maize and sorghum, since these are popular food crops. The only fodder crop to consider is Napier grass, which does not provide a high profit, but which is widely grown as fodder for zero-grazing dairy cattle. This is, however, interesting considering transport cost of alternative fodder, and advantage of terracing and boundaries.

Table 6. % Refugia in the surveyed districts in Kenya in 2003.

District	% Refugia short rains	% Refugia long rains
Bungoma	78	18
Bureti	72	31
Embu	32	19
Homa Bay	63	31
Kakamega	54	17
Kilifi	39	13
Kirinyaga	31	10
Kisii	52	27
Kitui	23	19
Kwale	19	5
Machakos	32	17
Makweni	16	11
Marakwet	95	24
Meru	42	14
Migori	66	21
Mt. Elgon	59	6
Mwingi	73	80
Nyamira	70	27
Teso	51	36
Tharaka	74	56
TransNzoia	90	16
Uasin Gishu	95	24
Vihiga	36	10
West Pokot	95	28
Mean	57	22

DISCUSSION

A suitable refugia species has to meet the stated criteria for effectiveness as an attractive host that supported development and reproduction of the stem borer. It also has to have economic value by having good market value or have alternative use. The laboratory studies showed sorghum and maize as the species with the best host of stem borers as shown by higher survival rates, high egg production, and supporting the highest larval weights. Field evaluation of the refugia showed Napier Kakamega 1, and Napier Kakamega 2, Columbus grass; Sudan grass; sorghums Sorghum 1 white, sorghum 2 brown, sorghum 3 red, and sorghum Seredo; and maize H622, H614D, Maize Mugindo and maize muzihana shaving traits that are desirable as refugia species. A choice of refugia species would allow choice of refugia for the different maize growing systems and ecologies that characterize Kenyan agriculture. Likewise, a wide selection of maize and sorghum species would provide farmers with choices to fit in the various maize growing ecologies in Kenya. A mix of species and varieties of differing maturities also fits into the model where moths emerging from Bt maize are likely to be delayed in their development, which would coincide with the delayed emergence of moths from alternate hosts such as sorghum or Napier grass.

The presence of natural and crops refugia is important. Districts with more than 20% refugia could have farmers with close proximity benefiting by not losing their land to refugia. Those in districts with less than 20% refugia will use inputs and forego maize optimum harvests in the refugia area. Such regions will require structured or augmented refugia to attain 20% refugia. Areas with less than 20% will require a structured refugia and frequent monitoring for resistance. The stakeholders used different criteria to arrive at their selection of refugia species, which shows the importance of engaging different stakeholders. The best ranked refugia options were conventional maize, sorghum and Napier grass. Though with differences, the stakeholders selected some common refugia among them were Napier Kakamega 2, maize Hybrid 614 and Local Sorghum brown. These are good choices as they are likely to be accepted by a wide group of farmers and hence the level of avoiding refugia would be minimal. These findings have implications in future IRM research on the selection of the most suitable refugia to be recommended to farmers in terms of most preferred sorghum varieties. There will be need to incorporate the growers concerns in the different regions while developing a proper refuge to be used on-farm. These will increase the possibility of growers complying with the recommended IRM plan when Bt maize is eventually released. Surveys on grower's awareness and

Table 7. Net profits for potential IRM strategy options (Bt maize + refugia) for the control of stem borer in Kenya.

Strategy	Benefit				% loss
	Maize	Refugia	Total	Loss	
Bt maize alone	37950	0	37950	0	
Bt + sorghum	27600	8320	35920	-2030	5.3
Bt + Conventional maize refugia	27600	6900	34500	-3450	9.1
Bt + Napier	27600	6583	34183	-3767	9.9
Bt + Coloured guinea	27600	5382	32982	-4968	13.1
Bt + Sudan grass	27600	4962	32562	-5388	14.2
Bt + Guatemala	27600	4896	32496	-5454	14.4
Bt + Giant setaria	27600	4230	31830	-6120	16.1
Bt + Columbus setaria	27600	3474	31074	-6876	18.1
Bt + Giant setaria	27600	2172	29772	-8178	21.5

Key: 1US$=75 KES.

adoption should be conducted before and after release of Bt maize, followed by similar annual surveys to asses growers' adherence to the recommended IRM strategies and finding out reasons for non- compliance so that relevant modifications are made to the IRM plans and results used to design further education programs and topics in order to strengthen growers' stewardship of the technology.

Economic analysis considering total cost, total revenue and net benefits of the refugia showed that Bt maize, conventional maize and sorghums produced large benefits. From the economic analysis, the likely option for structuring the refugia are conventional maize and sorghum, which are also popular food crops and Napier grass, which is widely grown as fodder. The economic analysis showed that all refugias produce a lower benefit than Bt maize. The most profitable ones are those with the highest profits, conventional maize and Napier grass, and these could be integrated into the IRM system. Still, while the benefits to refugia are public, the costs are borne privately by the farmers given the hope that Bt maize will also be approved and made available to neighbouring countries (Uganda, Tanzania), a regional approach will ultimately be needed to monitor resistance. Such a coordinated system will ultimately be decided by indivi-dual countries but could be promoted by regional bodies such as ASARECA.

Refugia are part of stewardship plan for the Bt maize. Education of all those involved with the Bt crop will therefore be priority in the IRM plan for Kenya. Aware-ness creation will be important to educate all those involved in the use of Bt technology to ensure that IRM is seen as an important stewardship tool to achieve maxi-mum benefit from Bt maize. However, more research is needed to fill in the missing information. Information is needed to determine the number of insects produced per unit area from potential refugia, as well as their develop-ment time and survival. There is need to understand the mating patterns and the effects of the different cropping patterns on behaviour of moths and larvae movement and development. We need to identify the most effective refugia patters and placement as well as the economics of refugia and other IPM strategies. There is also the need to understand moths better: their biology, seasonal fluctuation, and generations in different locations as well as the resistance mechanisms and genetic factors influencing the development of resistance, including initial frequency of resistance genes, the pest and natural enemies surviving on maize and in the different refugia species. From the farmer's perspectives, we need to know the perceived risks on use of refugia by farmers.

Conclusions

The study showed that there are several suitable refugia crops which could be part of an integrated resistance management strategy for maize farmers in Kenya. Most of these were being grown by the farmers. From farmer evaluation, the priority refugia include conventional sorghums, Napier grass and maize. Other fodder crops do not seem interesting. Many areas in Kenya appear to have sufficient natural refugia, but this may vary with seasons. These refugia could be arranged in structured or non-structured manner.

The IRM strategies to be used could be stratified into 4 based on 1) Presence of *B. fusca* or *C. partellus*, the most common and destructive species of stemborers in Kenya and 2) probability of existing refugia within existing cropping system based on the survey results. Areas with high probability of *B. fusca* with large commercial maize farms and less than 20% natural refugia could use non-

Bt. maize as structured refugia. Subsistence farmers in the same area could promote sorghum, improved Napier or high value, special trait maize. Areas with high incidences of *C. partellus* and more than 20% refugia within the cropping system will not require structured refugia, while the subsistence farmers in areas without enough refugia can use non-Bt. Maize, sorghum or Napier grass. More researchers need to understand pest biology, natural enemies, arrangement of refugia species, its influence by cropping patterns, resistance mechanisms, and its acceptance by farmers.

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