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A risk-minimizing argument for traditional crop varietal diversity use to reduce pest and disease damage in agricultural ecosystems of Uganda

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ABSTRACT

Much of the worlds' annual harvest loss to pests and diseases occurs as a consequence of crops grown in monocultures, or cultivated varieties with uniform resistance. This uniform resistance is met by the continuing evolution of new races of pests and pathogens that are able to overcome resistance genes introduced by modern breeding, creating the phenomenon of boom and bust cycles. One of the few assets available to small-scale farmers in developing countries to reduce pests and diseases damage is their local crop varietal diversity, together with the knowledge to manage and deploy this diversity appropriately. Local crop varietal diversity of banana and plantain (*Musa* spp.) and common bean (*Phaseolus vulgaris*) was measured at the community and household levels within farmers' fields in four agro-ecological areas of Uganda. Resistance of traditional and modern varieties of *P. vulgaris* to anthracnose, angular leaf spot, and bean fly and of traditional and modern varieties of *Musa* spp. to black sigatoka, banana weevils and nematodes was assessed from participatory diagnostics of farmer knowledge and cross-site on-farm and on-station trials. By performing cross-site on-farm experiments, it was possible to identify traditional varieties with higher resistance to pest and diseases when grown outside their home sites. Increased diversity of crop varieties, measured by number of varieties (richness) and their evenness of distribution, corresponded to a decrease in the average damage levels across sites and to a reduction of variance of disease damage. In sites with higher disease incidence, households with higher levels of diversity in their production systems had less damage to their standing crop in the field compared to sites with lower disease incidence. The results support what might be expected of a risk-minimizing strategy for use of diversity to reduce pest and disease damage.

1. Introduction

Banana and plantain (*Musa* spp.) together with common bean (*Phaseolus vulgaris)* are the most important carbohydrate sources in Uganda, where more than seven million people depend on them for their daily meals (Tushemereirwe et al., 2003). Common bean is also the most important plant-based protein source for the people of Uganda (Buah, 2010; Kimani et al., 2005). Net production of both common bean and bananas within Uganda remains below their full potential, mainly due to losses from diseases and insect pests (Wortman et al., 1998; Kimani et al., 2005; Singh, 2001). Serious common bean damage is caused by, among others, angular leaf spot (ALS) (*Phaeoisariopsis griseola*), anthracnose, and bean fly (Greathead, 1968; Wortman et al., 1998; Abate and Ampofo, 1996; Ojwang et al., 2010). Black sigatoka (*Mycosphaerella fijiensis*), Banana weevil (*Cosmopolites sordidus* (Germar) and plant parasitic nematodes have been identified among the major factors responsible for the decline in banana production (Gold et al., 1993, 1997; Kashaija et al., 1994; Kiggundu et al., 2003). Banana and plantain plantations, which previously lasted over 50 years, now start to deteriorate after only four years.

Different pest and disease control methods are available for both common bean and banana. For ALS and anthracnose, early planting, seed dressing, the removal of plant remains and fungicides are recommended. Fungicide use in Uganda is extremely low, as farmers believe that the additional yield obtained through fungicide use may not offset the associated input costs (Kisakye and Ugen-Adrogu, 1990). Control of banana weevil and nematodes is mainly by use of cultural methods combined with chemical application (Gowen and Quénéhervé, 1990; Gold et al., 2001). Chemical application, apart from having environmental concerns, has health risks associated with poor handling by the agricultural workers

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due to limited skills (Gold et al., 1993; Polidoro et al., 2008). Weevil resistance to pesticides has also been reported in Uganda (Gold et al., 1999) and elsewhere (Collins et al., 1991). The use of fungicides is also the currently recommended control method for black sigatoka, but not economically viable for most small-scale farmers in Uganda (Karamura et al., 2008; Ngambeki and Rubaihayo, 1996). Due to the airborne nature of the pathogen causing black sigatoka, coupled with the large plant habit, controlling disease spread and enforcing quarantine restrictions are difficult. Wild *Musa* species, especially *M. acuminata* ssp., have been reported to have resistant genes that can be used for breeding. However, the process is slow and expensive (Pinochet, 1996).

Integrated Pest Management (IPM) is a widely recognized ecosystem approach to crop production and protection that combines different management strategies and practices to grow healthy crops and minimize the use of pesticides with considerable success (ACCTPI, 2011, http://www.fao.org/agriculture/crops/core-themes/theme/pests/ipm/en/). IPM has concentrated mainly on reducing the amount of pesticide applied by using either regular pest sampling in fields (i.e., knowledge of biology and epidemiology), agronomic management, including crop rotation, and natural enemy control (Horn, 1988; Wilby and Thomas, 2007). Cultural techniques to modify crop environment are also potentially useful, but have been less central in most IPM discussions (at least from an entomology perspective; Ooi, 2005). Less attention has been given to the potential of effectively deploying intra-specific diversity, in the form of traditional crop varietal diversity, whether in mixtures or multi-lines, to reduce pest and disease damage (Finckh and Wolfe, 2006; Jarvis et al., 2007a,b; Thurston et al., 1999; Hajjar et al., 2008). This is in spite of the importance of local crop varieties for small-scale farmers and the role they play as a primary source of new resistant germplasm (Duvick, 1984; Trutmann et al., 1993; Thinlay et al., 2000; De Vallavieille-Pope, 2004).

Although bananas and beans have been intercropped for quite some time in Uganda, each crop is maintained as a mixture of different genotypes in farmers' fields (Nantale et al., 2008). The main purpose of genetic mixtures (crop variety mixtures) for pest and disease management is to slow down pest and pathogen spread (Wolfe, 1985). Several recent studies have shown that a diverse genetic basis of resistance is beneficial for the farmer because it allows a more stable management of pest and disease pressure than a monoculture allows (Trutmann et al., 1993; Thinlay et al., 2000; Thurston et al., 1999; Finckh, 2003; Di Falco and Chavas, 2007; Jarvis et al., 2007a,b). The effectiveness of a given mixture to do so depends not only on the resistance available but also on the nature and speed of the life cycles of the pathogens as well as their means of spread (Chakraborty et al., 1991; Finckh et al., 2000). For this reason our study examines specific pests and diseases where known variation in resistance of the host crop (common bean and banana) population exists within the country. Most pest and disease management strategies concentrate on reducing the current or coming season's crop loss to pest and diseases. Few crop management programmes are oriented to providing options that could reduce the risk to future crop loss, i.e., reducing genetic vulnerability within the farmers' fields. Vulnerability is intended here as the probability of crop loss due to a new biotype of pest or pathogen entering into the farmer's production system (Brown, 2008), a phenomenon more likely to occur in an area consisting of one or few varieties that share a very similar resistance structure. Our study concentrates on measuring different levels of host varietal non-uniformity in respect to pest and disease resistance linked with farmer's genetic diversity management choices to provide proxy measurements for vulnerability within the farmers' field.

2. Materials and methodology

2.1. Site description

The study was undertaken at four sites representing different ethnicity and ecological conditions of Uganda (Fig. 1). Nakaseke site is located in central Uganda dominated by the Baganda ethnic group in what has traditionally been described as the coffee–banana farming system. This area falls within the Central Wooded Savannah agro-ecological zone with an altitudinal range of 1086–1280 masl, mean annual rainfall of up to 1100 mm and temperatures ranging from 16 °C to 30 °C. Kabwohe site is located in western Uganda dominated by the Banyankole ethnic group in a predominantly banana–cattle farming system. The site falls within the western medium-high farmlands agro-ecological zone (1400–1500 masl) with mean annual rainfall of up to 1100 mm and temperatures ranging from 12 °C to 28 °C. Bunyaruguru site differs from Kabwohe mainly in elevation variability (900–1500 masl) with mean annual rainfall of up to 1100 mm and temperatures ranging from 15 °C to 29 °C. Rubaya site is located in the south western highlands with an altitude ranging from 1800 m to over 2200 masl with mean annual rainfall of up to 1100 mm and temperatures ranging from 11 °C to 25 °C. This site is dominated by the Bakiga ethnic group. The sites of Nakaseke and Kabwohe were used for both banana and bean studies whereas only beans were examined in Rubaya and only *Musa* spp. in Bunyaruguru.

2.2. Materials and experimental design

The experimental design had five linked components: (1) participatory diagnostics through standardized focus group discussions (Barahona and Levy, 2003) and household surveys to collect information collected from farmers on crop varietal diversity and disease management practices related to crop varietal diversity; (2) field observations of disease incidence for all varieties, traditional and improved; (3) on-farm and on-station trials; and (4) screen house trials for common bean (Table 1). Due to the perennial nature of banana and plantain, data was not yet available from the banana trials. Planting materials for on-farm, on-station, and greenhouse trials were collected for all traditional varieties encountered during focus group discussions (FGD) and household surveys from participating farmers at all sites and are listed in Table 2 for *P. vulgaris* and Table 3 for *Musa* spp.

2.2.1. Participatory diagnostics (*Musa* and *P. vulgaris*)

Participatory diagnostic sampling was carried out in each of the four agro-ecological sites, following a globally agreed set of guidelines described in Jarvis and Campilan (2006). Sampling was carried out at two levels: Focus Group Discussions (FGDs) and household surveys in 2007 and in 2008, respectively.

2.2.1.1. Focus group discussions. Each FGD had a minimum of 10 and a maximum of 12 people participating. For each crop, five FGDs were conducted per site, each FGD comprising a separate group category (leaders, young men, young women, old men and old women), giving a total of thirty FGDs. Young farmers were considered those under 30 years of age, old farmers those over the age of 30. A standardized set of questions grouped under seven themes (Jarvis and Campilan, 2006) was used to ensure that all the groups were asked the same set of questions. Questions were based on materials (traditional and modern plant materials for both *P. vulgaris* and *Musa* spp.) that farmers were asked to bring from their farms to the FGD. These materials were used as a basis for discussion among farmers and researchers to understand farmers' knowledge of varietal diversity, pest and disease symptoms, and host–pest/pathogen differences in plant health. Questions

Table 1
Summary of experimental design.

