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Growth model for morphological traits of buckwheat cultivars at sowing times[1]

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ABSTRACT - The objective of this study was to fit the Logistic growth model for plant height and number of nodes of two buckwheat cultivars at sowing times, as well as comparing the cultivars and sowing times. Twenty uniformity trials were carried out, formed by the combination of two buckwheat cultivars (IPR91-Baili and IPR92-Altar), sown at five times, for two consecutive years. Evaluations were carried out twice a week throughout the vegetative stage until the end of flowering. In each evaluation, five plants were randomly collected from each trial to measure plant height and count the number of nodes on the main stem. The logistic model was fitted with the values of the five plants of each evaluation. Model parameters were estimated, as well as their respective confidence intervals. The goodness of fit of the model was assessed through the coefficient of determination, Akaike information criterion, and residual standard deviation. The plant height and number of nodes of buckwheat, cultivars IPR91-Baili and IPR92-Altar, were described by the Logistic model. The Logistic model satisfactorily describes the growth of buckwheat plants, and a specific fit considering each cultivar and sowing time is needed.

Key words: Cover plants. Nonlinear models. *Fagopyrum esculentum* Moench.

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INTRODUCTION

Buckwheat (*Fagopyrum esculentum* Moench), also called common buckwheat, is an annual, dicotyledon species native to the central regions of Asia, grown for human food purposes since at least 1000 BC (WEI, 2019). It is an herbaceous plant belonging to the *Polygonaceae* family and unrelated to common wheat (SUBHASH *et al*., 2018). Its similarity to cereals in terms of processing, use, chemical composition and seed structure has caused this species to be often classified as a pseudocereal (KESKITALO *et al*., 2007). It is a rustic plant, with multiple uses and relatively short cycle, as well as high potential as a nutraceutical, dietary and medicinal food, thus constituting a valuable food source in several regions of the world (HORNYÁK *et al*., 2022). Due to its capacity to develop well in various types of soil, buckwheat can be used as a successor plant to grain crops such as soybean, maize and sorghum (GÖRGEN *et al*., 2016). It plays a fundamental role as a good previous cover crop, as it assists in the cycle of phosphorus (P), making P more available to subsequent crops (POSSINGER *et al*., 2013), in addition to assisting in the suppression of weeds through the production of allelopathic root exudates (CHENG, 2018; GFELLER *et al*., 2018).

As buckwheat is a fast-growing plant, it is essential that the cultural practices are carried out at the appropriate times, in the period when the plant is more responsive. Thus, it is necessary to understand how the crop grows and develops, which can be accomplished by fitting mathematical models.

Mathematical models are excellent system prediction mechanisms. They provide a simplified description of a system and are constructed to better understand the operation of a real system and the interactions of its main components (DOURADO NETO *et al*., 1998).

Among the models, those classified as nonlinear regression models can be used to describe the growth of individuals over time, as they have parameters with biological interpretation, thus facilitating decision making by the researcher (LÚCIO *et al*., 2016; SORATO; PRADO; MORAIS, 2014).

Among the most used models, the Logistic model has been applied in several studies in the agronomic area to evaluate for instance: dry matter accumulation of common bean (LIMA *et al*., 2019), germination of *Brachiaria brizantha* seeds (MACHADO *et al*., 2023), height of maize (MANGUEIRA *et al*., 2016; MORAIS *et al*., 2017), morphological traits of *Crotalaria juncea* (BEM *et al*., 2017) and sudangrass (PEZZINI *et al*., 2019), crown diameter (WYZYKOWSKI *et al*., 2015) and fruit growth of coffee (SENRA *et al*., 2022), fruit production of cherry tomato (LÚCIO *et al*., 2016), dry matter accumulation of weeds (AZARIAS *et al*., 2023), and growth of cashew fruits (MUIANGA *et al*., 2016), cacao fruits (MUNIZ; NASCIMENTO; FERNANDES, 2017) and peach fruits (SILVA *et al*., 2019).

Thus, the objective of this study was to fit the Logistic growth model for plant height and number of nodes of two buckwheat cultivars at sowing times, as well as comparing the cultivars and sowing times.

MATERIAL AND METHODS

Twenty uniformity trials (blank experiments) were conducted with buckwheat in an experimental area of the Department of Plant Science of the Federal University of Santa Maria, located at 29º42'S, 53º49' W and 95 m altitude. According to Köppen's classification, the climate of the region is classified as humid subtropical, Cfa, with hot summers and no defined dry season (ALVARES *et al*., 2013). The soil of the region is classified as *Argissolo vermelho distrófico arênico* (Ultisol) (SANTOS *et al*., 2018).

The 20 trials were formed by the combination of two cultivars, IPR91-Baili and IPR92-Altar, sown at five times, for two consecutive years, resulting in ten environments for each cultivar. Cultural management practices were carried out evenly throughout the experimental area, in order to provide the same conditions for all plants.

Prior to sowing, the area was prepared conventionally, with a light harrowing operation and application of basal fertilization at dose of 35 kg ha^{-1} of N, 135 kg ha^{-1} of P_2O_5 and 135 kg ha^{-1} of K_2O. Sowing was carried out in rows spaced 0.5 m apart, using 50 kg ha^{-1} of viable seeds for both cultivars.

Each uniformity trial had usable area of 153 m^2 (17 m × 9 m). Sowing in the first year of cultivation (2017/2018) was carried out on: November 8, 2017 (time 1), December 18, 2017 (time 2), January 3, 2018 (time 3), February 7, 2018 (time 4) and March 14, 2018 (time 5). In the second year of cultivation (2018/2019), the sowing dates were: November 6, 2018 (time 1), December 28, 2018 (time 2), January 30, 2019 (time 3), February 22, 2019 (time 4) and March 28, 2019 (time 5).

Plant collections and evaluations began when the plants had at least one expanded leaf. These evaluations were carried out twice a week throughout the vegetative stage until the end of flowering, comprising the entire growth period of the crop. For each evaluation, five plants were randomly collected from each trial to measure plant height (PH, in cm), as the distance from the soil surface to the insertion of the last expanded leaf of the main stem, and count the number of nodes of the main stem (NN). In the first year of cultivation, 19, 20, 18, 17 and 11 evaluations were performed at times 1, 2, 3, 4 and 5, respectively. In the second year of cultivation, 17, 17, 19, 15 and 16 evaluations were performed for the same sowing times, respectively. The Logistic model was fitted using the equation $y_i = a/[1 + exp(-b - cx_i)]$, where: y_i represents the i-th observation of the dependent variable, with i = 1, 2, ..., n; *a* is the asymptotic value or final growth value; *b* is the location parameter of the curve, having no biological interpretation, but being fundamental for the sigmoid shape of the curve; *c* is the maximum relative growth rate or earliness index; and x_i is the independent variable, that is, the number of days after sowing (DAS). Initial estimates of the parameters were performed by the ordinary least squares method.

The duration of the growth cycle of the cultivars (from sowing until the end of flowering) in the first year of cultivation (2017/2018) was 78, 80, 77, 68 and 57 days at times 1, 2, 3, 4 and 5, respectively. The duration in the second year of cultivation (2018/2019) was 72, 69, (68/78), 66 and 63 days at times 1, 2, 3, 4 and 5, respectively. At the third sowing time of the second year of cultivation, as previously mentioned, the cultivars showed different durations of their growth cycles; IPR91-Baili required 68 days to reach the final flowering stage, while IPR92-Altar reached this stage at 78 DAS.

