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Sweetpotato infestation by *Cylas* spp. in East Africa: I. Cultivar differences in field infestation and the role of plant factors

(*Keywords:* resistance, pest management, plant architecture)

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Abstract. Sweetpotato weevils (*Cylas* spp.) constitute a major constraint upon sweetpotato production and utilization world-wide. Attempts to breed for resistance to *Cylas* spp. have had limited success. However, there are reports of variation in the susceptibility to weevil attack in the field among cultivars in East Africa. Field trials were conducted at two sites (Ukiriguru and Kibaha) in Tanzania and at one site (Serere) in Uganda to determine the extent to which sweetpotato cultivars presently available in East Africa consistently differ in their susceptibility to field infestation by *Cylas* spp. and to identify the plant factors that determine the levels of susceptibility. Several methods to assess levels of field infestation were tested, and their relative merits are discussed. Significant cultivar differences in susceptibility to *Cylas* spp. infestation were observed for four out of six trials carried out over 2 years. The exceptions were cases where infestation levels were either very low or very high. Linear regression models of infestation suggest that the following plant characteristics are associated with low susceptibility to *Cylas* spp. infestation: increased distance of roots from the soil surface, fewer soil cracks, fewer exposed roots and a high foliage yield. Both the distance of the roots from the soil surface (shortest weevil distance) and foliage yield differ significantly between cultivars. The former cannot be approximated by measurement of root neck length, but must be measured *in situ*.

1. Introduction

Sweetpotato (*Ipomoea batatas* (L.) Lam.) is an important food security crop in East Africa where it is grown both for home consumption and to supplement household income by sale to local markets and urban centres.

Sweetpotato weevils, *Cylas* spp. (Coleoptera; Brentidae), constitute a major constraint to sweetpotato production and utilization world-wide (Villareal 1982, Sutherland 1986, Chalfant *et al.* 1990, Lenne 1991). *Cylas puncticollis* Boheman and *Cylas brunneus* Fabricius are the most prevalent species in East Africa (Wolfe 1991). The female sweetpotato weevil lays eggs singly in cavities excavated in either the vines or the accessible roots of sweetpotato. The developing larvae tunnel while feeding within the vine or root and are the most destructive stage. Plants may wilt or even die because of extensive stem damage, and damage to the vascular system can reduce the size and number of storage roots. While external damage to roots can affect their quality and value, internal damage can lead to complete loss. Losses of marketable yield as high as 60–97% have been reported (Ho 1970, Subramanian *et al.* 1977, Mullen 1984, Jansson *et al.* 1987, Smit 1997). Even low levels of infestation can reduce root quality and marketable yield because the plants produce unpalatable terpenoids in response to weevil feeding (Akazawa *et al.* 1960, Uritani *et al.* 1975).

Surveys carried out with farmers in East Africa indicated that weevil infestation and the short shelf life of roots were both major constraints upon sweetpotato production in the region (Bashaasha *et al.* 1995, Kapinga *et al.* 1995). Sweetpotato weevils are a particularly serious problem under dry conditions because the insects, which cannot dig, reach roots more easily through cracks that appear as the soil dries out. For this reason sweetpotato roots cannot be stored in-ground during dry seasons. Thus, given the perishability of the sweetpotato root after harvest, weevil infestation critically limits the potential of the crop as a secure food supply. Initial surveys of root quality in the markets of Tanzania have shown that at certain times of the year 15–20% of roots are infested (Kapinga *et al.* 1997). This is an underestimation of the total level of loss, since farmers usually leave infested roots in the field.

Historically, several attempts have been made to breed for resistance to *Cylas* spp. Slow progress has led some breeders to conclude that an adequate source of resistance may not exist within the sweetpotato germplasm (Talekar 1987). Nevertheless, there are numerous reports of variation among cultivars (cvs) in susceptibility to weevil attack (Mullen *et al.* 1985, Proshold 1986, Bhat 1987, Katwale *et al.* 1989). So far, East African germplasm has not been systematically evaluated, but observations suggest that susceptibility to weevil infestation does differ among cvs (S. Jeremiah, personal communication, 1997). This study was conducted to establish whether sufficient variation in susceptibility exists within the East African germplasm to be usable within a breeding programme, and to establish which cv.

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characteristics affect susceptibility. The magnitude of cv. effects on the susceptibility of sweetpotato roots to *Cylas* spp. infestation relative to plant characteristics that can be influenced by growing practices was investigated.

Of the four methods used for assessing weevil infestation, two distinguished only between clean and infested roots, whereas the other two took into consideration the extent of individual root damage. The methods considered to be more accurate, but time consuming, were compared with the more rapid methods.

2. Materials and methods

2.1. Field trial design and parameter assessment

Field trials were conducted at three sites in East Africa: Lake Zone Agricultural Research and Development Institute Ukiriguru (Ukiriguru), Tanzania at 2°42'S, 33°1'E, 1198 m above sea level (masl), with a mean annual rainfall range of 750–1200 mm; Kibaha Sugarcane Research Institute (Kibaha), Tanzania at 6°66'S, 38°40'E, 107 masl, with a mean annual rainfall range of 840–1722 mm; and Serere Agricultural and Animal Production Research Institute (Serere), Uganda at 1°32'N, 33°27'E, 1140 masl, with a mean annual rainfall of 1280 mm, in 1997 and 1998. At each site the same cvs and breeding lines were used in both years (table 1), however the cvs and breeding lines used differed between sites. The cvs and breeding lines were selected from popular local cvs in farmers' fields and national breeding programmes. Planting material was produced on station.

