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Effect of different planting techniques and sowing density rates on the development of quinoa

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Quinoa (*Chenopodium quinoa* Willd.) is a crop of increasing interest due to its agro-ecological adaptability and high nutritional properties. Few information is available on the adaptability of quinoa in the Sahel region, and on genotype's phenological, morphological and agronomical responses to different planting methods and sowing density rates. To test the effect of planting and sowing methods, two separate experiments were carried out in Burkina Faso to examine the performance of different genotypes (Titicaca, Puno, Pasankalla and Negra Collana) to multiple planting methods (ridges, dibbling, broadcasting, transplanting, traditional-pits and flat sowing) and sowing density rates (from 80,000 to 200,000 plants ha^{-1}). The results showed significant differences among genotypes in terms of growth attributes, with higher yields when sown in ridges (10.7, 8.4 and 5.7 g plant^{-1} Puno, Pasankalla and Titicaca, respectively). In addition, higher yields were observed under low density rates, with plant spacing being compensated by changes in branch system. However, higher yields were reported per unit area (Titicaca with 98.8 g m^{-2}) under high density treatments (200,000 plants ha^{-1}). As a conclusion, the use of short cycle varieties (Titicaca and Puno) sown in ridges at high density rates was recommended.

Key words: Africa, agricultural management, genotypes, phenology, physiology.

INTRODUCTION

In places where water is the main limiting factor there are multiple agronomic practices available for reducing soil erosion, increase soil moisture and improve crop yields (Belachew and Abera, 2010). Some practices are related to different sowing methods and planting density rates (Ali et al., 2020). Other strategies enhance crop's transpiration by augmenting biomass production per unit water transpired. An increase in biomass production per unit area can hold-back weed expansion and positively affect the yield performance. The harvest index (HI) can also be higher when large amounts of water are accessible by plants and used after antithesis (Van Den Boogaard, 1996). Several researchers have examined the advantages of high crop density with an adverse effect on weeds and positive impacts on crop's biomass, including yields, e.g. wheat (Kristensen et al., 2008), maize (Sharifi et al., 2009) and rice (Baloch et al., 2002). For maize, much research has been conducted on

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Table 1. Different sowing methods applied in experiment 1.

Type of technique	Sowing depth (cm)	Row distance (cm)	Plant distance (cm)
Broadcasting	0	-	-
Dibbling	1-2	50	0
Transplanting[1]	-	50	10
Flat	3	50	10
Ridges[2]	3	50	10
Traditional-pits[3]	1-2	50	50

[1]Transplanting occurred 15 days after sowing (DAS). [2]Ridges height 15 cm and width 17 cm. [3]Pits diameter 10 cm.

Table 2. Different sowing density rates applied in experiment 2.

Indicator	Row distance (cm)	Plant distance (cm)	Total number of plants (ha^{-1})
D1	50	10	200,000
D2	50	15	133,333
D3	50	20	100,000
D4	50	25	80,000
D5	65	15	102,564
D6	75	10	133,333

different planting methods such as broadcasting, ridges, raise bed and line cropping. Some of these studies reveal that heavier grains and maximum yields are produced under ridge planting, with lowest yields under broadcasting (Bakht et al., 2011).

Quinoa (*Chenopodium quinoa* Willd.) traditionally grows in the absence of fertilizers, with a high plant density, without thinning, nor weeding or hilling (Gomez-Pando et al., 2015). Various management practices can result in different responses with respect to canopy development, time to physiological maturity and grain yield among cultivars of quinoa (González et al., 2012). Plant density models, expressing yield as a function of plant density, simulate higher yields with 327 ± 220 plants m^{-2} (equivalent to 327,000 plants ha^{-1}) (Jacobsen et al., 1994). However, high standard deviation observed in various experiments is an indication that similar yields can be obtained with different plant density rates, because quinoa can compensate the remaining spaces by modifying the architecture of its branches (Jacobsen, 2015). Studies on quinoa's agro-morphological responses have shown a diversification of the branching type when selecting different genotypes and sowing density rates (Rojas, 2015). Quinoa genotypes largely differ with respect to seed characters (size and color) and panicle type, with distinctive morphological attributes in each agro-ecological region (Planella et al., 2015; Andrews, 2017). Different quinoa growth habits are directly dependent on plant density, that is, simple, branched to bottom third, branched to second third and branched with a main panicle undefined (Rojas and Pinto, 2013). High plant densities can slow down and prevent, to some extent, the development of diseases on quinoa (e.g. mildew). This can happen in areas with a high relative humidity, where farmers are recommended to space furrows and plants by 50 cm and 15 cm, respectively (Gandarillas et al., 2015).

