Research Article

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Parental Value for Tuber Yield in Potato Under High Temperature Environments in Climate Change Conditions

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Abstract: Potato crop is expanding to areas with temperatures higher than those required. Climate change is increasing temperatures in traditional areas of potato production, thereby affecting tuber yield. The International Potato Center has developed a population adapted to these new conditions, being more tolerant to high temperatures, resistant to late blight, virus PVX and/or PVY and early maturity. In breeding programs it is very important to know the parental value of the progenitors. The parental value of 34 selected potato clones was determined through general combining ability for marketable, total yield and average tuber weight under high temperatures. Using the line by tester mating design, the potato clones were crossed as lines and varieties Katahdin, Huagalina and clones CIP398098.204 and CIP302533.31 as testers. The field experiments were carried out in three locations in Peru: San Ramon, La Molina and Majes, where average temperatures at night were between 15.25 to 21.65°C, and during the day fluctuated between 21.47 to 27.20°C. We used a randomized complete block design, with three replications. At harvest the number and weight of marketable and non-marketable tubers were taken. Then the average tuber weight, marketable and total yield per hectare was calculated. 18 potato clones were identified with high parental value for marketable yield, seventeen for total tuber yield and 11 for average tuber weight; nine of them combine high parental value for the three characteristics studied. These clones with late blight resistance, heat tolerant, adapted to medium altitudes, growing period of 90 days and high parental value can be used as parents in breeding programs, to obtain new varieties under the new climate change scenarios with high temperatures. Crosses that presented high SCA are the most promising for the development of superior clones.

Keywords: Potato, Climate Change, Heat Tolerance, Combining Ability, Late Blight

1 Introduction

Potato crop is expanding to areas where conditions are not ideal for production due to high temperatures, which is one of the most significant factors affecting potato yield (Muthoni et al. 2015). Changes in temperates are brought on by climate change, which is affecting weather patterns in traditional areas for this crop (Levi and Villeux 2007), where unpredictable rains and pressure from pests and diseases are increasing farmers’ risk. In anticipation of these changes, the International Potato Center (CIP) has developed a population to obtain clones with Late Blight resistance and Heat Tolerance, named LBHT population and they are available for use by developing countries in the selection of new varieties or as parents in their breeding programs (Gastelo et al. 2012, 2015; CIP, 2014).

The potato crop is highly heterozygous, the most important economical characters are governed by additive and non-additive genes. General Combining Ability (GCA) is considered important for additive traits and Specific Combining Ability (SCA) for non-additive traits (Falconer 1981).

A breeding program for yield improvement is successful, when clones with high parental value are used, which is not only measured by its phenotypic value, but it is necessary to know its combining ability as an indicator of parental value (Luthra et al. 2006), selecting clones that when crossed with testers with a broad genetic base, have a high GCA value and can transmit it to their progeny to obtain high yields (Plaisted et al. 1962). High parental value (GCA) of these clones for tuber yield under high temperatures will allow to have a high percentage of the
progenies eligible for variety selection (Thompson and Mendoza 1984; Mendoza 1989).

Combining ability analysis is a method very useful for choosing better parents, and in the formulation of a crossing plan for a breeding program. GCA is one of the powerful tools in identifying clones with high parental value that can be used in crosses (Garafolo et al. 2005; Tai 1976; Gopal 1998; Mondal and Hossain 2006).

In various studies in potato, it has been found that the additive effects (GCA), are predominant for overall tuber yield, and average tuber weight (Reis et al. 2017). Da Silva et al. (2013), in a study to determine the combined capacity for tuber yield, found that General Combining Ability (GCA), was significantly superior than Specific Combining Ability (SCA), suggesting the predominance of additive effects of the genes in the control of this trait. Hirut et al. (2017), found that GCA was more important than SCA for total tuber yield, marketable tuber yield, average tuber weight under stress conditions. Beserra et al. (2001), found that the effects of GCA were more important than the effects of SCA for the yield in heat tolerant potato clones, indicates that the use of high GCA parents in a breeding program would allow us to obtain heat tolerant potato clones. Muhinyuza et al. (2016) in a study in Rwanda to estimate combining ability effects, for yield related traits and late blight resistance in potato, they found that additive gene action was predominant over non-additive gene action for both traits. Also Neele et al. (1991), found that for tuber yield, the number of tubers and the average tuber weight in potato, the general combining ability (GCA) was predominant, although the specific combining ability effects present were greater at late than at early harvests. In a study done by Manivel et al. (2009), to determine the effects of GCA and SCA on dry matter in potato, they found that there were variations of the effects of GCA and SCA through the potato generations, attributing to the genotype x environment interaction, recommending that the selection of the best parents for breeding Potato should be done based on years and generations.

However, in other studies, it has been found that the GCA and SCA effects are important for tuber yield, tuber number and average tuber weight in seedlings and clonal generations (Ruiz et al. 2006). Haydar et al. (2009), found that GCA and SCA are important for yield per plant, controlled by the additive and non-additive genes respectively.

This study documents the parental value of 34 advanced potato clones from LBHT population, through the estimation of GCA and SCA of average tuber weight, marketable and total tuber yield under high temperatures conditions and select the best parents and hybrids combinations to be included in breeding programs for heat tolerance under climate change scenarios in Asia, Africa and Latin America.