Table 1. Sweetpotato cvs and breeding lines used in Cylas *spp. susceptibility trials in Tanzania and Uganda*

	Ukiriguru, Tanzania	Kibaha, Tanzania	Serere, Uganda
1	SPN/0	SPN/0	Tanzania (SPN/0 or Osukut)
2	Mwanamonde	Mwanamonde	282
3	Sinia	Sinia	Epuramonjong
4	Budagala	Budagala	Sowola
5	SP/93/2	Elias	178
6	SP/93/23	Hali ya mtumwa	202
7	SP/93/34	Iboja	Ecuru
8	SP/93/5	Kibaha 10	29 (Bwanjule)
9	SP/93/30	Ukerewe	277
10	Bagazanentukuru	Maria	Kasira
11	Simbeichumu		271
12	Ipembe		Opejo
13	Mwananjemu		Odopelap
14	SP/93/17		Anyara
15	Polista		Araka[2]
16	SP/93/13		324
17			69
18			Okunguru-Dere
19			218
20			316
21			148
22			Esamiat
23			192[1]
24			Emadirait[1]
25			Akerekekolak[1]

[1]Used only in 1997 trials; [2]Used only in 1998 trial

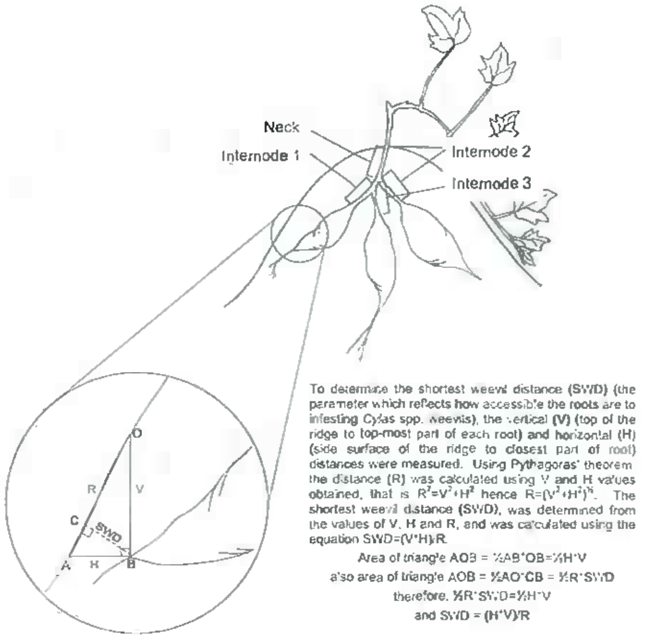
In Tanzania, five replicates (four at Ukiriguru in 1997) of each cv. were planted in a randomized complete block design. Each plot measured 3 × 3 m and consisted of three ridges 1 m apart. Ten apical cuttings were planted per ridge giving 30 plants per plot. Artificial releases of 30 laboratory-reared unsexed, mixed-age *C. puncticollis* were made in the centre of each plot at regular intervals to ensure a high weevil infestation pressure. The field study was harvested 5 and 6 months after planting (map) at Kibaha and Ukiriguru, respectively.

In Uganda, four replicates of each cv./breeding line were planted in a randomized complete block design. Each plot measured 6 × 3 m and consisted of six ridges 1 m apart. Ten apical cuttings were planted per ridge. The four inner ridges were used for data collection, the two outer ridges as guard rows. In 1997, 24 cvs/breeding lines were used; however, this was reduced to 22 in the 1998 trial due to a shortage of planting material. No artificial infestation of *Cylas* spp. was carried out as the infestation pressure was predicted to be sufficiently high. In 1997, the field study was set up in July and harvesting was carried out 4 and 6 map for each of the planting dates using two of the inner ridges at each harvest. This procedure was carried out because the maturity period of the sweetpotato cvs and breeding lines used varied from 4 to 6 months. In the 1998 field study, all four inner ridges were harvested 6 map.

At 3 map and/or at harvest the following variables were observed and recorded:

- Extent of insect caused foliage damage (using a 1–5 damage score, where 1 = 0%; 2 = 1–25%; 3 = 26–50%; 4 = 51–75%; and 5 = 76–100%, to assess the central 1 m section of the middle ridge of each plot) at 3 map.
- Number of plants and exposed roots per plot.
- Weight of sweetpotato foliage per plot.
- Weight and number of size categorized roots per plot:
    - Small (up to 25 mm in diameter at widest part of roots (wpor).
    - Medium (26–40 mm in diameter at wpor).
    - Large (41–80 mm in diameter at wpor).
    - Extra large ($>$ 80 mm in diameter at wpor).
- Number and weight of marketable roots with rough weevil, *Blosyrus* sp. (Coleoptera: Curculionidae) or clearwing moth, *Synanthedon* spp. (Lepidoptera: Sesiidae) damage per plot.
- Number of plants per plot with soil cracks. (In Uganda, a 1–4 soil crack score was used, where 1 = no plants with cracks/four ridges; 2 = $\leqslant$ 5 plants; 3 = 6–10 plants; and 4 $\geqslant$ 10 plants); roots protruding from soil; no roots.
- Neck and internode lengths; and crown diameter, and external and internal damage score, where 1 = 0%; 2 = 1–25%; 3 = 26–50%; 4 = 51–75%; and 5 = 76–100%, of five randomly chosen plants per plot (figure 1).
- Infestation by *Cylas* spp. as described below.
- Dry matter content, determined by oven drying three reps. of about 150–200g of finely chopped up root material each from one or two roots (in 1998 only).

In addition, in Uganda a more detailed method was used in order to record varietal rooting characteristics and weevil damage. The roots of five randomly selected plants/plot were carefully exposed and the following measurements recorded:



To determine the shortest weevil distance (SWD) (the parameter which reflects how accessible the roots are to infesting Cylas spp. weevils), the vertical (V) (top of the ridge to top-most part of each root) and horizontal (H) (side surface of the ridge to closest part of root) distances were measured. Using Pythagoras' theorem the distance (R) was calculated using V and H values obtained, that is $R^2=V^2+H^2$ hence $R=(V^2+H^2)^{½}$. The shortest weevil distance (SWD), was determined from the values of V, H and R, and was calculated using the equation SWD=(V*H)/R.

