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Estimates of repeatability coefficients and selection gains in Jatropha indicate that higher cumulative genetic gains can be obtained by relaxing the degree of certainty in predicting the best families

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ABSTRACT

The aim of this study was to estimate the repeatability coefficient of grain production in Jatropha, the minimum number of measurements needed to reliably predict the genetic value of selected families, and to determine the cumulative genetic gains when considering the selection of the best families based on different number of measurements. The experiment was conducted with 175 accessions (half-siblings progenies derived from selected plants in the field) that compose part of a germplasm collection. Such bank was established in a randomized block design with two blocks. In each block a given accession was represented in a 5 plant/plot scheme (half-siblings). For the analysis, yield data obtained in the years of 2009–2012 were considered. The results of this study indicate that the repeatability coefficient of grain production in Jatropha is low (0.37), but comparable to other perennial species, and that to achieve reliabilities of 70 and 80% in the prediction of breeding values of selected families, 4 and 7 years of evaluation, respectively, are needed. The results of this study also indicate that the efficiency of early selection seems to be small in Jatropha since the coincidence rate of selected genotypes at early age (1 or 2 years of evaluation) and genotypes selected in adult age (4 years assessment) is small (17–23%). Finally, taking into account the repeatability coefficients and coefficients of determination, in a hypothetical period of 21 years (which is equivalent to three selection cycles using seven consecutive measurements – $R^2 = 80\%$), this paper demonstrates that higher cumulative genetic gains can be obtained (159% over 108%) by relaxing the degree of certainty in predicting the best families ($R^2 = 65\%$ instead of $R^2 = 80\%$), since it makes possible to perform a greater number of selection cycles in the same period (7 cycles instead of 4).

1. Introduction

Physic nut (*Jatropha curcas* L.) is a non-edible, subtropical multipurpose crop that produces oil bearing seeds, which can be used for a wide variety of bio-based materials including biodiesel, biojet fuel and specialty chemicals. Because of its numerous economic and sustainable attributes, it has attracted the interests of the research and energy sectors (Durães et al., 2011; Dias et al., 2012 #4919). Several governmental incentive agencies worldwide have made a growing volume of resources available for research and development of the species (Dias et al., 2012). Moreover, several corporations, from the energy sector, are now promoting Jatropha as one of the most viable feedstocks for large-scale production of sustainable plant oil and as one of the most promising oil plant species for biodiesel and bio-kerosene (jet-fuel) production. As consequence of these efforts, large corporations have invested a great deal in its wide scale planting (Dias et al., 2012). For instance, China and India solely, have already more than 2.5 million hectares planted with Jatropha (Fairless, 2007), despite the fact that most of the genetic variability of the species is concentrated in the Central and South Americas (i.e. Mexico, Colombia, Guatemala and Brazil). In these regions Jatropha has also attracted attention. In Brazil for instance, Jatropha has been considered for some years now (Laviola et al., 2010b) as a major alternative species that can

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complement soybeans as a source of vegetable oil for production of biodiesel and bio-kerosene. In addition to good yield (Drumond et al., 2010) and oil quality favorable to the production of biofuels (Freitas et al., 2011), its wide adaptability to different regions of Brazil and its longevity has attracted the interest of various research groups (Durães et al., 2011). Currently there are at least 20,000 ha planted with Jatropha in the country, and with the interest of the private sectors this area is expected to rapidly increase.

However, despite its potential, the species is still under domestication, and there are no cultivars, nor validated production systems for different producing regions worldwide. Therefore, research and development initiatives led both by the public and private sectors have focused mainly on breeding (Durães et al., 2011; Laviola and Alves, 2011). Several studies have been conducted to determine physic nut genetic variability and breeding potential (Abdelgadir et al., 2012; Bhering et al., 2012a,b; Gurgel et al., 2011; Laviola et al., 2011, 2012c; Mastan et al., 2012; Pandey et al., 2012; Rocha et al., 2012b; Rosado et al., 2010; Silva-Junior et al., 2011). Most of these studies indicated that there are good prospects for the species' breeding in given the opportunity to select superior materials, although the genetic basis of material on the Active Germplasm Bank of Embrapa is small (Rosado et al., 2010). However, little is known about the repeatability of target traits (e.g. grain production in ages over 3 years, since studies on the subject consider only two years – Laviola et al. (2012c). In breeding of perennial plants, not only the determination of variability, but also the repeatability estimates of target traits are important for designing a breeding program, since the repeatability coefficient measures the ability of organisms in repeating the character expression over several periods of time. This allows verifying whether the superiority of some genotypes is maintained over the years, or whether it was due to some transient environmental condition. High values of repeatability indicate that it is possible to predict the actual breeding value of the individual based on few sequential measurements. From a practical standpoint, this parameter presents crucial importance in predicting genetic and genotypic values and in the inference about the increase of selective efficiency by using an established number of measurements per individual, which allow the determination of the number of crops to be adopted in a breeding program (Resende, 2002).