After fitting the Logistic model, the following parameters were calculated: maximum acceleration point (MAP) through $x_i = \left(\frac{-b}{c}\right) - \left(\left(\frac{1}{c}\right) * 1.3170\right)$ and $y_i = \frac{a}{4.7321}$; inflection point (IP) through $x_i = -\frac{b}{c}$ and $y_i = \frac{a}{2}$; maximum deceleration point (MDP) through $x_i = \left(\frac{-b}{c}\right) + \left(\left(\frac{1}{c}\right) * 1.3170\right)$ and; $y_i = \frac{a}{1.2679}$ and asymptotic deceleration point (ADP) through $x_i = \left(\frac{-b}{c}\right) + \left(\left(\frac{1}{c}\right) * 2.2924\right)$ and $y_i = \frac{a}{1.1010}$, where *a*, *b* and *c* are parameters of the model (MISCHAN; PINHO, 2014).

Comparisons between the two cultivars at each sowing time and year of cultivation and between the five sowing times for each year of cultivation and cultivar were performed using the criterion of overlapping confidence intervals (CI), as carried out in studies conducted by Bem *et al*. (2017) and Pezzini *et al*. (2019). For this, the lower and upper limits of the CI of parameters *a*, *b* and *c* were calculated with 95% confidence. For example: the comparison between the two cultivars was performed by checking the coincidence or not of the respective CIs, that is, when at least one estimate of the parameter of a given cultivar is contained within the CI of the parameter of the other cultivar, the estimates of the parameter do not differ between the cultivars. However, if none of the parameter estimates is contained within the CI of the parameter of the other cultivar, the parameter estimates are considered to differ between cultivars, at 5% significance level. This same criterion was used in the comparison of sowing times.

In order to evaluate the quality of fit of the Logistic model, the following parameters were determined: coefficient of determination (R^2), with the best fit being the one with the highest R^2 value; Akaike information criterion (AIC), with the best model being the one with the lowest AIC value; and residual standard deviation (RSD), with the best fit being the one with the lowest RSD value.

Curvature measures of nonlinearity of Bates and Watts (1988) were used to analyze the behavior of the models, where nonlinearity is decomposed into intrinsic nonlinearity (IN) and parameter-effect nonlinearity (PE), based on the geometric concept of curvature. The best fit is the one with the lowest IN and PE values. Statistical analyses were performed using R statistical software (R Development Core Team, 2021) and the Microsoft Office Excel® application.

RESULTS AND DISCUSSION

Tables 1 and 2 present the estimates of the Logistic model parameters for the traits plant height (PH, in cm) and number of nodes of the main stem (NN), as a function of the number of days after sowing (DAS), as well as the comparison of the parameters between the two cultivars at each sowing time and year of cultivation. The criterion of overlapping confidence intervals (CI) was adopted to compare the parameters, as applied by Bem *et al*. (2017) and Pezzini *et al*. (2019).

Table 1 - Estimates of the parameters and lower (LL) and upper (UL) limits of the 95% confidence intervals of the Logistic model fit for plant height (PH, in cm) and number of nodes (NN) of the buckwheat cultivars IPR91-Baili and IPR92-Altar, sown at five times in the first year of cultivation (2017/2018)

Trait	Time[(1)]	Parameter	[(2)]	Estimate	LL	UL	Estimate	LL	UL
				IPR91-Baili			IPR92-Altar		
PH	1	*a*	ns	96.9714	93.0308	100.9120	101.3901	96.7011	106.0791
PH	1	*b*	*	-5.7629	-6.9500	-4.5757	-4.1676	-4.8551	-3.4801
PH	1	*c*	*	0.1723	0.1358	0.2087	0.1181	0.0970	0.1392
NN	1	*a*	*	13.6223	12.8926	14.3521	14.8655	13.9575	15.7735
NN	1	*b*	ns	-2.6575	-3.2437	-2.0712	-2.4391	-2.8690	-2.0091
NN	1	*c*	ns	0.0947	0.0727	0.1167	0.0782	0.0622	0.0942

Continuation Table 1

PH	2	*a*	ns	144.8716	139.5304	150.2128	139.6041	134.6451	144.5630
PH	2	*b*	ns	-4.4170	-5.0734	-3.7606	-3.8892	-4.4501	-3.3282
PH	2	*c*	ns	0.1284	0.1083	0.1485	0.1201	0.1018	0.1384
NN	2	*a*	ns	16.2340	15.5539	16.9142	15.6101	15.0502	16.1700
NN	2	*b*	ns	-2.7940	-3.2122	-2.3758	-3.0614	-3.5905	-2.5323
NN	2	*c*	*	0.0920	0.0770	0.1070	0.1132	0.0932	0.1332
PH	3	*a*	*	117.7627	112.1676	123.3579	135.6067	129.5562	141.6572
PH	3	*b*	ns	-4.4499	-5.3528	-3.5471	-4.0847	-4.6919	-3.4775
PH	3	*c*	ns	0.1339	0.1055	0.1624	0.1129	0.0946	0.1312
NN	3	*a*	*	14.8148	14.3184	15.3112	16.2171	15.5575	16.8766
NN	3	*b*	ns	-3.1015	-3.6253	-2.5777	-2.8409	-3.3433	-2.3385
NN	3	*c*	ns	0.1126	0.0935	0.1318	0.0993	0.0811	0.1174
PH	4	*a*	ns	126.4021	121.3424	131.4617	124.3690	118.3425	130.3956
PH	4	*b*	ns	-4.9031	-5.8611	-3.9451	-4.1630	-5.0591	-3.2669
PH	4	*c*	ns	0.1803	0.1441	0.2166	0.1551	0.1203	0.1898
NN	4	*a*	*	13.7582	13.2010	14.3154	12.9677	12.3999	13.5356
NN	4	*b*	ns	-3.2415	-3.7975	-2.6855	-3.4028	-4.1740	-2.6315
NN	4	*c*	ns	0.1296	0.1063	0.1529	0.1502	0.1157	0.1846
PH	5	*a*	ns	89.8528	83.2114	96.4942	89.0624	83.7827	94.3422
PH	5	*b*	ns	-4.9664	-6.0173	-3.9155	-4.3784	-5.1336	-3.6232
PH	5	*c*	ns	0.1697	0.1307	0.2088	0.1579	0.1282	0.1877
NN	5	*a*	ns	12.0335	11.2226	12.8444	11.8742	10.9537	12.7946
NN	5	*b*	ns	-3.1053	-3.7349	-2.4756	-3.1439	-3.9413	-2.3465
NN	5	*c*	ns	0.1263	0.0981	0.1545	0.1320	0.0958	0.1681

(1) Time 1 (11/08/2017); Time 2 (12/18/2017); Time 3 (01/03/2018); Time 4 (02/07/2018); and Time 5 (03/14/2018). (2) This column represents the comparison of the parameters of the Logistic model between cultivars, i.e., * = significant at 5% probability of error and ns = not significant

Table 2 - Estimates of the parameters and lower (LL) and upper (UL) limits of the 95% confidence intervals of the Logistic model fit for plant height (PH, in cm) and number of nodes (NN) of the buckwheat cultivars IPR91-Baili and IPR92-Altar, sown at five times in the second year of cultivation (2018/2019)

