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Effect of drought and nitrogen fertilisation on quinoa (*Chenopodium quinoa* Willd.) under field conditions in Burkina Faso

Effetto della siccità e della fertilizzazione azotata su quinoa (*Chenopodium quinoa* Willd.) in Burkina Faso

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Abstract. *Chenopodium quinoa* (Willd.) is an herbaceous C3 crop originating in the Andean Altiplano. Quinoa possesses a great deal of genetic variability, can adapt to diverse climatic conditions, besides of having seeds with high nutritional properties. An experiment conducted in Burkina Faso has determined the response of two quinoa varieties (Titicaca and Negra Collana) to different planting dates (November vs December), irrigation levels (Potential evapotranspiration-PET, 100, 80 and 60% PET), and N fertilization rates (100, 50 and 25 kg N ha^{-1}). Main research findings have shown that quinoa can be highly performant under drought stress conditions and low nitrogen inputs, besides of coping with high temperatures typically of the Sahel. The highest yields (1.9 t ha^{-1}) were achieved when sown in November at 60 % PET and 25 kg N ha^{-1}. For this location, short cycle varieties, such as Titicaca, were recommended in order to avoid thermic stress conditions occurring prior to the onset of the rainy season (May-October).

Keywords. Sahel, agro-meteorology, extreme climatic conditions, abiotic stress, water management.

Abstract. *Chenopodium quinoa* (Willd.) è una coltura erbacea C3 originaria dell'Altiplano andino. La quinoa, la cui granella è dotata di ottime proprietà nutrizionali, è caratterizzata da un'elevata variabilità genetica e ben si adatta a diverse condizioni climatiche. Lo scopo della ricerca, condotta in un sito sperimentale in Burkina Faso, è stato di valutare la risposta di due varietà di quinoa (Titicaca e Negra Collana) a diverse date di semina (novembre vs dicembre), diversi livelli di irrigazione (evapotraspirazione potenziale - PET, 100, 80 e 60% PET) e diverse dosi di concimazione azotata (100, 50 e 25 kg N ha^{-1}). I risultati hanno dimostrato che la quinoa può essere altamente performante anche in condizioni di stress idrico e bassi input di azoto, oltre a riuscire ad adattarsi alle alte temperature tipiche dell'area del Sahel. Le rese più elevate

(1,9 t ha^{-1}) sono state ottenute per la quinoa seminata a novembre, irrigata al 60% di PET e fertilizzata con 25 kg di N ha^{-1}. In base ai risultati ottenuti, per l'area considerata si raccomanda l'utilizzo di varietà a ciclo breve, come il Titicaca, per evitare condizioni di stress termico che si verificano prima dell'inizio della stagione delle piogge (maggio-ottobre).

Parole chiave. Sahel, agrometeorologia, condizioni climatiche estreme, stress abiotico, gestione irrigua.

1. INTRODUCTION

Climate change affects agricultural productivity that needs to adapt to satisfy food demand. Agricultural adaptation becomes crucial in hot-spot regions of climate change, especially affected by drought and water scarcity (Morsy *et al.*, 2018). These areas often match with those having highest undernourishment rates and greatest population growth, low use of external inputs such as improved seeds and fertilizers; absence of mechanization; and poor linkage to markets. This makes agriculture highly vulnerable to climate change (Eroula *et al.*, 2013). Among scientists, quinoa (*Chenopodium quinoa* Willd.) is considered a climate resilient and superfood crop, while being promoted in regions vulnerable to climate change. It is a highly nutritional and gluten free crop, having a balanced composition of essential amino-acids sometimes scarce in legumes and cereals (Repo-Carrasco *et al.*, 2003); as well as for been rich in Ca, Fe, and Mg, with high content of vitamins A, B2 and E (Adolf *et al.*, 2013).

