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Adaptation of quinoa (*Chenopodium quinoa*) to Northern European agriculture: studies on developmental pattern

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Summary

Developmental patterns were studied in five groups of quinoa lines from different maturity classes in three years, and measured on five occasions between bud formation and seed set. Knowledge of how the developmental stage develops through the growing season is of importance in the breeding and selection of quinoa lines.

Ranking of lines for earliness was consistent over growing seasons, and therefore it was concluded that selection for earliness could be performed at an early stage, i.e. the beginning of July.

A growing period greater than 150 days would normally be regarded as too long and risky in Northern Europe, but in the three years under investigation it was possible to harvest lines of the green type with a longer growing period. The total growing period for the lines tested ranged from 109 to 182 days. The vegetative phase and the total growth period were significantly longer for green types than seed types in all years. Duration of the seed set period differed between seed and green types, and between years. In the spring and early summer of the drought year, 1992, both vegetative and seed set periods were shorter than for the other years.

It must be concluded that seed types originating from Chile were adapted for growth under North European conditions. Although seed harvest of green types can occur in Denmark, they should preferably be grown at a more southerly latitude.

Introduction

Quinoa (*Chenopodium quinoa* Willd.) is a native South American plant species. The crop has been cultivated in the Andean region for thousands of years. Presently there is increased interest in quinoa as a seed and fodder crop both in the USA and Europe. Hence, as a potential new crop in European agriculture, problems related to its breeding and selection may arise. Results from a recent experiment by Risi and Galwey (1989), describing 294 quinoa accessions, indicated that significant differences existed between them for the duration of all growth phases, with the period from two true leaves to bud formation ranging from 41 to 89 days, from bud formation to anthesis 7–53 days, while the period from anthesis to maturity lasted 65–137 days.

Stability over years of developmental stage and other characters was studied by Jacobsen et al. (1996). The present study was conducted to investigate the developmental pattern of five quinoa lines, representing different maturity classes, from which parental material suitable for a breeding programme could be identified. It had previously been shown that, with the exception of one line from Peru, only material originating from Chile and southern Bolivia was able to mature under Danish conditions (Jacobsen & Stølen, 1993). This investigation therefore included material from Chile as well as the Peruvian line.

Materials and methods

The experiment was carried out in 1991, 1992 and 1995 on sandy loam soil at the research station of the Royal Veterinary and Agricultural University in Tåstrup, Denmark. Five lines of quinoa, including the

Table 1. Origin and morphology of quinoa lines

Group/ line	Origin	Basic colour	Colour of top	Developmental stage for top colour expression	Leaf size
1/205	Baer × Faro (Chilean cultivars)	Green	Red	16–17	Large
2/210	Kcancolla × Amarilla de Marangani (Peruvian cultivars)	Green	Light red	15	Large
3/224	Germplasm collection Chilean origin	Green	White	11	Small
4/233, 240	Field selection from Chilean material	Green	Orange (→red)	14–15 (/16–17)	Medium
5/Olav	Standard variety Chilean origin	Green	Yellow	15	Large

standard variety Olav (previously KVL 8401), were grown at a target density of 200 plants/m^2. Seed rate was adjusted on the basis of a laboratory germination test and an estimated field germination of 60%. Actual plant density differed, however, due to varying field germination.

The origin of the six lines, shown in Table 1, can be regarded as representative of the five groups described by Jacobsen & Stølen (1993), which were known to differ markedly in length of growing period. Therefore all groups consist of one line except group 4, where line 233 was used in 1991 and 1995, while line 240 represented the group in 1992. Groups 1 and 4 were early, group 3 medium-early, group 5 medium-late and group 2 late maturing. All lines were uniform.

In 1991 the experimental design was a split-plot, with quinoa lines as sub-plots. The five lines were combined with row spacings of 25 and 50 cm, with and without hoeing. Each combination was represented by duplicate plots, totalling 40 sub-plots. Sowing took place on 24 April when the soil temperature was 8 °C. In 1992 and 1995 the experimental design was a randomized block design with three replicates of the five lines, totalling 15 plots. Row spacing was 25 cm, and plots were hoed to combat weeds. Plot size was 15 m^2 throughout. Sowing took place on 6 and 3 May in 1992 and 1995, respectively. In all years nitrogen was applied as a top dressing at a rate of 120 kg/ha two weeks after emergence.

In order to have a reliable estimate of number of plants, two samples were taken at random from each plot, each sample comprising plants harvested from a 25 cm length of row. Within each sample the number of plants was recorded. Developmental stage, according to the developmental scale shown in Table 2, was measured on five occasions (time 1–5) at fortnightly intervals from 1 July.

