



Developing Beans that Can Beat the Heat

In Africa and Latin America, the production of beans (*Phaseolus vulgaris*) is highly vulnerable to climate change impacts, which include higher temperatures and more frequent drought. Within the last 15 years, CGIAR researchers have registered key advances – particularly the development of drought-tolerant and disease-resistant varieties – that will help make production more resilient in the face of future threats.

Just within the last few years, however, climate modeling has suggested that, over the next several decades, higher temperatures will become the primary threat to bean production. According to recent projections, the area suited for this crop in eastern and central Africa could shrink up to 50% by 2050. Affecting mainly lowland areas, heat stress will pose a particularly serious problem for bean crops in Malawi and the Democratic Republic of the Congo (DR Congo), followed by Tanzania, Uganda, and Kenya. Across Latin America, the situation is also dire. Bean production in Nicaragua, Haiti, Brazil, and Honduras, as well as Guatemala and Mexico, would be most impacted.

In response to this concern, CIAT researchers have recently identified elite lines that show strong tolerance to temperatures 4 °C higher than the range that beans can normally tolerate. Many of these lines come from wide crosses between common and tepary beans (*Phaseolus acutifolius*), a species originating in the arid US Southwest and northwestern Mexico.

This document reports findings from research conducted over the last year, which confirm heat tolerance in selected bean lines and show their potential for adapting bean production in Africa and Latin America to future climate change impacts.

CGIAR global research

CGIAR is a global partnership for a food-secure future. Its science is carried out by the 15 centers who are members of the CGIAR Consortium in collaboration with hundreds of partner organizations.



Targeting heat-tolerant genotypes to vulnerable production areas by administrative units

Rationale

An analysis of the geographical extent of the effects of rising temperatures on bean productivity was carried out previously (Beebe et al., 2013).¹ Heat stress was estimated to be the abiotic constraint most likely to limit productivity on a global scale. Subsequent analyses on a global scale have confirmed this conclusion (data not shown). However, research on the ground is carried out within administrative boundaries that define partners and research sites. The current activity sought to translate bean production regions at risk of high temperatures into administrative names (e.g., municipalities) to facilitate communication with partners and planning of research and interventions.

Materials and methods

Data on distribution of bean production were compared with estimated future temperature rise at the level of administrative units and in a 16-year horizon to 2030, based on a 10-km pixel. This permits addressing rising temperatures at the local level. Expected average temperature for each administrative unit was compared with bean area within the administrative unit. For Latin America, the administrative unit was the department in Central America or

CGIAR research on beans

Often referred to as “the meat of the poor,” beans offer a crucial source of vitamins and protein as well as income for millions of people, particularly in Africa and Latin America. Decades of CGIAR research on beans have led to massive uptake of improved varieties, with significant impacts on food security in major bean-producing countries. With our partners, we develop more productive, nutritionally improved beans that show resilience under harsh growing conditions, which are becoming even worse as a result of climate change impacts.

the state in the case of Brazil and Mexico (still quite a gross measure, but one that can be refined). In Africa, to which CGIAR gives highest priority, the unit was the municipality. An arbitrary average temperature of 25 °C was used as a limit at which high temperature would become limiting. Bean area for which this temperature would be relevant was summed and is presented together with the total bean area per country in **Table 1**. The percent bean area under threat is presented.

Table 1. Area under bean production subject to heat stress of 25 °C or greater average temperature by 2030 in selected countries of Latin America and Africa.

	Area (ha) with > 25 °C	Total bean area (ha)	Percentage of total by country
AFRICA			
Malawi	51,436	143,963	36%
DR Congo	48,863	225,789	22%
Tanzania	82,531	696,282	12%
Uganda	53,304	693,998	8%
Kenya	46,340	825,175	6%
Ethiopia	526	219,331	0%
LATIN AMERICA			
Nicaragua	148,836	219,582	68%
Haiti	20,245	50,029	40%
Brazil	1,200,000	3,948,963	30%
Honduras	26,983	102,914	26%
Guatemala	15,809	127,698	12%
Mexico	197,263	1,636,509	12%

¹ Beebe S; Rao I; Mukankusi C; Buruchara R. 2013. Improving resource use efficiency and reducing risk of common bean production in Africa, Latin America, and the Caribbean. In: Eco-efficiency: From vision to reality (eds. Hershey C; Neate P). International Center for Tropical Agriculture (CIAT). p 117–134.

Results

Tables by administrative units within countries with expected average temperature and production were constructed for 13 bean-producing countries. While detailed results by states, departments, and municipalities are available in a separate file, summary results for 12 countries are presented in Table 1, eliminating Mozambique due to likely confusion of common bean with other legumes, especially cowpea. Latin America faces a much greater threat, with Nicaragua, Haiti, Brazil, and Honduras being especially susceptible to high temperatures. Nicaragua is a bread basket for Central America and may have more than 60% of its bean area under threat (assuming that planting dates are estimated correctly), while a vast area in Brazil will suffer high temperatures, especially the state of Bahia. In Africa, substantial bean

area in Malawi and DR Congo will suffer high temperatures, followed by Tanzania, Uganda, and Kenya.

Conclusions

In the short term, high temperatures will become limiting for common bean if they are not already a constraint. Latin America is especially susceptible, while some African countries, especially Malawi and DR Congo will suffer the effects of rising temperatures. Targeting of heat-tolerant common bean will be facilitated by estimates derived from this exercise.

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Potential benefits from heat-tolerant common beans under climate change

Rationale

Major effects of high temperatures on common bean are expressed as inhibition of pollen fertility. Field experience suggests that available sources of heat tolerance among breeding lines maintain pollen viability with up to 5 °C higher night temperatures, compared to those temperatures that are normally considered to be limiting (18 °C at night; see below). A modeling exercise to estimate the benefits of this magnitude of heat tolerance was undertaken, assuming a more conservative genetic gain of adaptation to 3 °C higher temperatures.