2 Materials and Methods

Three sets of 34 advanced clones from the LBHT population (Table 1), with resistance to late blight, which was evaluated in previous experiments under natural field conditions with high disease pressure (Gastelo et al. 2015), were evaluated to determine their parental value through their GCA and SCA, http://www.cipotato.org/catalogue. Set 1, 2 and 3 had 19, 6 and 9 clones respectively. In all sets, the line by tester mating design was used, (Hallauer and Miranda 1982; Kempterne 1957; Singh et al. 1985). We used as testers the varieties Kathadin (Solanum tuberosum spp tuberosum), an improved heat tolerant and Hualalina, a native variety. (Solanum tuberosum spp andigena), non-tolerant to heat and advanced potato clones CIP398098.204 and CIP302533.31 from LBHT population (mix solanum species: Solanum tuberosum, spp tuberosum, spp andigena, Solanum, demisum, etc.). The crosses were carried out under greenhouse conditions in 2012 and 2013, generating 57, 18 and 27 progenies in sets 1, 2 and 3 respectively.

In 2013, the botanical seeds of sets 1 and 2, were sown under greenhouse with the objective of obtaining seed tubers. We planted 200 botanical seed (genotypes) per progeny, at harvest, we took one tuber from each of the 120 best plants, these were divided into three groups of 40 seed tubers each for field experiments, which were seeded in spring-summer growing season 2013-2014.

In 2015, we planted seeds in set 3 and proceeded the same as set 1 and 2. The field experiments were started in the spring-summer growing season 2015-2016.

The field experiments of the three sets, were carried out in three warm environments in Peru: San Ramon, La Molina and Majes. Average temperatures at field in these sites at the time that the experiments at night, were between 15.65 and 21.65°C, and in the day were between 21.47°C and 27.20°C (Table 2). The air temperature was taken one meter above the ground. Night temperature is very important, since the night-time process of tuberization is inhibited above 20°C. In all experiments, we used randomized complete block (RCB) with three replications of 40 plants (genotypes) each. The sowing was done manually, the distance between rows and plants was 0.90 and 0.30 m respectively. The dose of fertilization was 180-180-160 NPK, applying a half dose of nitrogen to the planting
| #  | Clones   | Pedigree  | Color | Resistance | Tolerance |
|----|----------|-----------|-------|------------|-----------|
|    |          | Female    | Male  | Skin       | Flesh     | Tuber     | Eyes | LB | PVX | PVY | H | D |
| SET 1 |          |           |       |            |           |           |      |    |     |     |   |   |
| 1   | CIP398098.205 | CIP393371.58 | CIP392639.31 | Cr | Cr | El | S | R | ER | T | NT |
| 2   | CIP398098.231 | CIP393371.58 | CIP392639.31 | Cr | Cr | Ov | S | R | ER | T | NT |
| 3   | CIP398098.570 | CIP393371.58 | CIP392639.31 | Cr | Cr | Rd | S | R | ER | T | NT |
| 4   | CIP398098.65  | CIP393371.58 | CIP392639.31 | Cr/Pi | Cr | Ele | S | R |     | T | NT |
| 5   | CIP398180.289 | CIP392657.171 | CIP392633.64 | Cr | Cr | Ov | S | R | ER | T | T |
| 6   | CIP398180.292 | CIP392657.171 | CIP392633.64 | Cr | Cr | Ob | S | R | ER | T | T |
| 7   | CIP398190.615 | CIP393077.54  | CIP392639.2  | Cr | Cr | Ov | S | R | ER | T | NT |
| 8   | CIP398190.89  | CIP393077.54  | CIP392639.2  | Cr | Cr | Ov | S | R |     | T | NT |
| 9   | CIP398192.131 | CIP393077.54  | CIP392633.54 | Cr/Pi | Cr | Ov | S | R | ER | T | T |
| 10  | CIP398192.553 | CIP393077.54  | CIP392633.54 | Cr/Pi | Cr | Ov | S | R | ER | T | NT |
| 11  | CIP398193.158 | CIP393077.54  | CIP392633.64 | Cr/Pi | Cr | Ov | S | R | ER | T | NT |
| 12  | CIP398193.511 | CIP393077.54  | CIP392633.64 | Cr | Ye | El | S | R | ER | T | NT |
| 13  | CIP398201.510 | CIP393242.50  | CIP392633.64 | Pi | Cr | Ob | S | R | ER | ER | T | NT |
| 14  | CIP398203.5   | CIP393280.82  | CIP392633.64 | Re | Cr | El | S | R | ER | T | NT |
| 15  | CIP398208.219 | CIP393371.58  | CIP392633.64 | Cr | Cr | El | S | R | ER | T | T |
| 16  | CIP398208.33  | CIP393371.58  | CIP392633.64 | Cr | Cr | Ob | S | R | ER | T | T |
| 17  | CIP398208.620 | CIP393371.58  | CIP392633.64 | Cr | Cr | El | S | R | ER | T | NT |
| 18  | CIP398208.670 | CIP393371.58  | CIP392633.64 | Cr | Cr | Ob | S | R | ER | ER | T | NT |
| 19  | CIP398208.704 | CIP393371.58  | CIP392633.64 | Cr/Pi | Cr | Lg | S | R | ER | T | T |
| SET 2 |          |           |       |            |           |           |      |    |     |     |   |   |
| 1   | CIP302531.43 | CIP393280.82 | CIP396272.43 | Re | Ye | Ov | S | R | ER | T | NT |
| 2   | CIP302533.40 | CIP393371.159 | CIP396272.43 | Cr | Cr | El | S | R | ER | ER | T | NT |
| 3   | CIP302533.49 | CIP393371.159 | CIP396272.43 | Cr/Pie | Cr | Lg | S | R | ER | ER | T | NT |
| 4   | CIP302533.74 | CIP393371.159 | CIP396272.43 | Cr | Cr | El | S | R | ER | ER | T | NT |
| 5   | CIP302536.17 | CIP393371.159 | CIP396272.18 | Cr | Cr | El | S | R | ER | T | NT |
| 6   | CIP304079.10 | CIP393075.54  | Granola | Cr | Cr | Ov | S | R | ER | ER | T | NT |
| SET 3 |          |           |       |            |           |           |      |    |     |     |   |   |
| 1   | CIP398017.53 | CIP391002.6  | CIP392639.31 | Cr | Cr | Ov | S | R |     | T | NT |
| 2   | CIP398098.203 | CIP393371.58 | CIP392639.31 | Cr | Cr | Ov | S | R |     | T | T |
| 3   | CIP398098.204 | CIP393371.58 | CIP392639.31 | Cr/Pi | Ye | El | S | R |     | T | NT |
| 4   | CIP398190.200 | CIP393077.54  | CIP392639.2  | Cr/Pi | Cr | Ob | S | R |     | T | NT |
| 5   | CIP398190.605 | CIP393077.54  | CIP392639.2  | Cr/Pi | Cr | Ov | S | R |     | T | NT |
| 6   | CIP398192.592 | CIP393077.54  | CIP392633.54 | Cr | Cr | Ov/F | S | R | ER | T | NT |
| 7   | CIP398208.505 | CIP393371.58  | CIP392633.64 | Cr/Pie | Cr | Ov | S | R | ER | ER | T | NT |
| 8   | CIP302551.26 | CIP393385.47  | CIP396272.8  | Cr/Pi | Ye | Ov | S | R | ER | ER | T | NT |
| 9   | CIP304081.44 | CIP393075.54  | Monalisa | Cr | Cr | Ov | S | R |     | T | NT |
| TESTERS |         |           |       |            |           |           |      |    |     |     |   |   |
| 1   | CIP302533.12 |             |       |            |           |           |      |    |     |     |   |   |
| 2   | HUAGALINA  |             |       |            |           |           |      |    |     |     |   |   |
| 3   | KATAHIDIN |             |       |            |           |           |      |    |     |     |   |   |

