

Genetic Improvement of Barley (*Hordeum vulgare*, L.) in Brazil: Yield Increase and Associated Traits

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Abstract

Barley breeding program in Brazil has focused on characteristics associated with malting for beer purposes as the main economic application for this crop. The breeding process focused on selection for grain yield, disease resistance and malting quality. The objective of this work was to quantify the genetic gain in barley grain yield from 1968 and 2008 in Brazil and to identify the physiological characteristics associated with the increase of grain yield. Field experiments with five 2-row barley cultivars were tested from 2011 to 2013 in the absence of biotic and abiotic stresses and with mechanical restriction to lodging. The ANOVA showed no genetic gain until 1980 with average grain yield of 4.632 kg/ha. After 1980, there was a productivity increase of 59.9 kg/ha/year. No correlation was observed between total maturity biomass and the year of release of the cultivars, while harvest index and plant height, were significantly improved. The main component associated with grain yield was the number of grains/m², due to the higher number of spikes/m² associated to a greater contribution of the tillers in the modern cultivars.

Keywords

Barley, Grain Yield, Developmental Phases, Genetic Gain, Yield Components

1. Introduction

Genetic improvement of grain yield has been marked by the result of empirical selection based on trial and error, with grain yield per se being the dominant selection trait [1]. Although this methodology that has been successful for most crops, in recent years it was not been efficiently enough to keep up with the rapid production needed for the future. In this context, understanding of the physi-

ological processes associated with increase of productive potential in the past, can at present help to identify physiological characteristics and/or processes that can be used as additional selection criteria in future breeding programs [2] [3]. Studies of this nature, using old and modern genotypes aiming to understand the physiological processes associated with the advance in productive potential seem in the past, are widely described in the literature for several crops such as wheat [4], oats [5], corn [3] and soybean [6]. However, fewer additional studies are published in barley. According to Abeledo *et al.*, [7] despite the small number, most of studies have been limited to North America and Europe. In these studies, the genetic improvement contributed to the grains yield at the rate of 16 kg/ha/year in the USA [8], from 18 to 20 kg/ha/year in Canada [9] [10], 19 kg/ha/year in the United Kingdom [11], 41 kg/ha/year in Spain [12], 74 kg/ha/year in Italy [13], 41 kg/ha/year in Argentina [7], 21 kg/ha/year in Norway [14], 60 kg/ha/year in United Kingdom [15] and in the Netherlands [16]. The magnitude of the barley genetic gain in these studies should, however, be carefully because of the different and recent durations of the periods analyzed. In spite of this, the advance in genetic gain in those countries reflects not only the efficiency of the breeding process, but also the effect of the improved environmental conditions on grain yield gains.

Several authors [10] [11] [13] [17] have carried out studies on the genetic potential grain of barley associated with physiological traits. Wych and Rasmusson [17] in the USA and Abeledo *et al.*, in Argentina [7], observed the increased evolution of barley yield to be highly associated with the increase of the vegetative biomass. However, Riggs *et al.*, [11] in the United Kingdom, Jedel and Helm [10] in Canada and Martintello *et al.*, [13] in Italy, reported a weak association between vegetative biomass and barley grain yield. The grain yield was significantly correlated with the harvest index, indicating that the observed advance in the barley productivity was mainly due to the biomass partitioning to the reproductive organs.

Most of these studies in barley also reported a positive correlation between grain yield and number of grains/m² [7] [11] [17] [18]. However, in cultivars released in Italy [13] observed that the advance in grain yield was more associated with the weight than with the number of grains. The increase in the number of grains was more associated with the number of spikes/m² than with the number of grains per spike in two-row barley [7] [8] [11] [13] [17] [18].

In Brazil, barley breeding began in the middle of the 20th century, focusing on resistance to diseases, resistance to lodging, tolerance to different environmental stresses, malt quality, and grain yield (Minella, E. Personal Communication). However, the effect of genetic improvement of barley on some physiological attributes (harvest index, biological yield and yield components), has not being reported making it difficult for the scientific community to understand the performance of this crop under the unique growing conditions of southern Brazil. The studies of the effect of genetic improvement on the physiological traits that

determine the productivity of barley can help to identify in this environment, others traits of potential value for future breeding. To achieve these objectives, five representative barley cultivars released between 1968 and 2008 were studied in three field trials from 2011 to 2013.