In this study, we therefore examine how different sowing methods and density rates affect the phenological, morphological and physiological development of multiple cultivars of quinoa in the Sahel. We then fill the gap in literature by providing insights of crop´s responses to different sowing methods and density rates in new agro-ecological zones.

MATERIALS AND METHODS

Area of study and experimental design

This study was conducted during the dry season (November-May) of 2017-2018 at Institut de l'Environnement et Recherches Agricoles (INERA) Farako-Bâ Research Station (11°05'N and 4°20´W; 405 masl), located within the Soudanian agro-climatic zone of Burkina Faso. Two parallel experimentations were conducted to evaluate the effect of different sowing methods (Table 1) and density rates (Table 2) on the development and performance of multiple genotypes of quinoa. The first study tested six different sowing methods (Table 1) with three genotypes of quinoa (Puno, Pasankalla and Titicaca). The second study examined six planting density rates (Table 2) with three genotypes of quinoa (Pasankalla, Titicaca and Negra Collana). The two experiments were set-up in a split-plot design, with experimental units sizing 4 m^2 and each unit having 3 replicates. The total amount of quinoa seeds used in both trials was equivalent to 10 kg of seeds ha^{-1}. Before sowing, the soil was amended with 5000 kg ha^{-1} of compost, 400 kg ha^{-1} of phosphate (PO_4^{3-}) and 100 kg ha^{-1} NPK (14-23-14 units). Urea

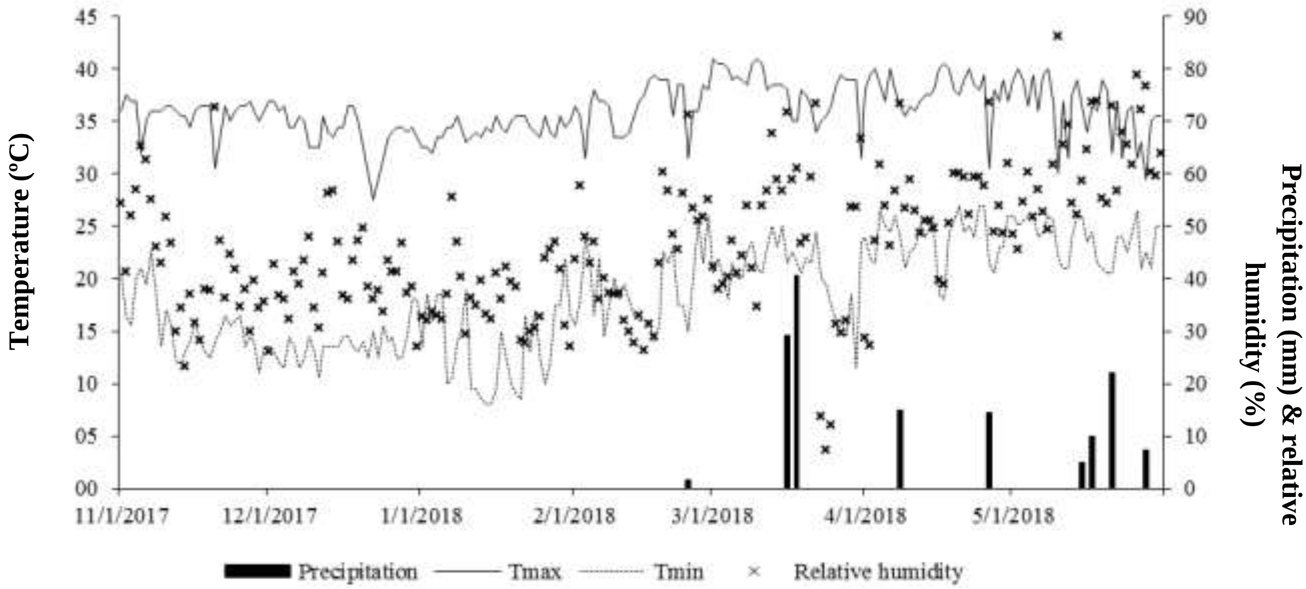

Figure 1. Meteorological conditions during the experiment.

(CH_4N_2O) was applied 30 days after sowing (DAS) at rate of 100 kg ha^{-1} (46% N).

Plant measurements and statistical analysis

For each crop parameter, plant samples were taken from the two middle lines in order to avoid side effects. Crop growth attributes such as plant height (PH in cm), branches per plant (BP in number), panicle diameter (PD in mm), stem diameter (SD in mm), and panicle length (PL in cm) were measured in 10 plants using a millimetric ruler and metric Vernier scale. Regarding plant phenology, the time to flowering was measured once 50% of the plants (Flo_{50} in days) had attained this phase. At harvest, the thousand-grain weight and volume (TGW in g, TGV in ml) was measured using an automatic seed counter machine and the grain yield per plant (GYP in g) was obtained from all the plants within the two middle lines.