Materials and methods

The EcoCrop model was used to produce simulations of potential climatic suitability globally. Parameters for currently cultivated common bean were derived from Beebe et al. (2011) and Jarvis et al. (2012). Suitability simulations were performed for a historical period (1960–1990, chosen to be a representative baseline) and then for four future periods (the 2030s, 2050s, 2070s, and 2080s) under the Representative Concentrations Pathway 6.0 (RCP6.0) (Moss et al., 2010). RCP6.0 was chosen since it is representative of a business-as-usual scenario, where +3 °C above preindustrial levels is reached approximately by 2100 (see below, the target heat tolerance here was +3 °C above current crop limits). For each future period, simulations were performed using 19 Global Climate Model (GCM) projections, statistically downscaled and bias corrected following Ramírez-Villegas and Jarvis (2010). These simulations are hereafter referred to as “control” simulations.

Adaptation simulations were then conducted by modifying heat-related model parameters (maximum optimum and maximum absolute temperature for cultivation), so that the crop was 3 °C more heat tolerant. The objective of these

model runs was to quantify the benefit from heat-tolerant common beans, with a particular focus on Central America and East Africa. These simulations were performed using the same set of future climate projections as for the control simulations (i.e., RCP6.0, 19 GCMs, four periods).

Results

The analysis indicates that heat-tolerant bean varieties would counter most (if not all) of the negative impacts of climate change. While currently cultivated bean varieties (represented by control simulations, black line in **Figure 1**) are projected to suffer a 20–50% loss in suitable area by 2050s, heat-tolerant breeding lines are projected to suffer little (<5%) or no suitability loss by the same period. Even by the end of the century, improved lines show <10% area loss – which is less than current cultivars at the lowest levels of climate change. These results are robust towards the choice of GCM for both regions.

Maps of the two regions show the distribution of climate change impacts and the variation in the benefit from heat-tolerant bean cultivars (**Figures 2 and 3**). In both Central America and East Africa, adaptation to heat stress significantly reduces areas where the crop becomes completely unsuitable (red areas in Figures 2 and 3), and also areas where the crop suitability is reduced (orange areas in Figures 2 and 3). Under adaptation, areas with increased (dark green) or constant (beige) suitability are substantial, as are potential areas for expansion (blue).

Potential areas for expansion, however, tend to decrease under higher levels of warming (i.e., by the 2080s, not shown), and hence claims of potential crop expansion under adaptation should be considered with care. Under current climates and at moderate-to-low levels of warming; nevertheless, it is clear that potential expansion of common bean cultivation is possible.

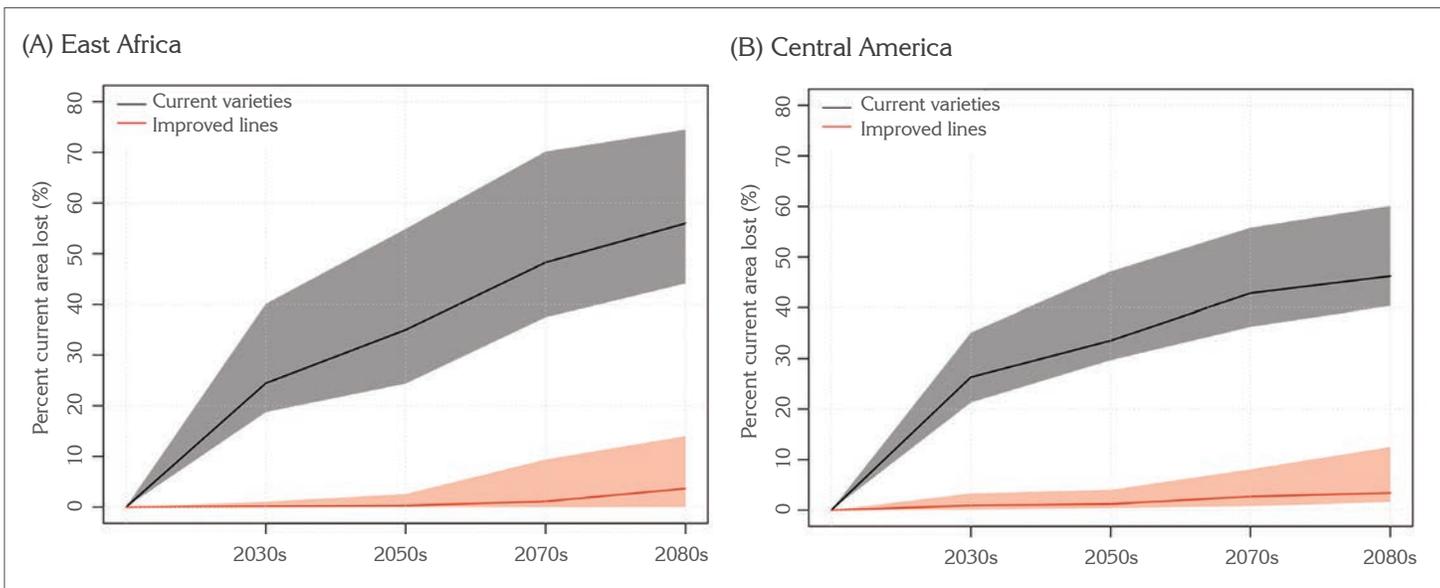


Figure 1. Projected loss in currently suitable area for East Africa (A) and Central America (B), for both currently cultivated germplasm (control, black) and heat-tolerant breeding lines (adaptation, red). Future simulations are based on an ensemble of 19 GCMs for RCP6.0. Continuous black and red lines represent the median of all simulations, and shading represents 5–95 % confidence interval.