2. Material and Methods

Field trials were carried out in 2011, 2012, and 2013, at the National Wheat Research Center at Passo Fundo (28°15'S, 52°24'W, 687 m), RS, Brazil. Five cultivars of two rowed spring barleys, released between 1968 and 2008 (**Table 1**) were used to estimate the progress of breeding in southern Brazil. These cultivars were chosen to represent each decade based on the significant participation in the barley cropped area in southern Brazil. Cultivar FM 404 was the first Brazilian cultivar released for commercial production. Cultivar BR 2 was the first developed by Embrapa Trigo. It was released in 1989 and since then, it has been widely used, taking up 90% of the area sown in 1997 [19]. The cultivar BR 2 traces back to a single plant selected in the F3 of the cross FM 424 (Brazilian)/TR 206 (Canadian, resistant to *Pyrenophora teres*). BRS 195 traces back to a single plant selection made in the F5 of the cross DEFRA/BR2, took up to 63 % in 1998-2007 period of the area sown in Brazil [20]. DEFRA is a cultivar from Germany that was introduced in breeding program for its resistance to mildew, lodging and malting quality. Cultivar BRS Elis was released in 2008 resulting from the cross BRS 195/Scarlett (Germany) obtained by the double haploidization method through another culture.

The cultivars were arranged in a randomized complete block design with four replications. The plots consisted of 12 rows, 0.20 m apart and 6 m long. Fungicide treated seeds were mechanically sown on June 17, 6, 6 in 2011, 2012 and 2013, respectively, in a sowing density of 400 viable seeds/m². Nine days after seedling emergence plots were thinned to 300 plants/m². The amount of fertilizer used was 250, 300, and 300 kg/ha (NPK 5-20-25), incorporated before sowing in 2011, 2012 and 2013, respectively. In 2011 was applied 32 kg/ha of N at the double ridge and awn primordium stages as topdressing [21]. In 2012 and 2013 was applied 30 kg/ha of N at same stages.

The maximum and minimum air temperature (°C) and accumulated precipitation

Table 1. Name, year of release and genealogy of barley cultivars.

Cultivar	Year of release	Genealogy
FM 404	1968	Selection of Alpha (Ci 939)
FM 434	1977	Quinn/Malteria Heda//FM 424
BR 2	1990	FM 424/TR 206
BRS 195	2000	Defra/BR 2
BRS Elis	2008	BRS 195/Scarlett

Source: Minella, *et al.*, [19] [20].

(mm) were recorded daily by meteorological station located close to the experimental fields (**Table 2**). Weeds were controlled by hand. Fungicide and insecticides were used to control or prevent biotic damages. To prevent lodging, nets were installed at 0.2 m, above soil surface, when plants were near of the awn primordium stage. The crop was also maintained free of water shortages. Plots were irrigated to assure sufficient water availability to plants from planting to maturity to supplement rain in two years.

Plant samples were taken at anthesis and at physiological maturity. Plants previously marked in an area of 0.2 m² were cut at ground level, when the respective stages were reached. Plants were then separated in stems (including leaf sheaths), blades of green/dry leaves, and spikes. These samples were weighted after drying for 48 h at 70°C. Number of spikes was also recorded. Grain weight was measured in a sub-sample of 250 grains and used to calculate number of grains per spikes and grains per m². Harvest index was calculated as grain yield relative to aboveground biomass for each plot. Plant height was measured from the soil surface to the base of the spike on four main stems per plot.

Results were subjected to analysis of variance and differences among treatment determined. The degree of association between different variables under study was estimated using linear and quadratic regression models.

3. Results and Discussion

3.1. Gain in Potential Grain Yield

In most cereals, grain yield gain was observed in the first half of the 20th century, followed by a high rate of gain in the second half due to genetic and technological advances [4] [22]. This pattern was also observed in this study, and was similar to

Table 2. Mean temperature, rainfall and irrigation, from May to December, in 2011, 2012 and 2013, Passo Fundo, RS, Brazil.