The interaction between planting techniques and sowing density rates with three-genotypes of quinoa was analysed using the software Statistical Analysis System (SAS version 9.3). First, an ANOVA test was run to find out the statistical differences between treatments ($p < 0.05$); then, a Tukey HSD post-hoc test was used to compare the means and determine the differences between groups.

Agrometeorological conditions

The weather during the experimental period (November-May) was characterized by warm (Tmax average of 36°C) and dry conditions (Figure 1). Heat stress conditions were observed from March to April, with temperatures often exceeding 40°C. The extreme warm conditions during March and April were interrupted by showers, exceeding in some cases 30 mm day^{-1} in mid-March. The relative humidity was highest (62%) at the start of the rainy season (May) and lowest (38%) during the boreal winter (December-January). Extreme dry conditions, with very low relative humidity (below 20%) were observed during dust storms at the end of March. In addition, the soil in the experimental field was characterized by having a sandy-loam texture, with a low water holding capacity (72.4% sand) and slightly acidic properties (pH 4.91) (Table 3). The organic matter (OM) and nitrogen content in the soil was relatively low (less than 1%), with a C/N ratio of 10. The total amount of phosphorus and potassium in the soil remained constant at different depths (75-71 ppm total P and 1721-1770 ppm total K, respectively at 0-20 and 20-40 cm)

RESULTS

Experiment 1: Sowing methods

The findings showed significant differences ($p < 0.05$) between quinoa cultivars and different phenological (time to flowering-Flo_{50}), morphological (plant height-PH, branches per plant-BP, panicle diameter-PD, stem diameter-SD and panicle length-PL) parameters and seed yields (thousand grain volume-TGV, thousand grain weight-TGW and grain yield per plant-GYP) (Table 4). The time to flowering of Pasankalla (Flo_{50}: 45.3 days) was longer compared to that of Puno and Titicaca (Flo_{50}: 40.2 and 37.5 days, respectively). The architecture of quinoa plants was very variable at a varietal level. This was reflected in terms of BP, SD and PL. For these crop parameters (BP, SD and PL), there were significant differences between genotypes, having Pasankalla the highest values, while Titicaca the lowest. The highest seed yields were observed in Puno (GYP: 6.28 g $plant^{-1}$), while the lowest in Titicaca and Pasankalla (GYP: 4.90 and 4.07 g $plant^{-1}$, respectively). For grain quality (volume and weight), the highest values were observed in Titicaca (TGV: 4.06 ml and TGW: 2.45 g) and the lowest in Puno (TGV: 2.68 ml and TGW: 1.54 g). As foreseeable, due to the high genotype variability, the ANOVA (with the

Table 3. Physic-chemical characteristics of the soil.

Parameter	Units	Soil layer (cm) 0-20	Soil layer (cm) 20-40
Sand	%	72.4	66.5
Silt	%	16.4	12.5
Clay	%	11.2	21.0
Texture		**Sandy-loam**	**Sandy-clay-loam**
pH (H_2O)		4.91	4.77
C	%	0.24	0.29
Organic matter	%	0.41	0.50
N	%	0.024	0.026
C/N		10	11
P total	ppm	75	71
P available	ppm	1.65	1.65
K total	ppm	1721	1770
K available	ppm	70.2	57.3

Table 4. Effect of different sowing methods on multiple genotypes of quinoa in terms of time to flowering (Flo_{50}), plant height (PH), branches per plant (BP), stem diameter (SD), panicle diameter (PD), panicle length (PL), thousand grain volume (TGV), total grain weight (TGW) and grain yield per plant (GYP).

Factor		Flo_{50} (days)	PH (cm)	BP (nº)	SD (mm)	PD (mm)	PL (cm)	TGV (ml)	TGW (g)	GYP (g)
Genotype	Titicaca	37.5^{c}	52.7^{c}	9.2^{c}	5.69^{b}	28.2^{b}	17.0^{b}	4.06^{a}	2.45^{a}	4.90^{ab}
	Puno	40.2^{b}	61.8^{b}	15.8^{b}	6.27^{b}	33.2^{a}	17.1^{b}	2.68^{c}	1.54^{b}	6.28^{a}
	Pasankalla	45.3^{a}	77.9^{a}	18.4^{a}	7.55^{a}	31.6^{ab}	29.7^{a}	3.28^{b}	1.60^{b}	4.07^{b}
Sowing method	Ridges	40.1^{ab}	72.1	17.4	7.33	35.1^{a}	24.1	3.43	1.94	8.27^{a}
	Dibbling	40.3^{ab}	66.5	15.6	6.80	31.9^{ab}	24.1	3.43	1.89	4.53^{b}
	Broadcasting	40.1^{ab}	60.7	13.3	6.05	28.0^{b}	18.9	3.02	1.83	4.82^{b}
	Transplanting	44.7^{a}	62.3	14.6	6.85	31.3^{ab}	21.0	3.30	1.84	4.29^{b}
	Traditional	39.6^{b}	65.1	14.5	6.39	32.0^{ab}	20.8	3.40	1.75	5.11^{b}
	Flat	39.9^{ab}	63.4	13.3	5.81	27.6^{b}	20.1	3.38	1.91	3.54^{b}