LB = Late blight,  
H = Heat,  
D = Drought,  
S = Susceptible,  
ER = Extreme resistance,  
R = Resistant,T = Tolerant,  
NT = Non-tolerant,  
Cr = Cream,  
Cr/Pi = Cream with pink,  
Cr/Pie = Cream with pink eyes,  
Pi = Pink,  
Re = Red,  
Ye = Yellow,  
Cr/Re = Cream with red,  
Ov = Oval,  
OB = Oblong,  
Lg = Large,  
El = elliptic,  
Rd = Round
and the other half to the hilling. In La Molina the irrigation was by the furrows, in San Ramon it was by sprinkling and in Majes by dripping. Pest control was done in a timely manner using Decis 2.5EC (Deltametrin) for Liriomyza huidobrensis and Epitrix sp.; for Phtorimaea operculrella was applied Vertimec 1.8Ec (Abamectin). No fungicide was applied to control diseases. The harvest was done 90 days after sowing.

At harvest the number and weight of marketable and non-marketable tubers per plot was taken. Then was calculated, the average tuber weight (ATW), weight of marketable and total tubers per hectare in tons (MTYha, TTYha).

The simple and combined analysis of variance of line (clones) by tester mating design were performed with statistical software, SAS V. 9.4 (SAS Institute Inc., Cary, NC, USA.). Proc anova and determination of the estimate effects of combining ability (GCA and SCA) were performed with Microsoft Office Excel 2013, using the formulas described by Singh and Chaudhary (1985). (Table 3). The following linear additive model was used for the analysis of variance of line x tester in an environment.

\[ Y_{ijk} = \mu + R_k + G_i + G_j + S_{ij} + \varepsilon_{ijk} \]

Where
\[ Y_{ijk} = \text{observed value in the } i \text{th line, } j \text{th tester and } k \text{th replication} \]
\[ i = \text{number of lines} \]
\[ j = \text{number of testers} \]
\[ k = \text{number of replication} \]
\[ R_k = \text{effect of the } k \text{th replication} \]
\[ G_i = \text{GCA effect of the } i \text{th line} \]
\[ G_j = \text{GCA effect of the } j \text{th tester} \]
\[ S_{ij} = \text{SCA effect of the crossing between the } i \text{th line and } j \text{th tester} \]
\[ \varepsilon_{ijk} = \text{effect of experimental error in the } ijk \text{th observation} \]

3 Results

The analyzes of variance of the three sets in each locality, show highly statistically significant differences for clones, testers and the interaction of clones by testers (\(P<0.01\)) for marketable and total tuber yield, and average tuber weight. In the experiment performed in san Ramon of the Set 3, there was no statistical differences for testers in average tuber weight (Table 4).

