Multi-environment Selection of Small Sieve Snap Beans Reduces Production Constraints in East Africa and Subtropical Regions

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Abstract. Small-sieve snap beans (Phaseolus vulgaris L.) are an important source of income for smallholder farmers in East Africa. In this region as well as in other tropical and subtropical environments, common bean rust, caused by Uromyces appendiculatus (Pers.:Pers.), and heat stress reduce the yield and quality of snap beans. Small-sieve rust-resistant snap beans and that are heat-tolerant were developed using heat-tolerant snap bean breeding lines that had broad-spectrum rust resistance conditioned by the combination of the Andean Ur-4 and Mesoamerican Ur-11 genes. The Ur-4 and Ur-11 rust gene combination confers resistance to 90 races of the hypervariable pathogen from different parts of the world, including East Africa, that are maintained at Beltsville, MD. Four breeding lines each having the combination of the two rust genes were crossed in a 4 × 5 diallel mating design with five susceptible small-sieve cultivars to give 20 F1 hybrids. The hybrid combinations were advanced through the F2, F3, and F4 generations with selection for heat tolerance, rust resistance, and pod quality to develop lines combining these traits. Twenty F4 breeding lines that had the combination of these traits were selected and evaluated in East Africa at four field sites selected on the basis of differences in altitude, climate, and virulence diversity of the bean rust pathogen and in Puerto Rico at a field site characterized by high temperatures. There was a significant positive correlation between ranks of heat stress influenced yield components (seeds per pod and total yield) at the hot field site and the controlled high-temperature (32/27°C) greenhouse. Four of the breeding lines developed, L5, L9, L13, and L17, combined heat tolerance and rust resistance in the desired plant type with high yield and good pod quality. These lines are the first known small-sieve snap beans with the combination of traits for heat tolerance and broad-spectrum rust resistance conferred by the Ur-4 and Ur-11 genes. These results demonstrate ability to combine heat tolerance and rust resistance as important traits for adaptation of specific market classes of common bean to tropical and subtropical environments through targeted selection of multiple traits in controlled environments.

Snap beans or green beans have been selected for high pod quality with reduced fiber and are consumed as green pods harvested for the fresh market or processing. Slender or “small-sieve” snap beans or green beans, also known as “French beans” are an important source of income for smallholder growers in East Africa who produce the crop for export markets typically in Western Europe [CBI, 2006; Centro Internacional de Agricultura Tropical (CIAT), 2006; Muchui et al., 2008; Okello and Roy, 2007], but they are also increasingly becoming important for domestic markets where they provide an important source of nutrition (CIAT, 2006; Kinyuru et al., 2011).

Production is concentrated at elevations above 1500 m at the east side of Lake Victoria, where they are grown during the rainy seasons and are harvested by hand up to six times in each season. The primary constraints to production are caused by high night temperatures, which restrict growing areas to higher altitudes, and airborne diseases in particular, common bean rust caused by the fungus Uromyces appendiculatus, which can severely limit the yield and quality of the snap bean crops (CIAT, 2006; Wasonga et al., 2010; Wortmann et al., 1998). Rust is a destructive disease of common beans in subtropical and tropical regions and is particularly severe in eastern and southern Africa (Kimani et al., 2002; Liebenberg et al., 2006; Wortmann et al., 1998). Heat stress and rust occur within the same production regions in East Africa (Wasonga et al., 2010) reducing both the quality and yields of snap bean crops generated.

The majority of snap bean cultivars grown in East Africa are highly susceptible to rust (Kimani et al., 2002; Wasonga et al., 2010). Use of genetic resistance in the management of bean rust has been difficult to achieve as a result of the extensive and shifting nature of virulence diversity of the pathogen (Araya et al., 2004; Liebenberg, 2003; Markell et al., 2009; Wright et al., 2008) coupled with lack of a single resistance gene that could confer resistance against all the races of the pathogen (Pastor-Corrales, 2006; Stavelly and Pastor-Corrales, 1989). The deployment of Andean Ur-4 in combination with Middle American Ur-11 rust-resistance genes provided effective resistance to rust at different test sites in East Africa (Wasonga et al., 2010).