Year	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Main temperature (°C)								
2011	14.1	11.4	12.4	13.4	15.4	18.3	20.2	21.2
2012	15.7	13.0	11.5	16.3	16.5	18.9	21.7	23.0
2013	14.6	13.2	12.0	12.0	15.2	17.7	20.8	23.2
Rainfall (mm)								
2011	137.1	226.7	340.0	254.4	47.3	194.7	77.1	91.2
2012	28.5	186.6	209.3	28.1	142.3	253.2	34.0	176.3
2013	85.2	127.6	81.4	364.3	184.0	186.4	103.8	66.4
Irrigation (mm)								
2011	-	-	-	-	-	-	-	-
2012	-	-	-	50	50	-	-	-
2013	-	-	50	-	-	-	-	-

that observed for wheat in southern Brazil [23].

The grain yield potential of barley differed statistically among cultivars (**Table 3**), with cultivar FM 434 released in 1977 as the less productive, not differing statistically from the oldest cultivar FM 404 released in 1968.

In general, most recent cultivars showed higher grain yields than older ones. A quadratic model described the change in grain yield as a function of the years of released: $y = 1.2562x^2 - 4950.5x + 5E+06$ ($r = 0.81$, $p < 0.01$) (**Figure 1**). These results indicate two distinct periods in the grain yield increased, where in the first (up to 1980) there was no genetic gain and the grain yield potential remained at 4.632 kg/ha. In the second period, the cultivars released showed a significant increase in grain yield potential at rate of 59.9 kg/ha/year, equivalent to

Table 3. Means of biological yield (BY), grain yield (GY), and grain-yield components: spikes/m² (SN); grains/m² (GN); grains/spike (GS); grain weight (GW) and harvest index (HI), in the 2011, 2012, and 2013 experiments*[†].

Cultivar	BY (kg·ha ⁻¹)	GY (kg·ha ⁻¹)	SN	GN	GS	GW (×10 ³ g)	HI (%)	Height (cm)
2011								
FM 404	9.543 ^a	4.688 ^c	434 ^c	9.842 ^c	23 ^a	41 ^a	43 ^c	93 ^a
FM 434	9.105 ^a	4.556 ^c	481 ^c	9.103 ^c	19 ^{ab}	44 ^a	44 ^c	86 ^b
BR 2	8.774 ^a	4.843 ^c	635 ^b	10.328 ^{bc}	16 ^{bc}	41 ^a	48 ^b	84 ^b
BRS 195	9.123 ^a	5.402 ^b	698 ^{ab}	11.377 ^{ab}	16 ^{bc}	42 ^a	52 ^{ab}	57 ^d
BRS Elis	9.324 ^a	5.911 ^a	769 ^a	11.869 ^a	15 ^c	43 ^a	55 ^a	63 ^c
C.V. (%)	4.51	3.91	9.38	5.80	8.81	4.42	3.8	2.82
2012								
FM 404	9.531 ^{bc}	4.481 ^b	469 ^d	10.163 ^b	22 ^a	38 ^{ab}	41 ^b	109 ^a
FM 434	9.430 ^{bc}	4.298 ^b	593 ^{cd}	10.014 ^b	17 ^b	37 ^b	40 ^b	96 ^b
BR 2	9.103 ^c	4.520 ^b	695 ^{bc}	10.209 ^b	15 ^b	39 ^a	43 ^b	86 ^c
BRS 195	10.360 ^{ab}	5.820 ^a	761 ^{ab}	13.477 ^a	18 ^b	38 ^{ab}	49 ^{ab}	72 ^d
BRS Elis	11.326 ^a	6.511 ^a	928 ^a	15.069 ^a	16 ^b	38 ^{ab}	50 ^a	76 ^d
C.V. (%)	5.22	6.04	10.77	6.16	8.48	1.31	3.80	2.35
2013								
FM 404	12.540 ^a	5.026 ^d	484 ^c	11.317 ^c	23 ^a	39 ^{ab}	35 ^c	126 ^a
FM 434	12.870 ^a	4.748 ^d	642 ^b	10.649 ^c	17 ^b	39 ^a	32 ^c	117 ^b
BR 2	11.466 ^a	5.429 ^c	693 ^b	12.206 ^c	18 ^b	39 ^{ab}	41 ^b	110 ^c
BRS 195	12.430 ^a	7.343 ^a	830 ^a	17.160 ^a	21 ^{ab}	37 ^{bc}	52 ^a	73 ^e
BRS Elis	11.374 ^a	6.100 ^b	890 ^a	14.652 ^b	17 ^b	36 ^c	47 ^a	81 ^d
C.V. (%)	6.01	4.84	6.74	5.52	10.37	1.70	6.12	1.86

*Means followed by the equal letters, within a column, were not significantly different ($p < 0.05$) as tested by Tukey's multiple range test. [†]Genotypes are ordered from oldest to newest cultivar. [‡]C.V. Coefficient of Variation.