Moreover, quinoa is well-known for its resilience to abiotic stresses being drought-tolerant, halophyte, pH versatile, and resistant to thermic variability. Most of the scientific research is focused on its adaptability to saline levels, being as high as those found in sea water (Jacobsen *et al.*, 2003; Razzaghi *et al.*, 2011; Hirich *et al.*, 2014a; Riccardi *et al.*, 2014; Fghire *et al.*, 2015). In fact, its salt tolerance is the result of osmotic adjustment, osmo-protection, sodium exclusion and xylem loading, potassium retention, gas exchange, stomatal control and water use efficiency (Adolf *et al.*, 2013). As a C3 crop, quinoa's crop water productivity (CWP), expressed in kg of biomass produced per m^3 of water applied, is generally low, lying between 0.3-0.6 kg m^{-3} in the Bolivian Altiplano while exceeding 1 kg m^{-3} in Morocco and Italy (Geerts *et al.,* 2009; Hirich *et al.*, 2014a; Riccardi *et al.*, 2014). Indeed, quinoa's transpiration rate is similar to that of reference evapotranspiration, hence having low water requirements, around 400 mm (Steduto *et al.*, 2012). Moreover, rapid stomata closure, restricting shoot growth and accelerated leaf senescence makes quinoa highly adaptable to drought stress conditions (Azurita-Silva *et al.,* 2015). In addition, it's capable of maintaining its turgidity with very low water potentials, while optimizing water use through minimum leaf gas exchange (Jensen *et al.*, 2000; Jacobsen *et al.*, 2003). It can also increase its assimilation efficiency by improving the ratio of photosynthetic rate over transpiration up to 2 (Vacher, 1998; Geerts *et al.*, 2008). Other morphological and anatomical responses are the presence of calcium oxalate crystals in leaf vesicles, reducing leaf-transpiration, besides of having a thick plant cuticle and sunken stomata (Azurita-Silva *et al.,* 2015).

Furthermore, the wide geographical distribution of quinoa has given the plant a great genetic variability, besides of increasing its coping-capacity under extreme climatic conditions (Ceccato *et al.*, 2015). Indeed, temperature is the environmental factor affecting the most crop′s cycle duration, germination, development and seed formation (Hirich *et al.*, 2014b; Bertero, 2015; Hassan, 2015). Further research on nitrogen (N) suggests that greater N fertilisation can result in a significant yield increase, but having no effect on seed size or weight (Shams, 2012; Benlhabib *et al.*, 2013; Piva *et al.*, 2015). Soils with higher clay content are the most suitable for growing quinoa, as N-uptake, organic matter, soil′s water holding capacity is highest (Razzaghi *et al.,* 2012).

To promote quinoa′s consumption in West Africa, the Food and Agriculture Organization of the United Nations (FAO) has developed Technical Cooperation Programs (TCP/SFW/3404 and TCP/RAF/3602) together with the Ministries of Agriculture.

The aim of this research was to investigate the adaptability and performance of two quinoa varieties when sown at different dates, under decreasing levels of irrigation and different N fertilisation rates.

2. MATERIALS AND METHODS

The experiment was carried out during the dry season, from November 2017 to May 2018, at Institut de l'Environnement et Recherches Agricoles (INERA), Farako-Bâ′s research station (11°05′N; 4°20′W). The area of study is within Burkina′s Soudanian agro-climatic belt, with a tropical savanna-wet and hot climate. The onset of the wet season is in May and offset in October, with a total amount of rainfall exceeding 900 mm year^{-1}; where mean annual temperatures can attain 28 °C.

The experimental field was organized in a randomized split-split block design with a multiple factor analysis of variance (ANOVA): 3 levels of irrigation according to the potential evapotranspiration (PET) (Full irrigation-FI: 100 % PET; Progressive Drought-PD: 80 % PET; Deficit Irrigation-DI: 60 % PET), 3 levels of N fertilisation (100, 50 and 25 kg N ha^{-1}), two quinoa varieties (Titicaca-short cycle-85 days, and Negra Collana-long cycle-150 days), and 3 repetitions. Quinoa seeds were sown in 54 plots, each of 7.5 m^2, in 50 cm row distance and 10 cm space between plants (200000 plants ha^{-1}), at a rate of 10 kg seeds ha^{-1}. The ANOVA was done using IBM SPSS software and Tukey´s HSD test with Minitab 2018.

Sowing was carried out in two dates: 4/11/2017 (hereinafter November) and 8/12/2017 (hereinafter December). The harvesting of November´s sowing was done at the beginning of February for Titicaca (89 days after sowing-DAS) and end of March for Negra Collana (139 DAS). Whereas the harvesting for December´s sowing, it was carried out beginning March for Titicaca (82 DAS) and end of May for Negra Collana (159 DAS).