Higher than optimal temperatures (heat stress) adversely affect crop growth and productivity (Challinor et al., 2007; Wahid et al., 2007). Snap bean production in East Africa is currently limited to cool highland areas above 1500 m, because higher night temperatures experienced at lower altitudes reduce yield and green pod quality. Furthermore, land areas that are suitable for snap bean production in the East Africa region are expected to reduce in size given climate change-associated temperature increases currently being experienced across sub-Saharan Africa (Hulme et al., 2001; King’uyu et al., 2000). These temperature increases in sub-Saharan Africa are expected to exceed projected global mean increase of 2.5 °C by 0.7 to 1.1 °C by the end of the 21st century (Christensen et al., 2007; Cline, 2007). There is therefore need to adopt crop-specific production approaches that would enable increased or sustained productivity under elevated temperature conditions.

Genetic improvement of snap bean for tolerance to high-temperature stress is a promising option for increasing yield and quality in heat-stressed environments (Porch and Jahn, 2001; Rainey and Griffiths, 2005). Wasonga et al. (2010) developed and tested in East Africa some heat-tolerant snap bean breeding lines that demonstrated potential for improving production in the region as well as other tropical and subtropical environments where high temperatures presently limit production and changing climatic conditions are likely to become more challenging.

Among the quality attributes used to categorize snap beans for East Africa production are a small pod diameter, commonly referred to as small-sieve, in a long, slender, dark green pod. Size is determined by the maximum width of the pod measured at right angles to the seam and is classified as follows: 1) extra fine: width of the pod not exceeding 6 mm (sieve size 1); 2) fine: width of the pod...
not exceeding 9 mm (sieve sizes 2 and 3); and 3) medium: width of the pod not exceeding 12 mm. Lines with pods not exceeding 9 mm (sieve sizes 2 and 3); and 3) medium: width of the pod not exceeding 12 mm. In East Africa, small-sieve snap bean cultivars producing extrafine and fine pods are the grades that growers desire for the markets served (Muchui et al., 2008). The small-sieve snap bean cultivars currently grown in East Africa lack the optimal combinations of traits for more efficient production that would be provided by incorporation of rust resistance and tolerance to high-temperature stress.

The overall goal was to improve snap bean for rust resistance and heat tolerance to increase production in environments experiencing these challenges need to ensure that the optimal traits are combined in desired market types that are high-yielding with good pod quality. The specific objectives of this study were to: 1) combine heat tolerance and optimal rust-resistance gene combinations in small-sieve snap bean genotypes; and 2) evaluate the snap bean lines in five locations in East Africa and one site in Puerto Rico, which differ in climatic conditions and virulence diversity for the bean rust pathogen.

Materials and Methods

Population development

Four parental snap bean breeding lines (HT1, HT2, HT3, and HS1) whose pedigrees are detailed in Wasonga et al. (2010) were used as sources for high-temperature tolerance and broad-spectrum rust resistance involving the Ur-4 and Ur-11 rust-resistance genes. HT1, HT2, and HT3 each had the combination of the traits for high-temperature tolerance and the two rust-resistance genes. HS1 had the Ur-4 and Ur-11 rust genes but lacked the trait for high-temperature tolerance and was included to enable the development of lines with low tolerance to high temperatures to be used as checks. The four lines were planted on 23 June 2008 and crossed in a 4 × 5 diallel mating design to five selected snap bean cultivars: ‘Amy’ (Seminis, St. Louis, MO), ‘Teresa’ (Seminis), and ‘PV712’ (Pop Vriend, Andijk, The Netherlands), which are currently grown in a fresh-market production in East Africa, but lack tolerance to high temperatures and/or effective rust resistance, and ‘Masai’ (Syngenta, Boise, ID) and ‘Bronco’ (Seminis), which are grown in the United States. ‘PV712’ is a new genotype targeted for East Africa that has the Ur-4 and Ur-11 rust-resistance gene combination but is highly sensitive to high temperatures (Wasonga et al., 2010). ‘Teresa’ has the Ur-5 rust-resistance gene but is also sensitive to high temperatures. ‘Amy’ is susceptible to the bean rust pathogen and also sensitive to heat stress. ‘Masai’ is a rust-susceptible and heat-sensitive cultivar grown for the small-sieve “whole bean” market in the United States and ‘Bronco’ is a fresh-market medium-sieve snap bean cultivar with some tolerance to higher temperatures but susceptible to rust (Wasonga et al., 2010). The parents were grown in a greenhouse with temperatures set at 24/21 °C (day/night) and crosses made through hand-pollination in a 4 × 5 diallel mating design.