The repeatability can vary depending on the nature of the trait, on the genetic properties of the population, and on the environmental conditions under which individuals are maintained (Cruz et al., 2004). Moreover, there are different methods for obtaining repeatability coefficient estimates. These methods have been used in several perennial species, with different applications and particularities. The method of analysis of variance, for example, is indicated in order to evaluate p genotypes in n repeated measures, considering the properties and constraints of an evaluation using the least-squares method (Cruz et al., 2004). On the other hand, methods based on principal components are considered the most appropriate in situations when the evaluated genotypes present cyclical behavior in relation to the trait studied, and when they do not meet the assumptions of variance homogeneity and random distribution of residues (Abeywardena, 1972; Rutledge, 1974). On the other hand, the method of structural analysis (Mansour, 1981) is also differentiated since it requires few assumptions, and differs itself from the method of principal components only by conceptual issues (Cruz et al., 2004).

Based on the aforesaid, the aim of this study was: (i) to determine the repeatability coefficient of grain production in Jatropha (considering evaluations over four consecutive years); (ii) to establish, based on the coefficients of repeatability and determination, the minimum number of measurements needed to predict with predetermined reliability the genetic value of the selected families; (iii) to verify the coincidence in the selection of the best families carried out in different years; and finally (iv) to determine the cumulative genetic gain when considering the selection of the best families based on different measurement numbers (i.e. with different degrees of certainty in predicting the best families). These results, together with those previously published, can help to establish strategies for Jatropha breeding that enables the rapid development of more productive varieties/cultivars.

2. Materials and methods

2.1. Plant material, experimental design and evaluation

The experiment was conducted with 175 Jatropha accessions (half-siblings progenies derived from selected plants in the field) from the germplasm bank of Embrapa Agroenergy, which is installed in the experimental area of Embrapa Cerrados, Planaltina, DF, Brazil (lat. 15°35′30″ S, long. 47°42′30″ W, and 1007 m alt. asl). The region presents a tropical climate with dry winter and rainy summer. The average temperature is 22 °C and the mean relative humidity is 73%. The total annual rainfall is about 1000 mm. The predominant soil in the location was classified as Oxisol with high clay content. The germplasm bank was established in 2008 in a randomized block design with two blocks. In each block a given accession is represented in a 5 plant/plot scheme (half-siblings). The plots were arranged in rows, spaced 4 m apart, and each plant was placed 2 m apart from the next plant in the row. In order to determine the repeatability coefficient, the data obtained for dry grains production, in four agricultural years were considered. Data was collected between January to June of 2009, 2010, 2011 and 2012. The plant management was performed according to the latest research results (Anitha and Varaprasad, 2012; Karanam and Bhavanasi, 2012; Laviola et al., 2012a; Resende et al., 2012a,b).

2.2. Estimates of repeatability coefficients

Data were subjected to analysis of variance and the genetic parameters estimated considering half-sib families, information within the plot and specific environmental conditions in Brazil (cerrado conditions – tropical climate with dry winter and rainy summer). To obtain the estimate of the repeatability coefficient, data were previously classified within each measurement, according to Cruz (2006b). The calculation of the repeatability coefficient was then performed by the following methods: (i) analysis of variance, in which the repeatability coefficient is estimated by the results of analysis of variance; (ii) principal components, based on the covariance matrix by applying the matrices of variance and phenotypic covariances; (iii) principal components, based on the correlation matrix, in which the estimator of repeatability is obtained based on the assumption that the repeatability coefficient is given by the correlation between each pair of measurements evaluated in different genotypes; and (iv) the structural analysis based on correlation matrix, in which the parametric correlation matrix between the genotypes is considered, in each pair of evaluation, with repeatability coefficient estimator based on structural analysis. For details about the methods, see Cruz (2006a).