Trait	Time(1)	Parameter	(2)	Estimate	LL	UL	Estimate	LL	UL
				IPR91-Baili			IPR92-Altar		
PH	1	*a*	*	62.1591	59.8270	64.4911	65.6015	62.9207	68.2823
PH	1	*b*	ns	-4.9932	-6.0523	-3.9342	-4.4734	-5.4775	-3.4693
PH	1	*c*	ns	0.1821	0.1430	0.2212	0.1656	0.1280	0.2033
NN	1	*a*	ns	10.2381	9.7457	10.7304	10.3078	9.7892	10.8263
NN	1	*b*	ns	-2.9010	-3.5865	-2.2155	-2.4922	-3.1147	-1.8697
NN	1	*c*	ns	0.1139	0.0868	0.1410	0.1026	0.0771	0.1281
PH	2	*a*	*	82.6813	78.9507	86.4119	78.0491	74.4124	81.6859
PH	2	*b*	ns	-3.9604	-4.7392	-3.1817	-4.0311	-4.8793	-3.1829
PH	2	*c*	ns	0.1439	0.1144	0.1734	0.1485	0.1161	0.1809
NN	2	*a*	ns	12.6630	12.0124	13.3137	12.3632	11.7270	12.9993
NN	2	*b*	ns	-2.5154	-2.9879	-2.0430	-2.7069	-3.2694	-2.1444
NN	2	*c*	ns	0.0989	0.0789	0.1189	0.1082	0.0846	0.1319

Continuation Table 2

PH	3	*a*	*	95.4656	91.5046	99.4267	112.6096	108.8760	116.3432
PH	3	*b*	ns	-4.2430	-5.0057	-3.4804	-4.3342	-5.0447	-3.6237
PH	3	*c*	ns	0.1544	0.1254	0.1833	0.1557	0.1295	0.1819
NN	3	*a*	*	11.5080	11.1465	11.8696	12.0039	11.6393	12.3686
NN	3	*b*	ns	-2.9641	-3.4255	-2.5027	-2.9727	-3.4765	-2.4688
NN	3	*c*	ns	0.1329	0.1120	0.1539	0.1321	0.1099	0.1543
PH	4	*a*	ns	126.8718	121.7411	132.0025	126.6993	121.8832	131.5154
PH	4	*b*	ns	-4.1550	-4.8330	-3.4770	-4.8809	-5.6344	-4.1273
PH	4	*c*	ns	0.1437	0.1190	0.1685	0.1601	0.1341	0.1861
NN	4	*a*	*	10.8929	10.4550	11.3308	11.5115	11.0880	11.9349
NN	4	*b*	ns	-2.9187	-3.6046	-2.2327	-3.3172	-3.9584	-2.6760
NN	4	*c*	ns	0.1302	0.1006	0.1597	0.1374	0.1109	0.1640
PH	5	*a*	ns	56.9422	54.8412	59.0432	57.3483	55.0696	59.6269
PH	5	*b*	ns	-3.7093	-4.2517	-3.1670	-4.3308	-5.0490	-3.6126
PH	5	*c*	ns	0.1457	0.1231	0.1683	0.1636	0.1351	0.1921
NN	5	*a*	*	8.5981	8.2798	8.9164	9.2263	8.8632	9.5894
NN	5	*b*	ns	-2.8881	-3.4157	-2.3604	-2.9384	-3.4790	-2.3978
NN	5	*c*	ns	0.1403	0.1143	0.1662	0.1378	0.1118	0.1638

(1) Time 1 (11/06/2018); Time 2 (12/28/2018); Time 3 (01/30/2019); Time 4 (02/22/2019); and Time 5 (03/28/2019). (2) This column represents the comparison of the parameters of the Logistic model between cultivars, i.e., * = significant at 5% probability of error and ns = not significant

As an example of application of this criterion, the estimates of the parameter *a* for PH at the fourth sowing time were compared (Table 1). It can be observed that, in this case, the estimates of the parameter *a* do not differ between the cultivars, because the estimate of *a* for IPR91-Baili at time 4 was 126.4021 and is within the CI of IPR92-Altar (118.3425 to 130.3956), and the estimate of *a* for IPR92-Altar, which was 124.3690, is within the CI of *a* for IPR91-Altar (121.3424 to 131.4617).

When only one estimate of the parameter of one of the cultivars is within the CI of the parameter of the other cultivar, as observed in the parameter *a* for PH at time 1, the effect is also not significant (Table 1). In this case, the estimate of *a* for IPR91-Baili (96.9714) is contained in the CI of *a* for IPR92-Altar (96.7011 to 106.0791), but the estimate of *a* for IPR92-Altar (101.3901) is higher than the upper limit of the CI of *a* for IPR91-Baili (100.9120).

When none of the parameter estimates of one of the cultivars is contained in the CI of the parameter of the other cultivar, the parameter estimates differ. For example, in relation to the parameter *a* for NN at the first sowing time, in the first year of cultivation, the estimate of *a* for IPR91-Baili (13.6223) was lower than the lower limit of the CI of *a* for IPR92-Altar (13.9575 to 15.7735), and the estimate of *a* for IPR92-Altar (14.8655) was higher than the upper limit of the CI of *a* for IPR91-Baili (12.8926 to 14.3521) (Table 1). In this case, it is considered that the estimates of parameter *a* differ at 5% significance level (significant effect). However, to affirm that the cultivars have a similar response, the parameters *a*, *b* and *c* must be not significant.

Regarding PH, it was observed that at times 2, 4 and 5 of the first year of cultivation and at times 4 and 5 of the second year of cultivation, the parameters *a*, *b* and *c* of the model did not show significant differences between the cultivars, which means that the growth curves are similar, that is, a single growth curve can be used to describe the cultivars at these times (Tables 1 and 2). On the other hand, at time 3 of the first year and at times 1, 2 and 3 of the second year there was a significant difference between the cultivars in relation to the asymptotic value (parameter *a*). It was observed that, except for time 2 of the second year of cultivation, the cultivar IPR92-Altar showed higher value of *a* compared to the cultivar IPR91-Baili, indicating a taller final stature. Also, at time 1 of the first year, the cultivars differed in relation to parameters *b* and *c*. Therefore, for these times the cultivars showed difference in the growth pattern.

Regarding NN, it was observed that at time 5 of the first year of cultivation and at times 1 and 2 of the second year of cultivation, the cultivars did not show significant differences (Tables 1 and 2). At times 1, 3 and 4 of the first year and at times 3, 4 and 5 of the second year, the cultivars differed in relation to the asymptotic value of the model (parameter *a*). It was observed that, except for time 4 of the first year, the NN of the cultivar IPR92-Altar was higher than the NN of the cultivar IPR91-Baili.

For the parameter *b* of the model, there is no direct practical interpretation, but it is important to maintain the sigmoid shape of the model. For this parameter, there was a significant effect between the cultivars, IPR91-Baili and IPR92-Altar, only for PH at the first sowing time, in the first year of cultivation (Table 1).