Breeding line selection

The 20 F1 hybrid combinations from crosses involving the four snap bean breeding lines and five snap bean cultivars were generated in July 2008 (Fig. 1). F1 phenotypes were visually compared with phenotypes of the corresponding parents to validate successful crosses from which the F2 hybrids were selected. The selected F1 hybrid seed were allowed to self-pollinate under greenhouse environment, 24/21 °C (day/night, 14-h photoperiod), in Geneva, NY, to produce 20 F2 populations (Fig. 1). In Jan. 2009, 40 plants from each of the 20 F2 populations were grown in the same greenhouse environment with similar environmental conditions as described previously. Single plants were grown in 20-cm diameter and 20-cm deep round plastic pots filled with “Cornell mix” growth medium (Boodley and Sheldrake, 1972). The pots were arranged in a randomized complete block design (RCBD) with four replications with each block replicate having 10 plants of each of the 20 F2 populations. The RCBD arrangement was adopted so to take care of possible temperature variability that could arise from uneven airflow within the greenhouse. The F2 populations were evaluated and a stratified selection approach followed to pick the best four individual plants from each F2 population on the basis of yield, small-sieve pods and small seed size. A total of 80 selections were made, representing four lines from each of the 20 possible cross combinations.

The 80 selected F2 and nine parental lines were planted in a greenhouse in Apr. 2009 for selection for tolerance to high temperatures, pod quality, and pod size among other phenotypic evaluations (Fig. 1) followed by selection based on yield components. During the evaluation of the F2 generation, temperatures in the greenhouse were 24/21 °C (day/night) for the first 3 weeks after planting and then adjusted to 32/27 °C (day/night) before the onset of anthesis. The high-temperature environment was maintained until plants ceased flower set.

Five yield components were documented: number of pods per plant, number of seeds per pod, total seed weight per plant, and mean seed weight (calculated from 100-seed weight) and used for the selection of the most promising lines, maintaining representation from all lineages. The best plants were identified from each of the 80 F2 lines based on rankings of seed size,
the mean number of seeds per pod, and the total seed yield under high-temperature stress. The 80 selected F3 lines were concurrently tested for the presence of Ur-4 and Ur-11 rust-resistance genes to identify lines fixed for the two genes and the lines were also increased for seed. The procedure followed for identifying plants with the presence of the Ur-4 and Ur-11 rust-resistance genes under greenhouse conditions at the USDA-ARS-BARC facilities is described in detail in Wasonga et al. (2010). The F3 lines, which were presumably fixed for the Ur-4 and Ur-11 rust-resistance genes, were identified. For each of the 20 lineages, four lines that were preliminarily determined to be fixed for the two rust-resistance genes and also ranked high in heat tolerance were selected. Heat-tolerant lines that were fixed or heterozygous for the Ur-11 gene were selected in situations in which less than four lines were fixed for the two rust-resistance genes in that lineage. This was undertaken to ensure equal lineage representation during subsequent field evaluation and selection; this resulted in 20 lines being selected for evaluation at the East African sites (Table 1). Four plants of each of the 20 lines were grown under greenhouse conditions with temperatures of 24/21 °C (day/night) to determine correlations between controlled-temperature testing and field performance.