Combined analysis of variance for marketable and total tuber yield per hectare (MTYha and TTYha) and average tuber weight (ATW), showed highly statistically significant differences (\(P<0.01\)) for Clones and testers, which are associated with the GCA, also the interaction of clones by tester associated with SCA, presented high statistical significance, except for ATW in experiment 1. The interaction with the environment was highly significant for clones and testers \(\times\) environments, and clones \(\times\) testers \(\times\) environments (Table 5).

The combining ability analysis was performed based on the combined analysis, the GCA showed a wide range of variability for clones and testers. In set 1, ten clones showed high significant effects of GCA for MTYha and TTYha and 8 for ATW (\(P<0.01\)). Seven clones

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Table 2: Coordinates and average temperature of the experimental sites for potato field experiments in Peru

| Site       | Altitude masl | Latitude   | Longitude   | Agroecological Zone      | Temperature Average °C | Temperature °C  |
|------------|---------------|------------|-------------|--------------------------|-------------------------|-----------------|
|            |               |            |             |                          | Day | Night | Min. | Max. | Average |
| San Ramon  | 828           | 11°08'S   | 75°20'W    | Humid Tropical Mid-elevation | 27.20 | 21.65 | 19.57 | 28.15 | 24.84   |
| La Molina  | 150           | 12°05'S   | 76°56'W    | Arid Tropical Lowland     | 25.28 | 21.53 | 19.47 | 26.68 | 23.35   |
| Majes      | 1294          | 16°28'S   | 72°06'W    | Arid tropical Mid-elevation | 21.47 | 15.25 | 14.02 | 22.01 | 18.39   |
Table 3: Formulas to estimate the effects of combining ability (GCA and SCA) and its standard error (SE)

| Effects and Standar Error | One Environment | Across Environments |
|---------------------------|-----------------|---------------------|
| GCA (Lines (Clones))     | $X_{i..}/rt - X_{...}/rlt$ | $X_{i..}/rt - X_{...}/rlte$ |
| GCA (Testers)            | $X_{j.}/rl - X_{...}/rlt$ | $X_{j.}/rl - X_{...}/rlt$ + $X_{i..}/rt - X_{...}/rlt$ |
| SCA                      | $X_{ij.}/r - X_{i..}/rt - X_{...}/rl + X_{...}/rlte$ | $X_{ij.}/r - X_{i..}/rt - X_{...}/rl + X_{...}/rlte$ |
| SE (GCA for line (clone))| $(MSe/rt)^{1/2}$ | $(MSe/rlte)^{1/2}$ |
| SE (GCA for tester)      | $(MSe/rl)^{1/2}$ | $(MSe/rte)^{1/2}$ |
| SE (SCA)                 | $(MSe/r)^{1/2}$ | $(MSe/re)^{1/2}$ |
| SE (GCA_i - GCA_j line (clone)) | $(2MSe/rt)^{1/2}$ | $(2MSe/rlte)^{1/2}$ |
| SE (GCA_i - GCA_j tester) | $(2MSe/rl)^{1/2}$ | $(2MSe/rte)^{1/2}$ |
| SE (SCA_ij - SCA_kl)     | $(2MSe/r)^{1/2}$ | $(2MSe/re)^{1/2}$ |

Where:

$X_{i..} =$ sum of the i-th line
$X_{j.} =$ sum of the j-th tester
$X_{...} =$ total sum
$X_{ij.} =$ total sum of the cross of the i-th clone with the j-th tester
$MSe =$ Mean Square of error
$r =$ replications
$t =$ testers
$e =$ environments

Table 4: Analysis of variance of three sets in three sites for ATW, MTYha and TTYha

| Source of Variation | SET 1 | ATW | MTYha th$^{-1}$ | TTY ha th$^{-1}$ | SET 2 | ATW | MTYha th$^{-1}$ | TTY ha th$^{-1}$ | SET 3 | ATW | MTYha th$^{-1}$ | TTY ha th$^{-1}$ |
|---------------------|-------|-----|-----------------|------------------|-------|-----|-----------------|------------------|-------|-----|-----------------|------------------|
| Replications        | 2     | 114.13** | 2.64** | 0.88ns          | 2     | 198.57 | 1.47** | 4.16** | 1.16** | 1202.02** | 11.66** | 1.16** | 1406.35** | 18.79** | 13.77** |
| Clones              | 18    | 158.63** | 20.02** | 22.91**         | 457.50** | 123.88** | 147.50** | 1055.71** | 45.19** | 48.17** |
| Testers             | 2     | 24.46** | 262.27** | 295.96**         | 37785.35** | 693.274** | 131.96** | 21625.41** | 506.34** | 340.07** |
| Clones x Testers    | 36    | 80.30** | 6.63** | 7.34**          | 104.4ns | 78.30** | 1473.41** | 45.98** | 60.93** |
| Error               | 112   | 10.27 | 0.35 | 0.46            | 108.01 | 10.34 | 13.96 | 229.99 | 5.06 | 6.53 |
| C.V. %              | 3.53  | 3.46 | 3.81 | 3.12            | 12.12 | 17.64 | 17.71 | 15.44 | 15.90 |