Area of triangle AOB = ½AB*OB=½H*V
also area of triangle AOB = ½AO*CB = ½R*SWD
therefore, ½R*SWD=½H*V
and SWD = (H*V)/R

Figure 1. Measurements used to describe the rooting depth at Ukiriguru and Kibaha and the shortest weevil distance to root at Serere.

- Shortest weevil distance (shortest distance from the soil surface to the root) (figure 1) was measured for each root, and the mean per plant recorded. This was considered to provide the best estimate of the shortest distance that a weevil would need to burrow through the soil to reach the root.
- Root girth, root length, root size and neck length.
- *Cylas* spp. infestation, as described below.
- *Blosyrus* sp. infestation score of each root measured (a 1–5 score recorded the percentage of damaged root surface, where 1 = 0%; 2 = 1–25%; 3 = 26–50%; 4 = 51–75%; and 5 ⩾ 75%).

2.2. Cylas *infestation measurement*

2.2.1. Method A: Non-destructive damage scoring of infestation levels. Roots from each plot were separated into different categories depending on the percentage of the external surface showing *Cylas* spp. damage. A five-point score was used in 1997, where 1 = 0%; 2 = 1–25%; 3 = 26–50%; 4 = 51–75%; and 5 ⩾ 75%; a six-point score was used in 1998, where 1 = 0%; 2 = 1–10%; 3 = 11–25%; 4 = 26–50%; 5 = 51–75%; and 6 ⩾ 75%. The mean root score was calculated for each plot.

2.2.2. Method B: Percentage (marketable) infested roots (by number). Using the same data obtained for Method A, the percentage number of roots with any *Cylas* spp. damage was calculated. This was only measured for the marketable roots (roots with diameters > 25 mm) in Tanzania, while in Uganda it was measured for all roots harvested.

2.2.3. Method C. Percentage clean (marketable) yield (by weight). The percentage weight of roots that were clean (category 1—uninfested) was calculated. This was done for only the marketable roots (roots with diameters > 25 mm) in Tanzania, while in Uganda it was done for all roots harvested.

2.2.4. Method D: Destructive measurement of percentage infested portion of roots. Marketable roots were separated into infested and non-infested (clean) groups. The infested portion of the infested roots was removed by cutting to separate the clean and infested parts. This method divided the harvest into the following three parts, and the infested portion of the roots was weighed and then expressed as a percentage of the whole:

- Completely clean (non-infested) roots, suitable for marketing.
- Clean parts of infested roots (edible), suitable for household use, but with short shelf life.
- Infested portion of roots, useless for most purposes.

2.3. Data analysis

ANOVAs were conducted using GENSTAT. For multiple linear regression modelling of cv. infestation levels, factors were chosen for each trial independently. Before regression analysis, principal component analysis and correlation analyses were used to determine the relationship between variables so that only independent variables were selected. The regression analysis was carried out in stepwise backwards mode ($p = 0.05$ accept, $p > 0.1$ reject) using SPSS. Those factors that appeared in all or most of the models for each trial were included in the final models. These were retested by stepwise forward regression using GENSTAT.

3. Results

3.1. Cylas *spp. damage assessment methods*

Of the four methods used to assess *Cylas* spp. damage, B and C distinguished only between clean roots and those showing any signs of infestation. Method C involves weighing roots, whereas Method B only involves counting roots and is more rapid. Method D considers the portion of the harvested crop, by weight that is damaged (including whole and parts of roots) after cutting up infested roots, whereas Method A attempts to approximate this by scoring individual roots for levels of externally visible damage.

The methods are compared for two trials (Kibaha 1998, Ukiriguru 1998) both covering a wide range of infestation levels (figure 2a–c). The relationship between Methods A and D is linear, as is that between Methods B and C, suggesting that the more rapid methods (A and B) give a reasonable approximation for Methods D and C, respectively. Not surprisingly, the relationship between Methods C and D was not linear, as with increasing infestation the percentage of clean roots fell more rapidly than the increase in actual weight of infestation.

The ranking of the cvs was similar for all four damage assessment methods used (table 2), suggesting that the method of assessment is not critical. Full details of the ranking of the different cvs for each trial are given in Stathers *et al.* (1999).

3.2. Cultivar differences in susceptibility to Cylas *spp. infestation*

Yield differed greatly between years at all three sites (figures 3–5). Mean cv. yield and the level of infestation