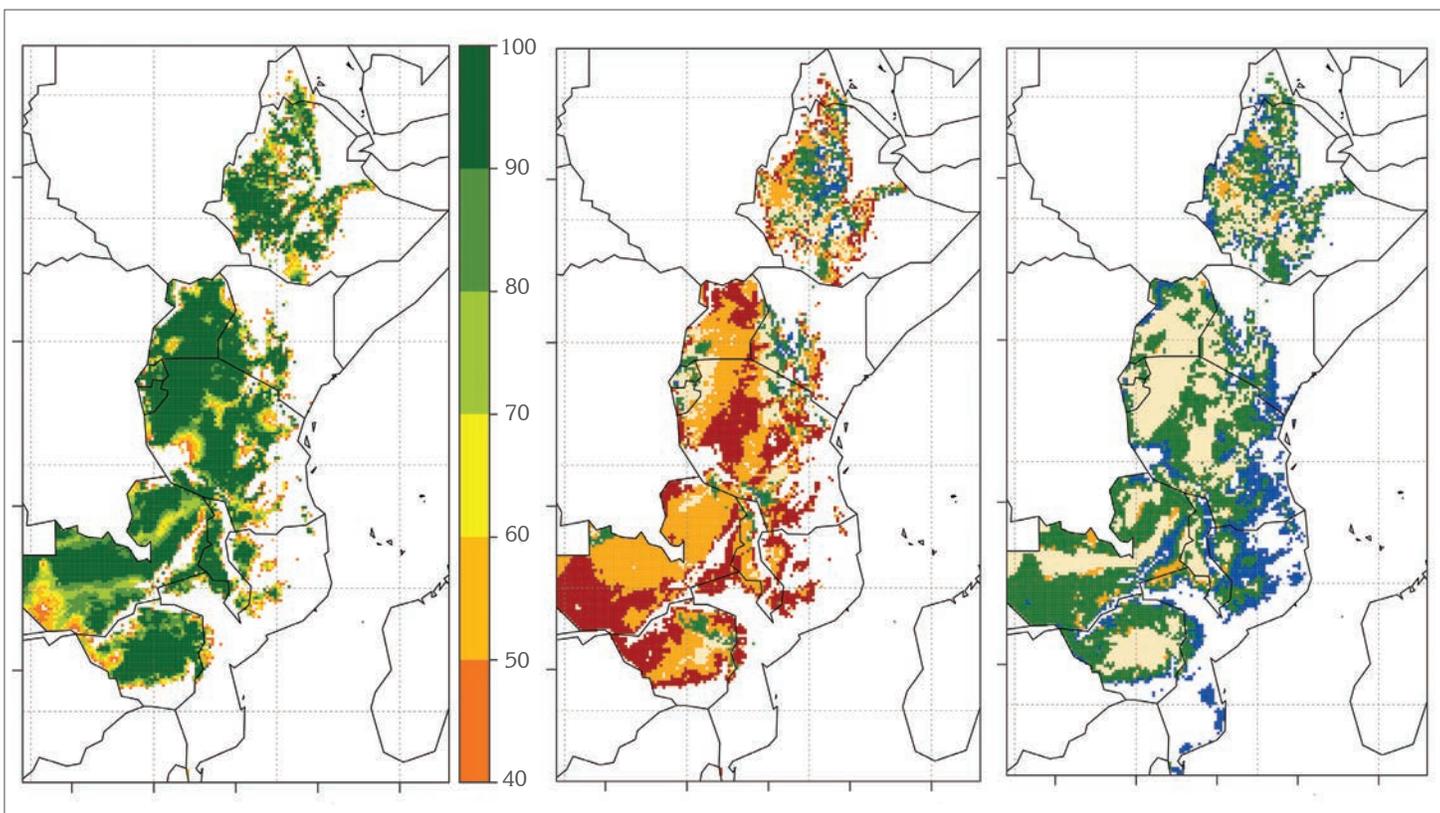


Figure 2. Historical and future (2050s) common bean suitability simulations for East Africa. **Left:** suitability of currently cultivated common bean for historical climate. **Middle:** projected impact of climate change for control (no adaptation) simulations. **Right:** projected impact of climate change for adapted common beans. For middle and bottom panels: red=areas that become unsuitable, orange=areas that remain suitable but reduce their climatic suitability, beige=areas that stay suitable with equal suitability to historical, green=areas that stay suitable but increase their climatic suitability, and blue=new areas.