Prior to sowing the soil was amended with compost (50.2 % organic matter) at a rate of 5 t ha^{-1}, as well as with phosphate (26.7 % P_2O_5) at a rate of 400 kg P ha^{-1}. Nitrogen fertilisation, in the form of urea (46.2 % N), was split into two doses and was applied 25 and 40 DAS. Weed removal was carried out manually every 3/4 weeks to avoid weed interference with actual crop water requirements. Seeds were treated with fungicides/insecticides (Permethrin 25 g kg^{-1} + Thirame 250 g kg^{-1}) at a rate of 25 g per 10 kg of seeds, and through foliar application (Cypermethrin) at a rate of 1 litre ha^{-1}.

Prior to sowing and post-harvesting, soil samples were extracted at 0-20, 20-40 and 40-60 cm for the determination of its main physic-chemical characteristics. Leaf chlorophyll was recorded at 30 and 68 DAS using a Leaf Chlorophyll Meter SPAD 502 Plus with a total of 25 observations per plot. The canopy cover was measured at 40 DAS (sowing November) and 56 DAS (sowing December) using the Canopeo app. developed by the University of Oklahoma. The rest of the parameters, including plants height (10 per plot); biomass and seed yield (12 per plot); 1000 seeds weight (3 per plot); branching, panicle size, panicle width, stem diameter (5 per plot); root depth and root length (1 per plot), were done at physiological maturity.

Daily evapotranspiration was calculated using the following formula (Hargreaves and Samani, 1985):

$$ET_o = 0.023\ (T\ mean + 17.78)\ R_o\ (T\ max - T\ min)^{0.5}$$

Where: R_o = solar radiation at a given month and latitude (Allen *et al.*, 1998); T mean = mean daily temperature; T max = daily maximum temperature; T min = daily minimum temperature.

Moreover, crop evapotranspiration ($ETc = Kc{*}ET_0$) was calculated using the crop´s coefficient (*Kc*) for quinoa´s different phenological phases (Garcia *et al.*, 2003): 0.52 at emergence, 1.0 at maximum canopy cover and 0.70 at physiological maturity. Net irrigation requirements were estimated using ET_c daily data and adjusted according to the level of irrigation: ETc*1.0 (FI); ETc*0.80 (PD) and ETc*0.60 (DI). In fact, ETc was adapted according to the growing cycle of both quinoa varieties. A water-counter was placed at the entrance of each irrigation block to estimate the amount of water applied. The drip irrigation flow rate was of 1.05 l hour^{-1}, varying according to the water pressure, maximum 1 bar, and the frequency of water application, between 2 to 4 times a week depending on the growing stage of the plant.

3. RESULTS

The experimental field was characterised for having a sandy-loam texture in the first soil layer (0-20 cm) with high infiltration rate, low water holding capacity and very poor organic matter content, below 0.5 % (Table 1 and 2). Mineral nitrogen (ammonium and nitrate) was negligible (0.03 %), while soil pH was slightly acidic (pH 6.5). As a result of low soil carbon content and mineral nitrogen, the C/N ratio remained low (8.8

Tab. 1. Main soil physic-chemical characteristics before sowing (average of 5 samples).
Tab. 1. Principali caratteristiche fisico-chimiche del suolo prima della semina (media di 5 campioni).

Parameter	Units	Soil layer (cm)		
		0-20	20-40	40-60
Sand	%	67.2	54.6	41.3
Silt	%	17.6	16.5	15.7
Clay	%	15.2	28.9	43.0
Texture		Sandy-Loam	Sandy-Clay-Loam	Clay
pH (H_2O)		6.51	5.95	6.05
C	%	0.28	0.23	0.23
Organic matter	%	0.48	0.39	0.39
N	%	0.032	0.026	0.027
C/N		8.8	8.7	8.4
P available	mg/kg	4.0	1.70	1.02
K available	mg/kg	79.73	74.97	58.70

Tab. 2. Main soil physic-chemical characteristics post-harvesting (average of 3 samples).
Tab. 2. Principali caratteristiche fisico-chimiche del suolo dopo la raccolta (media di 3 campioni).