| Source of Variation | SET 1 | ATW | MTYha th$^{-1}$ | TTY ha th$^{-1}$ | SET 2 | ATW | MTYha th$^{-1}$ | TTY ha th$^{-1}$ | SET 3 | ATW | MTYha th$^{-1}$ | TTY ha th$^{-1}$ |
|---------------------|-------|-----|-----------------|------------------|-------|-----|-----------------|------------------|-------|-----|-----------------|------------------|
| Replications        | 2     | 9.85ns | 0.45ns | 0.45ns          | 125.28** | 4.65** | 6.31ns | 21.15ns | 0.93ns | 1.17ns |
| Clones              | 8     | 267.03** | 10.43** | 10.43**         | 676.87** | 123.75** | 125.17** | 28.06** | 2.39** | 3.39** |
| Testers             | 2     | 483.15** | 190.93** | 190.93**        | 11588.79** | 948.56** | 776.89** | 9.15ns | 10.46** | 8.04** |
| Clones x Testers    | 16    | 443.21** | 2.86** | 2.86**          | 221.73** | 28.80** | 42.25** | 30.22** | 2.59** | 3.33** |
| Error               | 52    | 45.74 | 0.34 | 0.34            | 41.98 | 1.60 | 2.64 | 11.74 | 0.47 | 0.62 |
| C.V. %              | 10.01 | 4.33 | 4.33 | 7.93            | 6.89 | 7.72 | 3.88 | 4.79 | 5.34 |

MTYha = Marketable tuber yield per hectare, TTY ha = Total tuber yield per hectare, * = highly statistically significant (P<0.01)
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of them with heat tolerance and high resistance to late blight: CIP398098.570, CIP398098.65, CIP398192.213, CIP398201.510, CIP398208.620, CIP398203.5, and CIP398208.670, showed significant effects GCA, for the three characteristics under study. In set 2, three clones showed significant effects of GCA for MTYha and TTYha and one for ATW (P < 0.01) and in set 3, five clones showed significant effects of GCA for MTYha, four for TTYha and 2 for ATW (P<0.01). The clones CIP398098.203 and CIP304081.44, showed significant effects GCA, for MTYha, TTYha and ATW (Table 6).

The testers, CIP398098.204 and the heat tolerant variety, Katahdin, presented good effects of GCA, for the three characteristics in study in the three sets. The tester Huagalina, a variety not tolerant to heat, did not present significant GCA effects (Table 7).

The clones CIP302533.74 from Set 2, CIP398017.53 and CIP398192.592, both from set 3, presented significant effects of GCA for ATW, but they were not significant effects of GCA for MTY and TTY, probably because of the tubers despite having a good average weight, but the number of tubers per plant was very low resulting in low tuber yield.

11 progenies showed high effect of SCA, statistically significant, for ATW, MTYha and TTYha in the three sets, pooled over locatons: CIP398180.292xHuagalina, CIP398190.615 x CIP398098.204, CIP398190.89 x Huagalina, CIP398193.158 × Huagalina, CIP398208.704 × Katahdin, CIP302531.43 × Kathadin, CIP302533.40 × Huagalina, CIP302533.74 × CIP302533.31, CIP304079.10 × Huagalina, CIP304081.44 × CIP398098.204, and CIP398017.53 × Kathadin (Table 8).

4 Discussion

The potato clones (LBHT), used in this study, are adapted to high temperatures in warm environments. Temperature is a very important factor that affects the production of tubers in the potato crop under climatic change conditions.

The potato crop is highly heterozygous and the tuber yield is governed by additive and non-additive genes, associated with the GCA and SCA respectively, in this study the analysis of variance shows significant differences between clones and testers, associated with the GCA, indicating us that there is enough variability for the parental value (GCA), allowing the identification of clones with high parental value. Likewise, significant differences

| Source of variation | SET 1 | SET 2 | SET 3 |
|---------------------|-------|-------|-------|
|                     | df    | ATW   | MTYha | TTYha | df    | ATW   | MTYha | TTYha | df    | ATW   | MTYha | TTYha |
| Environment (E)     | 2     | 1556.27** | 609.02** | 1121.55** | 2     | 20775.41** | 313.59** | 707.55** | 2     | 8954.96** | 542.60** | 1310.92** |
| Replica. tion/E     | 6     | 298.87 | 19.42** | 67.18** | 6     | 935.65** | 10.64** | 12.33** | 6     | 52.10 | 2.01 | 2.65 |
| Clones              | 18    | 720.51** | 89.58** | 101.27** | 5     | 1377.97** | 145.36** | 165.64** | 8     | 390.79** | 46.05** | 46.16** |
| Testers             | 2     | 39164.67** | 1271.99** | 587.42** | 2     | 13010.54** | 610.03** | 214.20** | 2     | 2763.06** | 754.27** | 655.18** |
| Clones x Testers    | 36    | 228.14** | 62.83** | 77.34** | 10    | 2241.85** | 34.13** | 48.36** | 16    | 213.08** | 12.80** | 19.04** |
| Clone x E           | 36    | 475.66** | 49.76** | 58.65** | 10    | 1248.58** | 79.31** | 91.30** | 16    | 290.59** | 45.26** | 46.42** |
| Tester x E          | 4     | 10135.28** | 94.95** | 90.82** | 4     | 1866.06** | 174.86** | 350.56** | 4     | 4659.01** | 197.84** | 160.33** |
| Clones x Tester x E | 72    | 168.75 | 29.05** | 35.54** | 20    | 1011.79** | 37.69** | 43.09** | 32    | 234.94** | 10.39** | 14.18** |
| Pooled Error        | 336   | 116.09 | 5.25 | 6.98 | 102 | 322.92 | 2.43 | 2.77 | 156 | 32.87 | 0.80 | 1.19 |
| C.V. %              | 12.34 | 13.74 | 14.44 | 19.69 | 11.79 | 11.01 | 7.23 | 5.82 | 6.67 |
Table 6: Estimates of General Combining Ability (GCA) effects for lines (clones), pooled over locations for average tuber weight, marketable and total tuber yield in three sets of clones from LBHT population

