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Progress in breeding of irrigated wheat for the Cerrado region of Brazil

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ABSTRACT - *This study aimed to quantify the progress obtained by breeding programs of irrigated wheat in the state of Minas Gerais, Brazil, from 1976 to 2005. The efficiency of the programs was evaluated based on yield data obtained in Value for Cultivation and Use (VCU) trials. The genetic and environmental progress was estimated by the methodology of Vencovsky et al. The mean annual progress rate from 1976 to 2005 in mean yield was estimated to be 48 kg ha^{-1} yr^{-1} (1.84% per year). Environmental and technological improvements were important for the increased yield during the study period, accounting for 32.8% of the total gain. Over the years, 33% of the genotypes used in the improvement programs of irrigated wheat were replaced.*

Key words: breeding, genetic gain, genotype evaluation, *Triticum aestivum* L.

INTRODUCTION

Since its release in Brazil, wheat is being grown predominantly in the temperate climate zone, extending from Rio Grande do Sul to Parana. Many researchers considered this region the most adequate for commercial production of the cereal. Moreover, since the 1970s, wheat cultivation has expanded into central West Brazil, where cultivation in the Cerrado (open Brazilian savannah) region appears to be promising (Souza and Ramalho 2001, Cargnin et al. 2006).

Irrigated wheat can be cultivated across almost the entire state of Minas Gerais, comprising all areas at over 400 m asl. Since the cereal is not a host for diseases such as sclerotinia, rhizoctonia or fusariosis, it has become the main option for crop rotation, as for example with bean in autumn/winter. In the state of Minas Gerais irrigated wheat is sown from April 10 through May 31.

In the late 1970s, breeding programs in Minas Gerais focused on the release and experimental testing of cultivars of several national and international institutions. Germplasm for irrigated cultivation was introduced from the International Corn and Wheat Breeding Center (CIMMYT), Mexico. From 1980 to 1993, a selection program was developed with segregating populations, initially together with the Cerrado Research Center (CPAC) and later the National Wheat Research Center (CNPT), of the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). After 1993, the Universidade Federal de Viçosa (UFV) took part in the state wheat breeding programs, contributing with hybridizations and releases of the CIMMYT line.

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Genetic breeding plays a major role in obtaining adapted and superior genotypes for production, i.e., wheat cropping is made possible by the development of regionally adapted cultivars. Estimates of the progress achieved by breeding programs are valuable tools that can be used to quantify the efficiency of a study carried out by one or more research institutions. Besides, understanding the efficiency of breeding programs is important to evaluate the strategy applied and to make better use of the resources available. Thus, before new cultivars are released, researchers need to know whether the newly developed lines are actually genetically more advanced than the existing commercial cultivars and to determine the superiority.

When evaluating the genetic gain of new wheat cultivars in Southern Brazil, Nedel (1994) found that yields were substantially higher than of the older cultivars, with increases of 17.3 kg ha^{-1} yr^{-1}, in the period from 1940 to 1992. However, a sample of only 15 cultivars (under no-tillage) had been used to estimate the progress over 52 years. Mellado (2000) evaluated the cultivars obtained in different periods by the Genetic Wheat Breeding Program in Chile but did not confirm genetic gains for grain yield. In this case, rather than due to genetic gains, the cultivars had been substituted due to better sanitation.

Some methodologies were developed to quantify the progress in breeding. One possibility is to carry out experiments with cultivar samples used in the comparison periods. In this case, older cultivars are compared to newer ones. However, not only are the costs of such experiments high but also some of the cultivars developed during a particular period may no longer be available.

It is therefore necessary to search for alternative methods to monitor genetic progress. Ideally, the methods should use information obtained in previous trials (Atroch and Nunes 2000). As an alternative, Vencovsky et al. (1986) suggested using data from cultivar evaluation trials conducted by research institutions, as done in various studies assessing the contribution of genetic breeding to several crops under Brazilian conditions (Moresco 2006).

This study aimed to quantify the progress obtained by irrigated wheat breeding in the state of Minas Gerais from 1976 to 2005.

MATERIAL AND METHODS

Irrigated wheat yield data obtained from Value for Cultivation and Use (VCU) trials were used in experiments carried out in Minas Gerais, Brazil, under the direction of the Empresa de Pesquisa Agropecuária de Minas Gerais (EPAMIG) together with other institutions, from 1976 to 2005. Every year, genotypes (cultivars and/or lines) that did not perform well in the trials were discarded and substituted by others. Conversely, well-performing genotypes were maintained in continuous evaluation; depending on the annual performance, a genotype would thus be evaluated for two or more years.