Parameter	Units	Soil horizon (cm) and Nitrogen fertilisation (kg N ha^{-1})								
		0-20cm			20-40cm			40-60cm		
		100kgN	50kgN	25kgN	100kgN	50kgN	25kgN	100kgN	50kgN	25kgN
Bulk density	g/cm^3	1.55	1.66	1.63	-	-	-	-	-	-
C	%	0.43	0.41	0.51	0.40	0.38	0.46	0.38	0.39	0.40
Org. Matter	%	0.75	0.71	0.89	0.68	0.66	0.79	0.66	0.66	0.69
N	%	0.035	0.038	0.051	0.032	0.034	0.044	0.029	0.033	0.037
C/N		12.5	10.8	10.0	12.4	11.2	10.5	13.4	11.7	10.9
P total	mg/kg	95.8	97.6	85.0	83.8	91.6	90.0	93.5	106.6	103.5
K total	mg/kg	711.9	879.6	993.4	1101.7	1123.5	1405.3	1535.5	1741.3	1881.7

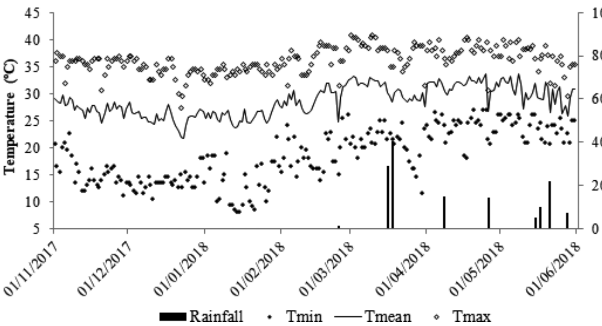

Fig. 1. Meteorological observations at INERA Farako-Bâ research station during the growing period.
Fig. 1. Dati meteorologici misurati nel sito sperimentale (INERA Farako-Bâ) durante il periodo di crescita.

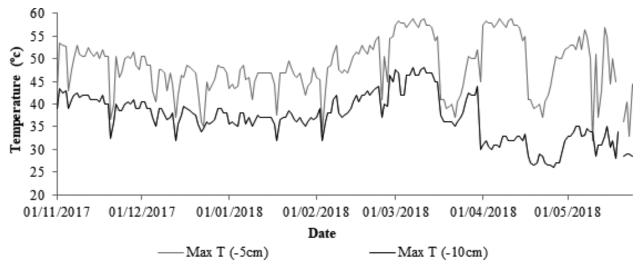

Fig. 2. Soil temperatures at 5 and 10cm depth during the growing period.
Fig. 2. Temperatura del suolo a 5 e 10 cm misurata durante il periodo di crescita.

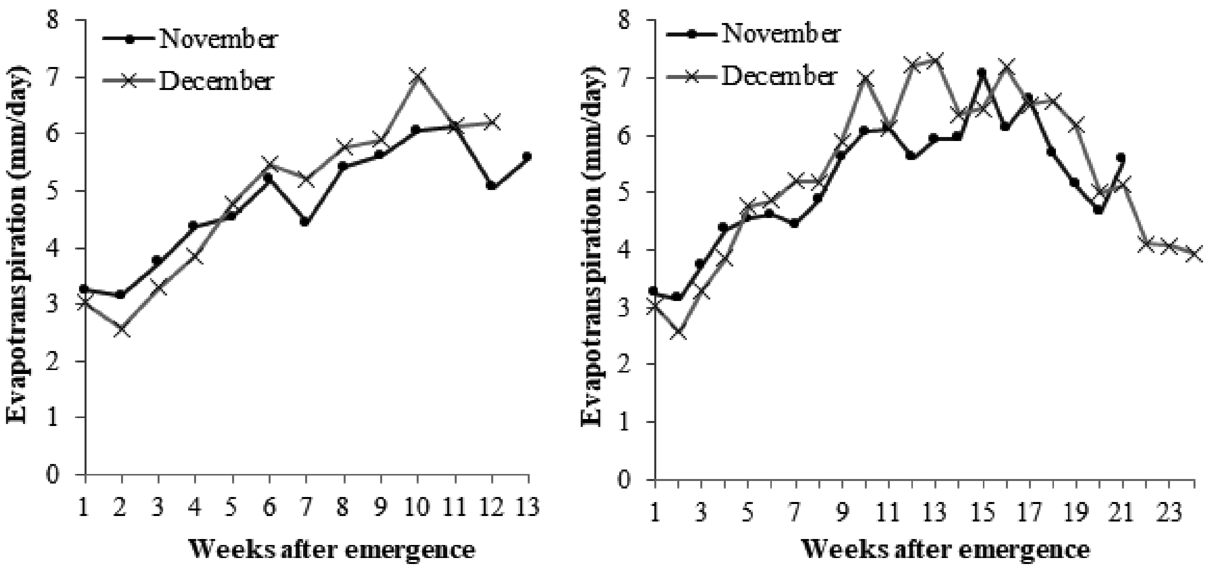

Fig. 3. Daily evapotranspiration for Titicaca (left) and Negra Collana (right).
Fig. 3. Evapotraspirazione giornaliera della vareità Titicaca (sinistra) e Negra Collana (destra).