For the analyses of variance a successive test was used, in which all factors in the model were tested sequentially. Since it had already been demonstrated that the number of plants had an effect on inflorescence size and height (Jacobsen, 1993), it was included as a covariate in the analysis of variance in order to reduce the error variance. Differences between lines were tested using a Ryan-Einot-Gabriel-Welsch multiple range test.

Results

In 1991 spring and early summer was wet and cold, especially April and June. In 1992 drought was experienced in May-June. In 1995 the spring was very cold, whereas July-August was dry and warm.

From the analyses of variance in 1991 (Table 3) it is apparent that an effect of plant type from time 1 (plants having ca. 16 leaves), lasting throughout the growing season, is that seed and green types do not develop similarly. The significant effect of number of plants from time 2 onwards, when plants had ca. 20 leaves, justifies the inclusion of this as a covariate in the model. For all characters measured, there was a general lack of significance of replicates, indicating that the experimental area was relatively homogeneous. In 1992 differences

Table 2. Developmental stages in quinoa (Jacobsen & Stølen, 1993)

Stage	Description	Stage	Description	Stage	Description
0	**Vegetative phase**	**8**	**Anthesis**	**14**	**Seed set**
1	**Bud formation**		onset of flowering		33% seed set
	bud covered	9	50% flowering	15	50% seed set
2	bud visible	10	100% flowering	16	67% seed set
3	bud distinct	**11**	**Floral dehiscence**	17	100% seed set
4	bud app. 0.5 cm long		onset	**18**	**Maturity**
5	bud app. 1.0 cm long	12	majority of		plant colour:
6	onset of		flowers dehisced		green > yellow
	pyramid shape	13	only wilted	19	yellow > green
7	distinct		anthers present	20	mature
	pyramid shape			21	wilted

Table 3. Analyses of variance for developmental stage, measured five times

Source	df	MS time 1	MS time 2	MS time 3	MS time 4	MS time 5
1991						
No. of plants	1	0.27	6.85**	9.20***	8.47***	0.00
Types	1	3.16**	95.52***	47.09***	66.40***	17.56***
Lines	3	0.75	6.94***	4.63**	7.91***	0.97
Reps	3	0.20	0.00	1.44	0.21	0.08
Error	11	0.27	0.73	0.93	0.63	0.26
1992						
No. of plants	1	37.64***	14.96***	16.10***	6.60***	6.37***
Types	1	28.21***	31.69***	37.97***	18.33***	14.13***
Lines	3	5.82***	2.39**	1.24***	1.42***	1.06***
Reps	2	0.41	0.05	0.02	0.09	0.13
Error	7	0.16	0.39	0.03	0.08	0.07
1995						
No. of plants	1	3.79	0.20	0.74	1.57*	0.81*
Types	1	15.65	4.17*	6.64*	8.71***	4.10***
Lines	3	2.04	3.40*	0.77	0.30	0.31
Reps	2	0.00	0.66	0.06	2.79**	0.22
Error	7	3.52	0.81	0.70	0.18	0.08

* P = 0.05–0.01, ** P = 0.01–0.001, *** P < 0.001, df = degrees of freedom.

in developmental stage for plant types and lines, and the covariate number of plants, were significant over the entire growing season, whereas in 1995 these effects were generally less pronounced than in the other two years (Table 3).

The number of days spent in the various growth phases, together with the total growing period, counted from emergence, is shown by Table 4. In 1991 a difference of eight days in the vegetative phase, including bud formation, was noted between the earliest and the latest line. Onset of flowering occurred between July 17 and 25. Differences between lines were most pronounced at seed set, which lasted from 32 to 75 days. For the earliest line (233), which reached maturity (stage 18) in mid-September, the total growing period was 127 days, while the latest line (210), with a growing period of 182 days, did not mature until November. Differences between the lines at the early growth stages became more pronounced during seed set. Ranking of lines for earliness was, however, consistent throughout the experiment.