2.3. Selection gain and coincidence of selected families

In addition to the estimation of repeatability, a selection intensity of 10% was applied aiming to estimate the coefficient of coincidence in the selection of the 17 best genotypes (mass selection) between years of evaluation. A dispersion graph was also generated for genotypes behavior between the first two years (P_{12}) and in the last two years of evaluation (P_{34}) in order to visualize the individual and overall performance of the genotypes over the first four years (and to identify families with increased phenotypic

Table 1
Analysis of variance of grain yield (g plant^{-1}) generated after the evaluation of 175 Jatropha accessions during four consecutive agricultural years, demonstrating the existence of genetic variability that can be exploited by the breeding programs.

SV	DF	MS
Blocks	1	1,599,740.50
Genotypes (G)	174	56,548.69*
Years (Y)	3	49,038,970.32*
G × Y	522	32,718.10*
Residue	696	18,381.64
Total	1399	

SV, source of variation; DF, degrees of freedom; MS, mean square.
* Significant at 1% probability.

stability over the four years). All analyses were performed using the GENES software (Cruz, 2006a).

3. Results and discussion

3.1. Variability, heritability and coefficient of experimental variation for grain production

The fact that this work was based on a four-year evaluation (2009–2012) makes it one of the most complete studies ever made in the culture of Jatropha to date, even though it address specific environmental conditions in Brazil. In this context, it is important mentioning that the results obtained by ANOVA indicate the existence of genetic variability that can be exploited by the breeding program, assuming a 1% level of probability for grain production between the 175 genotypes evaluated (Table 1). This is extremely relevant, since it confirms previous studies carried out while the plants were at early ages. Such studies (Bhering et al., 2012b, 2013; Laviola et al., 2010a,b, 2012b,c) had already demonstrated the existence of genetic variability for grain production, and the prospect of selection gain for grain production in the same population, even with a limited genetic base (Rosado et al., 2010). It can be argued that not only grain production is an important trait in this crop, and that other traits should be evaluated, but given the fact that improved cultivars have not been developed yet, this trait certainly is the most important in evaluations. This is corroborated by the fact that research results published so far, indicate the existence of a loose connection between the yield components with oil production (Bhering et al., 2012b, 2013; Laviola et al., 2010b, 2011, 2012b,c; Rocha et al., 2012a; Spinelli et al., 2010). Thus, one should focus directly on breeding for grain production to increase the oil productivity per hectare.

Moreover, with respect to grain yield, it can be observed in Table 2 that in general there is an upward trend in the population's average over the years, mainly between the third and fourth harvest. This trend is also accompanied by a downward trend in the experimental coefficient of variation over the years. Such trends must be related (i) to the fact that in the early stages of growth, plants are more sensitive to environmental variations and (ii) to the fact that young perennial plants often have their metabolism toward vegetative rather than reproductive growth (Larcher, 2004).

Table 2
Mean (g plant^{-1}), broad-sense heritability (h^2) and coefficient of variation (CV%) for grain yield of 175 Jatropha accessions evaluated during four consecutive agricultural years.

Agricultural year (plants age)	Mean (g plant^{-1})	h^2	CV (%)
2009 (1 yr)	11.32	0.69	76.43
2010 (2 yr)	175.94	0.62	32.23
2011 (3 yr)	329.73	0.31	33.57
2012 (4yr)	874.35	0.54	27.54

Table 3
Repeatability coefficients (r) and coefficients of determination (R^2) for grain yield obtained by different statistical methods, after the evaluation of 175 Jatropha accessions evaluated during four consecutive agricultural years.

Method	r	R^2 (%)
ANOVA/structural – COV	0.37	70.18
Principal components – COV	0.37	70.25
Principal components – COR	0.37	70.25
Structural – COR	0.37	70.18

COV, method of covariance; COR, method of correlations.