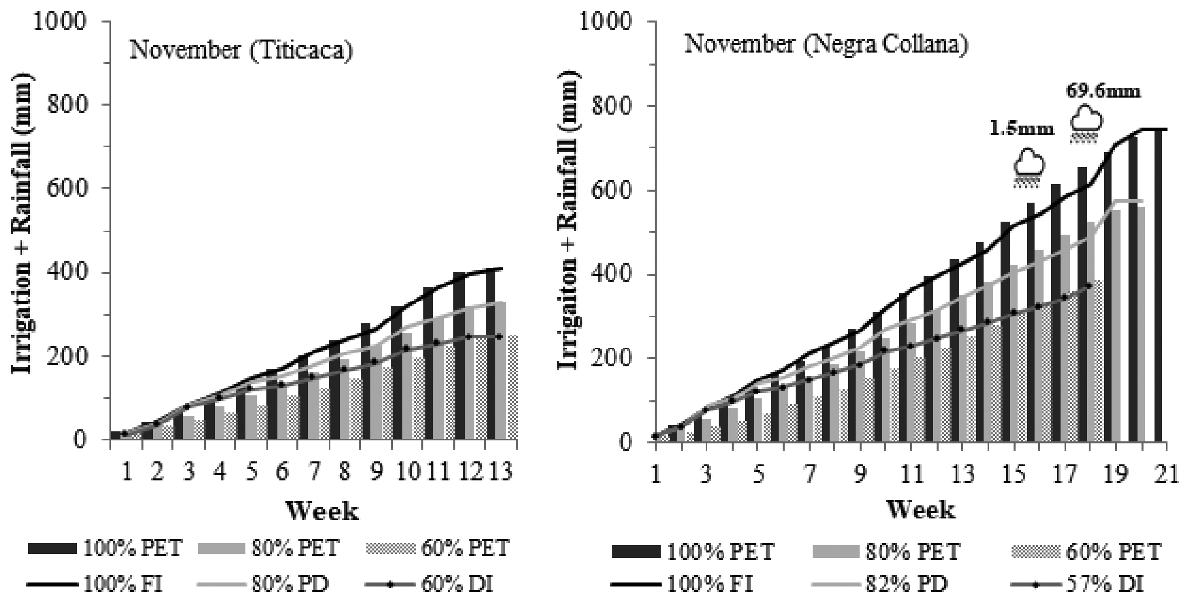

Fig. 4. Full Irrigation (FI-100% PET), Progressive Drought (PD-80% PET), and Deficit irrigation (DI-60% PET) for Titicaca (left) and Negra Collana (right) for first sowing date (November).

Fig. 4. Full Irrigation (FI-100% PET), Progressive Drought (PD-80% PET), Deficit irrigation (DI-60% PET) per le varietà Titicaca (sinistra) e Negra Collana (destra) alla la prima data di semina (novembre).

Note: bars showing Potential Evapotranspiration (PET); lines irrigation applied, and clouds week rainfall; total PET (columns) and irrigation applied (lines) do not always match at the end of the growing period.