Type of assessment/experiment	What was done	Plot size (m^2)	No. of seasons	No. of accessions	No. of varieties
P. vulgaris on-farm assessment of ALS, anthracnose and bean fly during household surveys	Severity was calculated from 30 plants sampled at 10 different points across the farmers' field by assessing three plants front, left and right, (for each variety or in the case of bean mixture, each mixture). The plants were assessed using a scale of 0 for lack of diseases, 1 for low, 2 for moderate and 3 for high severity.	1,770 (average per household)	1	30	21 (average for the three sites)
Musa spp. on-farm assessment of black sigatoka, Weevils and Nematodes	Severity of black sigatoka was estimated by counting the number of green leaves and the total number of leaves per plant. The difference in the number of leaves indicated the number of affected leaves per plant and this was recorded for all the varieties in the household. Assessment of nematodes and weevil damage was conducted by counting the number of tunnels on the corm of the harvested plants for weevils and the number of snapped/toppled plants due to nematodes; these were recorded per variety.	13,295 (average per household)	1	30	32
Nematode diversity	Three gunny bags of roots were collected from harvested corm and taken to the laboratory for nematode extraction, identification and population density estimation. Roots were collected from a 20 cm × 20 cm × 20 cm cube dug close to the plant base. The roots were chopped, mixed thoroughly and 10 subsamples of 5 g each were drawn for nematode extraction, using a modification of the Baermann-funnel maceration–filtration technique (Hooper, 1986). Five roots were picked randomly from each sample, trimmed to a length of about 10 cm and split longitudinally to expose the root cortex and stele. One half of each root was examined for necrosis, thus each of the five root pieces represented 20%. Percent root necrosis was scored by estimating the proportion of necrotic cortical tissue (reddish-purple lesions) on each half root. The percentages for each of the five root pieces were added up to get total percent root necrosis (Bridge and Gowen, 1993). A weighted average percent root necrosis was calculated.	13,295 (average per household)	1	Varied 2–10	32
On-farm and on-station trials for *P. vulgaris*	The trials were laid in a completely randomized block design. Within each block, climbing varieties were planted separate from the bush varieties to avoid any microclimatic effect of the climbers on bush varieties. The varieties were sown each in a 6 m long rows spaced 0.5 m apart and 10 cm between plants for bush type; 20 cm between plants for the climbing type and left under natural bean fly, anthracnose and ALS infestation. The rows were replicated three times. Data collection for both on-farm and on-station trials started 14 days after planting (DAP) and ended at 49 DAP. Data collected on BSM included: incidence, plant mortality, larvae/pupal numbers and yield. At each sampling, twenty plants were randomly selected per plot. Pupae and larvae were recovered by dissecting dead plants and their number was recorded. Species identification was based on the colour of pupae as described by Greathead (1968). Disease incidence and severity was assessed for ALS and Anthracnose where data on presence or absence of disease symptoms was recorded as well as scores for the percentage of leaf area showing symptoms. Yield data was taken at physiological maturity when whole plots were harvested, threshed and the seed yield recorded. Disease development and progress was assessed using disease symptoms on the first trifoliate leaf. Six plants from each row were selected at 1 m intervals and assessed for disease incidence and severity at the three key bean developmental stages namely: at flowering (R6), pod initiation (R7) and pod filling (R8) stages. Disease incidence was first recorded as 0 or 1; whereby 0 = no disease and 1 = disease present. The disease severity was assessed using the 1–5 scale described by Inglis et al. (1988).	144	3	30	48
Screen house experiments for Angular Leaf Spot and Anthracnose	Each variety was planted in a bucket and replicated three times.The buckets were then laid out in a completely randomized design. At 21 days post-planting, they were inoculated with mixture of *P. griseola* isolates collected from bean fields in Nakaseke, Kabwohe and Rubaya. The inoculated plants were placed in a humid chamber for 4 days after which they were removed. Disease evaluations were done at 10, 12, 14, 17, and 21 days after inoculation (Mahuku et al., 2004), using the 0–5 scale (Inglis et al., 1988), whereby, 0 = no disease symptoms, 1 = 1–10% leaflet area with lesions, 2 = 11–25% leaflet area with lesions, 3 = 26–50% leaflet area with lesions and limited chlorosis, 4 = over 50% lesions and extensive chlorosis and 5 = complete defoliation.	–	–	129	43

Table 2
Comparison of mean scores of bean variety resistance from focus group discussions with mean severity of angular leaf spot in the screen house and on-station trials.

Variety	Study sites	Type	Mean rank score of resistance from FGD[a]	Mean severity from screen house trials[b]	Mean severity from field trials[b]
Kigome	Rubaya	Traditional	8	–	–
Rukumbyabagurusi	Rubaya	Traditional	7	–	–
Kanyamunyu	Rubaya	Traditional	6.5	–	–
Mahega	Kabwohe	Traditional	6.4	4.7	1.9
Kabenga	Kabwohe	Traditional	6.3	–	–
Washonje	Kabwohe	Traditional	6.3	–	–
Kankulyembarukye Purple	Rubaya, Kabwohe	Traditional	6	2.3	2.4
Kankulyembarukye army green	Rubaya, Kabwohe	Traditional	6	2.3	1.9
Nvunakingi	Rubaya	Traditional	6	–	–
Mamesha	Rubaya	Traditional	6	3.3	1.4
Yellow short	Nakaseke	Traditional	5.7	4.7	1.8
Khaki	Kabwohe, Nakaseke	Traditional	5.6	4.8	2
Ngwinorale	NACCRI	Modern	5.5	–	2.3
Kihura	Rubaya	Traditional	5.4	–	–
Sugar 31	NACCRI	Modern	5.3	2.3	5.3
Nyinamamesha	Rubaya	Traditional	5.3	–	–
Bwanaresi	Rubaya	Traditional	5.3	–	–
Nkirizabana	Rubaya	Traditional	5.3	–	–
Kabanyarwanda	Rubaya	Traditional	5.3	–	–
Kishoga	Kabwohe	Traditional	5.3	2.1	1.6
Rushoga	Kabwohe	Traditional	5.2	–	–
Kihura	Rubaya	Traditional	5	4.3	1.7
Nambale long	Nakaseke,Kabwohe	Traditional	5	1.6	4.7
Yellow long	Nakaseke	Traditional	5	4.6	1.5
Kahikye	Rubaya	Traditional	4.7	–	–
Nambale short	Nakaseke, Kabwohe, Rubaya	Traditional	4.7	1.4	4.7
Kisenyi	Rubaya	Traditional	4.7	–	–
Nambale	NACCRI	Modern	4.7	–	–
Kiribwaobwijegire	Kabwohe	Traditional	4.6	–	–
Kanyobwa	Nakaseke	Traditional	4.6	3	1.9
Rutukura	Kabwohe	Traditional	4.3	–	–
Kanyebwa	Nakaseke	Traditional	4.3	–	–
Kachwekano	NACCRI	Modern	4.3	4.9	2.6
Kakira	Rubaya	Traditional	4.3	–	–
Nshemererwa	Rubaya	Traditional	4.3	0.2	1.2
Nyinakigote	Rubaya	Traditional	4.2		
Kahura short	Nakaseke, Kabwohe, Rubaya	Traditional	4.2	1.4	4.2
Obote	Nakaseke	Traditional	4.2	–	–
Kabwejagure	Rubaya	Traditional	4	4.6	4
Rugundura	Rubaya	Traditional	4	–	–
Namunye	Nakaseke	Traditional	4	–	–
Kajerejje	Kabwohe	Traditional	3.8	–	–
Gantagasize	Kabwohe	Traditional	3.7	2.3	3.7
Bwiseri	Rubaya	Traditional	3.7	3.8	1.6
Nakyewogola	Nakaseke	Traditional	3.7	4.2	1.5
Rushare Purple	Kabwohe	Traditional	3.7	3.4	1.6
Ekibamukunde	Kabwohe	Traditional	3.3		
Bukanja	Rubaya	Traditional	3.3	–	3.2
Katosire	Kabwohe	Traditional	1.3	1.5	1.3
Mexic 54	NACCRI	Modern	–	0	1.2
NABE 10c	NACCRI	Modern	–	1.1	1
Brown Niko	Nakaseke	Traditional	–	2.6	2
NABE 13	NACCRI	Modern	–	2.8	1.2
NABE 14	NACCRI	Modern		2.8	-
Kayinja	Nakaseke	Traditional	–	3.7	1.2
Nakawunde	Nakaseke	Traditional	–	4	1.9
Akeru long	Nakaseke	Traditional	–	4	1.6
Akeru short	Nakaseke	Traditional	–	4.3	1.2
Obote	Nakaseke	Traditional	–	4.6	4.2
Kalorina	Nakaseke	Traditional	–	4.8	1.8
Kasirira	Bunyaruguru	Traditional	–	5	1.3
Manyigamulimi	Nakaseke	Traditional	–	5	1.6
Naka beauty	Nakaseke	Traditional	–	5	2.4
Naka brown dotted	Nakaseke	Traditional	–	5	2.1
Naka small red traditional	Nakaseke	Traditional	–	5	1
Kakulungu	Kabwohe	Traditional	–	5	3.1
Mahega short	Kabwohe	Traditional	–	1.6	6.4
	Mean for all modern varieties	4.95	2.3	2.3	
	Mean for all traditional varieties	4.87	3.7	2.3	

Key: Scale of resistance used in FGDs: 1-no resistance, 2-low resistance, 3-medium resistance, 4-high resistance. Scale of resistance used in trials: 0 = no disease symptoms, 1 = 1–10% leaflet area with lesions, 2 = 11–25% leaflet area with lesions, 3 = 26–50% leaflet area with lesions and limited chlorosis, 4 = over 50% lesions and extensive chlorosis, 5 = complete defoliation.

[a] Mean rank of resistance from FGDs refers to the total value of ranks from the FGDs for each variety divided by the number of FGDs. In the column for mean rank of resistance from FGD refers to no data available because these varieties were never mentioned during the discussions but were found during the household surveys.

[b] ALS mean severity refers to the total number of ratings of disease severity assessed using the 1–5 scale described by Inglis et al. (1988) divided by the total number of affected plants per variety. In the columns for mean severity from screen house and field trials refers to no data available because there was no germplasm for these varieties to be included in these trials.

Table 3
Resistance of banana varieties to pest and diseases as ranked by farmers in the Focus Group Discussions.