The heritability, in its broad-sense, also showed a downward trend over the years. However, it must be considered that the coefficient of heritability estimated on young perennial plants are often inflated by genotype × year interactions (Resende et al., 2001). In fact, when analyzing the effect of genotype × year interactions it is noticed that it was also significant at 1% level of probability (Table 1), indicating the existence of genotypes with different performance over the years in terms of grain production. This fact was expected, since the significant interaction between genotypes and years is recurrent in evaluation of perennial plants, and it is commonly caused by the effect of the environment on trait expression (Resende, 2002). Thus, these results indicate that it is necessary that evaluations are carried out over many years until the grain production is stable, since Jatropha is a perennial species. In this context, this is one of the first studies to bring the results of careful evaluation of Jatropha plants older than 36 months.

3.2. Repeatability coefficient and minimum number of measurements

From the data collected in four years of evaluation (2009–2012) and based on different biometric methods, the coefficients of repeatability and determination were determined (Table 3). As mentioned before, the repeatability coefficient measures the ability of organisms to repeat the expression of a trait over several periods of time, whereas the coefficient of determination (R^2) measures the degree of certainty in predicting the real value of an individual. It was observed that, regardless of the method, the repeatability coefficient (r) did not vary, indicating that the adoption of one or another strategy does not affect the estimate. This result is interesting, since in some cases the option for either method can improve the efficiency of breeding programs. For example, Bhering et al. (2013), when comparing different selection methods in Jatropha, verified that the combined selection is more suited than other methods for rapid improvement of this species.

In relation to the estimated value of the repeatability coefficient, this value is considered low, especially when comparing it with the values found for this same population (when only two evaluations were considered) (Laviola et al., 2012c). Nevertheless, when comparing the value obtained with the repeatability coefficient for production in other perennial species, it is observed that it is in fact somewhat similar. This is because the genotype stabilization did not occur until the fourth harvest year. According to Cruz et al. (2004), grain production is a complex trait and it is determined by different gene pools, and it is possible that different gene pools are expressed at different stages, and even within a given group, some genes may be more or less expressed, according to the developmental stage of the genotypes. Thus, when a repeatability study is conducted in genotypes which are not stabilized yet, low repeatability may be found, which does not mean that the solution for the problem is the increase in the number of repetitions. In some cases, the absence of evaluation in early stages, in which there is no full manifestation of the genetic potential of the material studied, may increase the estimate of repeatability. In this study, as it is shown in Table 2, the coefficient of environmental variation in the first

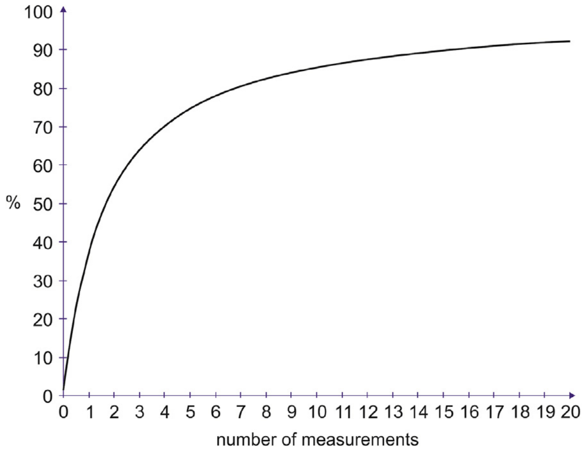

Fig. 1. Graphic analysis of the minimum number of measurements required to reach a determined degree of certainty in the selection of the best genotypes of Jatropha for grain production according to different methods (analysis of variance, principal components based on the covariance matrix, principal components based on the correlation matrix and structural analysis).

Table 4
Selected sets of Jatropha genotypes based on grain yield (g plant^{-1}) considering the information of each year individually, the four years average (P_{1234}) and the mean of the first two years (P_{12}) and of the last two years (P_{34}).