In 1992 the lines emerged on 20 May. A difference of 16 days was seen between the earliest and latest line in the vegetative phase, with the onset of flowering

Table 4. Mean squares from the analysis of duration of growth stages. Letters a–e indicate significant differences between lines within time (P < 0.05)

	df	Veg. phase/ bud formation 0–8	Anthesis 8–11	Floral dehiscence 11–14	Seed set 14–18	Total 0–18
1991						
Types	1	104.98***	98.60***	0.05	2901.34***	
Lines	3	7.75	0.76	44.33*	303.25***	
Reps	3	10.40	3.03	8.84	1.85	
Error	12	2.80	3.42	8.08	10.65	
Rank						
Type		2 76.50 a	2 10.43 a	2 18.33 a	2 63.73 a	2 168.99
		1 71.10 b	1 5.20 b	1 18.21 a	1 35.34 b	1 129.85
Line		210 77.53 a	Olav 10.83 a	224 23.27 a	210 75.40 a	210 181.99
		Olav 75.47 ab	210 10.03 a	210 19.03 ab	Olav 52.07 b	Olav 156.00
		233 72.13 bc	205 5.73 b	Olav 17.63 ab	205 39.83 c	224 134.00
		224 72.00 bc	224 5.00 b	233 17.27 ab	224 33.73 c	205 128.83
		205 69.17 c	233 4.87 b	205 14.10 b	233 32.47 c	233 126.74
1992						
Types	1	448.53***	48.13***	381.63***	232.41***	
Lines	3	71.89***	16.39**	34.56*	84.10***	
Reps	2	0.01	0.36	0.49	9.61	
Error	8	1.05	2.37	7.63	7.05	
Rank						
Type		2 55.75 a	2 12.50 a	2 21.50 a	1 47.33 a	2 130.13
		1 46.08 b	1 9.33 b	1 12.58 b	2 40.38 b	1 115.32
Line		210 58.50 a	210 13.50 a	210 24.25 a	224 53.25 a	210 135.00
		Olav 53.00 b	Olav 11.50 ab	Olav 18.75 b	205 46.00 b	Olav 125.25
		224 50.75 c	205 11.00 ab	224 14.50 bc	240 42.75 bc	224 125.25
		240 45.50 d	240 10.25 b	205 13.25 bc	Olav 42.00 bc	205 112.25
		205 42.00 e	224 6.75c	240 10.00 c	210 38.75 c	240 108.50
1995						
Types	1	72.90**	62.50	0.90	0.01	
Lines	3	16.28	14.94	36.28	21.24	
Reps	2	0.00	0.90	84.10*	32.40	
Error	8	5.56	13.23	11.77	20.18	
Rank						
Type		2 68.83 a	2 14.83a	1 19.67 a	1 54.89 a	2 157.66
		1 64.33 b	1 10.67 b	2 19.17 a	2 54.83 a	1 149.56
Line		210 70.67 a	210 15.00 a	224 22.67 a	233 58.00 a	210 160.34
		Olav 67.00 ab	Olav 14.67 a	205 21.33 a	210 56.67 a	Olav 155.00
		224 66.33 ab	233 13.67 a	Olav 20.33 a	224 53.33 a	224 152.33
		205 64.67 ab	224 10.00 a	210 18.00 a	205 53.33 a	233 148.67
		233 62.00 b	205 8.33 a	233 15.00 a	Olav 53.00 a	205 147.66

occuring between July 1 and 17. The difference in length of the seed set period was 14 days. The earliest line, 240, reached maturity on September 6, after a total growing period of 109 days, while the latest line, 210, with a growing period of 135 days, matured on October 2.

In 1995 the lines emerged on 13 May, ten days after sowing. In the vegetative phase the difference between the earliest and the latest lines were nine days, with the onset of flowering occuring between July 14 and 23. In the seed set period there was no difference between the earliest and latest lines. The earliest line, 205, reached

Table 5. Mean squares from the analysis of duration of growth stages, combined over years. Letters a–d indicate significant differences between lines within time (P < 0.05)

	df	Veg. phase/ bud formation 0–8	Anthesis 8–11	Floral dehiscence 11–14	Seed set 14–18	Total 0–18
Types	1	560.88***	200.41***	143.11***	392.16***	
Lines	3	66.76***	10.89	65.25**	94.52***	
Years	2	2530.05***	98.97***	49.63*	483.23***	
Reps	3	2.46	8.44	17.04	12.80	
L × Y	8	19.13***	9.05	48.65***	460.47***	
Error	32	2.90	5.06	10.24	11.92	
Rank						
Type		2 65.90 a	2 12.58 a	2 19.85 a	2 51.72 a	2 150.05
		1 59.06 b	1 8.49 b	1 16.40 b	1 46.00 a	1 129.95
Line		210 67.86 a	210 12.91 a	210 20.81 a	210 55.12 a	210 156.70
		Olav 63.94 b	Olav 12.25 a	224 19.58 ab	Olav 48.32 b	Olav 143.40
		224 61.80 c	233/240 9.66 b	Olav 18.89 ab	224 47.42 b	224 136.00
		233/240 58.44 d	205 8.62 b	205 15.93 bc	205 46.35 b	205 127.85
		205 56.95 d	224 7.20 b	233/240 13.68 c	233/240 44.24 b	233/240 126.02
Year		91 73.26 a	95 12.33 a	95 19.47 a	95 54.87 a	95 152.80
		95 66.13 b	92 10.60 a	91 18.26 a	91 46.70 b	91 145.51
		92 49.95 c	91 7.29 b	92 16.15 a	92 44.55 b	92 121.25