In most years the trials were arranged in a randomized block design, with four replications, to determine mean yields of cultivars and/or lines in each year. The means were repeated k times for each genotype, according to the number of trials and number of replications.

The trials that originated the data used here were carried out at 19 locations in Minas Gerais. Wheat was sown in the recommended period (between April 10 and May 31). No fungicide was applied, except in the experiments in São Gotardo. The common crop practices of season and region were used in the other trials.

The methodology of Vencovsky et al. (1986) was used to calculate the gain. This approach allows for an estimation of the mean progress based on data of genotype groups evaluated over a particular period of time. It is assumed that, every year, new genotypes are produced by breeding programs and incorporated into competition trials together with others, maintained under evaluation in view of their yield capacity, adaptability and, mainly, acceptance by producers. Genotypes that for some reason are eventually surpassed are excluded.

The difference between mean yields of the common genotypes every two years is used to estimate the year effect. The annual genetic advance is calculated by the difference between the mean genotype yield of a given year and of the immediately preceding year, excluding the year effect. Thus, considering two consecutive years, the genetic gain is estimated by the genetic difference, according to the expression: $gd_{21}=td_{21}-ed_{21}$, where: $td_{21}=(\bar{Y}_2 - \bar{Y}_1)$ is the total difference between the mean of all treatments of year 2 and that of all treatments in year 1, where $\bar{Y}_2$ and $\bar{Y}_1$ are the means of all treatments in years 2 and 1, respectively; $ed_{21}=(\bar{Y}_{(21)2} - \bar{Y}_{(21)1})$, the environmental difference between the mean of the genotype groups related to the pair of years 2 and 1, in which $\bar{Y}_{(21)2}$ and $\bar{Y}_{(21)1}$ are the means of the genotypes common to both years, obtained in years 2 and 1, respectively.

In this way, the increase in the variable is estimated considering the improvement in the genotypes available and environmental conditions. Based on "a" years, "a-1" genetic and environmental differences between each pair of successive years are computed. The sum of all *gd* and *ed* values represents the increases in the variable, from the beginning to the end of the study period, as a result of genetic and environmental improvement over the years studied. To obtain the mean increase per year, the accumulated progress is divided by the number of years in the period. This last estimate, divided by the overall mean of the experiments in the first year (reference mean) and multiplied by 100, gives the mean annual genetic gain in percentage (Vencovsky et al. 1986). The significance of the mean annual genetic gain estimate was verified by the t test; $t = \frac{\hat{\bar{g}} - 0}{\hat{s}(\hat{\bar{g}})}$ with *n-2* degrees of freedom; with $\hat{s}(\hat{\bar{g}}) = \sqrt{\frac{1}{n}\left(\frac{\sum(\hat{g} - \hat{\bar{g}})^2}{n-1}\right)}$, according to Moresco (2006).

The rates of the genotypes included (%I), excluded (%E), maintained (%M) and replaced (%R) from one year to another were also estimated, according to the following equations (in percentage): $\%I = \frac{100I}{M+E+I}$; $\%E = \frac{100E}{M+E+I}$; $\%M = \frac{100M}{M+E+I}$ and $\%R = \frac{100I}{M+I}$, where: I: number of genotypes included in the subsequent year; E: number of genotypes excluded the year before ; M: number of genotypes maintained from one year to the next.The significance of the mean annual genetic gain estimate was verified by the t test; with *n-2* degrees of freedom; with, according to Moresco (2006).

The rates of the genotypes included (%I), excluded (%E), maintained (%M) and replaced (%R) from one year to another were also estimated, according to the following equations (in percentage): ; ; and , where: I: number of genotypes included in the subsequent year; E: number of genotypes excluded the year before ; M: number of genotypes maintained from one year to the next.

All analyses were performed using the statistical software package GENES, developed at the Universidade Federal de Viçosa (Cruz 2006).

RESULTS AND DISCUSSION

The number of trials, number of genotypes and mean grain yields of the cultivars/lines per year in the VCU trials over the study period are shown in Table 1. The number of trials per growing season varied from one to eight per year, totaling 116, a number very close to that of other, however less time-extensive studies of genetic gain in other crops, e.g., rice (Breseghello et al. 1999). between 14 and 29 genotypes were evaluated per year, totaling 193 genotypes.