Variety	Study sites	Type	Mean rank of resistance[a]
Kisubi	Kabwohe, Nakaseke, Bunyaruguru	Traditional	4.9
Embiire	Kabwohe, Nakaseke, Bunyaruguru	Traditional	4.5
Entaragaza	Kabwohe, Nakaseke, Bunyaruguru	Traditional	4.5
Endyabwali	Kabwohe, Bunyaruguru	Traditional	4.4
Nzirabahima	Kabwohe, Bunyaruguru	Traditional	4.3
Bukumu	Kabwohe, Nakaseke, Bunyaruguru	Traditional	4.1
Enzirabushera	Kabwohe, Bunyaruguru	Traditional	4.1
Mukuba kkonde	Kabwohe, Nakaseke, Bunyaruguru	Traditional	4
Ntundu	Kabwohe, Bunyaruguru	Traditional	4
Fia 17, 25	Kabwohe, Nakaseke, Bunyaruguru	Modern	3.9
Nakabululu	Kabwohe, Nakaseke, Bunyaruguru	Traditional	3.8
Nakinyika	Kabwohe, Nakaseke, Bunyaruguru	Traditional	3.7
Kibuzi	Kabwohe, Nakaseke, Bunyaruguru	Traditional	3.6
Nkonza	Bunyaruguru	Traditional	3.6
Nakyetengu	Nakaseke	Traditional	3.5
Mayovu	Nakaseke	Traditional	3.5
Enyeru	Kabwohe, Bunyaruguru	Traditional	3.5
Musakala	Kabwohe, Nakaseke, Bunyaruguru	Traditional	3.3
Gonja	Kabwohe, Nakaseke, Bunyaruguru	Traditional	3.3
Namwezi	Nakaseke	Traditional	3.3
Lusumba	Nakaseke	Traditional	3.1
Nakijumbi	Nakaseke	Traditional	3
Kafuba	Nakaseke	Traditional	3
Lwewunzika	Nakaseke	Traditional	3
Kabula (Mbidde)	Nakaseke	Traditional	3
Salalugazi	Nakaseke	Traditional	3
Nasabba	Nakaseke	Traditional	3
Namunwe	Nakaseke	Traditional	3
Nambi	Nakaseke	Traditional	3
Kisansa	Nakaseke	Traditional	3
Nakawere	Nakaseke	Traditional	3
Kitika	Nakaseke,Bunyaruguru	Traditional	3
Namwezi	Nakaseke	Traditional	2.9
Kabaragara	Kabwohe, Nakaseke, Bunyaruguru	Traditional	2.9
Mbwazirume	Kabwohe, Nakaseke, Bunyaruguru	Traditional	2.8
Bogoya	Kabwohe, Nakaseke, Bunyaruguru	Traditional	2.8
Nandigobe	Kabwohe, Nakaseke, Bunyaruguru	Traditional	2.7
Siira	Nakaseke	Traditional	2.5
Mpologoma	Nakaseke	Traditional	2.5
Muzira nyama	Kabwohe, Nakaseke, Bunyaruguru	Traditional	2.3
Katwalo	Nakaseke	Traditional	2.2
Nakamaali		Traditional	2
Muvubo	Kabwohe, Nakaseke, Bunyaruguru	Traditional	2
Kivuvu	Kabwohe, Nakaseke, Bunyaruguru	Traditional	1.9
Kayinja	Kabwohe, Nakaseke, Bunyaruguru	Traditional	1.9

[a] Mean rank of resistance from FGDs refers to the total value of ranks from the FGDs for each variety divided by the number of FGDs.

were asked regarding the farmers' knowledge of varietal diversity, the traits the farmers use to distinguish their varieties, and the value – be it agronomic, adaptive, or quality or use traits – for the different varieties of each crop. Plant materials were assigned by the farmers into groups of plants which were determined to be the same variety. Importance was given to ensuring consistency of variety names and descriptions of varieties given by the farmers (Sadiki et al., 2007). An individual farmer volunteer per variety led the documentation of describing the specific variety, with inputs from the other farmers. Documentation included recording the name or names given by the group to the variety, whether the variety was traditional or modern, and the morphological, agronomic, adaptive and quality traits used by the group to describe the variety. This information was then organized by the researchers in a table of traits versus varieties. The final step was to check this table with the farmers to ensure there was agreement across the groups. To determine farmers' knowledge and perceptions of pest and diseases and host–pest/pathogen interactions, farmers were asked first to divide the plant materials they brought to the discussion into two groups—healthy and non-healthy plants. Then the farmers again divided the group of unhealthy plants into what they perceived to be damaged from different pest and diseases based on the symptoms they recognized on the plants. Descriptions of the plant symptoms for the diseases and pests observed were gathered, including a list of the symptoms on the different plant parts (leafs, stem, fruit, root) and at different growth stages. Farmers were also asked to clearly define what they perceived as different growth stages of the plants. Pictures of other diseases, not brought by farmers to the meeting, were then shown and farmers were asked to identify and give any names they had for these diseases. Farmers were then asked to rank the severity of damage from the different pests and diseases identified and finally to rank varieties according to their level of resistance to the complex of pest and diseases in their systems. Farmers were also asked to draw what they believed was the source of the different pests and diseases in their systems and to describe the practices they use to select good planting materials and to manage pests and diseases.

2.2.1.2. Household surveys. Households at each site were selected using a randomly stratified design (by village), to ensure geographic representation across the target villages within each agro-ecological site, totalling 240 households (60 households for *Musa* spp. and 180 households for common bean). Sixty households were interviewed per site for each of the three sites for *P. vulgaris*,

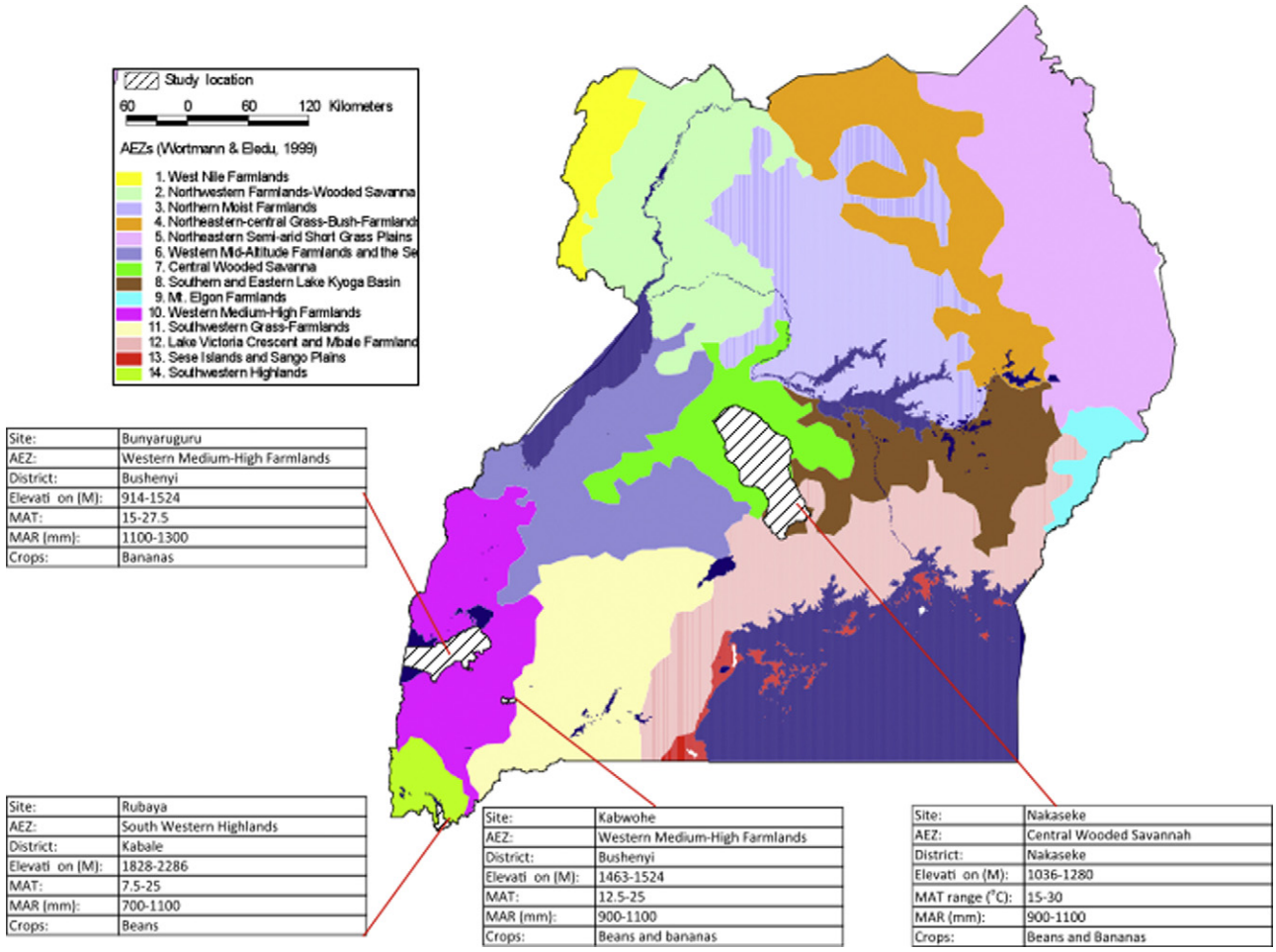

Fig. 1. Map of Uganda showing agroecological zones and project sites.

and for the one site, Kabwohe, for *Musa* spp. Logistic difficulties were encountered in sampling at the household level in the other two *Musa* sites (Nakaseke and Bunyaruguru) and data at the household level is not available for those two sites. During the household surveys, a deliberate effort was made to ensure that both male and female farmers were involved in equal numbers as respondents. The household survey was designed to complement information collected in the FGDs and to link crop varietal diversity on farm to observations of damage by target pests and diseases in the farmers' fields discussed below. Information was collected at the household level on the area planted to each variety the farmer grew, for both modern and traditional varieties, based on the agreed variety description from the FGD. Levels and frequency (number of applications) of chemical inputs (pesticides and fertilizers) were recorded and quantities checked by examining volumes of purchased chemicals and levels of dilution used by the farmers. Alternative pest and disease management practices, which involved crop varietal choices, mixtures of different varieties in the field, and plant or seed selection practices, were noted. Belief statements (Heong and Escalada, 1999) were used to test the level of knowledge and attitudes of farmers towards modern and traditional varieties, planting mixtures and monocultures, and how all these influence the crop resistance to pests and diseases.

2.2.2. Disease assessment in surveyed farmers' fields

On-farm disease severity due to (i) angular leaf spot (ALS), anthracnose (ANT) and bean fly (BFY) for *P. vulgaris*, and (ii) to black sigatoka for *Musa* spp. was estimated for each variety grown by the 60 surveyed farmers per site of the households surveyed described above.