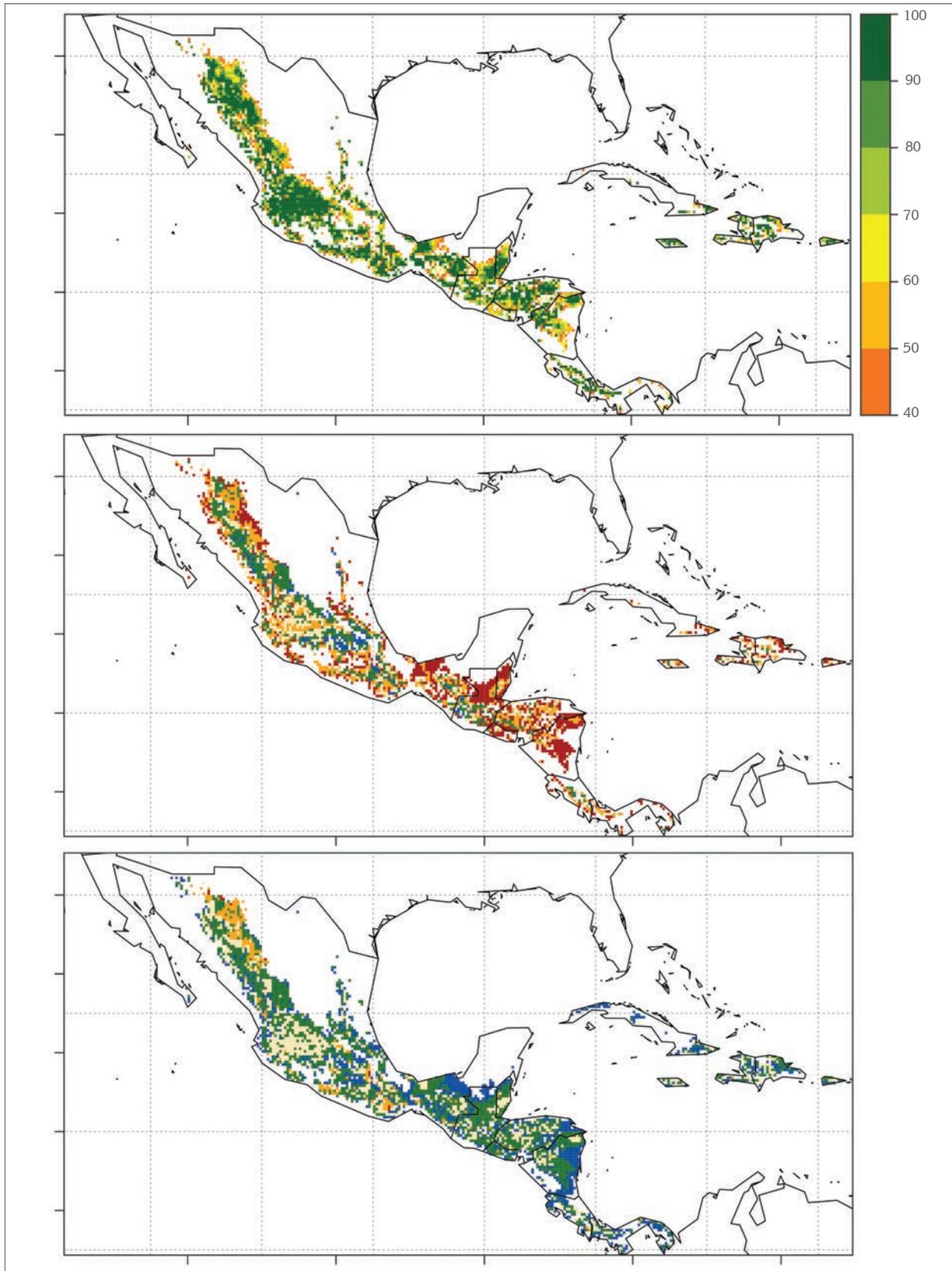


Figure 3. Historical and future (2050s) common bean suitability simulations for Central America. **Top:** suitability under current climates. **Middle:** projected impact of climate change for control (no-adaptation) simulations. **Bottom:** projected impact of climate change for adapted common beans. For middle and bottom panels: red=areas that become unsuitable, orange=areas that remain suitable but reduce their climatic suitability, beige=areas that stay suitable with equal suitability to historical, green=areas that stay suitable but increase their climatic suitability, and blue=new areas.

Conclusions

These results suggest that from a crop suitability perspective, enhancing the capacity of common bean to resist high temperatures (i.e., up to about 30 °C) is a very promising adaptation strategy globally, and more specifically also for Central America and East Africa. EcoCrop, however, is a very simple model of climatic suitability that does not account for daily extremes and does not provide any indication of potential impacts on crop productivity. Therefore, further work is required to determine the extent to which daily extremes can limit the potential benefits shown here, and also to quantify potential productivity gains associated with heat tolerance improvement.

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Evaluation of germplasm to identify heat-tolerant genotypes

Rationale

Bean production zones could experience unprecedented heat stress because of global climate change. Heat sensitivity is a major limiting factor that can reduce yields and product quality, and lead to restricted geographic adaptation. Improving heat tolerance in common bean would increase yield stability, protect against global warming, and maintain and extend the geographic range of cultivation. We evaluated the heat adaptation of elite lines from the on-going breeding program with the objective of quantifying genotypic differences in resistance to heat stress under field conditions.

Materials and methods

Different germplasm sets with more than of 1,000 lines of common bean (including a group of Andean and Mesoamerican gene pool lines, interspecific SEF and INB lines, and advanced SER lines) developed for improving adaptation to drought, low fertility, and/or heat were evaluated for heat tolerance at a field site of the University of Tolima in Armero, Colombia, at 352 meters above sea level (masl). Beans are sensitive to night temperatures higher than 18 °C, and the minimum air night temperature at this field site during the crop growing season was 22.8 °C (Figure 4). Experimental units consisted of two rows 3.72 m long by 0.7 m. Since bean germplasm that has not been previously selected for heat tolerance is mostly very sensitive and yields little or nothing, this large set of lines was not evaluated for yield, but superior lines were identified based on visual observation. At the time of harvest, visual evaluation of grain formation (formation and not formation, and quality of grain) was determined.

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Results and discussion

Armero – Heat stress: During the crop growing season, maximum and minimum air temperatures were 35 °C and 23 °C, respectively. A group of 40 genotypes belonging to Mesoamerican gene pool INB 604, INB 818, INB 841, PEB 51, SAB 259, SAP 1, SEF 10_SI Motilonia, SEF 12, SEF 16, SEF 42, SEF 56, SEF 59, SEN 97, SEN 100, SEN 107, SER 20, SER 22, SER 118, SER 289, SER 320, SIN 524, SIN 525, SIN 526, SMC 137, SMC 140, SMN 51, SMN 57, SXB 412), three families of (ALB 91xSCR 16)F1 X SMC 143), one of (SMC 40xSCR 16)F1 X SMC140), one of (SMC 33xSMN 38)F1 X (SEF 100xSMC 140)F1, and two of (SMC 47xSMN 40)F1 X (SCR 16xSMC 21)F1 were identified as heat tolerant. The lines with INB, SEF, and SIN codes all are derived from *Phaseolus acutifolius*, as are the lines SMC 137, SMC 140, and SMC 143. Seven genotypes belonging to the Andean gene pool were identified as heat tolerant (DAA 9, DAB 937, DAB 942, LPA 732, LPA 736, SAB 259, and SAP 1-16).