The parameter *c* of the model is associated with growth, expressing the earliness index, so that the higher its value, the faster the asymptote is reached. The PH of the cultivar IPR91-Baili, in the first year of cultivation, had a higher estimate of *c*, indicating that maximum PH is reached in a shorter time interval, so this cultivar is earlier than IPR92-Altar (Table 1). In relation to NN, at time 2 of the first year of cultivation, the response of the cultivars was inverse, that is, the estimate of the parameter *c* for IPR91-Baili (0.092) was lower than that for IPR92-Altar (0.113). Different responses of the cultivars were also observed by Pezzini *et al*. (2019) in growth curves of sudangrass.

For each trait, year of cultivation and cultivar, comparisons were made between the five sowing times (Table 3). It can be observed that, among all comparisons, the estimates of all model parameters (*a*, *b* and *c*) for the traits PH and NN did not differ only in the comparison between the times 2 and 3 (2 × 3) for the cultivar IPR92-Altar in the first year of cultivation (2017/2018). Thus, it can be inferred that at these two times the cultivar IPR92-Altar showed the same growth pattern. Thus, the use of a single model, for each trait, would be adequate to describe the growth of plants sown at these two times.

In the other comparisons, the times differed in at least one parameter of the model (Table 3). In most cases, the growth of the cultivars IPR91-Baili and IPR92-Altar occurred differently between the sowing times, highlighting the need to fit specific models for each trait, cultivar and sowing time. Different responses between sowing times have also been reported by Bem *et al*. (2017) and Pezzini *et al.* (2019) in *Crotalaria juncea* and sudangrass, respectively.

Table 3 - Comparison of the estimates of the parameters of the Logistic model, fitted for the traits plant height (PH, in cm) and number of nodes (NN), between the five sowing times (1 × 2, 1 × 3, 1 × 4, 1 × 5, 2 × 3, 2 × 4, 2 × 5, 3 × 4, 3 × 5 and 4 × 5), of the buckwheat cultivars IPR91-Baili and IPR92-Altar, in two years of cultivation (year 1 = 2017/2018; year 2 = 2018/2019)

Trait	Year	Cultivar	Parameter	1 × 2	1 × 3	1 × 4	1 × 5	2 × 3	2 × 4	2 × 5	3 × 4	3 × 5	4 × 5
PH	1	IPR91-Baili	*a*	*	*	*	*	*	*	*	*	*	*
PH	1	IPR91-Baili	*b*	*	*	ns	ns	ns	ns	ns	ns	ns	ns
PH	1	IPR91-Baili	*c*	*	*	ns	ns	ns	*	*	*	ns	ns
NN	1	IPR91-Baili	*a*	*	*	ns	*	*	*	*	*	*	*
NN	1	IPR91-Baili	*b*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
NN	1	IPR91-Baili	*c*	ns	ns	*	*	*	*	*	ns	ns	ns
PH	1	IPR92-Altar	*a*	*	*	*	*	ns	*	*	*	*	*
PH	1	IPR92-Altar	*b*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PH	1	IPR92-Altar	*c*	ns	ns	*	*	ns	*	*	*	*	ns
NN	1	IPR92-Altar	*a*	ns	*	*	*	ns	*	*	*	*	*
NN	1	IPR92-Altar	*b*	*	ns	*	ns	ns	ns	ns	ns	ns	ns
NN	1	IPR92-Altar	*c*	*	*	*	*	ns	*	ns	*	ns	ns
PH	2	IPR91-Baili	*a*	*	*	*	*	*	*	*	*	*	*
PH	2	IPR91-Baili	*b*	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
PH	2	IPR91-Baili	*c*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
NN	2	IPR91-Baili	*a*	*	*	*	*	*	*	*	*	*	*
NN	2	IPR91-Baili	*b*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
NN	2	IPR91-Baili	*c*	ns	ns	ns	ns	*	*	*	ns	ns	ns

Continuation Table 3

PH	2	IPR92-Altar	*a*	*	*	*	*	*	*	*	*	*	*
PH	2	IPR92-Altar	*b*	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
PH	2	IPR92-Altar	*c*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
NN	2	IPR92-Altar	*a*	*	*	*	*	ns	*	*	*	*	*
NN	2	IPR92-Altar	*b*	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
NN	2	IPR92-Altar	*c*	ns	*	*	*	*	*	*	ns	ns	ns

Times of year 1: 1 (11/08/2017); 2 (12/18/2017); 3 (01/03/2018); 4 (02/07/2018); and 5 (03/14/2018). Times of year 2: 1 (11/06/2018); 2 (12/28/2018); 3 (01/30/2019); 4 (02/22/2019); and 5 (03/28/2019). Comparisons between sowing times performed based on overlapping confidence intervals. * = significant at 5% probability of error. ns = not significant

Table 4 - Fitting quality indicators and nonlinearity measures of the curvature of the Logistic model fitted for the traits plant height (PH, in cm) and number of nodes (NN) for the buckwheat cultivars IPR91-Baili and IPR92-Altar at five sowing times in two years of cultivation (year 1 = 2017/2018; year 2 = 2018/2019)

Trait	Year	Cultivar	Time(1)	RSD	AIC	R^2	IN	PE
PH	1	IPR91-Baili	1	12.1575	5.0582	0.8900	0.1549	0.3340
PH	1	IPR91-Baili	2	14.3415	5.3846	0.9200	0.1035	0.2903
PH	1	IPR91-Baili	3	14.6066	5.4291	0.8657	0.1332	0.3881
PH	1	IPR91-Baili	4	14.4438	5.4104	0.9051	0.1424	0.3248
PH	1	IPR91-Baili	5	10.2514	4.7624	0.8952	0.1436	0.4724
NN	1	IPR91-Baili	1	1.6289	1.0385	0.8208	0.1248	0.5312
NN	1	IPR91-Baili	2	1.4961	0.8652	0.8990	0.0873	0.3803
NN	1	IPR91-Baili	3	1.2659	0.5378	0.8929	0.0962	0.3255
NN	1	IPR91-Baili	4	1.3607	0.6857	0.9010	0.1072	0.3449
NN	1	IPR91-Baili	5	1.1201	0.3344	0.8888	0.1148	0.5466
PH	1	IPR92-Altar	1	10.9472	4.8484	0.9059	0.1111	0.3788
PH	1	IPR92-Altar	2	13.2731	5.2310	0.9187	0.0954	0.2854
PH	1	IPR92-Altar	3	12.7153	5.1517	0.9175	0.0941	0.3695
PH	1	IPR92-Altar	4	15.9975	5.6145	0.8717	0.1479	0.3900
PH	1	IPR92-Altar	5	8.1184	4.2960	0.9232	0.1128	0.4001
NN	1	IPR92-Altar	1	1.4760	0.8412	0.8691	0.0970	0.6367
NN	1	IPR92-Altar	2	1.5844	0.9800	0.8782	0.1051	0.3162
NN	1	IPR92-Altar	3	1.4574	0.8195	0.8811	0.0967	0.4087
NN	1	IPR92-Altar	4	1.6100	1.0225	0.8430	0.1441	0.3749
NN	1	IPR92-Altar	5	1.3559	0.7167	0.8392	0.1482	0.6388
PH	2	IPR91-Baili	1	7.2735	4.0384	0.8702	0.1436	0.3152
PH	2	IPR91-Baili	2	9.6131	4.5961	0.8824	0.1300	0.3698
PH	2	IPR91-Baili	3	10.3293	4.7393	0.9086	0.1245	0.3323
PH	2	IPR91-Baili	4	11.3600	4.9387	0.9204	0.1021	0.3434
PH	2	IPR91-Baili	5	4.9001	3.2528	0.9325	0.0967	0.3000
NN	2	IPR91-Baili	1	1.1734	0.3898	0.8225	0.1323	0.4790
NN	2	IPR91-Baili	2	1.2449	0.5081	0.8723	0.1034	0.5076
NN	2	IPR91-Baili	3	0.9522	-0.0280	0.9153	0.0942	0.2807
NN	2	IPR91-Baili	4	1.0294	0.1371	0.8481	0.1274	0.4363
NN	2	IPR91-Baili	5	0.8088	-0.3501	0.8925	0.1102	0.3320