Field and greenhouse evaluation of breeding lines

Plant material and trial design. The 20 F3 small-sieve snap bean breeding lines were increased and evaluated for reaction to rust and yield components in a high-temperature greenhouse adjusted to 32/27 °C (day/night), in Geneva, NY, and under field conditions at four sites in East Africa and one in Puerto Rico together with the donor parents HT1, HT2, HT3, and HSi and cultivar parents Amy, PV 712, Teresa, Masai, and Bronco as checks. Other cultivars adapted for production in other geographical regions and previously tested under field conditions in East Africa (Wasonga et al., 2010) were included as additional checks during the field evaluation, including: ‘PV 698’ (Pop Vriend) developed for East Africa; ‘Barrier’ and ‘Juilet’ (Alpha Seeds, Henley on Klip, South Africa) developed for Southern Africa; ‘Palati’ (Syngenta, Boise, ID) developed for Northern Africa; ‘Opus’ and ‘Brio’ (Seminis) developed for the southeast United States; and ‘Hystyle’ (Harris Moran, Modesto, CA) developed for northeast United States. There were 36 entries in total for the field performance trials. The entries were grown in a RCBD with four replications per site at four field sites in East Africa and at one site in Puerto Rico (Homabay, Kenya; Kakamega, Kenya; Kitale, Kenya; Arusha, Tanzania; Juana Diaz, Puerto Rico). The lines were evaluated in a greenhouse with controlled temperatures at 32/27 °C (day/night) to determine correlations between controlled-temperature testing and field performance. A set of 12 differential cultivars was also planted at four sites in East Africa with the aim of determining the virulence diversity/spectrum of common bean rust isolates present at the field sites. Six of the differential cultivars (with their rust-resistance genes in parenthesis) were from the Andean gene pool and included ‘Early Gallatin’ (Ur-4), ‘Redlands Pioneer’ (Ur-13), ‘Montcalm’ (unknown rust-resistance genes), ‘Pompadour Checa (PC) 50’ (Ur-9, Ur-12), ‘Golden Gate Wax’ (Ur-6), and ‘PI 260418’ (unknown rust-resistance genes); whereas the cultivars from the Middle American gene pool included ‘Great Northern 1140’ (Ur-7), ‘Aurora’ (Ur-3), ‘Mexico 309’ (Ur-5), ‘Mexico 235’ (Ur-3), ‘Compuesto Negro Chimaltenango’ (CNC; unknown rust-resistance genes), and ‘PI 181996’ (Ur-11).

Field trial locations and descriptions. The field trials were carried out between March and June 2010 during the long rainy season at four sites in East Africa: Arusha in Tanzania (AVRDC-RC), Homabay (at the Farmers Training Center), Kakamega and Kitale in Kenya (KARI sites), and between July and Sept. 2010 in Juana Diaz, Puerto Rico (University of Puerto Rico). The sites were selected on the basis of differences in soils, altitude, and climate as detailed in Wasonga et al. (2010). The altitude at the East African sites were 1235, 1172, 1585, and 1829 m above sea level at Arusha, Homabay, Kakamega, and Kitale, respectively. Mean minimum and maximum temperatures, respectively, at the sites during the field trial period were: Arusha (13.0/24.3 °C), Homabay (17.0/33.5 °C), Kakamega (15.5/28.9 °C), Kitale (13.6/25.7 °C), and Puerto Rico (23/35 °C). The lowest and the highest mean temperatures were recorded at Arusha and Puerto Rico, respectively. The field sites were tractor-plowed to a fine till before planting. Planting dates were 10 Mar. (Arusha), 22 Mar. (Kakamega), 24 Mar. (Kitale), 26 Mar. (Homabay), and 1 June (Puerto Rico). Single rows of 25 seeds were planted per block for each of the 36 entries. A planting density in which seeds were placed at 0.5 m between rows and 0.1 m within rows was used. A compound inorganic fertilizer (10N–11.3P–8.3K) was applied at planting at a rate of 200 kg ha–1 at all African sites except Arusha whose soils were considered fertile. A compound inorganic fertilizer (10N–10P–10K) was applied in Puerto Rico at a rate of 400 kg ha–1. The African trial plots were rain-fed but supplemental irrigation was applied to avert potential water stress resulting from low rainfall during the early stages of the trial. In Puerto Rico, drip irrigation was used to irrigate the plot. The plots were kept weed-free on a biweekly basis through hand cultivation starting soon after emergence.

Data collection and analysis

The snap bean entries and differential cultivars were monitored for symptoms of rust and the date on which the first disease symptoms were observed at each site was noted so as to enable accounting for possible site differences in rust severity and its effect on yield. During an earlier trial at these sites, it was observed that reduction in yield that was attributed to rust on susceptible genotypes was more pronounced when the disease manifested at a site earlier in the season compared with later in the season (Wasonga et al., 2010). A recording of the dates on which the disease was first observed at the sites enabled an accounting of site yield differences for specific genotypes, especially at sites where early- and late-season infections were observed.