These materials were identified on the basis of pod formation, implying viable pollen and successful pollination. This is undoubtedly an important step in heat tolerance, but large differences were also observed in grain filling, indicating that photosynthate mobilization to grain is also important under heat stress. In an observational nursery planted by colleagues with the Colombian Corporation of Agricultural Research (Corpoica) on the north coast of Colombia, many SEF lines as well as INB 604, SMC 137, and SEN 97 stood out, while among the Andean lines, only DAB 942, LPA 736, and SAB 259 showed some slight pod formation, while SAP 1 and SAP 1-16 were far superior to Andean check G 122 reported in the literature as highly tolerant.

Conclusions

Conclusions: Many lines with a degree of heat tolerance are derived from interspecific crosses with tepary bean, but a few lines of purely common bean parentage have been identified. While pollen fertility seems to be indicated by pod and seed formation, grain filling must also be improved.

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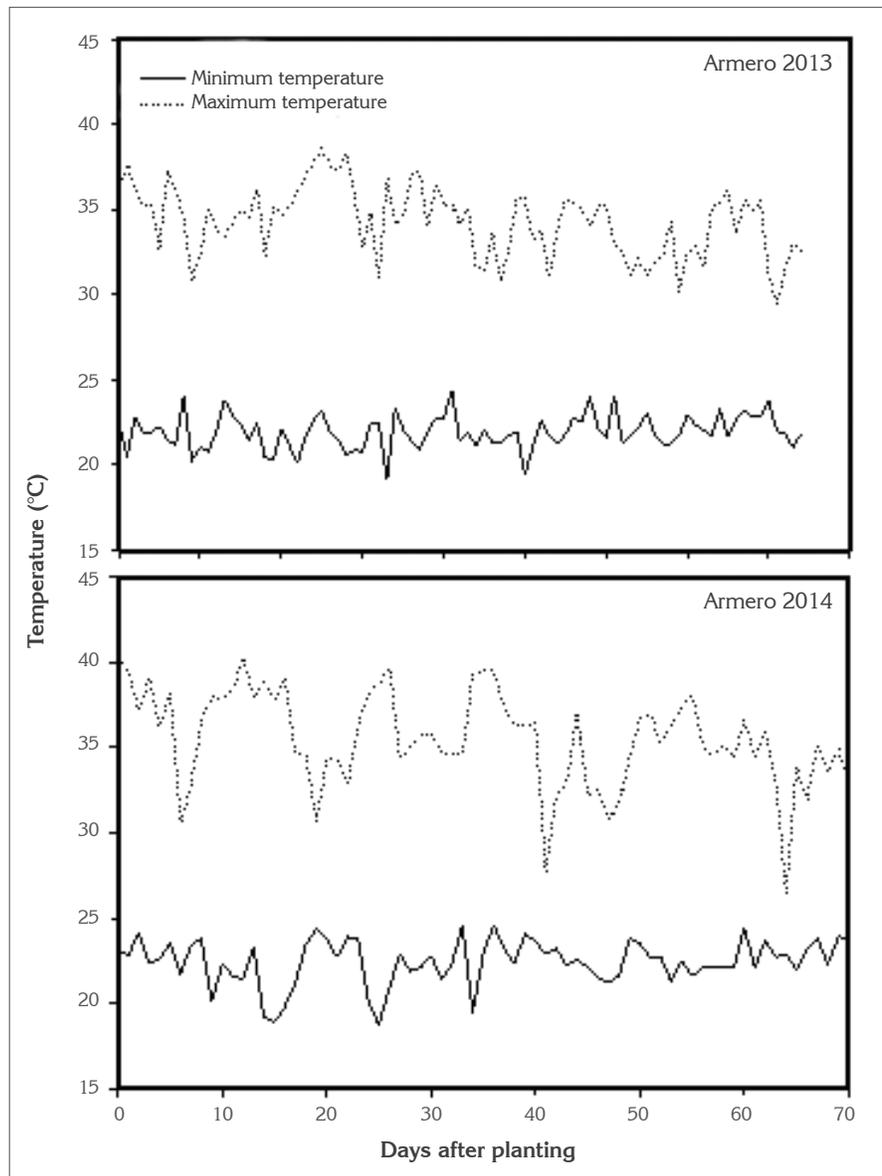


Figure 4. Maximum and minimum temperatures during crop growing period at Armero in 2013 and 2014.

Phenotypic differences in heat tolerance between 36 SEF and 25 INB elite lines

Rationale

Bean production zones could experience unprecedented heat stress because of global climate change. Heat stress during the reproductive phase adversely affects pollen viability,

fertilization, pod set, and seed development leading to abscission of flowers and pods and substantial losses in grain yield. We conducted field studies to evaluate phenotypic differences in resistance to heat stress and identify target traits for improved abiotic adaptation in common bean. We evaluated heat stress of 36 elite SEF lines including checks, and 25 INB lines including checks from the on-going

breeding program with two main objectives: (i) to quantify phenotypic differences in tolerance to heat stress under field conditions and (ii) to identify target traits for improved heat stress adaptation.