Continuation Table 4

PH	2	IPR92-Altar	1	8.0682	4.2458	0.8521	0.1468	0.3458
PH	2	IPR92-Altar	2	9.6453	4.6026	0.8703	0.1400	0.3819
PH	2	IPR92-Altar	3	11.3722	4.9250	0.9171	0.1159	0.2689
PH	2	IPR92-Altar	4	11.1031	4.8935	0.9337	0.1033	0.3074
PH	2	IPR92-Altar	5	5.6076	3.5219	0.9229	0.1166	0.3164
NN	2	IPR92-Altar	1	1.1368	0.3265	0.8118	0.1306	0.5497
NN	2	IPR92-Altar	2	1.3610	0.6865	0.8516	0.1181	0.4888
NN	2	IPR92-Altar	3	1.1109	0.2731	0.8937	0.1047	0.2692
NN	2	IPR92-Altar	4	1.0097	0.0985	0.8876	0.1109	0.3623
NN	2	IPR92-Altar	5	0.8964	-0.1443	0.8903	0.1116	0.3487

[(1)] Times of year 1: 1 (11/08/2017); 2 (12/18/2017); 3 (01/03/2018); 4 (02/07/2018); and 5 (03/14/2018). Times of year 2: 1 (11/06/2018); 2 (12/28/2018); 3 (01/30/2019); 4 (02/22/2019); and 5 (03/28/2019). RSD: residual standard deviation; AIC: Akaike information criterion; R^2: coefficient of determination; IN: intrinsic nonlinearity; PE: parameter-effect nonlinearity

The coefficients of determination (R^2) were greater than or equal to 0.8118, indicating a good fitting capacity of the models to explain the growth and development curves of the crop in relation to PH and NN as a function of DAS (Table 4).

The low values of Akaike information criterion (AIC ≤ 5.6145), residual standard deviation (RSD ≤ 15.9975), intrinsic nonlinearity (IN ≤ 0.1549) and parameter-effect nonlinearity (PE ≤ 0.6388) confirm the good fit of the Logistic model for the PH and NN of the cultivars IPR91-Baili and IPR92-Altar at five sowing times in the two years of cultivation (Table 4). According to Sari *et al.* (2019), models with R^2 close to one and parametric measures of nonlinearity below this value are considered the most appropriate, indicating a good fit of the model to the evaluated traits. The reduced scores of IN and PE indicate that the model shows a behavior closer to linear, which is desired to better describe the growth curve of the crop. These results corroborate those found by Muianga *et al.* (2016) and Pezzini *et al.* (2019), who evaluated growth curves in different species and indicated a good fit of the Logistic model.

The representative curves of each model contain important points, called critical points, which have specific meanings (Table 5). From these points, it is possible to infer about the growth of the crop and establish important periods for performing management operations and cultural practices.

Maximum acceleration point (MAP) and inflection point (IP) occurred with a lower number of days for the NN trait compared to PH (Table 5). For example, at the first sowing time of the cultivar IPR91-Baili, the values of x_i (25.8090) and y_i (20.4925), referring to MAP, indicate that the plant begins the period in which the growth rate is higher at 25.8090 DAS, when plant height is 20.4925 cm. For the NN of this same cultivar and sowing time, the model indicates that this MAP occurs before, that is, at 14.1537 DAS, when the plants have 2.8787 nodes on their main stem.

The period between MAP and IP is very important, as it is the stage in which the growth rate increases to a maximum value. It is the stage in which the crop most needs water and nutrients to obtain good growth and development. Predicting this period is fundamental for better management of the crop. After the plant reaches the IP, its growth rate decreases up to the maximum deceleration point (MDP), corresponding to the point at which the plant is in the final stage of its growth cycle and close to reaching its maximum growth, identified by the asymptotic deceleration point (ADP). Identifying the ADP becomes important because it allows predicting the end of the crop cycle.

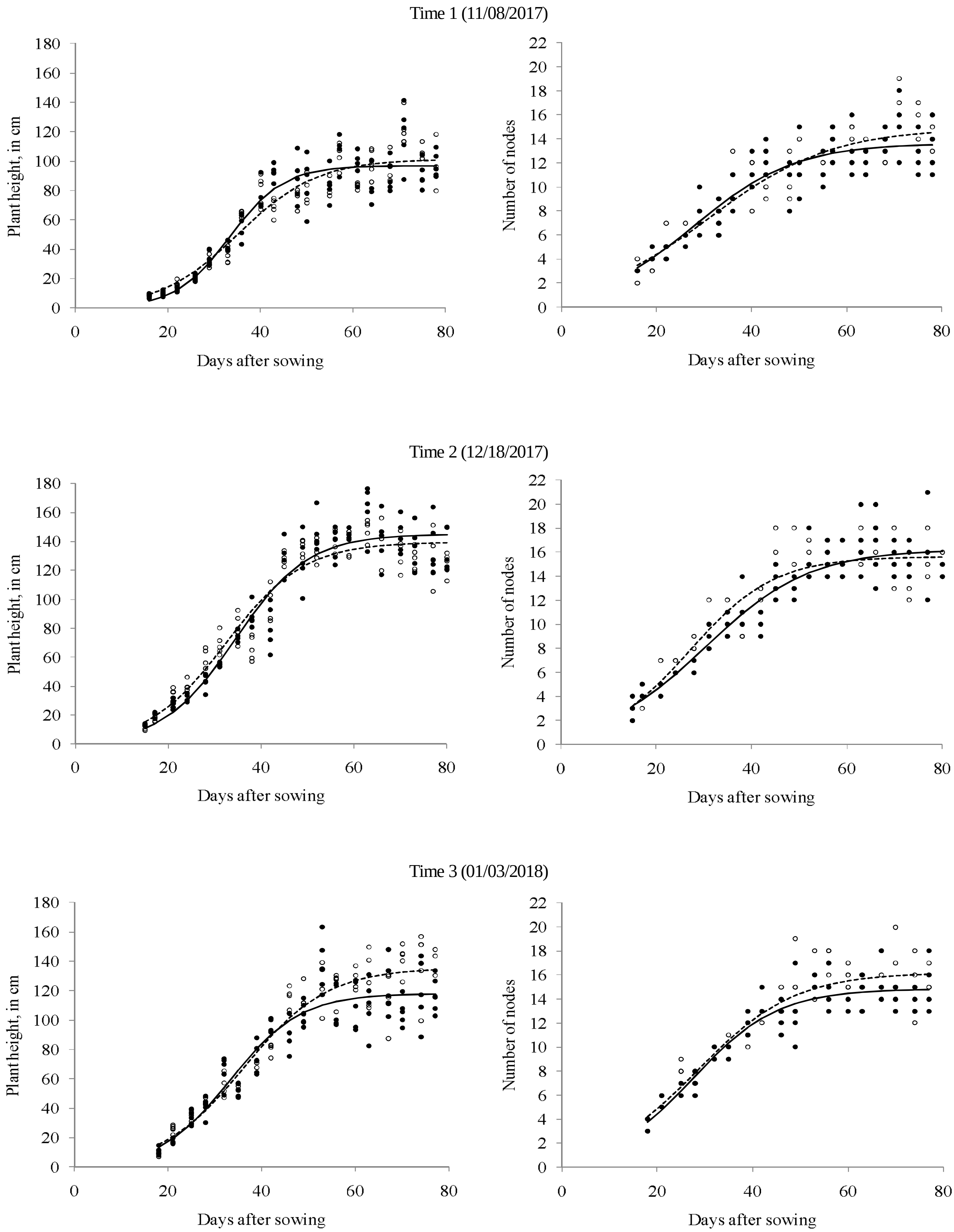
In the first year of cultivation (2017/2018), the cultivars IPR91-Baili and IPR92-Altar showed very similar growth at the first and second sowing times, with very similar values of plant height and number of nodes throughout their growth cycle (Figure 1). The greatest difference for PH and NN between the two cultivars was observed at time 3 of the first year of cultivation, when the cultivar IPR92-Altar had higher PH and higher NN than the cultivar IPR91-Baili. This difference was more evident from 40 DAS, when the plants reached approximately 50% of their growth. This response can be associated with the genetic characteristics of IPR92-Altar, which is taller and consequently has a greater number of nodes than the cultivar IPR91-Baili. At times 4 and 5, the growth pattern of the two cultivars was again very similar, and it was possible to observe a sharp decrease in PH and NN at time 5, indicating a period when buckwheat growth and development are compromised.