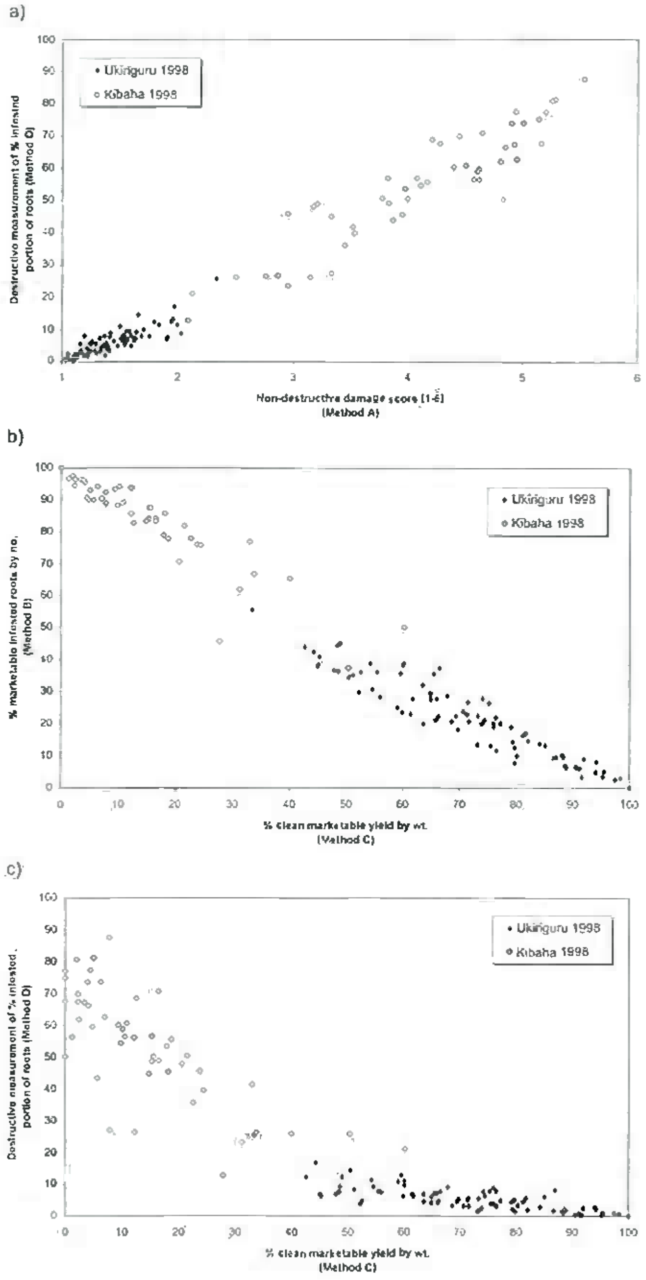


Figure 2. Comparison of the different methods for assessing damage by Cylas *spp. during sweetpotato trials at Kibaha and Ukiriguru, Tanzania, in 1998: (a) comparison of two methods that consider the extent of individual root damage (Method D versus A); (b) comparison of two methods that distinguish only between clean and infested roots (B versus C); (c) comparison of one method considering the extent of individual root damage with one method that distinguishes only clean and infested roots (D versus C).*

expressed as the clean (marketable) yield and as the percentage clean (marketable) yield (Method C) for each of the trials are summarized in table 3. There was a large range in all parameters between trials, with average yield ranging from 2.9 to 13.9 t/ha.

Natural *Cylas* spp. infestation was used at Serere, while trials at Ukiriguru and Kibaha were artificially infested. Thus, levels of infestation were very variable. At Kibaha, the average percentage clean marketable yield varied from 95.1% in 1997 to 14.4% in 1998. This large range may have been due to the effect of environmental factors such as heavy rainfall on the efficiency of artificial *C. puncticollis* infestation.

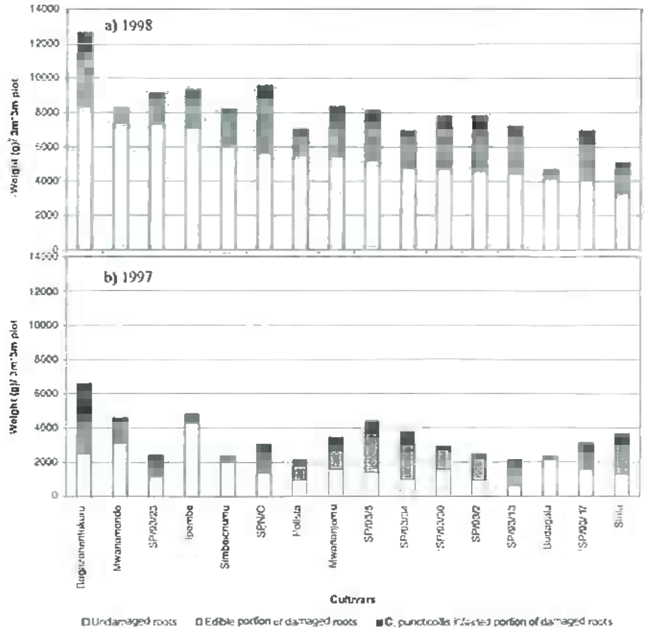


Figure 3. Comparison of Cylas puncticollis *damage on the mean marketable yield of 16 sweetpotato cultivars at Ukiriguru, Tanzania, in (a) 1998 (n = 5) and (b) 1997 (n = 4).*

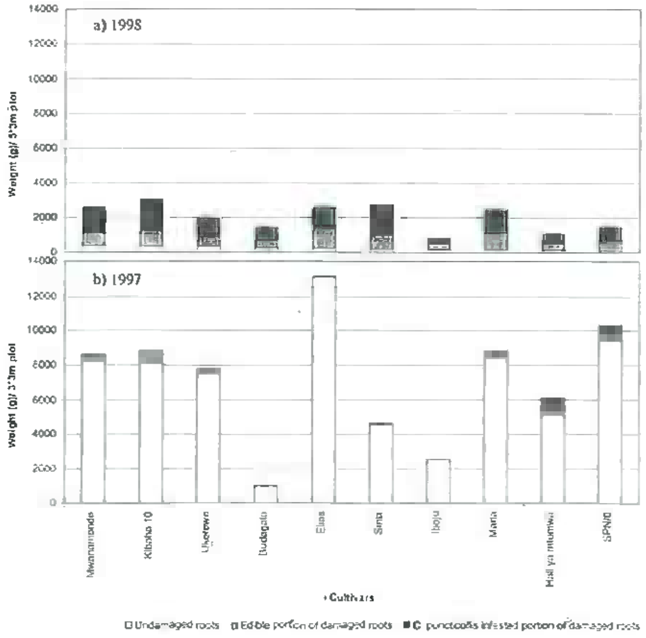


Figure 4. Comparison of Cylas puncticollis *damage on the mean marketable yield of 10 sweetpotato cultivars at Kibaha, Tanzania, in (a) 1998 and (b) 1997 (n = 5).*

There was a notable range in both yield and infestation levels between cvs within trials. An ANOVA established the cv. effect on percentage clean marketable yield was significant to less than 10% in all but two trials (table 3), which had the highest and lowest percentage clean marketable yield, respectively.