From 1976 to 2005 the mean grain yield of cultivars evaluated per year increased, evidencing yield gain, which was highest in the first 10 years (Table 1). In the 1970s, the mean crop yield was around 2.000 kg ha^{-1}; today, means exceed 4.000 kg ha^{-1}; however, at a mean height of over 800 m asl there are some locations where yields exceed 7.500 kg ha^{-1}.

The dynamics of a breeding program is quantified in the genotype substitution rate, which contains the rate of the included, excluded, maintained and replaced genotypes from one year to the next (Cruz and Carneiro 2003). The genotype replacement rate of the irrigated wheat breeding programs over the evaluated period was good (mean of 33%) (Table 2), indicating the vitality of the breeding programs in releasing cultivars and supplying farmers with new crop options. Soares et al. (1999) and Atroch and Nunes (2000) found renewal rates of 44 and 46% in rice, respectively, and reported that these values reflect the high vitality of the breeding programs.

The mean maintenance rate of 55% (Table 2) allowed a good estimate of environment variation between the evaluated years, since the environmental effect is a function of contrast between the genotypes in the years considered (Atroch and Nunes 2000). Thus, the higher the number of treatments in each pair of years, the more accurate is the estimated environmental effect. This condition is in fact highly relevant for the methodology proposed by Vencovsky et al. (1986) to estimate genetic gain, since the gain estimates are more reliable and misinterpretations caused by experimental errors and genotype x year interactions are, consequently, reduced.

The relevance of this study lies in the fact that the evaluation of year effects was not limited to a few common genotypes. The final trials (VCU) conducted by the Brazilian Wheat Research Commission included all recommended cultivars, which, because there were only a few, were always included as checks. The best lines tested were always reevaluated in the following year as well, thereby increasing the maintenance rate. In general, the genotype maintenance rate in this study is considered good since mean maintenance rates of 56 and 38% were verified in rice by Soares et al. (1999) and by Atroch and Nunes (2000), respectively. More recently, Moresco (2006) found a mean maintenance rate of 44% in cotton and

Table 1. Number of trials Value for Cultivation and Use (VCU), number of genotypes evaluated and mean annual yield of irrigated wheat in Minas Gerais

Year	Number of trials	Number of genotypes	Yield (kg ha^{-1})
1976	1	16	2604
1977	4	25	2076
1978	3	18	2377
1979	2	20	2656
1980	2	22	2146
1981	2	25	3007
1982	2	29	2267
1983	4	21	2566
1984	4	18	3124
1985	5	16	3841
1986	6	14	3438
1987	4	18	3830
1988	5	20	3481
1989	4	20	4228
1990	4	18	3314
1991	4	20	3665
1992	2	20	4777
1993	2	20	4446
1994	4	20	4714
1995	5	15	3445
1996	6	15	4331
1997	5	16	3978
1998	1	16	5045
1999	3	22	4450
2000	2	23	3695
2001	3	15	3746
2002	7	24	3845
2003	6	23	3945
2004	8	20	4268
2005	6	24	4746
Period	**116**	**193**	**3602**

inferred that this rate allowed a good estimate of environmental variation in the evaluated years.

Ideally, the trials should be set up using new seed from the main irrigated wheat cultivars released during the different breeding periods. This avenue, however, has some drawbacks, e.g., it requires more financial investment, besides the fact that some of the older cultivars are no longer available. On the other hand, the approach proposed by Vencovsky et al. (1986), according to Moresco (2006), reflects field conditions more realistically, i.e., it takes the fact into consideration that annually, a certain number of cultivars are recommended, but only some farmers adopt the new technology, while the majority prefers to use the same plant material as in previous years.

In the process of estimating genetic and environmental progress, the magnitudes of total differences, due to the environmental and genetic variations from one year to another varied considerably (Figure 1). The variation in the total differences was strongly associated with the differences of environmental effects between the years. This was most likely due to the greater or lesser importance of the environmental effects on grain yield during that same pair of years. According to Carvalho et al. (1980), climatic conditions (environment) are the main determining factor in mean grain yield variations between years. Year and/or the environment are important parameters to estimate progress. In a study conducted from 1979 to 1984, Feyerherm et al. (1989) estimated a wheat yield gain of 8.8 kg ha^{-1} yr^{-1} in Montana,

Table 2. Genotype substitution rates (%) in Value for Cultivation and Use (VCU) trials of irrigated wheat in each pair of years, in Minas Gerais