| #  | Lines (Clones) | Traits | Average tuber weight | Marketable Tuber Yield th^{-1} | Total Tuber Yield th^{-1} |
|----|---------------|--------|-----------------------|---------------------------------|---------------------------|
| SET 1 |               |        |                       |                                 |                           |
| 1  | CIP398098.205 | -3.38  | -0.63                 | -0.42                           |
| 2  | CIP398098.231 | -3.70  | -1.71                 | -1.57                           |
| 3  | CIP398098.570 | 2.23*  | 0.54*                 | 0.82*                           |
| 4  | CIP398098.65  | 3.90*  | 1.34*                 | 1.05*                           |
| 5  | CIP398180.289 | -3.01  | -1.18                 | -0.91                           |
| 6  | CIP398180.292 | 0.66   | 0.01                  | -0.08                           |
| 7  | CIP398190.615 | -9.34  | -4.11                 | -4.62                           |
| 8  | CIP398190.89  | -10.03 | -3.56                 | -3.63                           |
| 9  | CIP398192.213 | 6.58*  | 1.39*                 | 1.30*                           |
| 10 | CIP398192.553 | 5.11*  | 0.59*                 | -0.29                           |
| 11 | CIP398193.158 | -5.48  | -1.05                 | -1.19                           |
| 12 | CIP398193.511 | 0.71   | -0.65                 | -0.67                           |
| 13 | CIP398201.510 | 10.08* | 0.87*                 | 0.85*                           |
| 14 | CIP398203.5   | 3.99*  | 0.65*                 | 0.74*                           |
| 15 | CIP398208.219 | -2.86  | 0.57*                 | 0.54*                           |
| 16 | CIP398208.33  | 0.00   | 2.56*                 | 2.63*                           |
| 17 | CIP398208.620 | 2.99*  | 1.33*                 | 1.14*                           |
| 18 | CIP398208.670 | 2.15*  | 3.18*                 | 3.75*                           |
| 19 | CIP398208.704 | -0.28  | 0.29                  | 0.62*                           |
|     | S.E gca       | 2.07   | 0.44                  | 0.51                           |
|     | S.E (gi-gj)   | 2.93   | 0.62                  | 0.72                           |
| SET 2 |               |        |                       |                                 |                           |
| 1  | CIP302531.43  | -6.00  | 1.44*                 | 1.19*                           |
| 2  | CIP302533.40  | 3.00   | -0.63                 | -0.53                           |
| 3  | CIP302533.49  | -9.00  | -2.45                 | -1.95                           |
| 4  | CIP302533.74  | 11.00* | -2.88                 | -3.59                           |
| 5  | CIP302534.17  | 2.00   | 2.09*                 | 2.06*                           |
| 6  | CIP304079.10  | 0.00   | 2.41*                 | 2.83*                           |
|     | S.E gca       | 3.45   | 0.30                  | 0.32                           |
|     | S.E (gi-gj)   | 4.89   | 0.42                  | 0.45                           |
| SET 3 |               |        |                       |                                 |                           |
| 1  | CIP302551.26  | 0.23   | 0.45*                 | 0.24                           |
| 2  | CIP304081.44  | 5.30*  | 0.59*                 | 0.58*                           |
| 3  | CIP398017.53  | 0.86   | -0.77                 | -0.60                           |
| 4  | CIP398098.203 | 5.15*  | 2.12*                 | 1.70*                           |
| 5  | CIP398098.204 | -7.58  | -2.14                 | -2.18                           |
| 6  | CIP398190.200 | -1.99  | 1.29*                 | 1.68*                           |
| 7  | CIP398190.605 | -1.95  | -1.08                 | -0.91                           |
in the progenies (clone by tester interaction) allow us to identify promising progenies to develop clones with high yield potential under environments with high temperatures in climate change conditions.