Years	Selected Jatropha individuals
1	61 74 75 12 64 63 33 2 101 22 143 102 123 23 173 103
2	61 74 173 31 172 101 83 35 140 25 62 76 158 33 47 123 165
3	4 6 3 81 5 171 76 172 8 9 34 82 122 2 1 94 7
4	31 7 22 33 159 73 102 163 25 155 94 139 154 111 157 81 29
P_{1234}	31 7 22 33 81 159 4 94 25 61 155 73 102 139 30 5 12
P_{12}	61 74 173 31 172 101 83 35 140 33 62 81 25 76 123 158 47
P_{34}	31 7 22 4 33 159 81 73 94 155 6 5 25 102 154 139 30

P_{1234}, mean of four years; P_{12}, mean of the first two years; P_{34}, mean of the last two years of evaluation.

season was quite evident, which may have contributed to reduce the repeatability coefficient of grain production. In relation to the study of Laviola et al. (2012c), in which high repeatability was verified, the lower range of variation of the mean and CV may have contributed to the result. Thus, in future studies, the exclusion of the first season and the others belonging to periods in which there is no genotypic stabilization may be a more appropriate way for estimating the coefficient of repeatability and predicting with greater accuracy the genetic value of Jatropha families and individuals.

In relation to the estimated coefficient of determination, it is observed that except for minor decimal variations, the result was essentially the same, regardless of the methodology used (Table 3). It is noteworthy that the value found allows good reliability in the prediction and selection of genotypes. The evolution of the minimum number of measurements related to the degree of certainty (R^2) in the selection of the best genotypes (prediction of the actual value) is shown in Fig. 1. According to this result, the use of four repeated measurements leads to a coefficient of determination of 70%, whereas seven sequential measurements are required to achieve an accuracy of 80%. These results are consistent with those published for other perennial species such as oil palm and eucalypts (Chia et al., 2009) and also with those published by Laviola et al. (2012c), which showed that at least four measurements were necessary for achieving reasonable selective accuracies based on the evaluation of young plants.

3.3. Coincidence in the selection of the best families in different years

As there is the possibility of selecting the best families based on different numbers of evaluations, it is important to know if the breeder will be selecting the same genetic material while doing the selection based on different strategies. In order to explain this issue, the top 17 genotypes (selected considering a selection intensity of 10%) selected for each year were compared (Table 4) using the coefficient of coincidence. In order to compute the coefficient of coincidence in the selection of the 17 best genotypes, different combinations were considered: year × year, year × selection based on the averages of four years (M), and selection based on the mean of the first two years (P_{12}) × selection based on the mean of the last two years (P_{34}) (Table 5).

In general, plants which stand out in one of the years are not the same plants that present best performance in the following year (Table 4). This behavior tends to limit the selection of plants in the juvenile phase, based on the evaluation of one or a few years, since the plant which has better yield potential is the one that maintains its superior performance after stabilizing its productivity (Cavalcante et al., 2012; Cruz et al., 2004; Resende, 2002). This observation is corroborated by the estimated coefficient of coincidence. The coincidence of selected genotypes is low in all combinations year × year, indicating that there is a low maintenance of productive stability of genotypes in the first four years (Table 5).

The magnitude of the coefficient of coincidence between genotypes selected in the first and last year permits the evaluation of the efficiency of early selection. In year × year comparisons, it would be interesting to find high coefficient of coincidence among genotypes selected in early ages (1 or 2 years of evaluation) and those selected at the last year of evaluation (representing adulthood), as this might allow early selection of superior families/individuals. However, the coincidence of these comparisons was low (Table 5), which demonstrates that the selection based on a single season and at ages equal or less than 3 years does not reflect the production at older ages. These results confirm the low repeatability coefficient found in the 4 initial seasons (Table 3). In juvenile phase, perennial plants may present great variation among genotypes for (re)production, since in this period the majority of expressed genes are associated with the formation of vegetative organs and present greater stability at older ages (Larcher, 2004). The comparison among the genotypes selected in the 4th year (A4) and the genotypes selected using information from all years (Table 5) presented the highest coefficient of coincidence (70.59%). This result is typical of perennials, whose annual grain production is still on an upward trend, being the last harvest the most important in the selection of the best families.

Table 5
Coefficient of coincidence in the selection for the 17 best accessions for grain yield (g plant^{-1}) considering the combination of two consecutive years ($A_{\_} \times A_{\_}$), the combination of individual years with the mean of the four consecutive years ($A_{\_} \times$ M) and the average of the first two with the average of the last two years ($P_{12} \times P_{34}$).