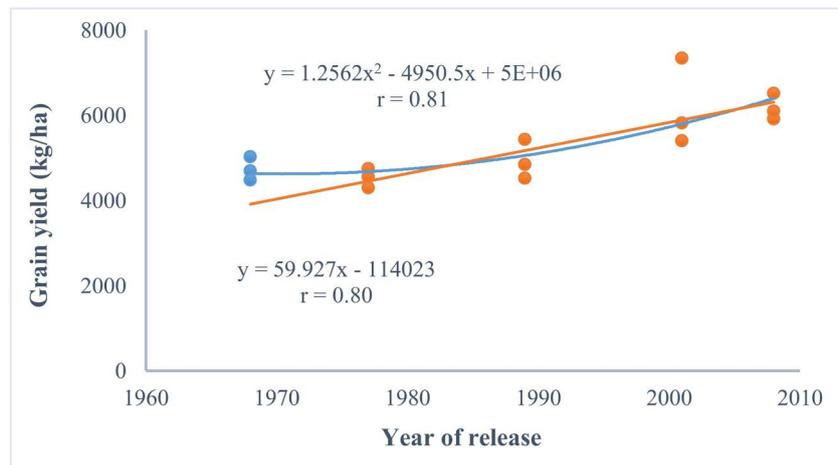


Figure 1. Grain yield of barley cultivars released at different decades in southern Brazil in relation to their years of release for the 2011, 2012 and 2013 experiments. The genetic gain were estimated using only the period when the linear model was significant ($p < 0.05$).

a relative genetic gain of 1.1% per year (Figure 1). This pattern is in agreement with the quadratic pattern reported for barley in Argentina [7] and for wheat in England [24], New Zealand [25], Argentina [2] [4], Canada [26], Australia [27] and Brazil [23]. A study of Abeledo *et al.*, [28], also revealed a biphasic model where until mid-1950s, the effect of breeding on barley grains gain was negligible.

The productive behavior of the barley observed in the present study may be a result of the adoption of different strategies in the selection of plants during this period. In this sense, the behavior of the cultivars released in Brazil until 1980, possibly reflects the objective of breeding until then, in the selection of genotypes for resistance/tolerance to diseases, lodging resistance and aluminum toxicity instead of yield potential. Resistance to lodging, low utilization of N inputs due to the size of the plants at the time (Table 3) and the great concern with the high protein content may have contributed to the low advance in grain yield potential in this period.

The regression of grain yield on years of release was statistically significant ($r = 0.80$, $p < 0.05$), and a genetic gain of 59.9 kg/ha/year was observed (Figure 1). This gain was greater than those described in the studies of Abeledo *et al.*, [28], which showed a gain of 16 kg/ha/day in the United States [8] but lower than the gain of 74 kg/ha/year obtained in Italy [13]. Afterwards, Abeledo *et al.*, [7] in Argentina obtained a genetic gain of 41 kg/ha/year for the 1973-1998 period, also lower than that observed in this study. However, the estimate of genetic progress observed in Italy [13] and in the United Kingdom [11], are representative of very short and very long periods, respectively, making it difficult to compare with the present study. It is also added that the genetic gain calculated in this way (kg/ha/year) is highly affected by the environmental conditions during the experiment. For comparison purpose, Austin *et al.*, [24], and Perry and

D'Antuono [27] have suggested the use of relative estimates of genetic gain (the relationship between the regression coefficient and the mean production of the experiment). In this sense, the relative genetic gain in the present study (1.1% per year) was the same as the one observed in Italy and more consistent from the 2000s when BR 195 cultivar, which has one dwarf gene, was released.

3.2. Biomass and Harvest Index

The biomass production of the cultivars did not show a significant correlation with the year of release ($r = 0.18$, ns), indicating that the yield gain observed in the analyzed period was not caused by the biomass gain. On the other hand, the increase in barley yield was strongly correlated with the harvest index, which confirms the biomass gain for reproductive organs (Figure 2).

Similar results have been observed in the UK [11] and in the USA [17] [8]. However, in Argentina, Abeledo *et al.*, [7] observed that the increase of grain yield in barley, in the period of 1944-1998, was more associated to the biomass gain than to the harvest index. In the same study, no correlation was observed between grain yield and the plant height.