Means that do not share a letter were significantly different, $p < 0.05$, according to Tukey HSD test.

ensemble of genotypes) did not show significant responses to planting techniques ($p > 0.05$) for PH, BP, PL, TGV and TGW. However, plants sown in ridges developed wider panicles (PD: 35.1 mm) and much higher yields (GYP: 8.3 g plant^{-1}) when compared with the rest of techniques (PD: 30.2 mm and GYP: 4.6 g plant^{-1}, average of all planting techniques except ridges). The interaction between factors (genotype and sowing method) was significant ($p < 0.05$) for all crop parameters, except for TGV and TGW (Table 5). The best sowing method varied according to the genotype. For example, ridges seemed to favor Pasankalla and Puno in terms of seed yield; but not Titicaca, without significant differences among sowing methods. However, the highest seed yields (5.75 g plant^{-1}) for Titicaca were observed under ridges, broadcasting and traditional sowing methods (Table 5). For Pasankalla, the highest values, in terms of PH, BP, PD, SD, PL and GYP, were observed under ridges, while the lowest under broadcasting and flat sowing. Significant differences ($p < 0.05$) between planting techniques were reported with respect to crop yield of Pasankalla, with four times higher values when cultivating in ridges when compared to broadcasting or flat sowing (GYP: 8.43, 2.38 and 1.61 g plant^{-1}, respectively). Similar pattern was observed in Puno, with a two-fold increase in yields when sown in ridges when compared to the rest of planting techniques. For Titicaca, most of the significant responses ($p < 0.05$) were reported in terms of PH, BP and SD, but without a clear pattern in respects to the sowing method. Overall, results showed that transplanting had a similar effect on all the three genotypes of quinoa by delaying the

Table 5. Interaction effect of different genotypes of quinoa and sowing techniques on time to flowering (Flo_{50}), plant height (PH), branches per plant (BP), stem diameter (SD), panicle diameter (PD), panicle length (PL), thousand grain volume (TGV), total grain weight (TGW) and grain yield per plant (GYP).

Genotype	Sowing method	Flo_{50} (days)	PH (cm)	BP (nº)	SD (mm)	PD (mm)	PL (cm)	TGV (ml)	TGW (g)	GYP (g)
Titicaca	Ridges	36.3^{b}	56.4^{a}	7.8^{b}	5.87^{ab}	27.6	18.4	4.07	2.41	5.73
	Dibbling	36.7^{b}	47.4^{b}	8.0^{b}	4.97^{b}	27.7	14.9	4.25	2.40	4.55
	Broadcasting	37.0^{b}	51.2^{ab}	9.6^{ab}	5.50^{ab}	27.9	16.2	3.45	2.42	5.72
	Transplanting	41.7^{a}	52.1^{ab}	12.5^{a}	6.65^{a}	26.2	17.8	3.80	2.34	4.29
	Traditional	37.0^{b}	53.8^{ab}	7.9^{b}	5.45^{b}	29.7	17.7	4.30	2.49	5.75
	Flat	36.3^{b}	52.8^{ab}	9.5^{ab}	5.42^{b}	29.4	17.3	4.35	2.76	3.87
Puno	Ridges	40.3^{ab}	69.5	20.1^{a}	7.03	36.3	20.7^{a}	2.40	1.40	10.66^{a}
	Dibbling	39.3^{b}	60.4	16.1^{ab}	6.02	31.3	18.2^{ab}	2.55	1.70	5.50^{b}
	Broadcasting	39.7^{b}	52.7	12.4^{b}	5.82	29.2	14.5^{b}	2.50	1.49	6.36^{b}
	Transplanting	43.3^{a}	55.9	15.2^{b}	6.05	36.3	14.1^{b}	3.10	1.63	4.18^{b}
	Traditional	38.0^{b}	63.8	16.3^{ab}	6.53	34.9	18.3^{ab}	2.50	1.43	6.06^{b}
	Flat	40.3^{ab}	68.5	12.1^{b}	6.55	30.8	15.7^{ab}	2.55	1.52	4.98^{b}
Pasankalla	Ridges	45.5^{ab}	98.3^{a}	22.9^{a}	9.85^{a}	39.3^{a}	34.8^{a}	3.50	1.83	8.43^{a}
	Dibbling	45.0^{ab}	85.4^{ab}	20.0^{ab}	8.80^{ab}	36.7^{a}	34.1^{a}	3.23	1.59	3.54^{bc}
	Broadcasting	43.7^{b}	72.5^{bc}	18.0^{bc}	6.67^{cd}	27.0^{c}	27.9^{bc}	3.10	1.48	2.38^{cd}
	Transplanting	49.0^{a}	73.3^{bc}	15.5^{c}	7.87^{abc}	31.4^{b}	29.6^{b}	3.16	1.54	4.40^{b}
	Traditional	43.7^{b}	77.8^{bc}	17.2^{bc}	7.20^{bcd}	30.6^{bc}	27.6^{bc}	3.40	1.58	4.06^{b}
	Flat	44.5^{ab}	67.0^{c}	18.4^{abc}	5.73^{d}	21.7^{d}	24.8^{c}	3.30	1.62	1.61^{d}