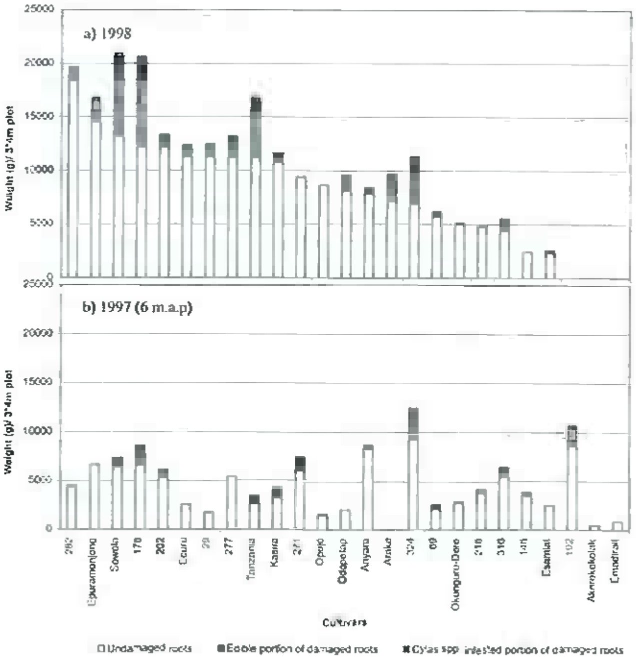
3.3. Consistency of cvs between seasons and sites

The consistency of cv. behaviour between seasons (i.e. genotype effect) is indicated by correlating clean marketable yield and percentage clean marketable yield for the two seasons (table 4). Significant correlations were obtained for Ukiriguru and

Table 2. Sweetpotato cvs included in the Ukiriguru (1998) trial ordered by susceptibility to infestation as determined by four methods for assessing Cylas *spp. damage*

Degree of susceptibility to *Cylas* infestation	Cv and cv. effects for each of the *Cylas* spp. infestation measurement methods							
	Non-destructive damage score (Method A)		Percentage marketable roots with *Cylas* spp. infestation (by no.) (Method B)		Percentage clean marketable yield (by wt) (Method C)		Destructive percentage infested portion of roots (Method D)	
Lowest susceptibility	Mwanamonde	−0.3	Budagala	−22.2	Mwanamonde	28.5	Mwanamonde	−5.0
	Budagala	−0.3	Mwanamonde	−21.0	Budagala	26.7	Budagala	−4.6
	Polista	−0.3	Simbeichumu	−20.6	SP/93/34	24.6	Polista	−4.1
	Simbeichumu	−0.3	Polista	−19.6	Simbeichumu	23.8	Simbeichumu	−3.7
	SP/93/34	−0.2	SP/93/34	−16.1	Polista	23.6	SP/93/23	−3.1
	SP/93/23	−0.2	SP/93/23	−15.1	Ipembe	20.3	SP/93/5	−2.7
	SP/93/5	−0.2	Ipembe	−14.2	SP/93/23	19.1	Ipembe	−2.6
			SP/93/5	−9.6	SP/93/5	15.7	SP/93/30	−2.0
							SP/93/34	−1.4
	SP/93/17	−0.2	SP/93/17	−8.5	Bagazanentukuru	14.2		
	SP/93/30	−0.2	Bagazanentukuru	−7.9	SP/93/13	13.8	SPN/0	0
	Ipembe	−0.8	SP/93/30	−7.5	SP/93/17	12.8	SP/93/13	0.2
	SP/93/13	−0.1	SP/93/13	−2.6	Mwananjemu	7.5	Mwananjemu	0.6
	Bagazanentukuru	−0.1	Mwananjemu	−2.2	SP/93/30	6.4	Bagazanentukuru	0.6
	Sinia	−0.1	Sinia	−1.5	Sinia	2.8	SP/93/17	0.8
	Mwananjemu	−0.0	SPN/0	0	SPN/0	0	Sinia	2.9
	SPN/0	0						
Highest susceptibility	SP/93/2	0.1	SP/93/2	5.4	SP/93/2	−3.4	SP/93/2	5.1

Values are cv. effects relative to SPN/0, i.e. assuming cv. effect for SPN/0 is zero.
The ranking of cvs was determined using multiple regression analysis to remove the effects of variation in plant characteristics caused by variation in growing environment across the trial (percentage plants with soil cracking around the roots, root neck length and root number per plot), as described in Section 3.2.



Note: The cv. Araka was included only in the 1998 trial, while 192, Akerekekolak and Emadirait were only included in the 1997 trials.

Figure 5. Comparison of Cylas puncticollis *damage on the mean marketable yield of sweetpotato cultivars harvested 6 months after planting at Serere, Uganda, in (a) 1998 and (b) 1997 dry season (n = 4).*

Serere, but not for Kibaha, where extreme levels of infestation were recorded.

Four cvs (Mwanamonde, Budagala, Sinia and SPN/0) were included in the trials at both Kibaha and Ukiriguru. A degree of consistency was seen; at both sites Budagala and Mwanamonde were less susceptible than Sinia and SPN/0 (figure 6).

3.4. *Plant characteristics with varietal differences and their effect on* Cylas *spp. infestation*

For each trial correlation analysis was used to determine which field characteristics were related to *Cylas* spp. infestation, and for each characteristic identified an ANOVA was conducted to determine if a significant range existed among cvs (table 5). All four assessment methods were considered.