Materials and methods

As a complement to trials of SEF lines under stress from drought, low P and/or aluminum reported under PL-1, the same lines were evaluated under heat stress. Heat field trials were conducted at the University of Tolima-Armero, July to October 2014, located at 352 masl, to determine genotypic differences in tolerance to heat stress conditions. One trial (SEF lines) included 36 genotypes: SEF 1, SEF 9, SEF 10, SEF 11, SEF 14, SEF 15, SEF 16, SEF 17, SEF 28, SEF 29, SEF 42, SEF 43, SEF 44, SEF 45, SEF 47, SEF 49, SEF 50, SEF 52, SEF 53, SEF 55, SEF 56, SEF 60, SEF 62, SEF 64, SEF 68, SEF 69, SEF 70, SEF 71, SEF 73, and SEF 74; checks EAP 9510-77, SER 16, and G 40001; and parents of SEF lines ALB 74, INB 841, RCB 593. A 6 x 6 partial balanced lattice design with four replicates was used. A second field site was selected for heat tolerance evaluation of the SEF lines in collaboration with Corpoica in the Caribbean region (Corpoica-Caribia). A second trial (INB lines) was planted in Armero and included 25 genotypes: INB 603, INB 604, INB 605, INB 606, INB 816, INB 818, INB 820, INB 825, INB 826, INB 829, INB 830, INB 833, INB 837, INB 841, SEF 13, SEF 46, SEF 54, SEF 61, SEF 75, G 122, SXB 412, BAT 477, SEN 52, SER 118, and SEF 60. A 5 x 5 partial balanced lattice design with three replicates was used.

Experimental units consisted of four rows 3.72 m long by 0.7 m. A number of plant attributes were measured at flowering; these plant traits included canopy biomass per area and pollen viability. At the time of harvest, grain yield and yield components were determined. Pod partitioning index (dry weight of pods at harvest/dry weight of total biomass at mid-podfill x 100), pod number per area, seed number per area, and pod harvest index (dry weight of seed at harvest/dry weight of pod at harvest x 100) were also determined.

Pollen viability was determined in flowers collected one day before anthesis, stored in plastic vials containing a 1:3 solution of glacial acetic acid with alcohol of 96%. Pollen grains were removed from the anthers and added to a drop of 1% acetocarmine stain. To determine the viability of each flower bud, more than 100 pollen grains per replication were read; pollen grains stained red are those that remain viable, and pollen grains that were not stained are considered as not viable. After counting, the percentage viability is determined by the proportion of stained pollen grains relative to the total pollen grain.

Results and discussion

During the crop growing season, maximum and minimum air temperatures were 35 °C and 23 °C, respectively. This study with data from 2 years identified one germplasm accession of *P. acutifolius* (G 40001), one interspecific line (INB 841), and five SEF lines (SEF 15, SEF 16, SEF 14, SEF 60, and SEF 43) as superior in their level of heat tolerance based on grain yield. The second trial, which included 25 elite lines that were identified as heat tolerant last year in Armero, and this trial presented some problems of root rots. INB 604 and INB 818 showed grain production under combined stress of heat and drought during pod development and seed filling. Two undergraduate students participated in evaluations: one agronomy student (Nadia Orjuela) from University of Tolima was trained in field evaluation, and one biology student (Natalia Viña) from ICESI in Cali was trained in laboratory and field evaluation of heat tolerance in common bean.

At the site on the Caribbean coast, the trial of 30 SEF lines along with six checks was planted in two seasons, one with heat and drought stress and the other with only heat stress. From the first evaluation, one germplasm accession of *P. acutifolius* (G 40001) was identified as superior in its level of heat and drought tolerance based on grain yield. In the second evaluation, reliable yield data were not obtained for the entire trial due to disease pressure, but among surviving plots, G 40001, INB 841, SEF 15, SEF 16, SEF 14, SEF 60, and SEF 43 were identified as superior in their level of heat tolerance based on grain yield. Results from Armero and Caribia confirm that interspecific progenies between common bean and tepary bean (*P. acutifolius*) constitute the majority of the promising materials (i.e., SEF and INB lines), evidencing the positive contribution of tepary bean towards improving heat tolerance.

Results from 2 years on pollen viability showed a good relationship between this trait and heat adaptation in common beans. Based on grain yield, the heat-tolerant lines G 40001, INB 841, SEF 60, SEF 16, SEF 14, and SEF 16 were outstanding in their pollen viability, with values superior to 64%, while the heat-susceptible lines SER 16, RCB 593, and ALB 74 showed poor pollen viability values that were less than 20%. The reduction of pollen viability of these lines compared with optimal conditions in Palmira was around 80% (Figure 5). Evaluation of pollen and ovule formation in 30 SEF lines along with six checks showed no effect of heat stress on formation of these reproductive structures (Figure 6).

Correlation coefficients between final grain yield of SEF lines and other shoot attributes under heat conditions at Armero, Colombia, indicated that greater seed yield was positively related to pod harvest index and pod partitioning index, and pod and seed number per area. The genotypes adapted to

heat conditions showed the ability for formation of pods and seeds (pod partitioning index), and to fill seeds as reflected by the positive associations between grain yield and pod harvest index under heat conditions. These correlations between grain yield and other plant attributes indicate that pollen viability and photosynthate remobilization are important traits

related to heat tolerance in common bean. Several SEF lines are already being incorporated into crosses for Central America, Colombia, and Africa. One graduate student (Néstor Chávez) from Costa Rica is obtaining a PhD based on field studies to evaluate genotypes for their tolerance to high temperature.