Table 5 - Critical points of the Logistic model fitted for the traits plant height (PH, in cm) and number of nodes (NN) for the buckwheat cultivars IPR91-Baili and IPR92-Altar at five sowing times in two years of cultivation (year 1 = 2017/2018; year 2 = 2018/2019)

Trait	Year	Time(1)	Axis	MAP	IP	MDP	ADP	MAP	IP	MDP	ADP
				IPR91-Baili				IPR92-Altar			
PH	1	1	*xi*	25.8090	33.4541	41.0992	46.7619	24.1416	35.2947	46.4477	54.7088
PH	1	1	*yi*	20.4925	48.4857	76.4789	88.0741	21.4263	50.6951	79.9639	92.0874
PH	1	2	*xi*	24.1446	34.4016	44.6586	52.2559	21.4185	32.3846	43.3508	51.4734
PH	1	2	*yi*	30.6150	72.4358	114.2566	131.5794	29.5018	69.8020	110.1022	126.7951
PH	1	3	*xi*	23.3912	33.2239	43.0565	50.3395	24.5153	36.1803	47.8452	56.4854
PH	1	3	*yi*	24.8862	58.8814	92.8766	106.9578	28.6571	67.8033	106.9496	123.1645
PH	1	4	*xi*	19.8850	27.1875	34.4900	39.8989	18.3518	26.8439	35.3359	41.6260
PH	1	4	*yi*	26.7119	63.2010	99.6902	114.8045	26.2823	62.1845	98.0868	112.9580
PH	1	5	*xi*	21.5026	29.2620	37.0215	42.7690	19.3851	27.7241	36.0631	42.2398
PH	1	5	*yi*	18.9881	44.9264	70.8647	81.6086	18.8211	44.5312	70.2413	80.8908
NN	1	1	*xi*	14.1537	28.0587	41.9637	52.2632	14.3457	31.1825	48.0192	60.4903
NN	1	1	*yi*	2.8787	6.8112	10.7436	12.3725	3.1414	7.4327	11.7240	13.5015
NN	1	2	*xi*	16.0578	30.3753	44.6928	55.2978	15.4117	27.0465	38.6814	47.2993
NN	1	2	*yi*	3.4307	8.1170	12.8034	14.7445	3.2988	7.8051	12.3113	14.1779
NN	1	3	*xi*	15.8449	27.5383	39.2317	47.8931	15.3544	28.6233	41.8921	51.7204
NN	1	3	*yi*	3.1307	7.4074	11.6841	13.4555	3.4271	8.1085	12.7900	14.7291
NN	1	4	*xi*	14.8473	25.0074	35.1675	42.6931	13.8904	22.6606	31.4308	37.9269
NN	1	4	*yi*	2.9074	6.8791	10.8507	12.4959	2.7404	6.4839	10.2273	11.7779
NN	1	5	*xi*	14.1600	24.5877	35.0154	42.7392	13.8418	23.8194	33.7971	41.1876
NN	1	5	*yi*	2.5430	6.0168	9.4906	10.9294	2.5093	5.9371	9.3649	10.7847
PH	2	1	*xi*	20.1892	27.4216	34.6541	40.0111	19.0556	27.0062	34.9569	40.8459
PH	2	1	*yi*	13.1358	31.0795	49.0233	56.4559	13.8632	32.8008	51.7383	59.5825
PH	2	2	*xi*	18.3692	27.5206	36.6720	43.4504	18.2800	27.1498	36.0196	42.5895
PH	2	2	*yi*	17.4726	41.3407	65.2087	75.0952	16.4937	39.0246	61.5554	70.8880
PH	2	3	*xi*	18.9566	27.4885	36.0205	42.3401	19.3776	27.8354	36.2932	42.5580
PH	2	3	*yi*	20.1743	47.7328	75.2914	86.7065	23.7972	56.3048	88.8124	102.2775
PH	2	4	*xi*	19.7432	28.9047	38.0662	44.8522	22.2580	30.4829	38.7078	44.8000
PH	2	4	*yi*	26.8112	63.4359	100.0606	115.2311	26.7747	63.3496	99.9246	115.0744
PH	2	5	*xi*	16.4156	25.4520	34.4884	41.1817	18.4182	26.4664	34.5146	40.4760
PH	2	5	*yi*	12.0333	28.4711	44.9089	51.7177	12.1191	28.6741	45.2291	52.0865
NN	2	1	*xi*	13.9076	25.4701	37.0326	45.5970	11.4538	24.2891	37.1244	46.6315
NN	2	1	*yi*	2.1636	5.1190	8.0745	9.2987	2.1783	5.1539	8.1295	9.3620
NN	2	2	*xi*	12.1178	25.4335	38.7493	48.6123	12.8423	25.0102	37.1781	46.1909
NN	2	2	*yi*	2.6760	6.3315	9.9870	11.5012	2.6126	6.1816	9.7505	11.2288
NN	2	3	*xi*	12.3918	22.2997	32.2076	39.5464	12.5355	22.5063	32.4771	39.8625
NN	2	3	*yi*	2.4319	5.7540	9.0761	10.4522	2.5367	6.0020	9.4672	10.9026
NN	2	4	*xi*	12.3065	22.4251	32.5438	40.0387	14.5565	24.1405	33.7245	40.8234
NN	2	4	*yi*	2.3019	5.4464	8.5909	9.8934	2.4327	5.7557	9.0788	10.4553
NN	2	5	*xi*	11.1996	20.5875	29.9754	36.9291	11.7655	21.3218	30.8782	37.9566
NN	2	5	*yi*	1.8170	4.2991	6.7811	7.8092	1.9497	4.6131	7.2765	8.3798