The main field cv. characteristics identified that could be related to susceptibility to *Cylas* spp. were: root number per plot; root weight per plot; foliage weight; soil crack score; number of roots exposed per plot; percentage plants with exposed roots; shortest weevil distance; root neck length; number of plants per plot; and percentage roots with *Blosyrus* sp. infestation.

The yield parameters, root number per plot and root weight per plot were positively associated with infestation levels at Ukiriguru (1997) and Serere (1998), and both parameters differed significantly between cultivars.

As *Cylas* spp. can burrow only very short distances through the soil (Jayaramaiah 1975, Smit 1997) and usually rely on soil

Table 3. Marketable root yield and yield clean of Cylas *spp. infestation for all trials*

Location and season of trial	Months from planting to harvest	No. of cvs	Total root yield (t/ha)		Marketable root yield (t/ha)		Clean (marketable) yield (t/ha)		Percentage clean (marketable) yield	
			Mean	Cv. effect	Mean	Cv. effect	Mean	Cv. effect	Mean	Cv. effect
Ukiriguru (1997)	5	16	4.0	***	3.5	**	1.8	*	53.5	*
Ukiriguru (1998)	6	16	9.6	*	8.7	*	6.1	*	71.1	**
Kibaha (1997)	5	10	10.0	***	8.0	***	7.6	***	95.1	n.s.
Kibaha (1998)	5	10	2.9	***	2.2	***	0.3	n.s.	14.4	n.s.
Serere (1997)	4	24	6.3	***	3.9	***	6.27	***	99.5	***
	6	24	8.2	***	5.7	***	7.05	***	89.8	+
Serere (1998)	6	22	9.2	***	6.8	***	7.51	***	85.5	***

$^{+}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$; n.s., not significant.

In 1997, some root theft occurred at Serere. At Serere the clean total yield and percentage clean total yield were measured.

Table 4. Correlations for cultivar clean (marketable) yield and percentage clean (marketable) yield between years at three locations

	No. cvs.	Correlation coefficient (r)	
		Clean (marketable) yield	% clean (marketable) yield
Ukiriguru (1998) versus Ukiriguru (1997)	16	0.57 *	0.67 **
Kibaha (1998) versus Kibaha (1997)	10	n.s.	n.s.
Serere (1998) versus Serere (1997) (at 6 map)	21	n.s.	0.49*

$^{*}p < 0.05$, $^{**}p < 0.01$; n.s., not significant.

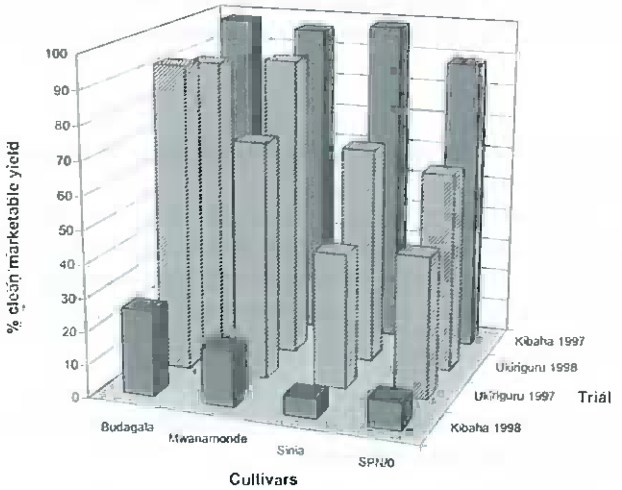


Figure 6. Percentage clean yield for four key sweetpotato cultivars in trials at Ukiriguru and Kibaha, 1997 and 1998.

cracks to reach the roots (Sherman and Tamashiro 1954), deep rooting can act as an escape mechanism. At Ukiriguru and Kibaha the burrowing distance was approximated by *root neck length*, while at Serere actual root position from the soil surface was used to calculate the *shortest weevil distance*. In three of the trials rooting depth correlated with infestation levels. However, the detailed shortest weevil distance measurement used at Serere showed a much more significant correlation with infestation than root neck length.

During the course of these field studies, the severity of damage to sweetpotato roots by the rough sweetpotato weevil *Blosyrus* sp. became apparent at Ukiriguru. In 1998, > 80% of marketable sized roots exhibited some degree of *Blosyrus* sp. damage in 10 of the 16 cvs. *Blosyrus* sp. larvae damage enlarging roots and reduce market value by gouging deep grooves in the surface. It was not considered an important pest in Uganda, although its presence is increasing in Soroti district. *Blosyrus* sp. has been reported as a sweetpotato pest in South Africa (Daiber 1994), Kenya, Tanzania, Burundi, Rwanda, Uganda (Allard and Rangi 1995) and Swaziland (Nsibande and McGeoch 1999), but very little information exists about this pest, its interaction with *Cylas* spp. and even less about effective management methods. Contradictory results were obtained for the relationship between the percentage roots with *Blosyrus* sp. infestation and the percentage clean yield, which was positive at Kibaha (1998) and negative at Serere (1998).