The entries were scored for incidence and severity of the bean rust pathogen at flowering (R6) and at pod filling (R8) developmental stages. Quantitative information on line reaction to rust and rust incidence was obtained by counting the number of rust infected plants per plot, whereas rust severity was determined by the number of visible rust pustules (0.5 mm
or greater) formed per leaflet in each of the four replicates. Correlation analysis of rust incidence and severity was used to visualize line differences in reaction to rust. In the correlation plot, genotypes that had no rust were considered highly resistant, whereas those with high rust incidence and severity were considered highly rust-susceptible (Wasonga et al., 2010). The genotypes that had high, moderate, or low rust severity on a few plants (low incidence) were assumed to be either partially rust-resistant or heterozygous for the rust-resistance genes.

The performance of the lines for yield was obtained by recording the number of pods produced per plant at the field sites in East Africa. In the greenhouse trial in New York and the field trial in Puerto Rico, where the goal was to test response to heat stress, data were collected for seed weight per plant and seeds per pod because these are considered most indicative of response to high-temperature stress. The total number of pods produced per plot were counted while excluding single plants at the end of the rows and then divided by the total number of plants examined within the plot.

The statistical model used in the data analysis was:

\[ y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \epsilon_{ijk} \]

where: \( y_{ijk} \) = \( k\)th response at combination \((i,j)\); \( \mu \) = overall mean; \( \alpha_i \) = main effect of line \( i \); \( \beta_j \) = main effect of site \( j \); \( \alpha\beta_{ij} \) = line/site interaction effect; and \( \epsilon_{ijk} \) = random error associated with \( k\)th response at combination \((i,j)\). The main effect of line \( \alpha_i \) was considered fixed, whereas the effect of site \( \beta_j \) was considered random.

JMP 8 software (SAS Institute Inc., Cary, NC) was used to conduct analysis of variance for disease severity, pods per plant, seed weight per plant, and seeds per pod, and pairwise comparisons of means were made using Tukey’s multiple means comparison method. Phenotypic correlation coefficients among the measured yield components in the greenhouse and field were calculated using Spearman’s rank correlation. Information on rust resistance, pod yield, plant type, and pod quality was used to select superior lines.

**Results and Discussion**

**Reaction to common bean rust under field conditions**

There was higher virulence diversity of the rust pathogen at the Kitale and Kakamega sites given the observation that more differential cultivars were susceptible at these two sites, which was expected because they are located at a higher altitude than the Homabay and Arusha sites. Most of the Andean differential cultivars were susceptible to rust at all four sites with the exception of ‘PI 260418’, which was resistant at all sites. Andean beans, ‘Redlands Pioneer’ and ‘PC 50’, were resistant at two and one of the sites, respectively (Table 2). Most of the Mesoamerican differential cultivars were resistant at three of the four sites with the exception of ‘GN 1140’, which was susceptible at all four sites, and ‘Aurora’, which was susceptible at Kakamega and Kitale. These results implied that the race structure of the rust pathogen prevalent at these four locations was Andean composed of races that are virulent only or mostly on common beans belonging to the Andean gene pool (Pastor-Corrales and Aime, 2004). Based on the reaction of the differential cultivars to rust at the sites, the bean rust races were determined to be: 21-1, 29-1, 31-3, and 31-3 at Arusha, Homabay, Kakamega, and Kitale sites, respectively (Table 2) (Steadman et al., 2002). Similarly, rust severity was highest in the higher altitude Kitale and Kakamega sites followed by Arusha and Homabay. The virulence spectrum of the races of the rust pathogen at the high altitude sites was broader compared with the lower altitude sites as illustrated by the reaction of ‘Aurora’ and ‘Redlands Pioneer’, which were rust-susceptible only at the high altitude site (Table 2).

The genotypes used as checks, HS1, HT1, HT2, ‘PV698’, and ‘PV712’, were rust-resistant at all sites. The observed overall susceptibility of ‘Early Gallatin’ (Ur-4) at four locations in East Africa suggests that the