maturity on October 8 after a growing period of 148 days, and the latest line, 210, on October 20 after 160 days. There were no significant effects of either type or line on duration of the growth periods after the vegetative stage.

For all three years the green types (type 2) had a significantly longer vegetative phase and hence a longer growing season than the seed types (type 1).

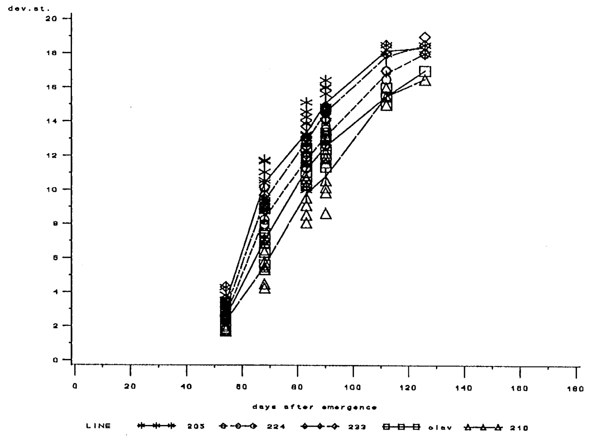
The overall results from the three seasons (Table 5) show that the vegetative stage was longest in the years of cold springs, 1991 and 1995. Anthesis, floral dehiscence and seed set periods were longest in 1995, when the summer was also dry. All growth periods were short in 1992, resulting in a total average growth period of 121 days, compared to 146 days in 1991 and 153 days in 1995. For each individual line duration of the vegetative phase and seed set period was affected by years (Table 6).

The development of lines as seen in Figure 1 presents a changing pattern from year to year. The curve for 1992, which favoured rapid emergence and early growth before drought appeared, resembles an exponential curve. The curves for 1991 and 1995 are more diffuse, and growth begins later in these two years than in 1992. In 1995 developmental rate decreased temporarily in the late summer between 110 and 135 days after emergence, following a dry summer and a rainy period which kept the plants green.

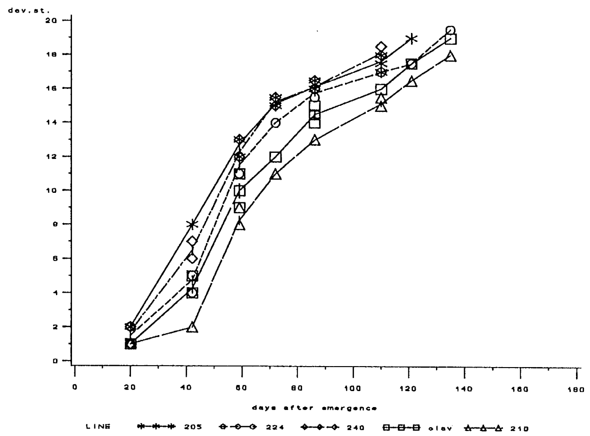
A correlation analysis between duration of the vegetative stage and the total growth period was strongly significant in 1991 and 1992 (P < 0.001), and in 1995 it was significant with a P-value of 0.05–0.01. This indicates that ranking of lines was consistent over the growth season.

Discussion

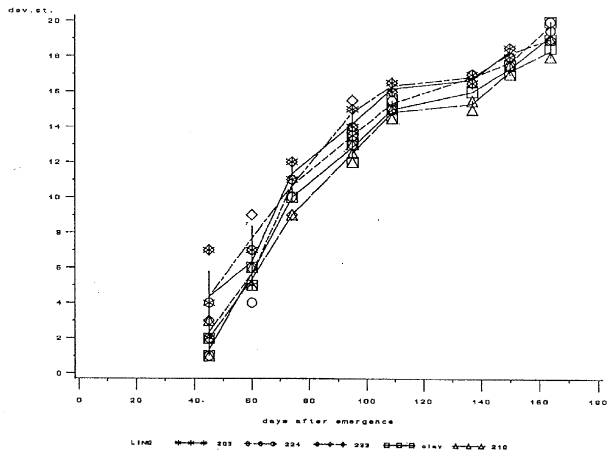
In 1991 differences in length of growing season of the lines investigated were mainly related to the period of seed set, but in the other years this was not so. Total growing period for the lines tested, which represents genotypes able to mature and yield satisfactorily under North European conditions, was 109–182 days. Among other genotypes, not included in the experiment, Nariño from Colombia did not flower under Danish conditions. Nariño followed the other lines in growth until August 1, when its growth rate



a) 1991



b) 1992



c) 1995

Figure 1. Developmental stage, 1991–95.