Disease severity for ALS, ANT and BFY for *P. vulgaris* was calculated based on observations from 30 plants sampled for each variety, made at 10 different points across the farmers' field and assessing three plants at each point—one in front, one on the left and the third on the right. The same procedure was used on the fields with single or mixed varieties. Fields with mixed varieties were sampled as a population where 30 plants were selected for each specific mixture the farmer grew. Disease severity of the 30 plants per variety was assessed using a scale of 0 for lack of diseases to 3 for high severity. Measurements were based on specific host symptoms that could be related to loss of productive capacity of the crop. For ALS and ANT; 0 indicated no disease symptoms, 1 indicated 1–50% leaflet area covered with lesions and limited chlorosis, 2 indicated over 50% leaflet area covered with lesions and extensive chlorosis and 3 indicated complete defoliation. BFY infestation was rated as follows: 0 = no pest infestation, 1 = stunted plants due to BFY, 2 = plants starting to wilt and 3 = dead plants.

Disease severity of black sigatoka in *Musa* spp. was estimated by counting the number of green leaves on plants at flowering stage, considering that plants with less than 10 leaves had a reduced productive capacity due to severe incidence of black sigatoka. This was recorded for all the varieties in the household.

Assessment of nematodes and weevil damage in *Musa* spp. requires destruction of the plant and therefore was conducted by counting the number of tunnels on the corm of the harvested plants for weevils and the number of snapped/toppled plants due to nematodes (Sasser and Freckman, 1987). Data was recorded

for each variety. Nematodes diversity was assessed from banana roots collected from the three sites and used as inoculum for a screen house experiment to assess resistance/tolerance of different banana cultivars to nematodes. The roots were collected from harvested corms wherever they were found on farms within the site, regardless of whether the farm was one of the selected 60 or not. A sample of the roots was examined for nematode damage before uprooting the whole corm. Samples for root necrosis assessment were collected from four selected farms per site (Bunyaruguru and Kabwohe), on 2–10 recently flowered banana plants per cultivar per farm. The number of sampled plants varied due to availability of recently flowered individuals. The sampled cultivars included Kibuzi, Nakitembe, Enyeru, Mbwazirume, Musakala and Enzirabahima. Following Bridge and Gowen (1993), the roots were collected from a 20 cm × 20 cm × 20 cm cube dug close to the plant base, kept in clear polythene bags, labelled and taken to the laboratory. Five roots were picked randomly from each sample, trimmed to a length of about 10 cm and split longitudinally to expose the root cortex and stele. One half of each root was examined for necrosis, thus each of the five root pieces represented 20%. Percent root necrosis was scored by estimating the proportion of necrotic cortical tissue (reddish-purple lesions) on each half root. The percentages for each of the five root pieces were added up to get total percent root necrosis. Since the number of observations per farm was very varied, a weighted average percent root necrosis was calculated. This was done by weighting the cultivar means by the number of observations on each farm. Another lot of roots from each sample was used for nematode extraction, identification and population density estimation. The roots were chopped, mixed thoroughly and 10 subsamples of 5 g each were drawn for nematode extraction, using a modification of the Baermann-funnel maceration–filtration technique (Hooper, 1986).

2.2.3. Field and on-station trials for P. vulgaris

2.2.3.1. Expanded on-farm trials. Expanded on-farm trials were conducted in Nakaseke, Kabwohe, and Rubaya, from 2009 to 2010 for three consecutive seasons, to observe levels of resistance under farmers' conditions of all traditional varieties of common bean collected during the household and focus group surveys together with resistance and susceptibility checks (Table 2). Mexico 54 was the resistant check and Kanyebwa the susceptible check for ALS; Nambale short, Nambale long and Kanyebwa were the susceptible checks for ANT; and Kigome as the susceptible check for BFY. A minimum of three replicates (different farms) were used. Varieties were planted with a different order in the different replication plots (CRBD) in order to minimize the neighbour effect. The trials were exposed to natural inoculums only, in order to avoid the spreading of diseases in farmers' fields. A minimum of 30 plants per variety were screened at different stages to assess the level of resistance of the different varieties to the target pests and diseases.

2.2.3.2. Research station trials. Research station trials for *P. vulgaris* were carried out at the National Crops Resources Research Institute (NaCRRI), Namulonge during the second season of 2010. The trials were laid in a completely randomized block design with the same checks as in the on-farm trials plus NABE 9C, also a susceptible check for BFY Within each block, climbing varieties were planted separate from the bush varieties to avoid any microclimatic effect of the climbers on bush varieties. Forty-eight varieties were obtained from farmers (mainly landraces) in the three study sites and from NaCCRI (released varieties) (see Supplementary materials for list of varieties and their origin). The varieties were sown each in 6 m-long rows spaced 0.5 m apart and 10 cm between plants for bush type; 20 cm between plants for the climbing type and left under natural bean fly, anthracnose and ALS infestation. The rows were replicated three times.

2.2.3.3. Data collection for both on-farm and on-station trials. Data collection for both on-farm and on-station trials started 14 days after planting (DAP) and ended at 49 DAP. Data collected on BSM included: incidence, plant mortality, larvae/pupal numbers and yield. At each sampling, 20 plants were randomly selected per plot. Pupae and larvae were recovered by dissecting dead plants and their number was recorded. Species identification was based on the colour of pupae as described by Greathead (1968). Disease incidence and severity were assessed for ALS and Anthracnose, where data on presence or absence of disease symptoms was recorded as well as scores for the percentage of leaf area showing symptoms. Yield data was taken at physiological maturity when whole plots were harvested, threshed and the seed yield recorded. Disease development and progress was assessed using disease symptoms on the first trifoliate leaf. Six plants from each row were selected at 1 m intervals and assessed for disease incidence and severity at the three key bean developmental stages—namely, flowering (R6), pod initiation (R7) and pod filling (R8) stages. Disease incidence was recorded as 0 or 1, where 0 = no disease and 1 = disease present. The disease severity was assessed using the 0–5 scale described by Inglis et al. (1988) (Table 2) where 0 = no disease symptoms, 1 = 1–10% leaflet area with lesions, 2 = 11–25% leaflet area with lesions, 3 = 26–50% leaflet area with lesions and limited chlorosis, 4 = over 50% lesions and extensive chlorosis and 5 = complete defoliation (Table 2).

2.2.4. Screen house experiments for angular leaf spot

Bean varieties from the on-farm trials in the screen house trials are listed in Table 2. All varieties with sufficient seeds were used. Forty-three farmer bean varieties (10 climbers and 33 bush types) were used (Supplementary materials—Common bean varieties and the study sites). Each variety was planted in a bucket and replicated three times. The buckets were then laid out in a completely randomized design. At 21 days post-planting, they were inoculated with a mixture of *P. griseola* isolates collected from bean fields in Nakaseke, Kabwohe and Rubaya. The inoculated plants were placed in a humid chamber for four days, after which they were removed. Disease evaluations were done at 10, 12, 14, 17, and 21 days after inoculation (Mahuku et al., 2004), using the 0–5 scale (Inglis et al., 1988) as described above.

2.3. Data analysis

Processed data was analyzed using descriptive statistics to score scale responses, frequency distributions and mean comparisons. Total area planted to each banana and/or bean variety, both traditional and modern, was calculated based on GPS measurements, farmers' diagrams and descriptions of their plots using the methods described in Jarvis and Campilan (2006). The proportion of the farm growing only traditional varieties was calculated and used as an estimate of the area. Standard diversity indices for crop varietal diversity (Jarvis et al., 2008), including richness (number of traditional varieties grown), and evenness estimated as a complement of D ($1 - D$), where D is the Simpson measure of dominance, were calculated and transformed logarithmically $1/(1 - \mathrm{LN})$ (Magurran, 2003; Jarvis et al., 2008). The average number of traditional varieties per household and mean household Simpson Index was calculated for each agro-ecosystem. The total agro-ecosystem richness was calculated by summing the number of distinct traditional varieties found across villages in the community. Also community richness and evenness were transformed logarithmically. For all diseases in this study a household and community weighted damage index (WDI) was calculated based on

Table 4
Farmers' descriptors of healthy and non-healthy plants based on the visual assessment by farmers during FGDs.

	Healthy plants	Non-healthy plants
P. vulgaris	Fresh unfolded green leaves; leaves without holes; thick stem; many branches; strong tap root; many strong roots; no insects; no white on stems; many flowers; many big thick pods; seeds without holes; round seeds	Spots on leaves and stems; stunted plant; dying leaves; white spikes; black spikes; sterile spikes; small spikes; wilting plants; plants with rust; leaf deformation; weak stem; small grains
Musa spp.	Dark green leaves; many leaves; strong, brown roots; big strong stem; strong sucker; big corm; big bunch, many fingers	Weak plant; yellow leaves; creased leaves; few leaves; hard stem; rotten roots; smell in the pseudostem; yellow liquid oozing from stem; dry male bud; deformed hand; short fingers; brown dots on finger; ripe immature fingers; black finger and stem

the product of the standard disease index (at the plot level) and the frequency of each variety present in the plot, as follows WDI = (D1 × A1) + (D2 × A2)/(A1 + A2). D1 and D2 are damage indices for variety 1 and 2, respectively, estimated from the (Average severity rating × Percentage of plants effected (incidence)/Total range of severity), and A1 equals the percent area covered by Variety 1, and A2 is the percent area covered by Variety 2 per household). WDI for each disease at household level were then correlated to diversity indices (traditional varietal richness and evenness) at the community level using Pearson correlation coefficient. Disease incidence and severity data were both subjected to analysis of variance (ANOVA). Data collected on bean stem maggot incidence, plant mortality, larvae, pupal numbers and yield were analysed using a computer software program GENSTAT Discovery edition. For banana nematodes, weighted average percent root necrosis was calculated. This was done by weighting the cultivar means by the number of observations on each farm.

3. Results

3.1. Farmer knowledge of pests, diseases and host resistance

In the focus group discussions (FGDs), farmers had specific criteria to differentiate healthy and non-healthy plants (Table 4). The symptoms on the host plants described by the farmers to be indicative of the target pest and diseases, including the identification of the plant parts affected and the plant stage effected and whether they were considered of high, medium or low importance to cause damage, are shown in Table 5.

3.1.1. Phaseolus vulgaris

Results from the 15 FDGs on *P. vulgaris* showed that particular traditional varieties were ranked higher in resistance than the modern varieties, although the mean rank for all traditional varieties (4.87) was not significantly higher than that of modern varieties (4.95) (Table 2). Kigome, Rukumbyabagurusi, Kanyamunyu, Mahega, and Kabenga were ranked highest in resistance and they are all traditional varieties. In the FDGs from Kabwohe the varieties that were ranked highest in resistance were Nambale short, Kanyobwa, Nambale Modern, Nambale Local and Kahura. In Nakaseke, the varieties that were ranked highest in resistance were Nakyewogola, Nambale short, Yellow short and Nambale local. In Rubaya, the varieties that were ranked highest in resistance were: Kigome, Bukanja, Ngwinorare, Kabwejagure and Nshemererwa. Of all these varieties, only Nambale Modern and Ngwinorale are modern varieties. In the household surveys, the respondents ranked the varieties' resistance differently even for some of the varieties that were common across sites.