Means that do not share a letter are significantly different, $p < 0.05$, according to Tukey HSD test.

flowering time.

Experiment 2: Sowing density rates

This experiment showed that quinoa cultivars were the main factor effect, when compared to sowing density rates, in terms of crop's morphological and agronomical responses (Table 6). Large differences ($p < 0.05$) were observed between genotypes in terms of Flo_{50} and PH. Negra Collana took longer (Flo_{50}: 54.1 days) to reach the reproductive stage when compared to Pasankalla and Titicaca (Flo_{50}: 46.9 and 42.9 days, respectively); whereas Pasankalla had the highest plants (PH: 84.4 cm). Morphological parameters, such as SD, PD and PL, showed more significant responses ($p < 0.05$) in Negra Collana and Pasankalla than in Titicaca. However, not for BP, where Titicaca plants had 15.7 branches, while Negra Collana and Pasankalla 9.0 and 8.7 branches, respectively. Yield components (GYP, TGV, TGW) of different genotypes of quinoa were significantly higher in Titicaca (GYP: 7.58 g plant^{-1}) when compared to Negra Collana and Pasankalla (GYP: 0.60 and 0.15 g plant^{-1}, respectively). Due to the longer vegetative stage and late sowing date, Pasankalla and Negra Collana cultivars were affected by heat stress at flowering and during milky grain formation. As a result, extraordinary yield losses were reported in Negra Collana and Pasankalla when compared with Titicaca. For the ensemble of genotypes, significant different responses were reported with respect to PD, with wider panicles (PD: 49.8 and 48.7 mm) under low sowing density rates (D3 and D4, respectively), and vice-versa under high density rates, D1 (PD: 39.3 mm).

The interaction between factors (genotype and sowing density) provided information about the effect of sowing density rates on growth attributes for different types of cultivars (Table 7). For Titicaca, lower plant density rates (D4: 80,000 plants ha^{-1}; D3: 100,000 plants ha^{-1}; D5: 102,564 plants ha^{-1}) resulted in a wider development of the branching system (BP: 16-18) when compared with high density rates (BP: 13-16 branches plant^{-1}). As a result, higher yields were depicted under D4, D3 and D5 (GYP: 9.18, 8.95 and 8.66 g plant^{-1}, respectively). Even though higher GYP´s were observed under low density rates, the overall production per unit of area (m^{2}) was higher under high density rates (e.g. Titicaca 98.8 and 98.6 g m^{-2} under D1 and D7, respectively) when compared to low sowing density rates (73.4 g m^{-2} under D4). For Negra Collana and Pasankalla, the highest GYP (1.04 and 0.33 g plant^{-1}, respectively) was observed under D6 (133,000 plants ha^{-1}), whereas the lowest (GYP: 0.43 and 0.07 g plant^{-1}, respectively) under high

Table 6. Effect of different sowing density rates on multiple genotypes of quinoa in terms of time to flowering (Flo_{50}), plant height (PH), branches per plant (BP), stem diameter (SD), panicle diameter (PD), panicle length (PL), thousand grain volume (TGV), total grain weight (TGW) and grain yield per plant (GYP).