Multiple linear regression analysis was then carried out to model root infestation levels by cv. for each year in terms of the field cv. characteristics identified above. Correlation matrices were used to determine where factors were related, in which case only one of these factors was considered. Some degree of subjectivity is inevitably involved in choosing the most appropriate models; however, those we considered to be the best models are given in table 6, along with the percentage variance which was accounted for by each. Models could be constructed for all trials except Kibaha (1997), which had very low levels of infestation. Apart from Serere (1997), the models accounted for more than 60% of variance between cvs in almost all cases. Several models include a root yield term (root number or root weight), indicating an increase in infestation with increasing yield. It is obviously not advantageous to select cvs for low root yield, so in these cases the variance accounted for by the yield term alone was included in order to give an indication of the importance relative to the other terms. Interestingly foliage weight appeared in all models at Ukiriguru and Kibaha, but

Table 5. Significant correlations between Cylas *spp. infestation levels (measured using methods A – D) and field cv. characteristics at the three trial sites*

		Correlation (r) with				
Trial (no. of cultivars)	Parameter	Non-destructive damage score (Method A)	Percentage marketable roots with *Cylas* spp. infestation (Method B)	Percentage clean marketable yield (Method C)	Destructive percentage infested portion of roots (Method D)	Cv. effect
Ukiriguru (1997) (16 cultivars)	Root number	0.557^{*}	0.593^{**}	-0.583^{*}	0.540^{*}	***
	Neck length	n.s.	-0.470^{*}	n.s.	n.s.	n.s.
Ukiriguru (1998) (16 cultivars)	Foliage weight	-0.592^{**}	-0.555^{*}	0.483^{*}	-0.558^{*}	^{***1}
	No. of plants per plot	-0.554^{*}	-0.580^{*}	0.592^{**}	-0.507^{*}	n.d.^{2}
	Crown diameter 3 months after planting			-0.550^{*}		n.s
	No. of roots exposed per plot	0.793^{***}	0.811^{***}	-0.847^{***}	0.810^{***}	n.s.^{1}
	Percentage plants with exposed roots	0.787^{***}	0.812^{***}	-0.867^{***}	0.819^{***}	n.s.^{3}
Kibaha (1997) (10 cultivars)	Crown diameter 3 months after planting		0.567^{+}	-0.655^{*}	0.687^{*}	n.s.
	Neck + node length		-0.554^{+}	0.539^{+}	-0.542^{+}	^{*4}
Kibaha (1998) (10 cultivars)	Root weight	0.596^{*}	0.516^{+}		0.539^{+}	***
	No. of plants per plot	0.671^{*}				**
	Neck + node length			-0.534^{+}		$^{+}$
	Percentage roots with *Blosyrus* sp. infestation	-0.622^{*}	-0.662^{*}	0.707^{*}		n.s.^{2}
Serere (1997) (24 cultivars)	Root weight		0.506^{*}	-0.576^{**}	n.s.	***
Serere (1998) (22 cultivars)	Root number		0.514	-0.534	0.455	***
	Root weight		0.622	-0.633	0.538	***
	Shortest weevil distance		-0.808	0.800	-0.812	***
	Root neck length		-0.443	0.463	-0.397	***
	Soil crack score		0.441	-0.477	n.s.	n.d.^{5}
	Percentage roots with *Blosyrus* sp. infestation		0.399	-0.397	0.486	*

For each relationship the r correlations are given.

$^{+,*,**,***}$Significant to < 10, < 5, < 1, $< 0.1\%$.

^{1}Log transformation of data.

^{2}No transformation was identified that could satisfy normality assumption.

^{3}Square-root transformation used.

^{4}Log transformation used (only two replicates of data).

^{5}Data did not satisfy constant variance assumption. No appropriate transformation could be found. Thus, an ANOVA could not be carried out.

was unfortunately not measured at Serere. Exposed roots and soil cracking appeared in models for Ukiriguru (1998) and Kibaha (1998). Shortest weevil distance was measured only at Serere, and was an important component of the models for Serere (1998). Crown diameter also appeared in the models for Serere (1998).

4. Discussion

Our data indicate that significant cv. effects on susceptibility to *Cylas* spp. infestation exist among East African sweetpotato germplasm, but that in order to obtain accurate information, it is necessary to have moderate but not excessive infestation. This agrees with previous research that concluded that existing levels of resistance are likely to be overcome by high insect population pressure (Collins and Mendoza 1991). *Cylas* spp. infestation levels whether natural or artificial are difficult to control, and this may be one reason why data on cv. effects is scarce. It is possible that the intentional release of *C. puncticollis* into each plot at two of the sites may have hidden any natural differences in attraction of the plants that may also affect infestation levels.

Earlier field trials have suggested that root size, shape, hardness and arrangement may play an important role in conferring resistance in the field (Cockerham and Deen 1947, Cockerham and Harrison 1952, Rolston *et al.* 1979, Mullen *et al.* 1980a, b, 1981, 1982, 1985, Pillai and Nair 1981, Singh *et al.* 1987, Talekar 1987, Ngeve 1994). However, despite considerable effort world-wide, not a single sweetpotato cv. has been bred, using previously identified sources of resistance and which is grown in any appreciable scale specifically to control sweetpotato weevil damage (Talekar 1987). Efforts have been thwarted by the instability of resistance as expressed by differences in weevil infestation among trials, locations, seasons and at times among replicates of a single accession in a trial, among plants in the same plot and even among storage roots within one plant (Talekar 1982). However, our data provide evidence of considerable consistency of cvs by season, at Ukiriguru and at Serere. Although the same range of cvs was not tested at different sites, there is an indication of consistency in the data between sites for the four cvs, Mwanamonde, Budagala, Sinia and SPN/0, grown at both Kibaha and Ukiriguru.

The multiple linear regression models indicate that most of the cv. variation observed could be explained by relatively few cv. characteristics: root yield (root number, root weight), foliage yield, crown diameter, soil cracking, exposed roots and shortest weevil distance. It is not unexpected that higher root yield is associated with increased levels of infestation, but clearly this is not a useful relationship in the context of breeding for reduced susceptibility. Note that agronomic changes to increase yield are likely to increase levels of infestation.