Results from the belief statements (at household level) revealed that 46% of the respondents in all sites believed strongly that modern varieties of *P. vulgaris* become more susceptible to diseases over time while 45% believed that the resistance of traditional varieties is not reduced over time. Sixty percent of the respondents in Rubaya and 63% of those in Nakaseke believed strongly that improved varieties become more susceptible to diseases over time yet only 15% of the respondents in Kabwohe believed so. Respondents also believed that varieties succumbed to pests and diseases at different levels in the wet and dry years. Only a small percentage of respondents in Nakaseke (22%) believed that monoculture is more susceptible to pests and diseases than mixtures while 29% of the respondents in all sites believed strongly that if you grow only one variety, you will have more insect attacks than when you grow more than one variety. Thirty-four percent of the respondents in all sites believed that planting more than one variety per plot gives more income, yet none of the respondents in all the sites believed that planting more than one variety per plot is more costly than uniform planting.

3.1.2. Musa

Information from 15 FGDs for the three *Musa* sites showed that in general farmers considered Kisubi, Embire, Entaragaza, Endybwali and Nzirabahima as varieties highly resistant to pests and diseases. Mukubakkonde and Ntundu were considered moderately resistant and the remainder of the traditional cultivars as susceptible (Table 3). Some traditional varieties were less affected by black sigatoka in Kabwohe while in Bunyaruguru and Nakaseke the damage was higher for the same varieties (Table 6). The percentage of people responding to black sigatoka was lower than those with views on weevils and sometimes zero. None of the households in Bunyaruguru and Kabwohe identified nematodes as a problem in their banana plots, whereas in Nakaseke, 13.3% of the households mentioned nematodes as a problem. All the households that identified nematodes as a problem were able to associate them with root damage, while 75% and 62.5% of the households associated nematodes with bunch quality and corm damage, respectively. In Nakaseke, only four households were able to rate banana cultivars for resistance to nematodes. Cultivars believed to be resistant to nematodes included the traditional varieties of cooking banana: Nakinnyika, Mayovu, Mbwazirume, Kisansa, Lusumba, Katwalo, Nakyetengu, Nakitembe and Namwezi. The introduced FHIA 17 was also mentioned.

For banana weevil, farmers in Kabwohe considered only Kawanda as highly resistant, Embire as moderately resistant and the remainder of the traditional cultivars as highly susceptible (Table 6). Observations of the corm damage showed a higher damage in Bunyanruguru (11 tunnels per corm), followed by Kabwohe (seven tunnels per corm) and Nakaseke (three tunnels per corm). Random varietal arrangements predominated by Nakitembe/Entaragaza and Enyeru in the three sites had less variation in host resistance to banana weevil. In Nakaseke, Nakinyika was considered highly resistant to the three constraints, namely, black sigatoka, nematodes and banana weevils, while Mpologoma was considered moderately resistant and the rest were

Table 5
Farmers' descriptors of target pests and diseases and the perceived importance in terms of causing damage in the farmers' production system.

Scientific name	*Colletotrichum indemuthianum*	*Phaeoisariopsis griseola*	*O. phaseoli*, *O. spencerella*	*Cosmopolites sordidus* (Germar)	*Helicotylenchus multicinctus* (Cobb), *Pratylenchus goodeyi* (Sher & Allen)	*Mycosphaerella fijiensis*
Common name	Anthracose	Angual leaf spot	Bean fly	Banana weevil	Nematodes	Black sigatoka
Farmers' name (s)	Sets of symptoms (no specific name)	Amatoloboijjo	Ekisanzire	Kajojo, Kayovu, Kisokomi, ekikoko	Lusensera, Enjoka	Sets of symptoms (no specific name)
Farmers' descriptors	Rotting of plant leaves beginning from the upper parts, water soaked pods, no seed formation, brown lesion form along leaf margins and stems	Rotten pods, damaged pods[a]	Yellow plants*	Corm tends to come out of the ground, leaves become yellowish, sheath dries and remains attached to the stem, holes in the corm when cut, dropping of the leaves at an early stage, bunch is dwarf and unpleasant, when the pseudostem is split coloured strip	Roots rot and dry, weakens roots leading to toppling, yield reduction, food hardening, at harvesting time the fingers become hard, dry and corrosive corm, the sheath bulges and splits, the root dries before it topples.	Leaves dry on the margins, drying of the leaf tips, dry spots on the leaves, plant dries but never drops, stunted finger, stem has black spots, dry middle leaf, the bunch fingers do not enlarge to the required size
Plant part effected (Farmers' descriptors)	Leaves, pods, stem	Pods	Root, stem, leaves	Corm, Stem	Roots	Leaves
Main stage of severity (Farmers' descriptors)	Flowering, podding	Flowering, podding	Seedling	Maiden, flowering, harvesting: all stages	All stages	Shooting
Farmers' importance given compared to other pests and disease in the farmers' system by site						
Nakaseke	High	High	High	High	High	Medium
Kabwohe	High	High	High	High	Low	Low
Rubaya	High	High	High	–	–	–
Bunyaruguru	–	–	–	High	High	High

[a] Farmers mentioned symptoms but never named the disease. High importance was also attached to these symptoms in all sites.

judged highly susceptible (Table 6). In Bunyaruguru all cultivars were ranked as highly susceptible to these three constraints of production. Examination of banana root samples collected from the three project sites revealed that the spiral nematode *Helicotylenchus multicinctus* (Cobb) Golden was less abundant than the lesion nematode *Pratylenchus goodey*i Sher &Allen. The burrowing nematode, *Radopholus similis* (Cobb) Thorne, was not found.

3.2. Household crop varietal diversity and weighted damage indices from farmers' fields

A summary of the key variables for measuring diversity indices and pest and disease damage at the household level are presented by crop in Table 7. Both common bean and banana showed high richness and evenness of traditional varieties at household levels, with the mean household richness for common bean being 2.37 and for banana being 8.02. Community richness was also high with mean number of varieties at the community level of 21.67 for bean and 32 for banana. Community variety richness differed significantly among common bean sites, ranging from 12 to 27. Evenness at both household and community levels was high for both crops. On-farm evenness (Simpson) ranged between 0.37 and 0.44 for beans and was 0.55 for banana. Community evenness (Simpson) was appreciably high for common bean ranging from 0.74 to 0.87, but much lower for banana (0.66). Divergence as a measure of the possibility of any two randomly chosen households within the same community to grow different varieties had a mean of 0.51 for common bean and 0.16 for banana.

Disease incidence, measured by the Weighted Damage Index (WDI) varied across sites (Table 4). In particular ALS incidence was significantly higher in Kabwohe than in the other two sites while anthracnose in Rubaya was significantly lower. Table 8 provides information on the Pearson correlation coefficients among the different variables measured at household level. The correlation between land size and number of varieties planted at the household level was positive and significant in Kabwohe and Nakaseke and overall significant across sites for beans. For banana it was not significant (Table 5). The correlation between richness and evenness and WDI was not always significant. However, it was significant when WDI was higher, as in Kabwohe and Nakaseke for anthracnose, and almost significant in Kabwohe for ALS. Table 8 and Figs. 2 and 3 show the relationships among the diversity estimates with the damage indices. Fig. 2a and b shows the relationship between household varietal richness and the weighted damage disease indices for ALS and anthracnose respectively while Fig. 2c and d is, respectively for black sigatoka and weevils. Fig. 3a and b shows the relationship of household varietal evenness and the weighted damage disease index for ALS (Fig. 3a), anthracnose (Fig. 3b), black sigatoka (Fig. 3c) and weevils (Fig. 3d).

3.3. Genetic diversity management practices and disease damage

Intra-specific spatial arrangements by farmers to control pest and diseases for *P. vulgaris* involved planting variety mixtures in patterns (e.g., random, rows, small plots, borders and rows in a plot). Planting mixtures was a common practice in Kabwohe (68% of farmers interviewed) and in Rubaya (63% of the respondents), while it was much less common in Nakaseke (30% of the respondents). Pesticide use to control pests and diseases for *P. vulgaris* was only in Rubaya by a few respondents (17%), who on averaged use 2.3 kg and 140 ml of pesticide per season. The most popular practice in Kabwohe to control pests and diseases for *Musa* spp. was decreasing spacing density, and it was carried out by 70% of the respondents. Planting mixtures was also a popular practice in Kabwohe used by 58% of the respondents.

Table 6
Farmers rating of resistance status of different *Musa* cultivars to black sigatoka and banana weevil from household surveys.