Factor		Flo_{50} (days)	PH (cm)	BP (nº)	SD (mm)	PD (mm)	PL (cm)	TGV (ml)	TGW (g)	GYP (g)
Genotype	Titicaca	42.9^{c}	58.7^{c}	15.7^{a}	7.5^{b}	43.2^{b}	24.1^{b}	3.54^{a}	2.23^{a}	7.58^{a}
	Negra Collana	54.1^{a}	71.0^{b}	9.0^{b}	9.6^{a}	49.8^{a}	46.2^{a}	1.69^{b}	0.92^{b}	0.60^{b}
	Pasankalla	46.9^{b}	84.4^{a}	8.7^{b}	10.3^{a}	46.1^{ab}	43.6^{a}	1.87^{b}	0.84^{b}	0.15^{b}
Density	D1 (50×10)	47.6	71.5	11.4	8.8	39.3^{b}	39.5	2.30	1.50	1.81
	D2 (50×15)	48.4	66.7	9.9	9.2	48.1^{ab}	41.0	2.17	1.34	2.47
	D3 (50×20)	46.1	75.0	12.2	8.9	49.8^{a}	36.5	2.39	1.34	3.24
	D4 (50×25)	48.8	71.0	11.1	9.3	48.7^{a}	36.2	2.36	1.20	2.78
	D5 (65×15)	49.1	68.7	12.2	8.9	44.7^{ab}	37.1	2.21	1.30	2.35
	D6 (75×10)	48.9	70.5	10.7	9.6	47.0^{ab}	36.8	2.59	1.48	2.92

Plant density rates corresponding to D1 (200,000 plants ha^{-1}), D2 (133,333 plants ha^{-1}), D3 (100,000 plants ha^{-1}), D4 (80,000 plants ha^{-1}), D5 (102,564 plants ha^{-1}) and D6 (133,333 plants ha^{-1}). Means that do not share a letter were significantly different, $p < 0.05$, according to Tukey HSD test.

Table 7. Interaction effect of different genotypes of quinoa and sowing density rates on time to flowering (Flo_{50}), plant height (PH), branches per plant (BP), stem diameter (SD), panicle diameter (PD), panicle length (PL), volume of thousand grains (VTG), total grain weight (TGW) and grain yield per plant (GYP).

Genotype	Density	Flo_{50} (days)	PH (cm)	BP (nº)	SD (mm)	PD (mm)	PL (cm)	TGV (ml)	TGW (g)	GYP (g)
Titicaca	D1 (50×10)	43.3	58.4^{ab}	15.9^{abc}	7.3^{ab}	38.9	22.8	3.45^{ab}	2.25	4.94
	D2 (50×15)	45.0	53.0^{b}	13.1^{c}	6.7^{b}	41.0	22.6	3.07^{b}	2.03	6.37
	D3 (50×20)	40.0	64.2^{a}	16.8^{ab}	8.5^{a}	49.5	25.8	3.23^{ab}	2.07	8.95
	D4 (50×25)	43.7	63.1^{ab}	17.6^{a}	7.7^{ab}	44.2	24.7	3.37^{ab}	1.90	9.18
	D5 (65×15)	45.5	59.3^{ab}	16.1^{abc}	7.6^{ab}	38.7	24.9	4.55^{a}	2.53	8.66
	D6 (75×10)	40.0	54.0^{ab}	14.3^{bc}	7.3^{ab}	43.6	23.1	4.05^{ab}	2.59	7.40
Negra Collana	D1 (50×10)	54.5	73.3^{a}	8.6	9.2	44.8	51.7^{a}	1.60^{ab}	0.95^{ab}	0.43^{ab}
	D2 (50×15)	53.7	70.0^{ab}	9.4	10.1	48.2	49.8^{ab}	1.70^{ab}	0.92^{ab}	0.83^{ab}
	D3 (50×20)	53.7	75.4^{a}	9.4	9.1	55.7	44.6^{ab}	2.05^{a}	1.03^{ab}	0.69^{ab}
	D4 (50×25)	54.7	65.3^{b}	8.9	9.6	56.9	39.8^{b}	1.43^{b}	0.77^{b}	0.38^{ab}
	D5 (65×15)	55.0	66.5^{b}	9.0	9.9	44.8	44.1^{ab}	1.57^{ab}	0.81^{b}	0.36^{b}
	D6 (75×10)	53.3	72.8^{a}	9.0	9.5	45.0	45.4^{ab}	1.90^{ab}	1.04^{a}	1.04^{a}
Pasankalla	D1 (50×10)	47.3^{ab}	74.9	9.7	9.4^{b}	36.0**d**	38.5^{b}	2.00^{ab}	1.05^{a}	0.07^{c}
	D2 (50×15)	45.5^{ab}	84.0	8.1	11.9^{a}	52.7^{a}	50.5^{a}	1.73^{ab}	0.92^{a}	0.21^{b}
	D3 (50×20)	44.0^{b}	85.3	9.3	9.3^{b}	44.6^{bc}	44.2^{ab}	1.45^{ab}	0.58^{b}	0.09^{c}
	D4 (50×25)	48.0^{ab}	84.7	6.9	10.7^{ab}	43.4^{c}	41.6^{ab}	2.27^{a}	1.02^{a}	0.10^{c}
	D5 (65×15)	44.0^{b}	85.1	9.5	9.3^{b}	50.7^{abc}	42.5^{ab}	1.30^{b}	0.55^{b}	0.13^{bc}
	D6 (75×10)	50.3^{a}	83.7	8.8	11.9^{a}	52.5^{ab}	48.6^{a}	2.30^{a}	1.01^{a}	0.33^{a}