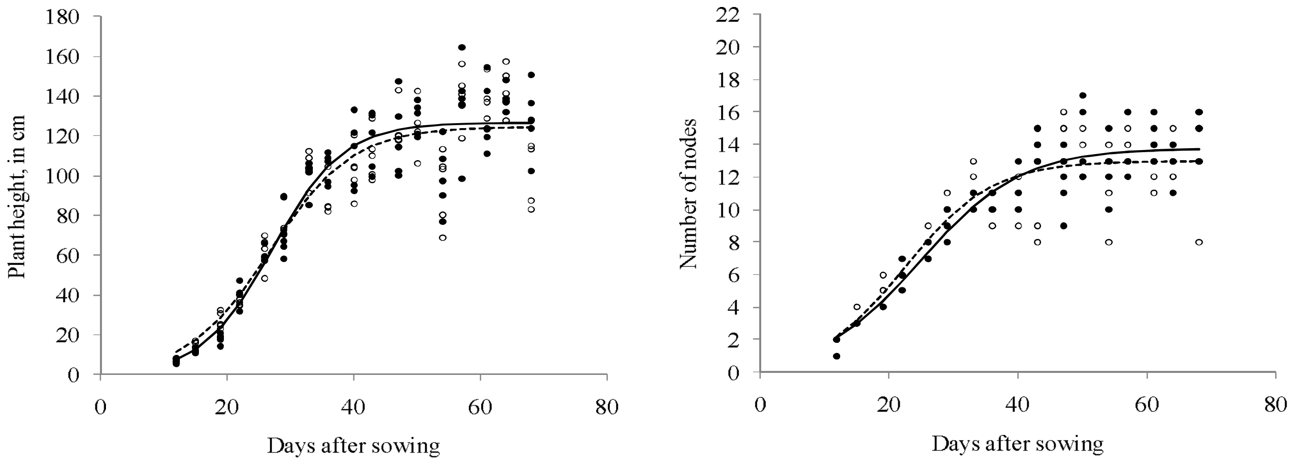
(1) Times of year 1: 1 (11/08/2017); 2 (12/18/2017); 3 (01/03/2018); 4 (02/07/2018); and 5 (03/14/2018). Times of year 2: 1 (11/06/2018); 2 (12/28/2018); 3 (01/30/2019); 4 (02/22/2019); and 5 (03/28/2019). MAP: maximum acceleration point; IP: inflection point; MDP: maximum deceleration point; ADP: asymptotic deceleration point

Figure 1 - Logistic model graphs for plant height and number of nodes of the buckwheat cultivars IPR91-Baili (___) and IPR92-Altar (----), at five sowing times in the first year of cultivation (2017/2018)

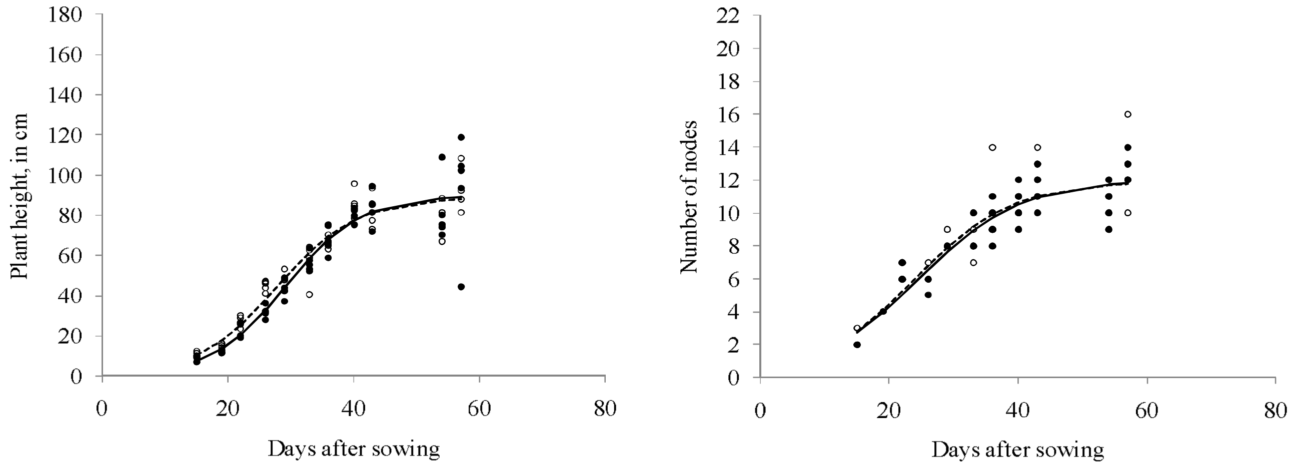


Continuation Figure 1

Time 4 (02/07/2018)



Time 5 (03/14/2018)



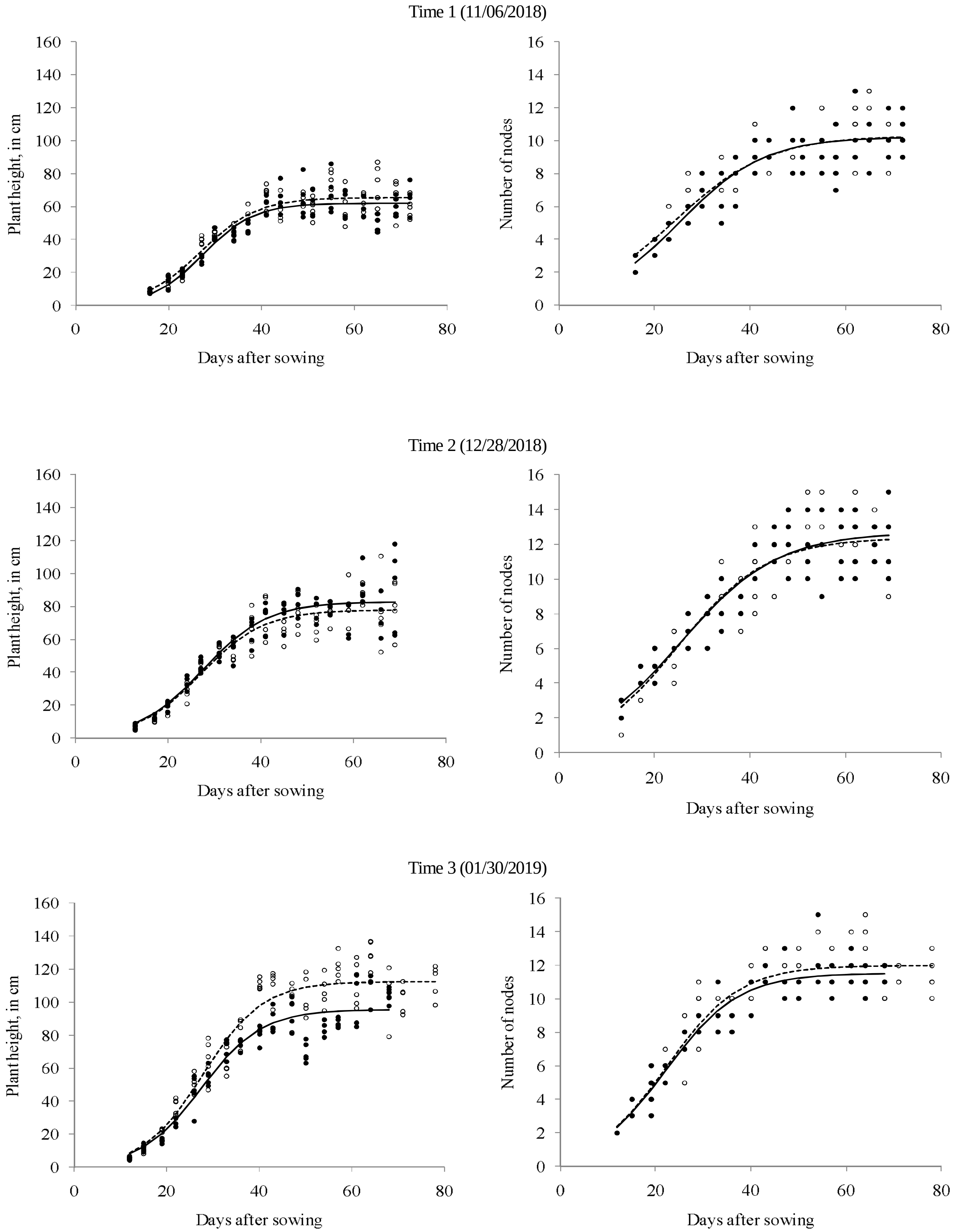
In the second year of cultivation, the growth and development pattern of the two cultivars was very similar at times 1 and 2, with no major differences between the cultivars for PH and NN (Figure 2). This information of earliness of one cultivar compared to another can be important for the planning of the production system and position of cultivars at this sowing time.