The regression analysis between harvest index and year of release showed a positive association ($r = 0.81$, $p < 0.01$), that is, the modern cultivars were more productive and reached higher values of biomass partition to reproductive organs. However, such values are very close to the partition limit values (Austin *et al.*, 1980), suggesting to future increase barley grain yield in southern Brazil, a small contribution of harvest index. On the other hand, with the maintenance of these high values of harvest index, the identification and exploration of genotypes showing a greater ability to produce biomass could be a way to increase the yield of barley in the region. The physiological basis for the increase of total biomass is usually related to the interception of the photo synthetically active radiation and the efficiency of its conversion into biomass [29]. Thus, the best

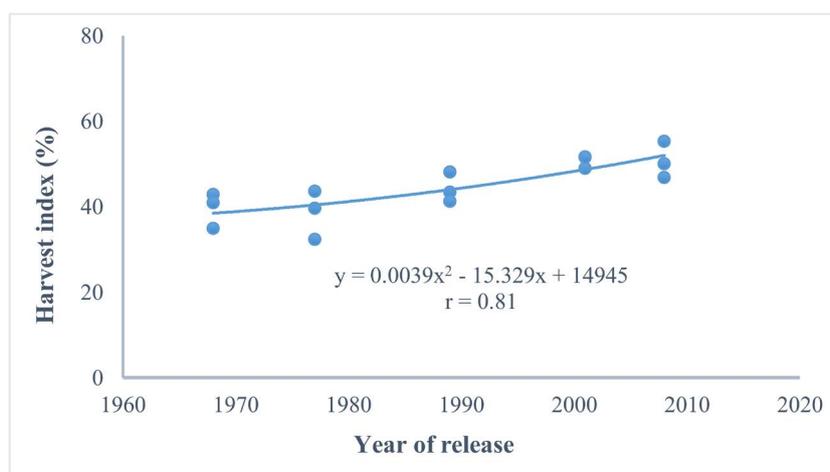


Figure 2. Relationship between harvest index of barley cultivars with year of released for the 2011, 2012 and 2013 experiments.

way to increase grain production under Brazilian conditions, where water deficiency often occurs, could be by increasing the conversion of radiation into biomass [30]. However, caution should be taken, since a high correlation has been observed between total biomass increase and plant height, which could favor lodging [31] [32].

3.3. Numerical Yield Components

The grain yield of barley was significantly correlated with the number of grains/m² ($r = 0.96$, $p < 0.01$) (Figure 3). Whereas, grain weight was not significantly associated with yield (Table 3), remaining at about 40 mg during the period analyzed. Therefore no relationship was found between number of grains/m² and grain weight, characterizing the absence of modification of this component by genetic improvement. Such behavior may be a reflection of the strong selection pressure of the breeding program in the past, by the increase of the weight and size of the barley grains, focusing on the quality for malting.

Abeledo *et al.*, [7] [28] reported a positive correlation between barley grain yield and number of grains/m² in several countries in Europe, in the USA and in South America. In addition, a positive and significant correlation between grain yield and grain weight was observed in Italy and in the USA, contrary to what was observed in this study. However, especially for the USA, the long duration of the period analyzed by Wych and Rasmusson [17] does not allow a fair comparison in this trait with the results obtained here.

The number of spikes/m² was significantly associated with the year of release ($r = 0.93$, $p < 0.01$) (Figure 4) at a rate of 9.4 ears/m²/year and was, unlike the number of grains/ears ($r = 0.07$ ns), significantly associated with the number of grains/m² ($r = 0.86$, $p < 0.01$) (Figure 5).