Plant density rates corresponding to D1 (200,000 plants ha^{-1}), D2 (133,333 plants ha^{-1}), D3 (100,000 plants ha^{-1}), D4 (80,000 plants ha^{-1}), D5 (102,564 plants ha^{-1}) and D6 (133,333 plants ha^{-1}). Means that do not share a letter were significantly different, $p < 0.05$, according to Tukey HSD test.

density treatments-D1 (200,000 plants ha^{-1}). The TGV showed significant differences between D5 and D2 for Titicaca, between D3 and D4 for Negra Collana, as well as between D4 and D6 with D5 for Pasankalla. In addition, no significant differences ($p > 0.05$) were depicted in terms of crop responses when genotypes were grouped, and sowing density levels separated (Table 8).

Table 8. Main factor effect of different density levels (plant and row distance) with the ensemble of genotypes.

Density	(cm)	Flo_{50} (days)	PH (cm)	BP (nº)	SD (mm)	PD (mm)	PL (cm)	TGV (ml)	TGW (g)	GYP (g)
Plant distance	10	48.3	71.0	9.2	11.0	42.9	38.2	2.45	1.45	2.37
	15	48.7	67.7	9.0	11.0	46.5	38.7	2.19	1.31	2.40
	20	46.1	75.0	8.9	12.2	49.8	36.5	2.39	1.34	3.24
	25	48.8	71.0	9.3	11.1	48.7	36.2	2.36	1.20	2.78
Row distance	50	47.8	71.3	9.1	11.2	46.6	38.3	2.30	1.34	2.58
	65	49.1	68.7	8.9	12.2	44.7	37.1	2.21	1.30	2.35
	75	48.9	70.5	9.6	10.7	47.0	36.8	2.59	1.48	2.92

Means that do not share a letter were significantly different, $p < 0.05$, according to the Tukey HSD test.

DISCUSSION

Quinoa exhibits a different growing pattern in response to various genotypes, planting techniques and, to a lesser extent, sowing density rates. The range of variation in the morphological, phenological and agronomical characteristics of different genotypes of quinoa is the result of a high varietal variability. In the present experiment, all three genotypes display higher yields when planting in ridges (Puno: 10.7 g plant^{-1}; Pasankalla: 8.4 g plant^{-1}; Titicaca: 5.7 g plant^{-1}). The large volume of the panicle (PD × PL) when planting in ridges (≈ 422.1 cm^3) explains the high performance in terms of yield, and vice-versa under broadcasting (≈ 159.7 cm^3) and flat sowing (≈ 91.7 cm^3). In addition, increase in-depth tillage and soil aeration when preparing the ridges has supported the development of the root system. Alvar-Beltrán et al. (2019a) also report a low root development of Titicaca in sandy-loam soils, characterized by a high bulk density during the dry season. Bakht et al. (2011) report maximum yields when planting in ridges, whereas minimum yields under broadcasting. Soil aeration benefits the plant by enhancing the nutrient and water uptake from the soil to the aboveground parts of the plant (Bakht et al., 2011). For this reason, plants sown under different planting techniques perform differently. The transplanting technique shows to be prejudicial for the plant (e.g. Puno and Titicaca). For these two varieties, the transplanting shock increases the time to flowering and decreases the yield performance. There are multiple adverse effects of transplantation in tropical environments. This is because of the high evapotranspiration rates found at low-latitudes (Alvar-Beltrán et al., 2019b), besides of the mechanical injuries occurring to the root system resulting in a slow regeneration and adaptation to new soil conditions. Similar results are reported with pearl millet in Zimbabwe, with a delay in time to flowering and maturity when transplanting (Murungu et al., 2006).