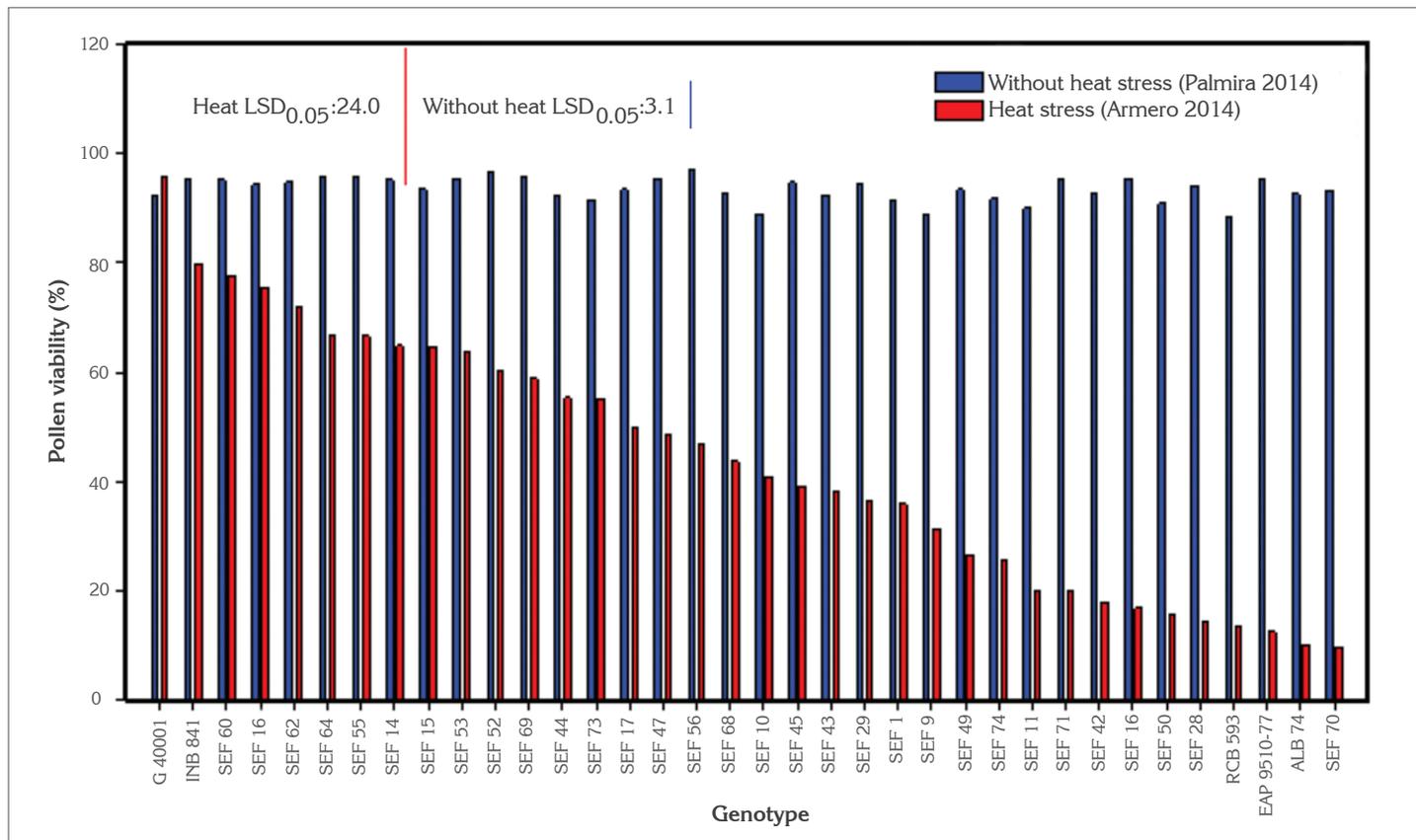


Figure 5. Effect of heat stress on pollen viability in 30 SEF lines along with six checks under field conditions at Armero 2014.

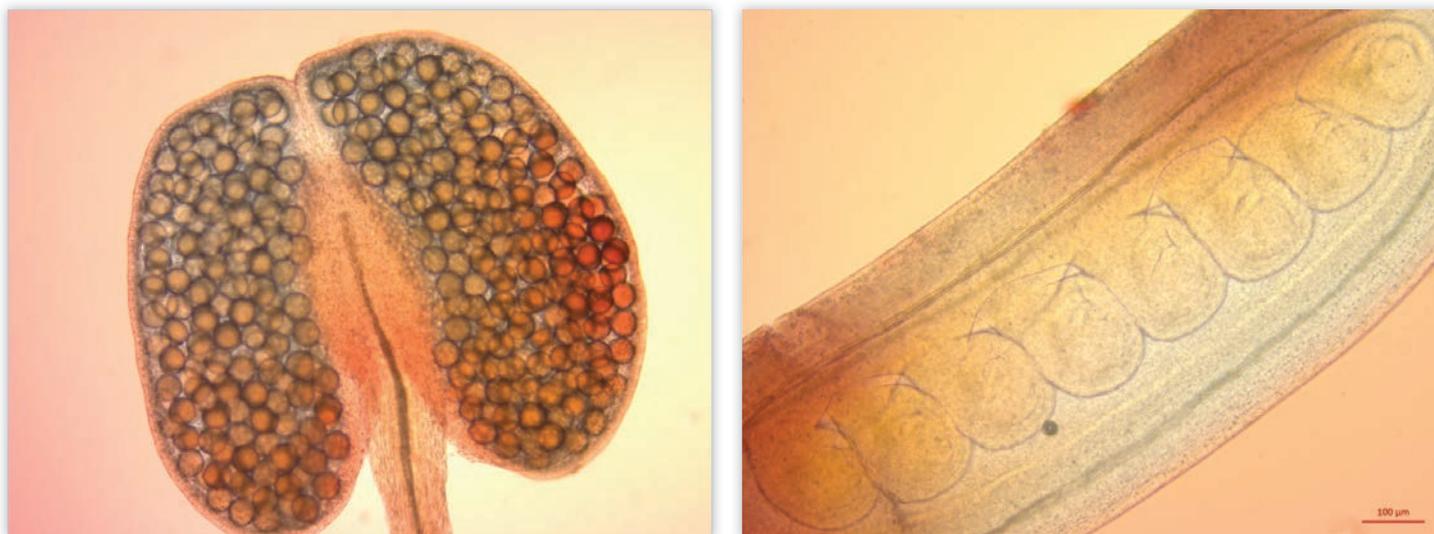


Figure 6. Development of pollen and ovules in two SEF lines under heat stress in field conditions at Armero, Colombia, during 2014.