Variety name	Kabwohe SITE						Nakaseke SITE						Bunyaruguru SITE					
	Black sigatoka			Weevils			Black sigatoka			Weevils			Black sigatoka			Weevils		
	n	% farmer response	% Rating highly resistant	*n*	% farmer response	% Rating highly resistant	*n*	% farmer response	% Rating highly resistant	*n*	% farmer response	% Rating highly resistant	*n*	% farmer response	% Rating highly resistant	*n*	% farmer response	% Rating highly resistant
Kawanda	10	0	0	10	90	67	.	.	.	–	–	–	.	.	.	–	–	–
Embire	32	3	100	32	81	46	.	.	.	–	–	–	.	.	.	–	–	–
Enyeru	56	4	100	56	84	26	.	.	.	–	–		19	37	14	19	79	20
Mujuba	24	0	0	24	79	16	.	.	.	–	–	–	.	.	.	–	–	–
Kibuzi	39	5	100	39	85	15	10	20	0	10	80	0	16	63	0	–	–	–
Mushankara	15	0	0	15	100	13	.	.	.	19	74	7	.	.	.	–	–	–
Enzirabushera	10	10	100	10	100	10	.	.	.	–	–	–	.	.	.	29	76	0
Bogoya	41	5	50	41	85	9	.	.	.	–	–	–	20	70	14	20	85	0
Entaragaza	56	4	100	56	84	6	39	8	0	39	74	14	46	54	20	46	78	8
Kabaragara	38	5	50	38	84	6	.	.	.	–	–	–	.	.	.	–	–	–
Enjagaata	37	5	100	37	86	0	.	.	.	–	–	–	22	59	15	22	86	5
Mbwazirime	25	4	100	25	88	0	21	19	0	21	67	21	12	58	14	12	92	0
Kisansa	.	.	.	.	.	.	12	17	50	12	83	10	.	.	.	–	–	–
Lusumba	.	.	.	.	.	.	27	0	0	27	67	6	.	.	.	–	–	–
Mayovu	.	.	.	.	.	.	21	19	50	21	67	29	.	.	.	–	–	–
Mpologoma	.	.	.	.	.	.	21	20	40	21	81	41	.	.	.	–	–	–
Musakala	.	.	.	.	.	.	19	11	0	11	73	0	.	.	.	–	–	–
Muvubo	.	.	.	.	.	.	11	0	0	12	67	25	.	.	.	–	–	–
Nakabululu	.	.	.	.	.	.	12	17	100	13	69	56	.	.	.	–	–	–
Nakinyika	.	.	.	.	.	.	13	46	17	12	58	0	.	.	.	–	–	–
Nakyetengu	.	.	.	.	.	.	12	14	0	10	50	0	.	.	.	–	–	–
Nambi	.	.	.	.	.	.	10	0	0	14	64	22	.	.	.	–	–	–
Namwezi	.	.	.	.	.	.	14	29	0	–	–	–	.	.	.	27	74	5
Ekigonza	.	.	.	.	.	.	.	.	.	–	–	–	22	50	9	22	73	19
Endyabwari	.	.	.	.	.	.	.	.	.	.	.	.	27	27	0			
Enzirabahima	.	.	.	.	.	.	.	.	.	.	.	.	29	45	15			
Kabwengye	.	.	.	.	.	.	.	.	.	.	.	.	19	35	0			
Kahinja	.	.	.	.	.	.	.	.	.	.	.	.	20	24	0			
Mujuba	.	.	.	.	.	.	.	.	.	.	.	.	22	27	33			
Muziba	.	.	.	.	.	.	.	.	.	.	.	.	11	91	0			
Rweru	.	.	.	.	.	.	.	.	.	.	.	.	10	70	0			

Key _ Refers to (No data). 0 refers to (No response). *N* = Number of farms with a particular cultivar. *R* = percentage (%) of farmers who responded out of (*N*). RH = % of farmers who ranked a cultivar as highly resistant.

Table 7
Mean diversity and weighted damage indices (WDI) at household and community levels[a].

Site	Crop	Total area(m^2) per site[b]	Average area(m^2) for crop/household[c]	HH richness[d]	HH simpson	Community richness	Community simpson[e]	Divergence[g]	WDI[f] ALS	WDI AN	WDI black sigatoka	WDI weevils
Rubaya	Bean	62,055.6	993.4	2.4	0.38	26	0.87	0.56	17.58	8.41	N/A	N/A
Kabwohe	Bean	100,643.9	1677.4	2.45	0.37	27	0.86	0.57	35.18	16.42	N/A	N/A
Nakaseke	Bean	158,291.7	2638.2	2.27	0.44	12	0.74	0.41	13.04	16.74	N/A	N/A
Average	Bean	106,997.1	1770	2.37	0.40	21.67	0.82	0.51	21.93	13.86	N/A	N/A
Kabwohe	Musa	784,400	13,295	8.02	0.55	32	0.66	0.16	N/A	N/A	64.31	55.86

[a] The household and community weighted disease index (WDI) were estimated from the product of the disease index (at the plot level) and the frequency of each variety present in the plot. The area planted with each variety was estimated by using local area measurements.
[b] The area planted with each crop per household was estimated by using GPS, converted to square meters and then added up to get the total area covered by a particular crop per site.
[c] The average area for crop was obtained by dividing the total area covered by the crop with the number of households growing the crop.
[d] Household (HH) richness is the number of varieties per household while community richness is the sum of the number of distinct varieties found across the target villages in the community.
[e] Following Magurran (2003), Community Simpson (evenness) was estimated as a complement of d (1-D), where D is the Simpson measure of dominance. *Divergence (the partition of diversity between and within farms) was calculated as the difference between community and farm index values divided by the community Simpson index (Jarvis et al., 2008).
[f] Weighted damage index (WDI) was estimated from the product of the standard disease index (at the plot level) and the frequency of each variety present in the plot.
[g] Divergence is a measure of the possibility of any two randomly chosen households within the same community to grow different varieties.

3.4. *Phaseolus vulgaris* field trials

All varieties screened in the field were infected with ALS, including the susceptible (Kanyebwa) and resistant (Mexic 54) checks (Table 2). There was a significant difference ($p < 0.001$) among varieties in their disease severity levels. Naka small red, a traditional variety, showed the least disease severity levels with a score of 1. The other varieties, which showed low reaction to ALS with a mean severity score of between 1.1 and 1.4, included, Rushare II, NABE 10c, Mexico 54 (resistant check), NABE 13, Kahura, Kayinja, Akeru short, Kasirira, Shemenoha, Nambale short and Kahura short. These results were similar to the information given by the farmers on some varieties ranked as highly resistant (e.g., Nambale short and Kahura short).

Two bean fly species were recorded at all the study sites namely; *Ophiomyia spencerella* and *Ophiomyia phaseoli. O. spencerella* was more abundant than *O. phaseoli* in Bushenyi, Kabale and Wakiso (Namulonge Station), while the opposite was observed at Nakaseke. The incidence of plants with bean stem maggot (BSM) damage symptoms was generally lower in Nakaseke compared to the other two locations (Table 9). The percentage of plants showing symptoms of BSM infestation differed significantly ($p < 0.001$) between varieties. Kaki short, Katosire, Kasirira, and Kishoga were the least damaged varieties in all the locations. Kaddugala, Kishoga climber, Kanyebwa long, Mahega II, Rushare old, Kihura long and Kahura bush had higher damage in all the three on-farm sites. The susceptible check, Kigome, had an intermediate percentage incidence of 35.9%. Significant effects ($p < 0.001$) on varieties were obtained for the percentage of dead plants with BSM, numbers of larvae and pupae per plant and seed yield. The percentage of plants with BSM ranged from 0 to 100%. The number of pupae per plant ranged from 0 to 16, whilst the number of larvae ranged from 0 to 6. Among the top 10 high yielding varieties, Kaki short, Nyinakigote and Nambale long registered less than 50% of dead plants when infected with BSM. All the lower ten yielding varieties registered more than 60% dead plants when infected with BSM, but with the highest figures recorded for Akeru short, Ngwinorare and Kankulyembalukye. A simple linear regression of the number of pupae and larvae (independent variables) to mortality (number of dead plants) (dependent variable) showed significant positive relationships for the two variables: pupae–intercept (a) = 1.978, slope (b) = 0.024 ± 0.009, t-value = 25.89, $p < 0.001$ and coefficient of determination (r^2) = 43.7; larvae-intercept (a) = 1.809, slope (b) = 0.437 ± 0.016, t-value = 27.38, $p < 0.001$ and coefficient of determination (r^2) = 46.5, showing that BSM is an important cause of bean loss.

3.5. *Phaseolus vulgaris* screen house evaluation

The results from the screen house disease evaluation showed that there is a significant difference ($p > 0.001$) between *P. vulgaris* varieties in their reactions to ALS. Only Mexico 54 (the resistant check) showed no reaction at all. Few other varieties which showed low severity to ALS included; Shemenoha, Katosire, NABE 10c, Kishoga, Ngwinorale (NABE 8c), Kankuryemebarukye, Kankuryembarukye purple, Brown Nico, NABE 13 and NABE 14 (Shemenoha having the least severity). Most of the varieties screened however had very high disease scores with up to 15 varieties (Table 2) having the maximum disease severity score of 5. Overall, the screen house experiment recorded higher severity scores than the field observations. In field trials none of the varieties displayed the maximum severity score of 5. Some of the varieties, however, namely; Mexico 54, Shemenoha, NABE 10c and NABE 13 showed low disease severity levels both in the field and in the screen house. Of these Nshemenoha is a traditional variety, while the rest are improved.

Table 8
Correlation of diversity indices and weight damage indices (WDI).

	Rubaya (beans)	Kabwohe (beans)	Nakaseke (beans)	Overall beans	Kabwohe banana/ plantain
Richness × ALS WDI	0.03	−0.17	0.04	−0.02	NA
Evenness × ALS WDI	0.03	−0.09	0.06	−0.02	NA
Richness × AnthrWDI	−0.09	−0.37**	−0.13	−0.22*	NA
Evenness × AnthrWDI	0.05	−0.37**	−0.22*	−0.19	NA
Richness × Farm area	0.16	0.47**	0.31*	0.24*	0.22
Richness × black sigatoka	NA	NA	NA	NA	−0.17
Evenness × black sigatoka	NA	NA	NA	NA	−0.02
Richness × weevils	NA	NA	NA	NA	0.12
Evenness × weevils	NA	NA	NA	NA	−0.21

NA refers to no data available because logistic difficulties were encountered in sampling at the household level in the two *Musa* sites (Nakaseke and Bunyaruguru).
* Correlation significant at $p < 0.05$.
** Correlation significant at $p < 0.01$.

4. Discussion

In Uganda, as in many farming systems throughout the developing world, small-scale farmers make use of intra-specific crop diversity, in the form of diversity sets of traditional and modern crop varieties, to reduce the damage caused by pests and diseases (Trutmann et al., 1993; Karamura et al., 2004; Abate et al., 2000; Buah, 2010). A diversity of traditional varieties within the production system gives the farmers' crop populations a better chance to adapt and evolve to adapt to changing environmental conditions by widening the genetic base of the crop populations they manage (Sagnard et al., 2008; Jackson et al., 2010; Bezançon et al., 2009; Jarvis et al., 2011). A diverse genetic basis of resistance is beneficial for a farmer as it allows a more stable management of disease pressure than a monoculture allows (Burdon, 1987; Mundt, 1991; Abate et al., 2000; Garrett and Mundt, 1999). Our work was to explore in detail the interactions between host diversity in the form of crop varietal diversity and crop damage to understand how this approach may both (i) reduce crop losses to pests and diseases in the current season and (ii) protect future yields and stabilize them year on year thus helping farmers to work in systems that are less vulnerable to emerging new pest and disease threats. Diverse forms of resistance seem to be widespread in traditional crop varieties (Teshome et al., 2001). This has been attributed to the long-term co-evolution in primary and secondary centres of diversity (Leppik, 1970; Milgroom et al., 2008). A prerequisite for crop varietal diversity to be considered a valid strategy for pest or disease management is that variation in resistance of the host population with respect to the pest or disease exists within the farmers' production system (Wolfe and Finckh, 1997). For this reason, the study concentrated on pests and diseases where there is known resistance within the host populations, and in known areas of high intra-specific traditional crop diversity for the target crops.