Pair of years	Inclusion	Exclusion	Maintenance	Renovation
1977/1976	43	11	46	48
1978/1977	17	40	43	28
1979/1978	33	26	41	45
1980/1979	23	15	62	27
1981/1980	15	4	81	16
1982/1981	22	9	69	24
1983/1982	34	52	14	71
1984/1983	28	38	34	44
1985/1984	28	36	36	44
1986/1985	16	26	58	21
1987/1986	42	25	33	56
1988/1987	33	26	41	45
1989/1988	17	21	63	21
1990/1989	21	25	54	28
1991/1990	31	23	46	40
1992/1991	0	0	100	0
1993/1992	31	28	41	43
1994/1993	0	0	100	0
1995/1994	22	44	33	40
1996/1995	6	6	88	7
1997/1996	40	36	24	63
1998/1997	0	0	100	0
1999/1998	47	27	27	64
2000/1999	4	0	96	4
2001/2000	26	52	23	53
2002/2001	38	0	63	38
2003/2002	0	4	96	0
2004/2003	18	29	54	25
2005/2004	41	29	29	58
Mean	**23**	**22**	**55**	**33**

and of 17.6 kg ha^{-1} yr^{-1} in Dakota, U.S.A., demonstrating the environmental effect on the gain estimate.

The annual genetic differences also varied considerably, oscillating from 218 to 220 kg ha^{-1} (Figure 1). However, the differences in mean yield due to genetic effect (genetic gain) were positive in practically all years, demonstrating the progress over the years, confirmed by the release of new cultivars in Minas Gerais by wheat breeding programs. The annual genetic difference or progress is obtained by the difference between mean genotype yield from one year to that of the year immediately before, excluding the year effect (Vencovsky et al. 1986).

Total progress, genetic and environmental gain of irrigated wheat breeding in Minas Gerais between 1976 and 2005, estimated by the methodology of Vencovsky et al. (1986), was 2142 kg ha^{-1} (Table 3). The genetic gain in the period was 1441 kg ha^{-1}, accounting for 67.2% of the estimated total progress. This gain represents an increase of 48.03 kg ha^{-1} yr^{-1} obtained by genetic breeding, that is, according to the methodology applied, there was a mean grain yield increase of 1.84%, compared to the reference mean yield in the period, obtained in 1976. The mean annual genetic progress, estimated at 48.03 kg ha^{-1} yr^{-1}, was significant ($P<0.01$) by the t test, and therefore considered efficient. It is also emphasized that the proper accumulated genetic progresses in kg ha^{-1} was close to the mean yield obtained in the wheat fields in Brazil (approximately 2000 kg ha^{-1}).

The progress obtained by genetic wheat breeding in southern Brazil was more recently examined by Nedel (1994) in only 15 wheat cultivars released for cultivation