**Table 2. Characteristics of 12 bean differential cultivars and reaction to common bean rust at Arusha, Homabay, Kakamega, and Kitale field sites in East Africa and implied virulence diversity of the pathogen at contrasting field sites in the region.**

| Differential cultivar | Rust resistance gene | Gene pool | Binary value | Reaction to rust by site*** |
|-----------------------|----------------------|-----------|--------------|-----------------------------|
|                       |                      |           |              | Arusha | Homabay | Kakamega | Kitale |
| Early Gallatin        | Ur-4                 | A/MA      | 1            | S      | S       | S        | S      |
| Redlands Pioneer      | Ur-13                | A         | 2            | R      | R       | S        | S      |
| Montclair             | Unknown              | A         | 4            | S      | S       | S        | S      |
| P.C. 50               | Ur-9 and Ur-12       | A         | 8            | R      | S       | S        | S      |
| Golden Gate Wax       | Ur-6                 | A/MA      | 16           | S      | S       | S        | S      |
| PI 260418             | Ur-P (unknown)       | A         | 32           | R      | R       | R        | R      |
| Great Northern 1140   | Ur-7                 | MA        | 1            | S      | S       | S        | S      |
| Aurora                | Ur-3                 | MA        | 2            | R      | R       | S        | S      |
| Mexico 309            | Ur-5                 | MA        | 4            | R      | R       | R        | R      |
| Mexico 235            | Ur-3                 | MA        | 8            | R      | R       | R        | R      |
| CNC                   | Unknown              | MA        | 16           | R      | R       | R        | R      |
| PI 181996             | Ur-11                | MA        | 32           | R      | R       | R        | R      |

*Table 2. Characteristics of 12 bean differential cultivars and reaction to common bean rust at Arusha, Homabay, Kakamega, and Kitale field sites in East Africa and implied virulence diversity of the pathogen at contrasting field sites in the region.*

*Differential cultivar with Unknown in the rust resistance gene column has an unidentified rust gene.*

*A = differential cultivars from the Andean gene pool; MA = those from the Middle American gene pool; A/MA = those differential cultivars occurring in both gene pools.*

*Binary value refers to the value that rust-resistance genes in the differential cultivars have been assigned based on the spectrum of virulent races of the bean rust pathogen they are able to control. The higher values are assigned to those genes that confer resistance to a wider spectrum of the rust races.*

*S and R = susceptible and resistant reactions, respectively. In the case of resistant reaction, rust symptoms are absent.*

*Based on susceptible reaction of the differential cultivars, the virulence diversity of the common bean rust at the sites was in the order of Arusha < Homabay < Kakamega = Kitale.*

**Fig. 2. Rust incidence (rust infected plants) and severity on 20 snap bean breeding lines (L1–L20) and 16 control lines evaluated in 2010. The data points are lines means over four field sites: Arusha, Homabay, Kakamega, and Kitale. HT1, HT2, HT3, HS1, Amy, Bronco Masai, PV712, and Teresa were the parents.**
rust resistance of the snap bean lines is derived from Ur-11, which had previously also been shown to effectively confer rust resistance at numerous sites in East Africa (Wasonga et al., 2010). ‘Teresa’ (which has Ur-5) was not completely resistant, because a few rust pustules were observed on 4% of the plants at four sites in East Africa (Wasonga et al., 2010) and present field studies (Fig. 1). The breeding lines L17 is also a rust-resistant selection derived from a cross of HT1 and ‘Teresa’ cross (Table 1), L17 is also rust-resistant and heat-tolerant. The line had good pod yield and pod set at the higher temperature Homabay site showed that, in addition to being rust-resistant, this selection has good agronomic traits such as early maturity, disease resistance, and high yield potential.

The breeding lines L1, L3, L4, L6, L7, L14, and L19 were heterozygous for the Ur-11 gene, which had previously also been shown to effectively confer rust resistance at numerous sites in East Africa (Wasonga et al., 2010). ‘Teresa’ (which has Ur-5) was not completely resistant, because a few rust pustules were observed on 4% of the plants at four sites in East Africa (Wasonga et al., 2010) and present field studies (Fig. 1). The breeding lines L17 is also a rust-resistant selection derived from a cross of HT1 and ‘Teresa’ cross (Table 1), L17 is also rust-resistant and heat-tolerant. The line had good pod yield and pod set at the higher temperature Homabay site showed that, in addition to being rust-resistant, this selection has good agronomic traits such as early maturity, disease resistance, and high yield potential.