4.1. Farmers' diagnostics of pests and diseases

Identification of the amount and distribution of diversity in respect to pest and disease resistance was based on linking participatory diagnostic information with field observations and experimental trials. Farmers identified significant differences in respect to disease and pest resistance for both traditional and improved bean and banana varieties. An important aspect of the methodology was to first understand, through focus group discussions, (i) the symptoms farmers used to identify the different

Table 9
Mean incidence (%) of BSM: Top 10 least and top 10 most infected varieties showing symptoms of BSM infestation in the field on farm. Mean percent incidence for each site is based on the total 65 varieties.

Variety	Kabwohe	Rubaya	Nakseke	Average % incidence
10 least infected varieties				
Kaki short	12.5	6.75	3	7.4
Kasirira	15.3	11.5	10.8	12.5
Kishoga	18.5	19.8	7	15.1
Katosire	24	17.8	9.8	17.2
Kayinja	29	37.3	27.8	31.3
Shemenoha	33.3	34.5	27.3	31.7
Kachwekano	34.8	37.6	24.3	32.3
Nabe 10 C	35.8	37.2	24.3	32.4
Nambale long	38.4	38.1	20.9	32.5
Mexic 54	36.5	36	25.3	32.6
10 most infected varieties				
Nabe 8C	42	42.8	31.3	38.7
Kanyebwa	42.6	44.5	30.5	39.2
Manyigamulimi	39.3	45.3	36.3	40.3
Kaddugala	42.6	48.3	37.3	42.8
Kishoga climber	48.3	58.5	52.3	53
Kanyebwa long	59.8	56.3	48	54.7
Mahega II	56.3	63.5	54.3	58
Rushare old	55.5	61.3	58.8	58.5
Kihura long	59	65.3	63.3	62.5
Kahura bush	66	66	64.5	65.5
Mean % incidence per site for all varieties	38.4	40.7	30.1	36.4
Kigome (susceptible check)	42.5	37.3	28	35.9

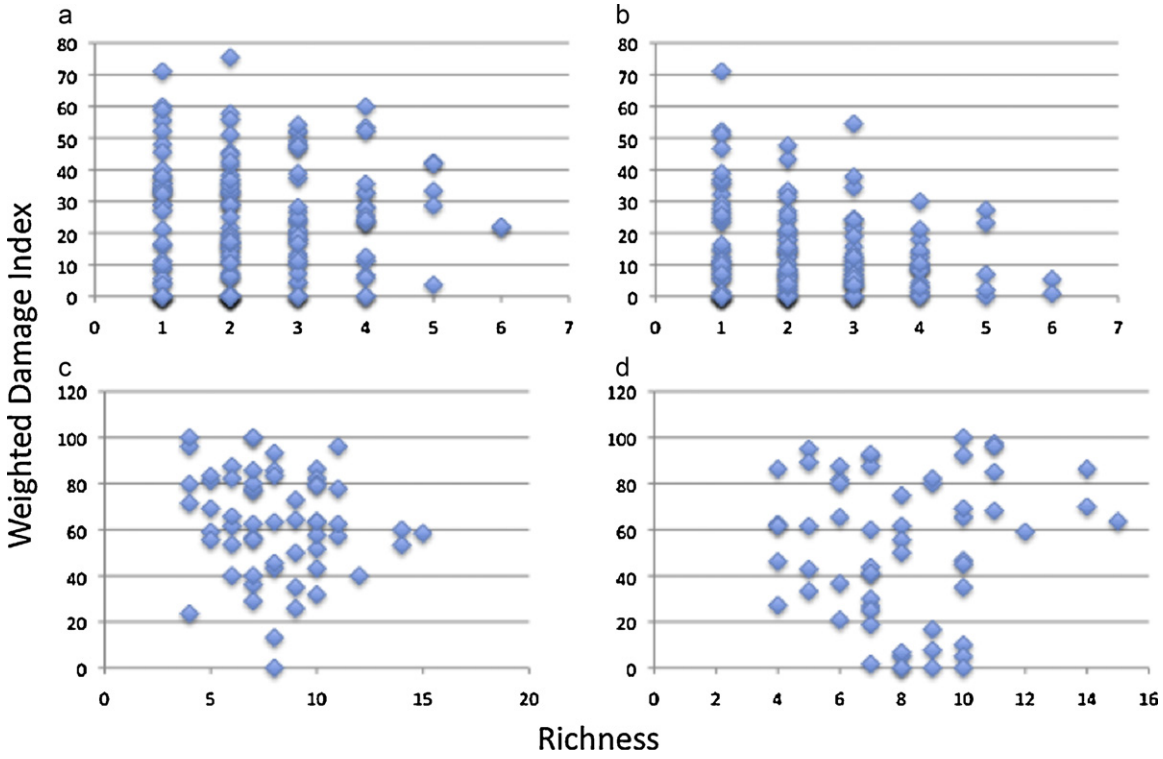

Fig. 2. Plots showing the relationship between richness and Weighted Damage Index (WDI = 0–100) for the common bean diseases: ALS (a) and anthracnose (b), and banana/plantain diseases: (c) black sigatoka (c) and weevils (d).

pests and diseases, to ensure farmer and researcher were discussing the same pest or disease, and (ii) to have an agreed understanding of levels of resistance based on these symptoms (Tables 4 and 5). The second step was to understand through household surveys farmers' knowledge of the resistance of the varieties they grow under their individual field and management conditions.

For both crops, *P. vulgaris* and *Musa* spp., individual traditional varieties scored highest in resistance, i.e., higher than the modern varieties. However, in the case of *P. vulgaris*, the mean score of

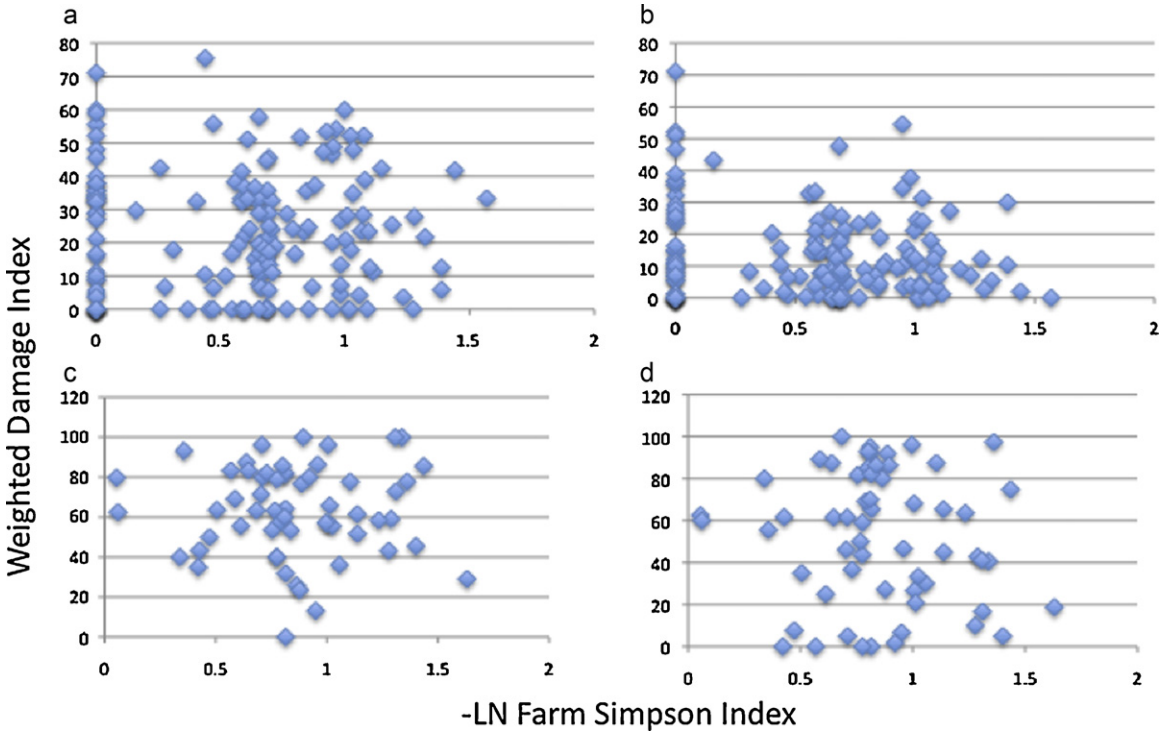

Fig. 3. Plots showing the relationship between Simpson (evenness) and Weighted Damage Index (WDI = 0–100) for common bean diseases (a) ALS and (b) anthracnose (b); and banana/plantain diseases (c) black sigatoka and (d) weevils.

resistance ranking for beans from the FGDs, modern varieties scored higher than traditional varieties. This ranking was not, however, confirmed by the screen house or the field trials, in which where the mean score for traditional varieties showed higher resistance to the targetted pests and diseases of the study than the modern varieties (Table 2). The traditional bean varieties Ngwinorale, Nambale short and Kahura short, which were ranked highest in resistance of all varieties by farmers, were also identified as having high resistance in the field trials compared to the other varieties and checks. Trutmann and co-workers (1996) noted in Rwanda that the majority of farmers attributed disease symptoms to sun, rain, poor soils and insects, with few farmers mentioning disease for common bean. In our focus group discussion, farmers divided the plant materials brought to the meeting into healthy and unhealthy plants, and then sub-divided the unhealthy plants into groups with different symptoms. Farmers were consistent in recognizing specific pest and disease symptoms, to the extent of giving names to some pests and diseases. However, they did not consistently distinguish whether these symptoms came from abiotic or biotic sources. Similar results were found for common bean in Ecuador, where farmers mentioned they believed diseases came from rain, neighbours, pesticides, and animals (Pazmino and Ochoa, 2011). Ochoa and co-workers also found, as noted in our study, that the majority of farmers had knowledge of plant transmission from diseased to healthy plants, suggesting that farmers are aware of epidemiological aspects of diseases (Pazmino and Ochoa, 2011).

Household level scoring of resistance of crop varieties (for diseases in general) for both *P. vulgaris and Musa* spp differed among farmers. This most probably reflected both the individual farmer's knowledge on host expression under his or her ecological conditions: different management practices; and possible differences in pathogen strains. Trutmann and co-workers (Trutmann et al., 1993) present earlier work in the Central African highlands documenting farmers' use of traditional varieties and multiple disease-management strategies, including mixtures, seed selection, sanitation practices and spatial management (density). They found high levels of resistance in farmers' bean mixtures for anthracose. They and others (Finckh and Wolfe, 2006) note, as our work here indicates, the positive advantages of mixtures for yield stability in low input agricultural ecosystems.