The high parental value for tuber yield under high temperature conditions found in this study, coincides with the results by Beserra et al. (2001), who found that in clones with heat tolerance, the GCA was more important, indicating that the use of clones with high parental value

### Table 6 continued: Estimates of General Combining Ability (GCA) effects for lines (clones), pooled over locations for average tuber weight, marketable and total tuber yield in three sets of clones from LBHT population

| # | Lines (Clones) | Traits | Average tuber weight | Marketable Tuber Yield th \(^{-1}\) | Total Tuber Yield th \(^{-1}\) |
|---|---|---|---|---|---|
| 8 | CIP398192.592 | 0.93 | -0.91 | -1.15 |
| 9 | CIP398208.505 | 0.19 | 0.87* | 0.99* |
| S.E gca | 1.10 | 0.17 | 0.30 |
| S.E (gi-gj) | 1.56 | 0.24 | 0.21 |

*Clones with significant high parental value \(P<0.05\)

### Table 7: Estimates of General Combining Ability (GCA) effects for testers, pooled over locations for average tuber weight, marketable and total tuber yield, in three sets of clones from LBHT population

| Testers | Average tuber weight | Marketable Tuber Yield th \(^{-1}\) | Total Tuber Yield th \(^{-1}\) |
|---|---|---|---|
| SET 1 | | | |
| 1 | CIP398098.204 | 9.62* | 2.11* | 1.67* |
| 2 | Huagalina | -17.45 | -3.08 | -1.99 |
| 3 | Katahdin | 7.82* | 0.98* | 0.31* |
| S.E. gca | 0.22 | 0.18 | 0.2 |
| S.E. (gi-gj) | 0.32 | 0.25 | 0.29 |
| SET 2 | | | |
| 1 | CIP398098.204 | 13.74* | 2.76* | 1.83* |
| 2 | Huagalina | -16.70 | -3.74 | -2.12 |
| 3 | Katahdin | 3.78* | 0.97* | 0.30* |
| S.E. gca | 2.44 | 0.21 | 0.23 |
| S.E. (gi-gj) | 3.45 | 0.30 | 0.32 |
| SET 3 | | | |
| 1 | CIP398098.204 | 2.47* | 1.36* | 1.46* |
| 2 | Huagalina | -7.03 | -3.69 | -3.45 |
| 3 | Katahdin | 4.05* | 2.04* | 1.74* |
| S.E. gca | 0.64 | 0.10 | 0.12 |
| S.E. (gi-gj) | 0.90 | 0.14 | 0.17 |

*Clones with significant high parental value \(P<0.05\)
| CIPNUMBER | Female       | Male          | Average tuber weight | Marketable Tuber Yield th⁻¹ | Total Tuber Yield th⁻¹ |
|-----------|--------------|---------------|----------------------|----------------------------|-----------------------|
| SET 1     |              |               |                      |                            |                       |
| CIP313072 | CIP398098.205 Huagalina | -1.99          | 2.32*                | 2.45*                     |
| CIP313073 | CIP398098.205 Katahdin | -0.50          | 1.11*                | 1.35*                     |
| CIP313075 | CIP398098.231 Huagalina | 2.88           | 2.61*                | 2.72*                     |
| CIP313079 | CIP398098.570 Katahdin | -2.97          | 1.40*                | 1.85*                     |
| CIP313070 | CIP398098.65 CIP398098.204 | 1.36           | 1.23*                | 1.57*                     |
| CIP313070 | CIP398098.65 Katahdin | 3.18           | 0.81*                | 1.01*                     |
| CIP313082 | CIP398180.289 Katahdin | 2.11           | 1.54*                | 1.31*                     |
| CIP313084 | CIP398180.292 Huagalina | 7.90*          | 1.04*                | 1.12*                     |
| CIP313122 | CIP398190.615 CIP398098.204 | 3.87*          | 3.30*                | 3.83*                     |
| CIP313089 | CIP398190.89 CIP398098.204 | -0.76          | 1.62*                | 2.05*                     |
| CIP313087 | CIP398190.89 Huagalina | 9.09*          | 2.81*                | 2.67*                     |
| CIP313091 | CIP398192.213 Katahdin | 1.69           | 2.24*                | 2.31*                     |
| CIP313125 | CIP398192.553 CIP398098.204 | 0.37           | 2.23*                | 3.18*                     |
| CIP313124 | CIP398192.553 Katahdin | 3.26           | 2.78*                | 3.29*                     |
| CIP313093 | CIP398193.158 Huagalina | 3.70*          | 1.77*                | 1.61*                     |
| CIP313098 | CIP398193.511 CIP398098.204 | -3.87          | 1.57*                | 1.23*                     |
| CIP313096 | CIP398193.511 Huagalina | 1.19           | 1.80*                | 2.30*                     |
| CIP313116 | CIP398201.510 CIP398098.204 | 1.60           | 1.13*                | 1.15*                     |
| CIP313100 | CIP398203.5 Katahdin | -1.21          | 2.69*                | 2.59*                     |
| CIP313106 | CIP398208.33 Katahdin | 1.34           | 0.94*                | 0.59                      |
| CIP313121 | CIP398208.620 CIP398098.204 | 1.15           | 3.39*                | 3.72*                     |
| CIP313108 | CIP398208.670 Huagalina | 2.29           | 3.61*                | 4.58*                     |
| CIP313112 | CIP398208.704 Katahdin | 4.17*          | 3.45*                | 3.12*                     |
| S.E sca   |              |               | 3.59                 | 0.76                       | 0.88                   |
| S.E (sij-skl)) |          |               | 5.08                 | 1.08                       | 1.25                   |
| SET 2     |              |               |                      |                            |                       |
| CIP313147 | CIP302531.43 CIP302533.31 | -7.63          | 0.64*                | 1.23*                     |
| CIP313149 | CIP302531.43 Katahdin | 11.11*         | 2.74*                | 2.62*                     |
| CIP313154 | CIP302533.40 Huagalina | 14.37*         | 0.78*                | 1.20*                     |
| CIP313157 | CIP302533.49 Huagalina | 5.26           | 1.79*                | 1.45*                     |
| CIP313159 | CIP302533.74 CIP302533.31 | 32.15*        | 1.52*                | 1.88*                     |
| CIP313151 | CIP304079.10 Huagalina | 8.81*          | 1.45*                | 2.53*                     |
| S.E sca   |              |               | 5.99                 | 0.52                       | 0.55                   |
| S.E (sij-skl)) |          |               | 8.47                 | 0.73                       | 0.78                   |
| SET 3     |              |               |                      |                            |                       |
| CIP315021 | CIP302551.26 CIP398098.204 | -6.69          | 0.59*                | 0.93*                     |
| CIP315020 | CIP302551.26 Katahdin | 1.51           | 0.67*                | 0.58*                     |
| CIP315024 | CIP304081.44 CIP398098.204 | 6.12*          | 1.24*                | 1.14*                     |
| CIP315025 | CIP398017.53 Huagalina | 1.17           | 1.98*                | 2.27*                     |
| CIP315026 | CIP398017.53 Katahdin | 2.65*          | 0.81*                | 0.96*                     |
| CIP315005 | CIP398098.204 Katahdin | -5.35          | 0.94*                | 1.32*                     |
| CIP315009 | CIP398190.200 CIP398098.204 | -2.14          | 1.22*                | 1.23*                     |
| CIP315015 | CIP398190.605 CIP398098.204 | -2.06          | 0.09                 | 0.63*                     |
in breeding programs will allow us to obtain a high percentage of heat tolerant potato clones.