### Yield under field conditions

The top five yielding lines at the four sites were L17 followed by L19, ‘Masi’, L9, and ‘PV698’ (Table 3). ‘Masi’, which was included as a heat-sensitive and rust-susceptible control, had lower yield in Homabay (which was the hottest of the sites) compared with its performance at the cool, high-altitude site in Kitale and was consistent with its performance at these two sites in 2009 (Wasonga et al., 2010). From the 12 rust-resistant entries, L5, L9, L13, and L17 were selected as the most promising on the basis of high yields, high pod quality, and upright bush plant phenotype (Table 3). L17 had a consistently high pod load in Arusha, where it was the highest yielding line. In Kakamega and Kitale, L17 was among the top three highest yielders and in Homabay it had a mean yield equal to the overall site mean yield (Table 3). L17 has high-quality pods—straight, fleshy, small-sized sieved pods—and an upright bush plant growth habit and small- to medium-sized leaves that makes its canopy relatively open. As a selection from the HT1 and ‘Teresa’ cross (Table 1), L17 is also rust-resistant and heat-tolerant. The line had good pod yield and pod set at the higher temperature Homabay site showed that, in addition to being rust-resistant, this selection has good agronomic traits such as early maturity, disease resistance, and high yield potential.
considerable level of heat tolerance compared with ‘Masai’, one of the parents from which it was derived, and may therefore have better adaptation and productivity in warmer, lower altitude sites. The high pod set trait derived from ‘Masai’ was verified at the cooler higher altitude sites such as Kitale (Table 3).

L9 is a rust-resistant selection derived from crossing HT1 with ‘PV712’ (Table 1). It has an upright bush habit with straight, fleshy, small-sieve pods. Its mean pod yield at each of the four sites was significantly higher than the mean of each of its parents, HT1 and PV712. Line L9 was ranked best among the 12 rust-resistant breeding lines and was the second best line among the 36 snap bean lines tested at the Homabay site (Table 3). The high yield of L9 at Homabay shows that it has good levels of heat tolerance and that it is more adapted to this low altitude site than its parents and the other lines tested.

Comparison of response to high-temperature conditions in the greenhouse and field

Response of the breeding lines to high-temperature conditions was evaluated using data from the greenhouse and field site in Juana Diaz, Puerto Rico. Two yield components: seed weight per plant and seeds per pod, which are more indicative of heat tolerance, were measured at these two environments (Table 4). In the evaluation under the two environments, the entries were compared for their relative ranking for the two yield components. Spearman’s rank correlation calculated for the 36 lines between the two sites were $R = 0.48$ with a $P \leq 0.005$ for mean seed weight per plant and $P \leq 0.01$ for seeds per pod. These results demonstrate the ability to select for heat tolerance traits in a controlled-temperature environment that have representative rankings in a field testing environment. The rank correlations implied that line performance in the controlled greenhouse environment ($32/27^\circ C$) was indicative of performance in the high-temperature field site in Puerto Rico in response to heat stress. The best lines at these two environments could therefore be considered to be more heat-tolerant relative to the other lines evaluated. In this regard, breeding line HT3 could be considered the most heat-tolerant, whereas ‘PV698’ and ‘Masai’ could be considered the most heat-sensitive based on the results from the 2010 trial (Fig. 3). The observed response of these lines under the greenhouse and field environments characterized by high temperatures is in part consistent with that made during the 2009 season (Wasonga et al., 2010) in which ‘PV698’ and ‘Masai’ were found to be heat-sensitive based on their responses at the high-temperature sites of Homabay and Puerto Rico. The breeding selections L5, L9, and L13 could be considered to have heat tolerance for small-sieve selections given their overall rankings among the 36 lines and specifically in relation to their parents: ‘Bronco’, ‘PV698’, and ‘Masai’, which ranked lower on average across the two environments.

Conclusions

Four small-sieve snap bean entries that were developed and combined the Ur-4 and Ur-11 rust-resistance genes and tolerance to high temperature stress (L5, L9, L13, and L17) demonstrate that these traits can be effectively combined into desired market types for the development of cultivars with better adaptation to the growing constraints. This research demonstrated that small-sieve snap beans with high yields and quality of pods can be developed and selected and would benefit significantly from broad-spectrum resistance to rust provided by the combination of Ur-4 and Ur-11 in a high-temperature tolerant genotype. Cultivars combining the Ur-4 and Ur-11 resistance genes would reduce dependence on fungicides in the control of rust, resulting in reduced production costs and increased crop quality. The high-temperature tolerance trait in the cultivars would enable increased production of high-quality snap beans in areas and seasons characterized by higher than optimal temperatures that are also subject to climate change.

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