Field observations of traditional *Musa* varieties confirmed variation in resistance to black sigatoka across sites. The low percentage of people responding to the question of resistance levels for black sigatoka was low at household level because many farmers were not aware of the black sigatoka disease and took the symptoms as normal drying of leaves. Sigatoka disease is not destructive compared to other diseases, such as banana bacterial wilt (*Xanthomonas campestris* pv. *Musacearum*), which attracts more attention from farmers. Field observations showed that the same traditional varieties were less affected by black sigatoka in Kabwohe than in the Bunyaruguru or Nakaseke sites. This may have been due to altitudinal differences across sites as Kabwohe is at a higher altitude (1469 m) compared to Bunyaruguru and Nakaseke, which are at 1150 m and 1133 m, respectively. Black sigatoka incidence reduces with higher altitudes where temperature and humidity are low and hence affect spore production, survival and germination and this difference may exert an influence on disease incidence (Tushemereirwe et al., 2003). Management practices may also have played a role in creating differences in black sigatoka damage across sites in that banana plantations in Kabwohe are better managed than those of Bunyaruguru and Nakaseke, as the farmers in Kabwoke perform timely pruning to remove old leaves which otherwise can become a source of inoculum, increasing disease incidence (Tushemereirwe et al., 2003). Studies from Ghana by Bodakpui and co-workers (1991) showed that pruning and burning of diseased leaves is an alternative to fungicide application to control black sigatoka on *Musa* spp. and could partially explain why there is less black sigatoka incidence in Kabwohe than in Nakaseke. The difference in level of corm damage due to weevils across the three sites could be attributed to the different weather conditions and management practices employed in the sites, favouring differential weevils survival among sites. The study by Traore and co-workers (1993) showed that weevils' eggs could not hatch beyond 32 degrees C, which implies that temperature differences among sites have an influence on the survival and activity of weevils.

While banana black sigatoka and weevils are easily recognized by the majority of farmers, nematode infestation is not easily detected due to the microscopic nature of the pest. Farmers in Bunyaruguru and Kabwohe did not recognize banana nematodes as a problem, although field results showed that plant parasitic nematodes do occur in the area. Percent root necrosis assessment showed damage to the banana roots in both Bunyaruguru and Kabwoke. This is in line with the earlier studies that recorded presence of banana nematodes in both sites (Gold et al., 1993; Kashaija et al., 1994; Davide and Marasigan, 1985). The weighted average percent root necrosis was higher for some cultivars than others in Kabwohe than they were in Bunyaruguru. It is probable that *Musa* plants on the different farms had been exposed to different population levels of nematodes, depending on the source of planting materials and history of the plot.

4.2. On-farm diversity and field resistance to pests and diseases

Farmers in the study sites maintain substantial amount of *P. vulgaris* and *Musa* spp diversity both at the level of their individual farms and at community level for each site. Similar high levels in Uganda for traditional *P. vulgaris* varieties have been reported by Grisley and Sengoba (1993, cited in Thurston et al., 1999) and more recently by Buah (2010); and for traditional *Musa* by Karamura and Karamura (1995). Uganda is a secondary centre of diversity for both crops. Richness of Musa spp. varieties was significantly higher than that of *P. vulgaris*. Clonal crops, particularly when they are major staples, have been shown to have higher richness than seed crops (e.g., cassava and potatoes in Peru, Jarvis et al., 2008; Zimmerer, 2003). Amounts of diversity both in terms of richness (number of varieties) and evenness (variance of frequencies - Simpson index) of varieties were not significantly related to the area of the farmers' field. This gives an indication that larger fields are not necessarily indicative of higher numbers or more even frequencies of varieties planted, in contrast with in natural ecosystems where the normal species diversity-area relationship area is positively related to levels of diversity (Siegel, 1956).

A general trend across sites for the two crops is that when the number of varieties (richness; Figure 2a-d) and their evenness (Figure 3a-s) increases, the average damage levels decrease across sites. This gives an indication that diversity in the form of the number and evenness of distribution of varieties across the landscape provides a regulating element to pest and disease incidence. The relationship of increased diversity to decreased damage is particularly evident when the damage of the disease is higher (Table 8; Figures 2 and 3). Thus, in sites with higher disease incidence, households with higher levels of diversity in their production systems had less damage to their standing crop in the field compared to sites with lower disease incidence. Whether crop varietal diversity reduces yield variance under low, and not high, pesticide use as shown by Di Falco and Chavas (2007), could not be tested in the on-farm observations as only two of the sampled farmers used chemical pesticides in the sites. Spatial varietal mixtures of *P. vulgaris* and *Musa* spp. was a common management method in all bean sites. Mixtures included random pattern, rows, small plots of different varieties, and borders around plots, with random arrangements

as the prominent spatial arrangement. Comparisons of different spatial arrangements of varieties with the weighted damage indices for anthracnose and angular leaf spot in Kabwohe and Rubaya were positive but weak. Random spatial mixtures of host genotypes, as opposed to growing pure stands (plots), or rows, is said to reduce autoinfection because each plant is likely to be next to another genotype instead of next to the same genotype (Garrett and Mundt, 1999), described by Mundt (2002) as the host genotype unit area. Recent work from Ecuador has shown a similar positive relationship with increased evenness of *Musa* varieties to decreased damage from black sigatoka and weevils (Suarez-Capello and Agama, 2011). The use of mixtures, and the positive trend noted in this study linking increased evenness of variety distribution to reduced pest incidence and disease severity, offers opportunities for improving current integrated pest management (IPM) strategies in Uganda. An even more striking trend is the reduction in variance of disease damage as diversity increases, an indication that some of the uniform farms may be fine in some cases, if they happen to be growing a winning variety, but if not, then these farms get hit far worse in terms of crop damage when there is a change in pathogen or pest biotype. The results support what might be expected in a risk-minimizing argument for diversity use to reduce pest and disease damage.

4.3. Host resistance in on-farm field and screen house trials for P. vulgaris

All traditional varieties of *P. vulgaris* that arose from the focus group discussions and household surveys in all the sites were grown at each site. The logic was that even if a bean variety did not flower outside of its home environment, because of very different climate conditions compared to its home site, measurements of disease resistance at early growth stages could still be seen and the foreign variety could be used for breeding within the national breeding programme. In both screen house and field experiments for common bean, ALS was present, however screen house infection levels were higher (0-5 compared to 1-3 in the field). This may be attributed to the fact that artificial inoculation was used in the screen house and also conditions of inoculation were specifically suitable for ALS disease development. In the field, the experiment relied completely on the field inoculums and the environmental conditions may have been unsuitable for disease development and progress. In addition, the on-farm trial fields used were fairly new, having been used only once to grow beans in the previous season, and thus had low levels of inoculums. A few varieties, namely Mexico 54 (the resistant check for ALS), Nshemenoha, NABE 10c and NABE 13, showed low disease severity levels both in the field and in the screen house. Of these, Nshemenoha is a traditional variety while the rest are improved, The fact that none of the above varieties showed complete resistance both in field trials and in the screen house demonstrates the difficulty of selecting for complete resistance to the disease (see Allen et al., 1989). We speculate that the difference in reaction could have been due to differences in pathogen pathotypes between isolates used in the screenhouse and those that were present in the field. We cannot confirm this speculation as we did not conduct pathogenecity tests on the isolates. It still needs to be tested whether the difference between disease severity in varieties due to ALS was due to other factors such as unevenness of infection.

Bean fly infestation and damage is affected by environmental factors such as temperature, relative humidity and rainfall (Talekar and Lee, 1989), as well as the timing of planting. In the study by Kamneria (2007), results showed that incidence of bean fly were significantly higher in the short rains than in the long rains. In the long rains early-planted crops had significantly lower bean fly incidence than late-planted crops. The lower infestation in Nakaseke can be attributed to early planting and the amount of rainfall as well as other environmental factors. The observation that varieties differ in their reaction to bean fly infestation and damage, ranging from low to high, is in agreement with earlier studies (Ojwang et al., 2010). For instance, Ojwang et al. (2010) screened 64 bean genotypes and identified seven resistant bean landraces. Similarly, Ogecha et al. (2000) identified 13 out 66 screened varieties to be tolerant to BSM. These studies, together with our observations, show the presence of probable resistant landraces currently being grown by farmers, and may in part explain the reasons for varietal mixing. The study has determined the reaction of some common bean landraces in Uganda to BSM infestation and damage and will act as a stepping-stone for the choice of varieties for integration into varietal mixture studies. However, further studies are needed to validate these findings before incorporating the varieties for mixture studies.

Kiggundu et al. (2003) reported that all traditional banana cultivars are susceptible to banana weevil with little variation, while some hybrids like Km5, FIAH 17 and Kayinja (traditional) are highly resistant. The differences in host resistance to banana weevil by different cultivars and corm damage across study sites observed by farmers may be partially attributed to sanitation management, which varies among farmers and across sites. Masanza et al. (2004) observed variation in sanitation levels among farmers and also observed that farms with good sanitation management had low weevil population and corm damage.

5. Conclusion

The study has revealed the high level of traditional varietal diversity of banana and plantain (*Musa* spp) and common bean *(P. vulgaris*) in respect to the pests and diseases investigated in this study is still found in farmers' fields in Uganda. Together with this crop varietal diversity is a diversity of knowledge and practices used by farmers to manage pests and diseases in these crops. The potential of the diversity in farmers' fields to control pests and diseases as well as to reduce genetic vulnerability if managed appropriately, was shown clearly from the study, particularly when the damage index was high (seen from the negative correlations among diversity measures and damage indices). In sites with higher disease incidence, households with higher levels of intra-specific diversity in their production systems had less damage to their standing crop in the field compared to sites with lower disease incidence. The use of mixtures, by providing increased evenness of variety frequencies in the farmers' field, assists in reducing pest incidence and disease severity, offering opportunities for improving current integrated pest management (IPM) strategies. The reduction in variance in disease damage with higher numbers of varieties at the household level is an important indication that increased crop varietal diversity may not only have the potential to reduce current crop damage but also have the potential to reduce the vulnerability to pest and disease infestations in the future, supporting the use of intra-specific crop diversity within the production system to reduce risk. By performing cross-site on-farm experiments, traditional varieties with higher resistance to pest and diseases when grown outside their home sites have been identified. These potentially resistant varieties have already been taken up by both the local farming communities for their own experimentation and by the national breeders involved in this project for further analysis for use in crop varietal mixtures and crop improvement.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agee.2012.02.012.

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