Table 6. Mean squares from the analysis of duration of growth stages for each line.

	df	Veg. phase/ bud formation 0–8	Anthesis 8–11	Floral dehiscence 11–14	Seed set 14–18
Line 205					
Years	2	760.20***	23.95*	63.18*	137.10*
Reps	3	1.36	0.11	16.00	5.29
Error	9	1.91	2.76	9.38	23.84
Line 224					
Years	2	431.09***	19.43**	86.29*	401.42***
Reps	3	0.00	0.93	0.01	0.07
Error	9	4.08	0.81	10.10	7.05
Line 233/240					
Years	2	635.16***	59.24	48.99	496.36***
Reps	3	1.36	0.44	15.47	5.76
Error	9	2.30	17.86	19.63	13.32
Line Olav					
Years	2	452.71***	12.90	5.53	133.79**
Reps	3	2.15	1.60	8.80	5.14
Error	9	1.99	2.75	8.49	5.61
Line 210					
Years	2	327.40***	19.66	40.25	1156.46***
Reps	3	4.55	9.82	4.99	0.19
Error	9	4.87	4.89	7.99	17.43

increased markedly, and from mid-August it was the tallest, reaching a height of 224 cm.

The period from anthesis to seed maturity lasted 60–104 days, which was less than the 65–137 days recorded by Risi and Galwey (1989). This was anticipated because the lines studied here were regarded as being more adapted to North European conditions than those used by Risi and Galwey. Their investigation revealed that the period from anthesis to seed maturity was shortest for the Chilean sea level genotypes, even though the vegetative period of these genotypes was just as long as the one of other genotypes. This was not entirely in accord with the Danish results, showing that the earliest lines developed fastest in all periods.

In a Peruvian experiment, reported by Flores (1977), differences in vegetative stage/bud formation between lines ranged from 61 to 117 days. This was mainly explained by a large difference in time of germination, probably due to inadequate seed bed preparations. In Denmark this period was only 42–78 days. The time between anthesis and floral dehiscence (11–31 days) was shorter than in Denmark (20–38 days), while the period for seed set in Peru (60–109 days) was longer than in Denmark (32–75 days). Total growth period in the Peruvian experiment was 131–200 days, while the normal growth period of quinoa in South America ranges from 110 to 190 days (Jacobsen and Stølen, 1993). In this experiment the total growth period was 109–182 days, comparable to that in South America.

Flowering of the lines examined lasted only 5–15 days. Gandarillas (1979) found that all flowers in the inflorescence opened within 12 to 15 days from the onset of flowering, while Rea (1948) found that every flower in the inflorescence stayed open from 5 to 13 days. These results indicate that flowering continues for approximately three weeks, which is longer than in Denmark. This could be related to differences in the genetic background or to climatic conditions.

Risi and Galwey (1989) suggested that the bud formation period was first to respond to differences in day length. The results obtained in the UK and Denmark indicate that if the lines examined constitute a wide variation in earliness, a wide variation in length of the vegetative phase will be found.

A growing period greater than 150 days would normally be regarded as too long and risky under North European conditions, but in the three years under investigation it was possible to harvest the crop even if the growing period was one month longer. Green types were much later than seed types, and there were larger differences in duration of growth periods between years. Even if there was a significant line × year interaction, it can be seen from Table 5 and Figure 1 that it was usually a non-crossover type.

Although seed harvest of green types can occur in Denmark, they should preferably be grown at a more southerly latitude. However, this might raise problems with genetic shift, if material is harvested under climatic conditions different from the intended growing site.

The important targets for further breeding and selection work in Denmark are varieties which have a consistently high seed yield, short, and uniformly early maturing. Size, shape and compactness of the inflorescence may be important for the rate of maturation (Jacobsen et al., 1996).

The conclusion from the Danish experiments is that seed types originating from Chile are adapted for growth under North European conditions. Ranking of lines for earliness was determined early in the growing season, probably by the beginning of July, and was consistent over years. The implications for plant breeders are that selection for earliness can take place at an early stage in plant development.

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