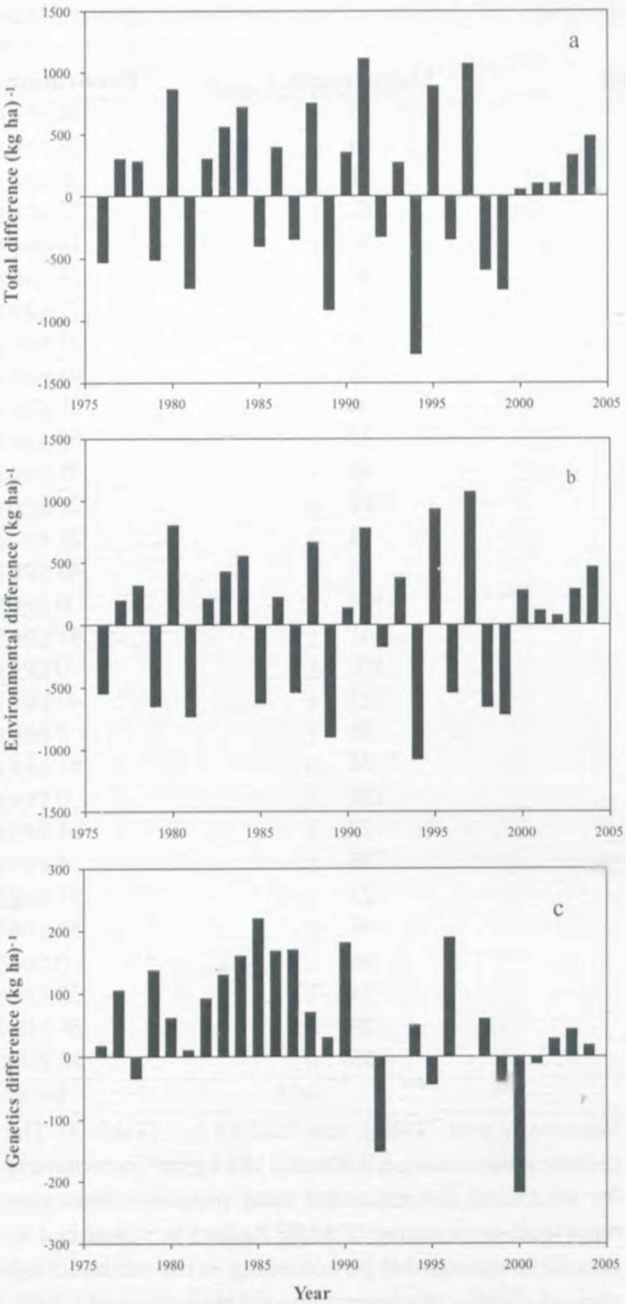

Figure 1. Total (a), environmental (b) and genetic (c) differences in Value for Cultivation and Use (VCU) trials with irrigated wheat for each pair of years, from 1976 to 2005, in Minas Gerais

in the period from 1940 to 1992 (52 years) by the no-till method, with an increase of 17.3 kg ha^{-1} yr^{-1}, in grain yield. In the U.S.A., Cox et al. (1988) reported an increase of 16.2 kg ha^{-1} yr^{-1}. However, the progress obtained by genetic wheat breeding in Mexico, by CIMMYT in the period from 1992 to 1988, was estimated by Sayre et al. (1997) at 67 kg ha^{-1} yr^{-1}.

The progress estimated in this study was considerable and comparable to results obtained by other authors for different annual crops. In a comparison with soybean, breeding resulted in annual gains between 1.3 and 1.8%, in Parana, from 1981 to 1986 (Toledo et al. 1990). In rice breeding, Soares et al. (1999) estimated progress between 0.84 and 1.6% per year in Minas Gerais, and Breseghello et al. (1999), from 1984 to 1993, in Northeastern Brazil, estimated genetic gain for this crop at 0.77% per year. Carvalho et al. (1997), evaluating the progress of herbaceous cotton in the northeastern region of Brazil, estimated a gain of 1.03% per year for cotton yield. In the state of Mato Grosso, Moresco (2006) estimated progress for cotton between 3.7 and 5.2% per year.

Similarly, an environmental and technological gain of 701 kg ha^{-1} was observed during the study period, accounting for 32.8% of the total progress obtained (Table 3). This gain, due to improved environment, accounts for an increase of 23.4 kg ha^{-1} yr^{-1} in mean grain yield. In fact, increased yields had been expected due to improved environment. Most of the area cultivated with irrigated wheat in Minas Gerais is in the Cerrado region (Brazilian savanna), where soils are improved by successive fertilizations. Furthermore the adoption of other technologies, e.g., a more effective irrigation management and disease control, play an important role in cultivar performance. These technologies were applied in the experimental areas, influencing the results.

The progress accumulated over 30 years of irrigated wheat breeding in Minas Gerais can be divided in three phases (Figure 2). In the first phase a genetic gain of low magnitude was obtained. In this phase, breeding consisted in introducing and testing cultivars from various national and, mainly, international institutions, such as the CIMMYT, from Mexico. Possibly, because they were from other regions, these cultivars did not adapt well to the local climate. Despite the low gains during the first years, breeding by cultivar introduction was very successful. For example, cultivar Anahuac 75, introduced from México and recommended since 1982, was cultivated until 1995. This cultivar Anahuac and others introduced from Mexico were also important in artificial crossing (hybridizations). During the second phase, from the early 1980s to 1993, characterized by higher gains and considerable progress in grain yield, EMBRAPA and CIMMYT

Table 3. Genetic and environmental gain obtained by irrigated wheat breeding in Minas Gerais from 1976 to 2005

Gain	kg ha^{-1} in period	% in period	kg ha^{-1} year^{-1}
Genetic	1441	67.24	48.03
Environmental	701	32.80	23.40
Total	**2142**	**100**	**71.43**

developed a selection program of segregating populations.