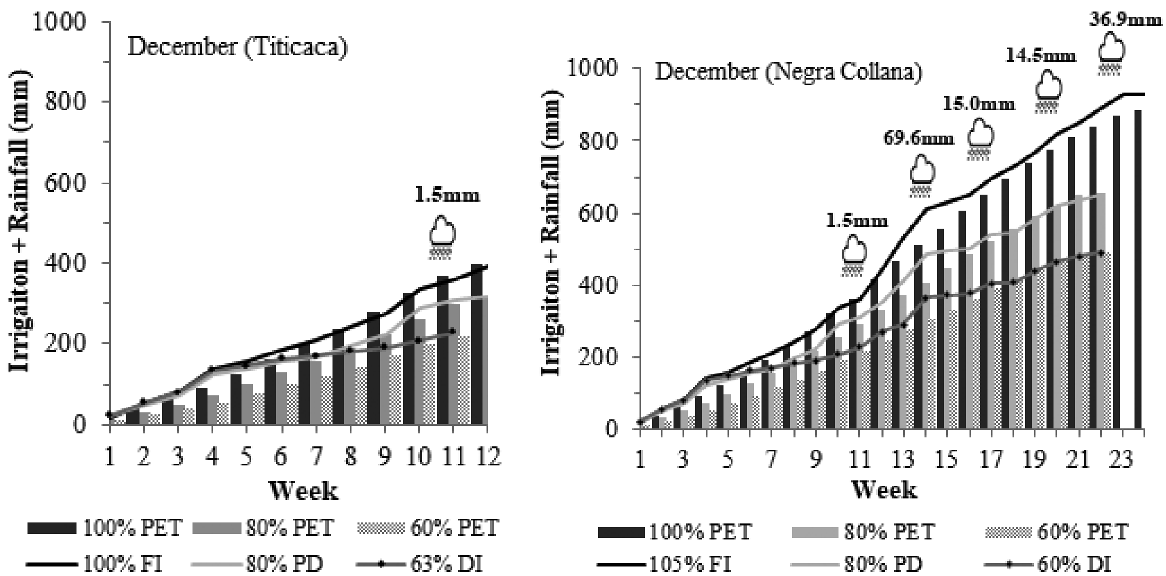

Fig. 5. Full Irrigation (FI-100% PET), Progressive Drought (PD-80% PET), and Deficit irrigation (DI-60% PET) for Titicaca (left) and Negra Collana (right) in the second sowing date (December).

Fig. 5. Full Irrigation (FI-100% PET), Progressive Drought (PD-80% PET), e Deficit irrigation (DI-60% PET) per le varietà Titicaca (sinistra) e Negra Collana (destra) alla la seconda data di semina (dicembre).

Note: bars showing Potential Evapotranspiration (PET); lines irrigation applied, and clouds week rainfall; total PET (columns) and irrigation applied (lines) do not always match at the end of the growing period.

Tab. 3. WUE (Water Use Efficiency in kg m^{-3}); GYP (Grain yield per plant in grams); HI (Harvest Index in yield/biomass); TGW (Thousand grain weight in grams); CL1-2 (Chlorophyll content); CC (Canopy Cover in %); PH (Plant Height in cm) of quinoa under the different treatments. Factors: a Variety (V) of Chenopodium quinoa Willd.; b Irrigation level (I) (100% PET; 80% PET; 60% PET); c Fertilisation (F) (100 kg N ha^{-1}; 50 kg N ha^{-1}; 25 kg N ha^{-1}). μ, σ, CV represents mean value, standard deviation and coefficient of variation of three repetitions, respectively.

Tab. 3. WUE (Efficienza d'uso dell'acqua in kg m^{-3}); GYP (resa per pianta in g); HI (Harvest Index in resa/biomassa); TGW (peso mille semi in g); CL1-2 (contenuto in clorofilla); CC (Canopy Cover in %); PH (altezza della pianta in cm) della quinoa nei diversi trattamenti. Fattori: a Vatrietà (V) di Chenopodium quinoa Willd.; b Livello irriguo (I) (100% PET; 80% PET; 60% PET); c Fertilizzazione (F) (100 kg N ha^{-1}; 50 kg N ha^{-1}; 25 kg N ha^{-1}). μ, σ, CV rappresentano rispettivamente la media, la deviazione standard e il coefficiente di variazione delle tre ripetizioni.