It can be observed that the delay in sowing, in both years, led to a reduction in the growth period of the crop, with a lower value at time 5 for both cultivars (Figures 1 and 2). This reduction of the cycle at time 5 indicates that this is not a preferential period for growing these cultivars, since this shortening of crop growth period results in a shorter period for accumulation of photoassimilates and, consequently, a lower production. These results corroborate those obtained by Toom *et al.* (2019), who observed a large decrease in the biomass accumulation of buckwheat due to the delay in the sowing time. Defining preferential times for sowing buckwheat is very important because, regardless of the purpose of use, if the crop is not planted at the ideal time, its production potential will be compromised, which may affect both the yield and the profitability of the agricultural activity.

From the results obtained in this study, it is possible to affirm that there is a difference between the cultivars for the same the sowing times and between the sowing times for the same cultivar. Thus, the Logistic model should be fitted considering each sowing time for each cultivar, and not in a generalized way.

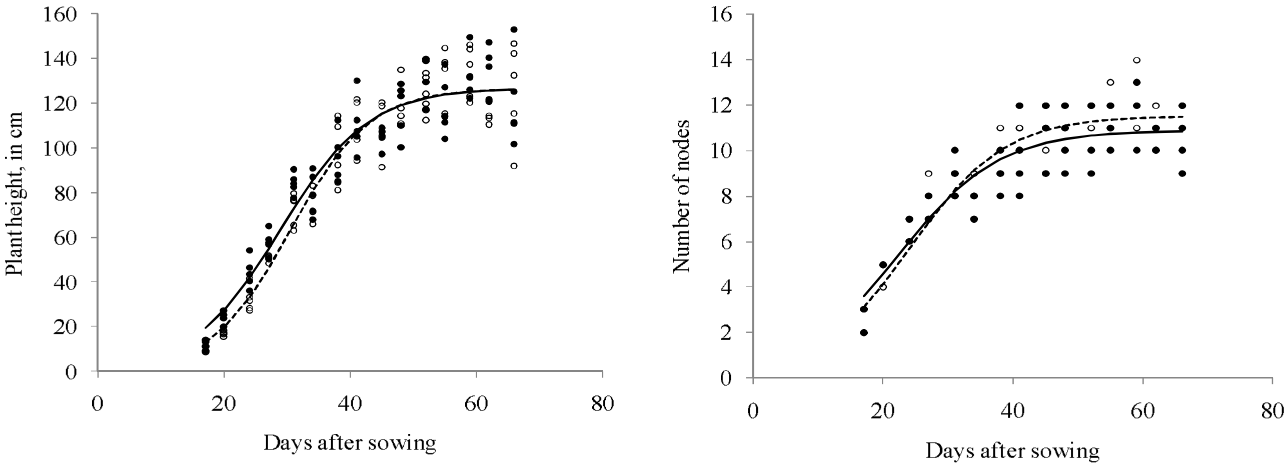
The results of the present study should serve as a reference for future research with buckwheat, because the Logistic model proved to be adequate to describe the morphological traits of this crop, showing good quality of fit.

Figure 2 - Logistic model graphs for plant height and number of nodes of the buckwheat cultivars IPR91-Baili (___) and IPR92-Altar (----), at five sowing times in the second year of cultivation (2018/2019)

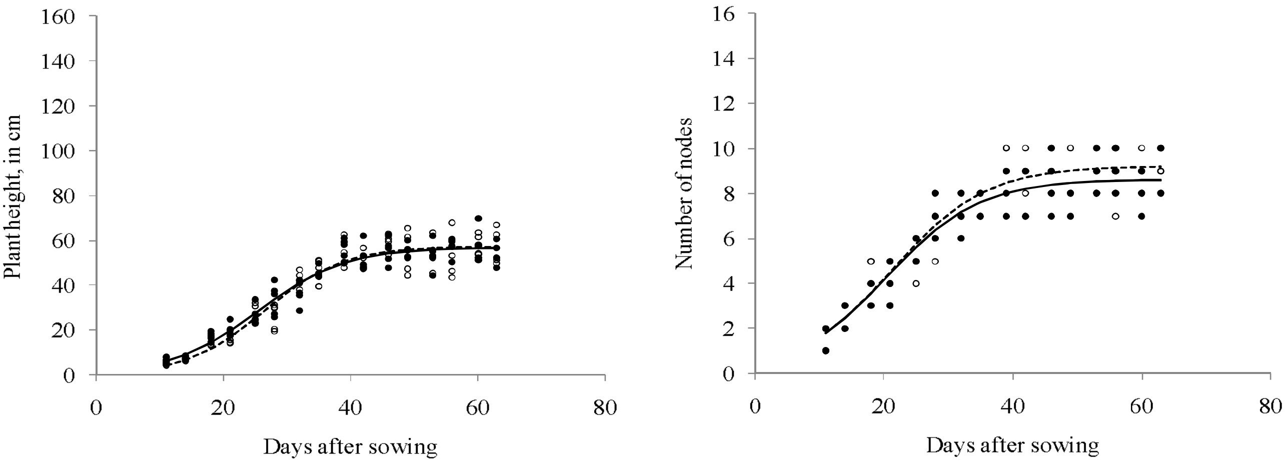


Continuation Figure 2

Time 4 (02/22/2019)



Time 5 (03/28/2019)



CONCLUSIONS

1. According to the results obtained for the fit of the model to the traits plant height and number of nodes of buckwheat, it is concluded that the Logistic model showed good quality indicators for the cultivars IPR91-Baili and IPR92-Altar;
2. The Logistic model satisfactorily describes the growth of buckwheat plants, and a specific fit considering each cultivar and sowing time is needed.

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