Measurements	Coincidence (n)	Coincidence (%)
$A_1 \times A_2$	6	35.29
$A_1 \times A_3$	2	11.76
$A_1 \times A_4$	4	23.53
$A_2 \times A_3$	2	11.76
$A_2 \times A_4$	3	17.64
$A_3 \times A_4$	3	17.64
$A_1 \times M$	6	35.29
$A_2 \times M$	4	23.53
$A_3 \times M$	5	29.41
$A_4 \times M$	12	70.59
$P_{12} \times P_{34}$	4	23.53

A_n, year; M, mean of four years; P_{12}, mean of the first two years of evaluation; P_{34}, mean of the last two years of evaluation.

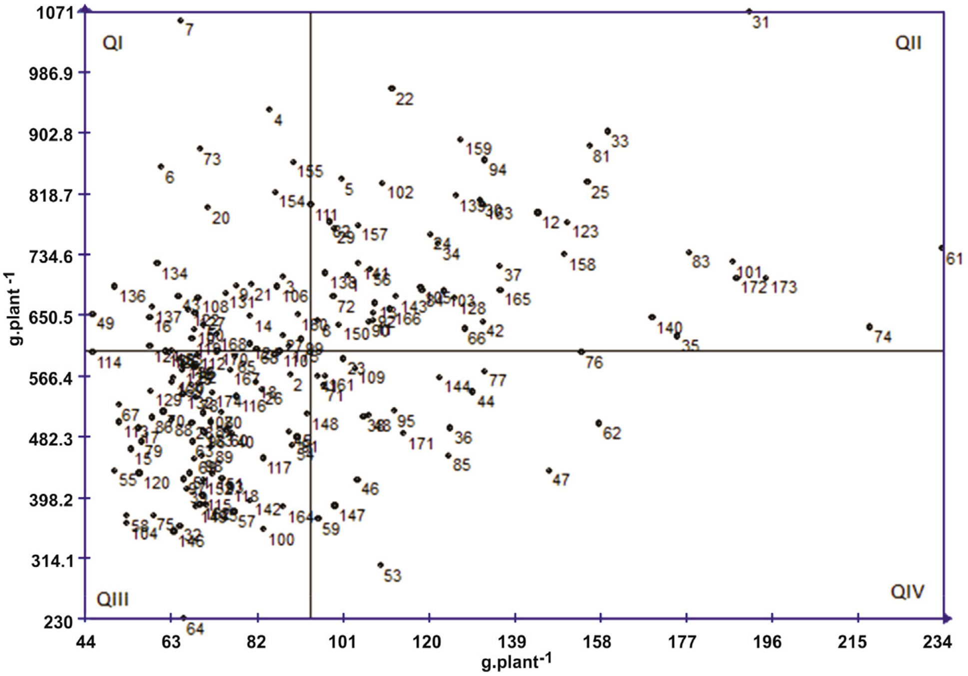

Fig. 2. Dispersion of the performance of the 175 Jatropha genotypes over the first and the last two years of cultivation. X axis – (P_{12}) and y axis – (P_{34}).

The dispersion of the performance ratio of the 175 genotypes in the first two years (P_{12}) and in the last two years (P_{34}) is also an interesting evaluation for identifying individual and overall performance of genotypes over the first four years (Fig. 2). In this graph, genotypes are plotted, on the x axis, according to production (g plant^{-1}) in the first two years; and according to production (g plant^{-1}) in the last two years, on the y axis. Thus, in quadrant two (QII), genotypes that showed above-average performance in the first and last two years are presented. Therefore, families observed in this quadrant are those that presented greater phenotypic stability over the four years. Examples are genotypes 33, 81 and 25, with average yield, in g plant^{-1}, of 159.38, 155.48 and 154.98 (first and second year); and 905.60, 885.06 and 835.36 (third and fourth year), respectively. In quadrant I (QI), the genotypes that showed low average yield in the first and second year are shown; nevertheless, they stood out for their high average yield in the third and fourth year. Genotype 7 is highlighted due to its low yield in the first two years, but it was the genetic material that presented the highest average in this quadrant. Yields shown during fourth year are those that contribute most to the selection of superior genotypes. Thus, the selection of genotypes in QI becomes quite interesting, since even though the genotypes presented below-average performance in the first two years they presented highest yields. Finally, in quadrant III and IV, the low yield families are presented (below-average production), in the evaluations of the yield in the years P_{12} and P_{34}. A large number of materials compose these quadrants and a high concentration and overlap of genotypes is observed in quadrant III. These genotypes should be discarded in the process of breeding for grain production, since they contribute little to the development of productive cultivars.