After 1993, the UFV joined the wheat breeding actions in the state, conducting hybridizations with adapted genotypes, besides releasing lines originated from CIMMYT. It should be emphasized that the introduced genotypes were included together with the already adapted ones. The progress tended to decline during this phase. This fact is mainly due to the changes in the breeding program actions in the state, targeting other important traits in cultivar selection, such as flour quality for bread making, which became an important requirement in the 1990s. Finally, over the last three decades, the cooperation and contribution of CIMMYT led the way.

Our results show that the efforts undertaken to find productive and adapting cultivars have achieved considerable gains in the irrigated wheat breeding programs conducted by state and federal agricultural research institutions for the selection, introduction, evaluation, and recommendation of new irrigated wheat cultivars in the state of Minas Gerais.

CONCLUSIONS

The genetic breeding of irrigated wheat ensured positive and significant results, expressed in the estimates of mean genetic gains in yield. The gains clearly indicated the efficiency of wheat breeding programs, thus contributing to the improvement of the crop. Aside from the significant contribution of genetic gains, environmental improvements also increased yields significantly.

ACKNOWLEDGEMENTS

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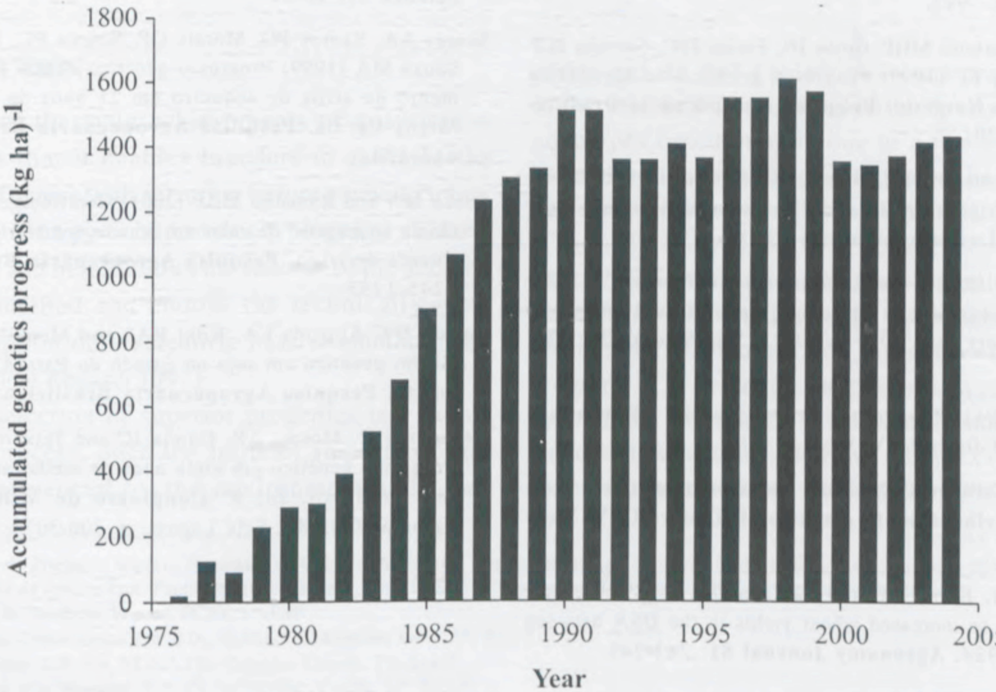

Figure 2. Genetic gain accumulated over 30 years (1976 to 2005) of irrigated wheat breeding in Minas Gerais

Progresso no melhoramento do trigo irrigado para a região do cerrado do Brasil

RESUMO - *Neste trabalho objetivou-se quantificar o progresso genético obtido pelos programas de melhoramento do trigo irrigado no Estado de Minas Gerais no período de 1976 a 2005. A eficiência dos programas de melhoramento de trigo irrigado foi estudada, utilizando-se os dados de produtividade de grãos obtidos nos ensaios de valor de cultivo e uso. Para a estimativa do progresso genético e ambiental foi utilizada a metodologia de Vencovsky e colaboradores. O progresso genético médio anual estimado no período de 1976 a 2005 foi de 48 kg ha^{-1} ano^{-1} (1,84% ao ano) na produtividade média de grãos. As melhorias ambientais e tecnológicas também foram importantes para o acréscimo na produtividade no período, representando 32,8% do progresso total obtido. Além disso, os programas de melhoramento de trigo irrigado promoveram 33% de renovação de genótipos ao longo dos anos.*

Palavras-chave: avaliação de genótipos, ganho genético, melhoramento, *Triticum aestivum* L.

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