Table 6. Models of *Cylas* spp. infestation in terms of plant characteristics

Location and season of trial	Percentage clean (marketable) yield (by wt) (Method C)		Percentage (marketable) roots with *Cylas* spp. infestation (by no.) (Method B)		Percentage infested portion of roots (Method D)		Non-destructive damage score (Method A)	
	Model	Var.	Model	Var.	Model	Var.	Model	Var.
Ukiriguru (1997)	$60.0+5.0FW-0.6R$	69 (29)	$33.0-4.7FW+0.6R$	65 (31)	$5.9-1.1FW+0.2R$	29 (24)	$1.5-0.06FW+0.008R$	57 (26)
Ukiriguru (1998)	$94.0+0.6FW-1.6ER-0.4SC$	88	$6.7-0.8FW+1.2ER+0.4SC$	78	$1.6-0.2FW+0.4ER+0.07SC$	68	$1.2-0.02FW+0.02ER+0.007SC$	74
Kibaha (1997)	No meaningful models could be constructed							
Kibaha (1998)	No meaningful model could be constructed		$70.4-2.6FW+5.6RW+3.2ER$	66 (36)	$30.4-2.4FW+7.8RW+4.7ER$	88 (46)	$3.1-0.2FW+0.4RW+0.2ER$	75 (49)
Serere (1997)	$97.4-0.9RW$	30	$1.7+0.6RW$	22	No meaningful model could be constructed		n.d.	
Serere (1998)	$23.0+7.5SWD+4.5CD-0.9RW$	70 (37)	$64.5-6.0SWD-4.2CD+0.6RW$	73 (36)	$25.7-2.3SWD-1.8CD+0.1RW$	74 (25)	n.d.	

FW, foliage weight [t/ha]; RW, root weight [t/ha]; R, root number [/Ha]; ER, percentage of plants with exposed roots; SC, percentage of plants with soil cracks; SWD, shortest weevil distance (cm); CD, crown diameter (mm); n.d., no data.

Var., percentage variance accounted for by model. Where models include a root yield term (R or RW), the variance accounted for by this term alone is given in parentheses.

Soil cracking, exposed roots and shortest weevil distance all relate to root architecture. In all but one location we approximated root depth by measuring neck length. Although this was related to infestation levels in several trials, we could not find any strong models containing this parameter. Root neck length measures the distance from the crown (soil level on plant stem) to the tip of the root when the harvested plant is held above ground. This measurement gives no indication of whether the roots have gone straight down into the soil or spread sideways (possibly very close to the edge of the ridge) and therefore is not a realistic measurement of accessibility of roots to *Cylas* spp. Measuring the shortest distance to the root is much more time-consuming, but future fieldwork studying cv. differences in *Cylas* spp. infestation levels would benefit from using this more accurate indicator of how accessible roots are to the infesting *Cylas* spp. weevils.

In our trials soil cracking was also associated with levels of infestation in several of the models. The fact that at Serere a cv. effect on soil cracking was found suggesting that it may be possible to breed for rooting habits that reduce soil cracking. Soil cracking and root neck length were also identified as characteristics that affect infestation levels independently of cultivar (data not shown), suggesting, not surprisingly, that agronomic practices that reduce soil cracking or promote deep rooting such as hilling up the soil around the roots (Smit 1997) would be advantageous. According to the models, a 1% decrease in plants with exposed roots leads to a decrease in infestation levels of more than 1% of total roots. While the Serere models suggest that an increase in shortest weevil distance of only 1 cm could reduce infestation levels by several per cent of the total roots.

In several models, high foliage weight was associated with reduced levels of infestation. An increase in foliage yield of 1 t/ha corresponds to a reduction in *Cylas* spp. infestation of between 1 and 5% of the total roots at Ukiriguru in 1998 and 1997, respectively. This suggests it might be advantageous to select for cvs that have increased foliage or whose foliage persists longer into the dry season. Increased foliage cover may maintain moisture in the soil and prevent the formation of soil cracks, or make them less accessible to the weevils. No significant correlation was found specifically between foliage weight and percentage plants with soil cracks, but interestingly there was a significant negative correlation between foliage weight and the number of exposed roots and also with percentage plants with exposed roots. In addition to maintenance of soil moisture, two alternative hypotheses are, first, that *Cylas* spp. damage to the crown may reduce foliage growth (a significant negative correlation was observed between foliage yield and external damage of crowns), or second, that there may be complex links between *Cylas* spp. feeding behaviour and oviposition, or between foliage and predatory insect numbers.

The positive relationship between crown damage by *Cylas* spp. and clean yield observed at Serere in 1998 is unexpected. Previous work has found either no direct relationship between these factors (Cockerham and Deen 1947) or a strong negative relationship, indicating that resistant shoots could play an important role in reducing weevil damage to the roots by reducing the weevil populations on the plant (Hahn and Leuschner 1981, Hahn *et al.* 1989). Some sweetpotato cvs are known to repair damaged crown tissue, with adventitious growth resulting in a thicker crown and normal root development (Talekar 1982).

The best strategies for assessing cvs may vary with location. In countries where sweetpotatoes are grown almost exclusively for marketing, roots infested by *Cylas* spp. have virtually no economic value. In contrast to this, in many developing countries the clean portion of partially infested roots can act as a food source, either fresh if consumed immediately, or sliced and sun-dried. Comparison of four methods for measuring *Cylas* spp. infestation indicated no great difference in subsequent ranking of the cultivars. For detailed studies the destructive measurement of the percentage infested portion of roots (Method D) is the most accurate representation of the way the sweetpotato harvest is used by farmers in East Africa. However, our data suggest that non-destructive damage scores (Method A) can be used as a rapid approximation, whereas if time is limited, either Method B or C would be appropriate. Differences between results of Methods A and D are likely to indicate the degree to which roots without many external signs of damage often have greater internal damage, as a result of burrowing and feeding by developing *Cylas* spp. larvae.

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