Factors			NOVEMBER								DECEMBER							
V^a	I^b	F^c	WUE	GYP	HI	TGW	CL_1	CL_2	CC	PH	WUE	GYP	HI	TGW	CL_1	CL_2	CC	PH
	60	25	1.69	9.56	0.48	2.40	55.3	21.9	6.26	59.4	0.50	1.27	0.32	1.91	47.9	37.7	7.44	33.5
	60	50	0.72	3.73	0.46	2.41	53.2	23.2	5.13	44.8	0.53	1.30	0.31	1.68	45.5	32.0	5.55	33.0
	60	100	0.21	0.85	0.25	2.01	50.3	21.1	1.39	28.7	0.23	1.29	0.29	1.78	41.6	30.6	6.06	32.4
	80	25	0.90	9.04	0.48	2.06	43.2	33.4	5.04	52.7	0.44	2.75	0.30	1.82	44.9	48.4	7.62	38.7
Titicaca	80	50	0.68	5.47	0.45	1.87	45.4	31.4	2.33	45.1	0.81	4.05	0.36	1.87	41.6	54.6	8.66	44.8
	80	100	0.08	0.56	0.35	1.92	50.4	29.2	0.87	25.7	0.55	2.70	0.35	1.84	45.4	44.3	6.59	38.6
	100	25	0.29	4.29	0.41	2.02	39.1	45.7	1.97	34.7	0.44	2.98	0.43	1.83	46.7	31.8	6.14	39.8
	100	50	0.43	5.16	0.38	1.85	44.6	35.5	1.74	44.0	0.42	2.19	0.42	1.67	45.8	35.0	4.68	34.0
	100	100	0.17	2.42	0.38	1.75	40.6	25.4	1.36	36.4	0.35	1.42	0.32	1.68	46.1	30.4	6.56	36.3
μ	-	-	0.57	4.57	0.41	2.03	46.9	29.7	2.90	41.3	0.48	2.22	0.35	1.79	45.1	38.3	6.59	36.8
σ	-	-	0.57	3.61	0.08	0.28	6.35	9.46	2.58	13.1	0.30	1.71	0.07	0.22	4.75	10.3	3.33	10.1
CV	-	-	0.32	13.0	0.01	0.08	40.3	89.4	6.67	171.8	0.09	2.91	0.01	0.05	22.6	104.9	11.1	101.0
	60	25	1.43	2.32	0.12	0.87	42.6	33.3	2.29	54.2	0.08	0.04	0.02	0.77	37.1	41.9	2.06	26.8
	60	50	0.96	0.91	0.07	0.84	41.8	43.6	1.22	47.3	0.02	0.04	0.02	0.77	36.2	45.7	1.96	35.0
	60	100	0.24	0.20	0.03	0.88	43.0	42.8	0.35	26.4	0.10	0.05	0.02	0.71	31.6	51.3	2.18	33.4
	80	25	0.64	1.46	0.10	1.38	39.5	32.5	1.48	60.5	0.18	0.10	0.02	1.07	38.9	55.4	3.21	49.8
Negra Collana	80	50	0.47	0.69	0.09	1.38	39.9	39.4	0.95	44.0	0.22	0.05	0.01	0.99	44.5	50.7	2.78	49.3
	80	100	0.07	0.08	0.05	1.13	48.1	38.6	0.42	21.9	0.20	0.09	0.01	1.11	43.0	51.3	3.84	49.4
	100	25	0.37	1.11	0.05	1.32	30.5	44.9	0.64	54.9	0.24	0.68	0.06	1.02	41.1	47.0	2.42	52.3
	100	50	0.22	0.38	0.05	0.98	36.2	44.0	0.86	54.3	0.28	0.48	0.05	1.03	42.9	52.2	2.25	51.6
	100	100	0.05	0.13	0.04	0.85	42.8	41.5	0.22	30.8	0.29	0.51	0.05	0.99	41.4	47.0	4.11	48.2
μ	-	-	0.50	0.81	0.07	1.07	40.5	40.1	0.94	43.8	0.18	0.22	0.03	0.94	39.6	49.2	2.76	44.0
σ	-	-	0.49	0.82	0.04	0.26	5.78	5.47	0.85	15.7	0.11	0.28	0.02	0.27	4.85	7.75	1.49	12.7
CV	-	-	0.24	0.67	0.00	0.07	33.4	29.9	0.72	244.9	0.01	0.08	0.00	0.07	23.5	60.1	2.23	161.3
μ	-	-	0.54	2.69	0.24	1.58	43.7	34.9	1.92	42.5	0.33	1.22	0.19	1.36	42.3	43.7	4.67	40.4
σ	-	-	0.53	3.21	0.18	0.55	6.83	9.29	2.15	14.4	0.27	1.57	0.17	0.49	5.49	10.5	3.21	11.9
CV	-	-	0.28	10.3	0.03	0.31	46.6	86.2	4.61	206.1	0.07	2.48	0.03	0.24	30.1	111.1	10.3	141.8

units of C per 1 unit of N), but slightly increased after organic amendment up to 10-12 C units per 1 N unit at 0-20 cm depth. As a result of phosphate fertilisation, P within the first layer had boosted from 4 mg kg^{-1} prior to sowing, up to 84-106 mg kg^{-1} after harvesting. Finally, bulk densities were of 1.66 g cm^{-3}.