Conclusions

Pollen viability in some interspecific lines is above 64% under severe heat stress, compared to less than 20% in checks of common bean, confirming the value of introgression from *Phaseolus acutifolius* into common bean. The effect of high temperatures appears not to be on pollen formation but rather on survival.

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Improved infrastructure to evaluate heat tolerance

Controlled conditions were established at CGIAR facilities in Colombia through the assemblage of polycarbonate greenhouses with automatic temperature control through funding for a special project financed by the Inter-American Development Bank (IDB). Two complete professional greenhouses with temperature control from Greenhouse

Megastore, West Sacramento, CA, USA, were installed during 2014. The frame of this structure is constructed from galvanized-steel roll-formed components, and is completely covered with 8-mm twin-wall polycarbonate instead of using poly film on the roof and sidewalls. The dimensions of each greenhouse are 15 m in length and 9.2 m in width (Figure 7).



Figure 7. Establishing infrastructure for evaluation of bean response to high temperatures in Colombia.

Release of a cultivar in Central America with enhanced heat tolerance

Rationale

A preliminary step in developing a breeding program for a given trait is to establish a baseline and to evaluate the reaction of existing germplasm. Although CGIAR only initiated intensive and directed work for heat tolerance in 2014, its facility near Cali is on the warmer margin of what is considered an optimal bean environment, and lines bred there may exhibit some degree of heat tolerance. For this purpose, lines selected through CGIAR's mainstream

breeding program were planted in low-altitude sites where beans would never normally be grown due to excessive temperatures. Some of these lines had been shared with national programs of Central America in previous years and had been selected for local adaptation.

Materials and methods

SEN 52 is a black-seeded line derived from the cross [(SXB 123 x DOR 677) x SEN 34] and was selected in CGIAR's mainstream breeding program in Cali and at the Popayán and Santander de Quilichao sites. SEN 52 was not subjected to any additional stress for heat tolerance, outside

of routine selection in Cali. It was originally developed for tolerance to drought, and in 2005 it yielded 908 kg/ha versus 738 kg/ha average for drought-selected lines, and 185 kg/ha for the commercial check DOR 390 that season. SEN 52 was coded as a line in 2005 and was distributed to partners in Central America for local evaluation, including the national programs of Costa Rica (Ministry of Agriculture) and Nicaragua (National Institute of Agricultural Technology, INTA).

In Nicaragua, SEN 52 advanced rapidly in the national evaluation scheme, completing the required steps in 2013. In Costa Rica, that same year it was evaluated in regional yield trials in two sites in three successive semesters, and in all 3 years under terminal drought.

SEN 52 was included in observation nurseries under heat stress in Armero, Colombia (altitude 352 masl; see report above), and in the north coast of Colombia on the Caribia Research Station (altitude 50 masl) of Corpoica. All data were subjective and observational.

Results and discussion

Although formal yield trials were not performed at this stage of evaluation for heat tolerance either in Armero or on the Colombian coast, most lines tested produced no pods at all, and the identification of “heat-tolerant” lines was for all practical purposes a qualitative evaluation of presenting or not any pods. In the observational nursery of the University of

Tolima in Armero, Colombia, SEN 52 was among the few lines that produced seed under night temperatures averaging above 22 °C. On the Colombian coast, SEN 52 presented far better formation of pods than other materials including G 122, which is reported in the literature as highly heat tolerant among available germplasm of *Phaseolus vulgaris* (see **Figure 8**). Night temperatures averaged about 23 °C during the flowering and podding period at this site. These were the first indications that SEN 52 was superior for heat tolerance among breeding lines.

SEN 52 had already passed through regional yield trials in Nicaragua and was released as INTA Negro Precoz (early black). This would be the first release of which we are aware of a line with markedly better heat tolerance. SEN 52 was the most stable of 12 experimental lines in Costa Rica and yielded the highest under moderately severe and severe drought, and fifth highest under moderate drought. Under severe drought, it produced 994 kg/ha versus 353 kg/ha for the local check.²

While quantitative data on heat tolerance of SEN 52 is not yet available, what is most significant is that one of the very few lines with enhanced pod formation under heat stress emerged as superior in two countries of Central America, suggesting that heat tolerance figured in its selection in these two sites. This implies that high temperatures are currently more limiting than previously realized. This emphasizes the urgency of addressing the issue of heat tolerance in common bean.



Figure 8. Heat-tolerant G 122 (left) and experimental line SEN 52 (right) planted on the north coast of Colombia on the Caribia Research Station of Corpoica.

² Hernández JC; Calderón R; Chaves N. 2014. Evaluación de líneas de frijol por su tolerancia a condiciones de sequía terminal. 59 Reunión del PCCMCA, Managua, Nicaragua. 28 de abril al 3 de mayo, 2014.

Conclusions

Among the very few advanced lines that expressed some degree of heat tolerance, SEN 52 outperformed other lines in Nicaragua and Costa Rica. This suggests that heat tolerance could be a beneficial trait even under current conditions in production environments.

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