3.4. Cumulative genetic gain considering different strategies according to the number of measurements

Provided that 3 additional measurements would be necessary to achieve 80% accuracy, besides the four measurements necessary for 70% accuracy (Table 6), it is important to assess whether a 10% increase in selection efficiency justifies an increase of 75% of the time to conclude the selection cycle (7 vs. 4 years). In order to make this comparison, the genetic gain was calculated by applying pressure of 10%. Such gain was later adjusted considering different selection efficiency (which corresponds to R^2 – 65, 70 and 80%). To make this comparison more realistic, it was considered that with the narrowing of the genetic base after a selection cycle, the selection gain in advanced generations would be decreased by 5%. Table 6 shows a projection of expected genetic gains in a Jatropha breeding program after 21 years of breeding. Table 6 also shows that, depending on the accuracy adopted by the breeder, within a predetermined period of 21 years, from 3 up to 7 selection cycles for grain production can be performed. Furthermore, higher cumulative genetic gains can be obtained by relaxing the level of certainty in the prediction of best families, since the total gain

Table 6
Simulation indicating the genetic gains expected for Jatropha grain yield (g plant^{-1}) in successive selective cycles, the number of selection cycles possible to be performed in a predetermined hypothetical period of 21 years of breeding and accumulated genetic gain for Jatropha in relation to the adoption of different coefficients of determination by the breeder.

Selective cycle	Expected gain (%)	Adjusted gain[a]		
		$R^2 = 65\%$[b]	$R^2 = 70\%$[c]	$R^2 = 80\%$[d]
1	50	32.5	35.0	40.0
2	45	29.2	31.5	36.0
3	40	26.0	28.0	32.0
4	35	22.7	24.5	
5	30	19.5	21.0	
6	25	16.2		
7	20	13.0		
Accumulated gain (%)		159.2	140.0	108.0

[a] Adjusted gain $R^2 = \text{Gain} \times R^2$.
[b] 3 years of evaluation/cycle.
[c] 4 years of evaluation/cycle.
[d] 7 years of evaluation/cycle.

provided by the strategy using 65% of certainty is 47% higher than that provided by adopting a strategy with 80% of accuracy. Through these comparisons, the adoption of three or four measurements in time (yield evaluations), despite having lower coefficients of determination, may allow greater accumulated genetic gains over several selection cycles. It can be argued that carrying out 7 selection cycles in 21 years, instead of just three, may lead to rapid depletion of genetic variability. This is a relevant concern indeed. However, as well discussed by Bhering et al. (2013) (when comparing the expected gains using different selection strategies), considering the growing demand for improved varieties of Jatropha in Brazil and abroad, there is a trend to the first strategy, since Jatropha breeding programs have to respond quickly to this demand by developing more productive varieties. Considering that the genetic basis of Jatropha in Brazil is already considered to be limited (Rosado et al., 2010), the addition of new sources of variability will be imperative in short/medium term, regardless of 7 or 3 selection cycles, since breeders should not wait until the genetic basis is exhausted to then seek for a solution.

4. Conclusions

In general, the results of this study allow us to conclude that: (i) the repeatability coefficient of grain production in Jatropha is low, but it is comparable to other perennial species, such as oil palm and eucalypts, (ii) based on the repeatability coefficient, 4 and 7 are the minimum number of measurements required to predict the genetic value of the selected families with reliabilities of 70 and 80%, respectively, in the evaluated environmental conditions, (iii) the coincidence in the selection of the best families carried out in different years is low; therefore, the efficiency of early selection is small, and (v) greater cumulative genetic gains can be obtained by relaxing the degree of certainty in the prediction of the best families.

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