The effect of genetic improvement on the number of grains/m² was associated with the increase in the number of spikes/m² more than the number of grains

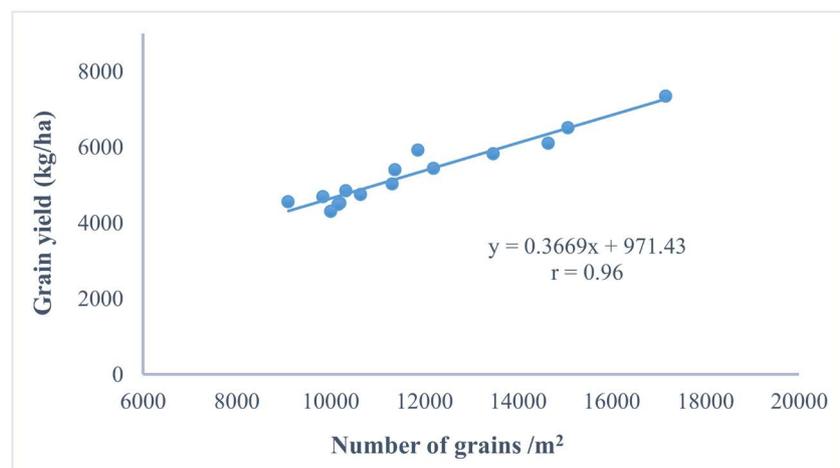


Figure 3. Relationships between grain yield and grain number of barley cultivars released in Southern Brazil between 1968 and 2008.

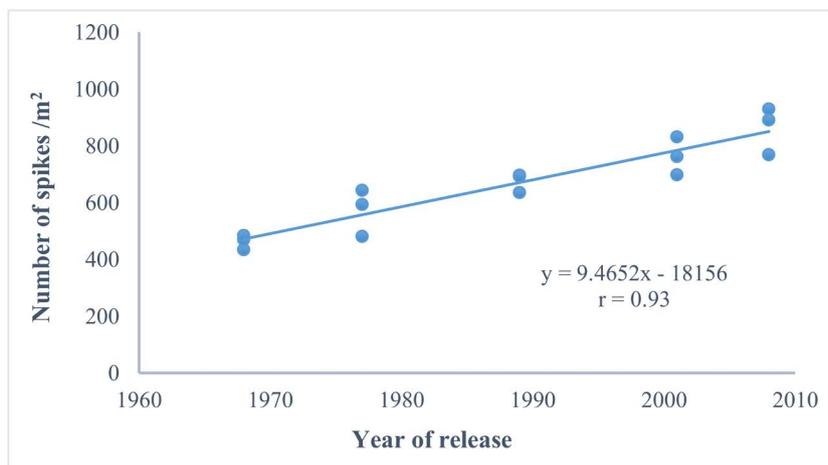


Figure 4. Relationships between number of spikes and year of released of barley cultivars for the 2011, 2012 and 2013 experiments.

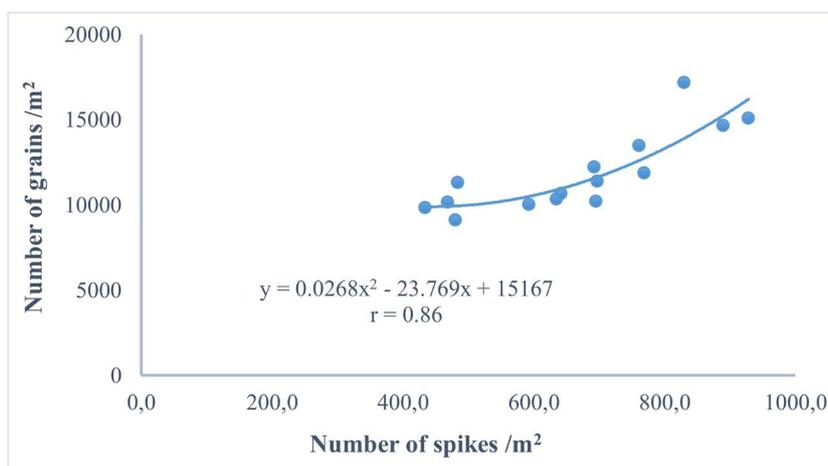


Figure 5. Relationships between number of grain and number of spike of barley cultivars released in Southern Brazil between 1968 and 2008.

per spike, which was reduced in the most recent cultivars. The increase of the number of spikes/m², could be attributed to the greater contribution of the ear bearing tillers.