Identification of clones with high parental value (GCA), for MTYha, TTYha and ATW, in this study, will allow to have the best parents that transmit these traits to their progenies, increasing the frequency of favorable genes and genotypes in potato crop for variety selection. These characters are affected considerably for high temperatures in climate change scenarios.

Some clones presented high GCA for ATW, but they do not have good GCA for MTYha or TTYha, probably because despite having tubers of adequate size, the number of tubers per plant is low, decreasing yields, this being frequent when clones are evaluated for heat tolerance. So is important to select parental potato clones that combine high GCA for ATW and MTYha and TTY under warm conditions.

The GCA is more important when selecting clones with high parental value, but it is also found that there are very promising crosses for their high value of SCA, which will allow us to select superior clones for the characteristics under study, coinciding with the results found by Ruiz de Galarreta et al. (2006), who found that both GCA and SCA were important for tuber yield, tuber number and average tuber weight, but differ from the results found by Da Silva et al. (2015), Hirut et al. (2017), who suggest the predominance of additive effects (GCA).

12 crosses with significant SCA, 50 percent of them were crosses by testers Katahdin and CIP398098.204 and the other half with Huagolina, probably because the clones crossed to Katahdin and the clone CIP398098.204 that are tolerant to the heat, increase the frequency of alleles for high yields against heat stresses, and crosses with Huagolina, would be exploiting the effect of heterosis by crossing two genetically divergent sources.

The resistance to the PVX and / or PVY viruses present in some of the clones with high GCA, could have influenced their capacity of performance, since under conditions of high temperatures the presence of insect vectors of virus is greater, being this characteristic very important when selected for heat tolerance, especially resistance to PVY virus.

In all sets, 18 potato clones were identified with high parental value for MTYha, 17 for TTYha and 11 for average tuber weight under high temperatures; nine of them combine high parental value for the three characters studied pooled over sites.

These clones with high parental value, high levels of late blight resistance, heat tolerant, adapted to tropical mid-elevation, a growing period of 90 days and high parental value can be used as parents in breeding programs of countries where these limitations exist in Africa, Asia or Latin America, in order to obtain progenies with high potential for new varieties with heat tolerance, high resistance to late blight, high tuber yield, tuber weight of suitable marketable value, under the new scenarios of high temperatures, as an effect of climate change.

The progenies that presented high SCA are the most promising for the development of superior clones for ATW, MTYha and TTYha.

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**Table 8 continued:** Estimates of Specific Combining Ability (SCA) effects in progenies, statistically significant pooled over locations for average tuber weight, marketable and total tuber yield

| CIPNUMBER | Female | Male          | Average tuber weight | Marketable Tuber Yield th⁻¹ | Total Tuber Yield th⁻¹ |
|-----------|--------|---------------|----------------------|-----------------------------|------------------------|
| CIP315013 | CIP398190.605 | Huagolina | 0.43                 | 2.05*                       | 1.83*                  |
| CIP315016 | CIP398192.592 | Huagolina | 0.32                 | 0.43*                       | 0.38*                  |
| CIP315017 | CIP398192.592 | Katahdin | 1.13                 | 0.68*                       | 0.81*                  |
| CIP315012 | CIP398208.505 | CIP398098.204 | 3.23*             | 0.33*                       | 0.13                   |
| CIP315010 | CIP398208.505 | Huagolina | -4.27                | 0.34*                       | 0.57*                  |

*Progenies with significant SCA P<0.05

| S.E sca | 1.91 | 0.30 | 0.36 |
| S.E (sij-skl) | 2.70 | 0.42 | 0.51 |
Conflict of interest: Authors declare no conflict of interest.

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