In the second experiment, large distance between plants (20 and 25 cm) resulted in a differentiated architecture of the branching system, with a typically branch to second third panicle as described by Rojas and Pinto (2013). Plants develop a wider but less compacted panicles among largely spaced plants. In this case, plants are displaying an intermediate shape between glomerulate (compacted) and amarantiform (loose) panicles (Rojas, 2015). In general, a common response of plants is to grow new branches in existing gaps. This is because canopy gaps and changes in red/far-red ratios of light are reflected by neighboring plants (Marshal and Roberts, 2000). Therefore, it increases stem elongation properties besides affecting branch orientation. These results are in harmony with those reported by Risi and Galwey (1991), showing an increase in the number of branches under low density rates for Amarilla de Marangani, Blanca de Junin and Baer (Risi and Galwey, 1991). In fact, Jacobsen (2015) highlights the ability of quinoa to compensate the remaining spaces between plants by changing the agro-morphological structure of its branches. Other studies in tropical environments, show a decrease in plant height with an increase in plant density (from 100,000 to 600,000 plants ha^{-1}), and an increase of the branching system under low sowing density rates (Spehar and da Silva Roca, 2009). Similar pattern is realized in the present study, with Titicaca and Negra Collana having the highest plants under low sowing density rates (D3)

This research findings show more productive plants per unit area (e.g. Titicaca with 98.8 g m^{-2}) at high density rates (D1: 200,000 plants ha^{-1}); but not in terms of GYP, with highest GYP under low density rates. This relationship (between production per unit area and density rate) is evident for Titicaca, but not as strong for Negra Collana nor Pasankalla. However, as highlighted by Jacobsen (2015), relatively high-density rates are preferred in order to secure uniform plants and similar time to maturity. High plant density rates can also slow down and prevent the development of diseases (Gandarillas et al., 2015). Other studies confirm that the optimum sowing density rates for obtaining the highest yields is 70-140 plants m^{-2}, with 12.5 cm row spacing, and the equivalent of 8-10 kg seeds ha^{-1} (Piva et al., 2015). However, draw-backs of high-density rates emerge in those locations where sowing, harvesting, thinning and weeding is done mechanically, as the distance required for preparing the furrows is approximately 80 cm (Peralta et al., 2012). In regard to TGV, observed differences were due to due to environmental conditions (heat-stress and water availability) during the grain formation and filling grain phase, and not because of different sowing density rates. Therefore, genotypes Pasankalla and Negra Collana, with much longer cycles, were affected by extreme heat-stress conditions occurring in March and April, both in terms of GYP and TGV, with similar findings reported by Alvar-Beltrán (2019b). A positive relationship between PH and GYP is also in line with Alvar-Beltrán (2019a) who reported a strong correlation (r: 0.88) between PH and GYP for genotype Titicaca. Benlhabib et al. (2015) show a positive correlation between GYP and plant height and fresh and dry weight. While Oyoo et al. (2015) and Rojas et al. (2015) observe a positive trend between the GYP and genotype, as well as for the following agronomical parameters: time to flower, milky grain, pasty grain and physiological maturity, just like panicle length and biomass production. In addition, Pasankalla plants have a longer vegetative stage and therefore more time to build up biomass and further develop higher plants (PH: 33 and 21% higher than Titicaca and Puno).

The agronomic, environmental and genetic implications of using short cycle varieties are multiple. First, water requirements of short cycle varieties (Titicaca and Puno) are likely to be much lower to that of long cycle varieties (Negra Collana and Pasankalla). This is a key aspect giving the water constraints within the Sahel region during the dry season. In addition, increased heat-stress conditions have adverse impacts on crop yields, and these are minimized when using short cycle varieties (Lesjak and Calderini, 2017; Alvar-Beltrán et al., 2019b). However, the branching system and, in particular, the wider stem diameter of Negra Collana and Pasankalla, highlights the ability of these genotypes to withstand harmattan winds. As acknowledged by Gandarillas et al. (2015), the direction of the furrows with regards to wind and field slope is fundamental. Therefore, genetic efforts need to move towards more wind resilient but high yielding varieties (Titicaca and Puno).

Conclusion

The present study demonstrates that genotypes and sowing methods, rather than sowing density rates, are the most determining factors affecting plant growth, development and yield performance of quinoa. The overall conclusion of both experiments is that genotype Puno, planting technique ridges (sowing depth: 3 cm; ridge height and width: 15 cm and 17 cm) under high density rates (D1: row and plant distance: 50 cm × 10 cm, equivalent to 200,000 plants ha^{-1}) is the most optimal agronomic technique in terms of yield. Further research is needed to better understand the phenological, morphological and agronomical response of short cycle varieties (Puno and Titicaca) to density rates higher than 200,000 plants ha^{-1}. Other planting techniques and/or practices that favour soil aeration need to be increasingly explored. For example, by incorporating different amounts of organic matter into the soil (increasing soil porosity), diversifying the types of tillage (zero, minimum and/or reduced, and deep tillage) and reducing the soil sodicity (impeding soil infiltration).

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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