3.4. Plant Height

The height of the cultivars released after 1968 was significantly reduced and this trend was maximized with the release of cultivar BRS 195, which was the first released dwarf cultivar (Table 3). This continuous and consistent reduction in plant height shows the efficiency and applicability of the selection method [33] used by the barley breeding programs in Brazil, with possible significant effects on the reduction of lodging. It should be noted that lodging is the main problem associated with barley cultivation under very favorable production conditions and was significantly reduced by plant height. This reduction allowed a more effective control of the nitrogen use, with positive effects in the concentration of

nitrogen in the grains and consequently in the quality for malting [34] [35]. In this sense, Laidig *et al.*, [36] reported that in Germany the reduction of plant height at the time was the most significant improvement in barley breeding. In this study, the barley height reduction rate was about 1.0 cm/year (Figure 6) ($r = 0.78$, $p < 0.01$), significantly reducing lodging and contributing to the advance in grain potential and quality. A study by Ortiz *et al.*, [37] observed a reduction of 0.2 cm/year during 1948 and 1988 in spring barley in Scandinavia. Similarly, Abeledo *et al.*, [28], analyzing results from several countries (Austria, England, USA, Italy, Canada and Argentina) also pointed out the marked effect of breeding programs on plant height reduction. Although differences between the countries analyzed were pointed out in the study, these were due to the dynamics of the reduction of stature in the analyzed periods. In this same study, the average height of the plants of the modern cultivars between the countries was between 75 and 95 cm.

Finally, the reduced size of the plants observed in the most recent and productive cultivars in the study could have been responsible for the greater growth of the spike, due to the reduction of stem growth and, consequently, the greater availability of photoassimilates for the growth of the spike. Kirby [38] observed that flower death coincided with the rapid growth of stem and spikes, demonstrating that competition for assimilates determines the magnitude of flower mortality and the number of fertile flowers at anthesis. Thus, the availability of assimilates partitioned for the spike make the flowers viable in the anthesis [39].

This strong reduction of the growth in the modern cultivars was the most significant step towards the high productivity and quality of the barley in the southern Brazil and it was obtained by the introduction of the gene of dwarfism through cultivar DEFRA in the early 2000s. This trait may have favored the growth of the spike in relation to the stem, improved the production of fertile flowers [40] [41] and the harvest index, sustaining the advance obtained in the

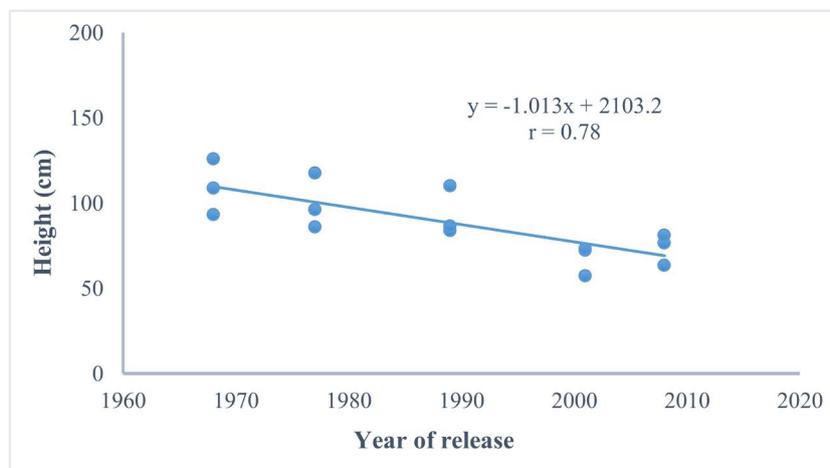


Figure 6. Relationships between height and year of released of barley cultivars for the 2011, 2012 and 2013 experiments.

production of barley grains in the analyzed period. However, the steady decrease in plant height obtained by the breeding program should be carefully monitored in the future to avoid the cultivation of cultivars with reduced heights that will negatively affect productivity due to a very dense canopy. Such a condition may favor the development of foliar diseases and reduce the uniformity of radiation interception and biomass production ability [42] [43] [44].

4. Conclusion

Barley breeding in Brazil has successfully increased grain yield through increases in the harvest index and number of grains/m² due to the higher number of spikes/m² (associated with an increase in the number of tillers) and the reduction of plant height in the modern cultivars. These traits allowed substantial improvement of grain yield, with a genetic gain equal to or greater than that obtained in other countries, larger producers of barley. In the future, it is expected that genetic improvement will keep increasing yield potential at least as efficiently as it has increased it during the last decades. Therefore, considering the advance obtained in partition efficiency (HI) by genetic improvement, the strategy of increasing radiation interception efficiency through early and rapid canopy establishment can be a promising path for the climate conditions of Brazil. The early and rapid establishment of the canopy can also offer an additional advantage in weed control in organic or conventional crop systems.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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