Mean daily temperature during the growing period was 28.6 °C (Figure 1). The 40 °C threshold was trespassed 14 times, especially in March and April. In addition, longer cycle varieties (Negra Collana) were affected to a larger extent than short cycle varieties (Titicaca) by maximum temperatures at flowering (> 39 °C). Finally, soil temperatures, at 5 and 10 cm depth, have shown that roots (average depth, 6.5 cm, for both varieties) were thermic-stressed throughout the whole growing period (Figure 2).

Estimated ETc (Figure 3) was lowest at plant emergence and two leaves stage (±3 mm day^{-1}), while steadily increasing at a rate of +0.5 mm $week^{-1}$ during the vegetative stage up to 6-7 mm day^{-1}. The plateau phase of maximum water requirements for Titicaca was reached after 6 weeks (ETc = ±6 mm day^{-1}). Once leaf senescence took place, ETc started to decline, thus depleting during pasty seed formation and physiological maturity of the plant, 10-13 weeks (ETc = ±5.5 mm day^{-1}). For Negra Collana, with longer cycle, the ETc reached its maximum after

Tab. 4. Post-hoc Tukey´s pairwise comparison test for different crop parameters and factors of study (variety, irrigation and fertilisation).
Tab. 4. Post-hoc Tukey´s pairwise test per I diversi paretri e fattori analizzati (varietà, irrigazione e concimazione).

Factor	Level	WUE		GYP		HI		TGW		**CL1**		**CL2**		**CC**		**PH**	
		NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.
Variety	Titicaca	0.57	0.48**A**	4.57**A**	2.22**A**	0.40**A**	0.35**A**	2.03**A**	1.79**A**	46.9**A**	45.1**A**	29.6**B**	38.3**B**	2.90**A**	6.59**A**	41.3	36.8**B**
	Negra	0.50	0.18**B**	0.81**B**	0.22**B**	0.07**B**	0.03**B**	1.06**B**	0.94**B**	40.5**B**	39.6**B**	40.1**A**	49.2**A**	0.94**B**	2.75**B**	43.8	44.0**A**
Irrigation	60	0.89**A**	0.24	2.93	0.67	0.23**A**	0.16**B**	1.57	1.27	47.7**A**	40.0**B**	31.0**B**	39.8**B**	2.78**A**	4.21	43.5	32.4**B**
	80	0.47**B**	0.40	2.88	1.62	0.25**A**	0.18**B**	1.60	1.45	44.4**A**	43.0**AB**	34.1**AB**	50.8**A**	1.85**AB**	5.45	41.6	45.1**A**
	100	0.26**B**	0.34	2.25	1.37	0.22**A**	0.22**A**	1.46	1.37	39.0**B**	44.0**A**	39.5**A**	40.6**B**	1.31**B**	4.36	42.5	43.7**A**
Fertilisation	25	0.89**A**	0.31	4.63**A**	1.30	0.27**A**	0.19	1.67**A**	1.40	41.7**B**	42.8	35.3	43.7	2.95**A**	4.82	52.7**A**	40.2
	50	0.58**B**	0.38	2.72**B**	1.35	0.25**A**	0.20	1.55**AB**	1.33	43.5**AB**	42.7	36.2	45.0	2.04**AB**	4.31	46.6**A**	41.3
	100	0.15**C**	0.29	0.70**C**	1.01	0.19**B**	0.17	1.41**B**	1.35	45.8**A**	41.5	33.1	42.5	0.77**B**	4.89	28.3**B**	39.7

Note: capital letter (significant difference between set of groups); "A" is the group with highest value when compared to the other sets of groups "B" or "C" (in all cases statistically significant different); NOV. corresponds to the sowing in November and DEC. to the sowing in December.

Tab. 5. ANOVA for different crop parameters and interactions between factors (variety, irrigation and fertilisation).
Tab. 5. ANOVA per diversi parametri misurati e interazioni tra fattori.

Source	WUE		GYP		HI		TGW		CL1		CL2		CC		PH	
	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.	NOV.	DEC.
V	ns	***	***	***	***	***	***	***	***	***	***	***	***	***	ns	*
I	***	ns	ns	ns	*	**	ns	ns	***	*	***	***	*	ns	ns	**
F	***	ns	***	ns	***	ns	**	ns	*	ns	ns	ns	***	ns	***	ns
V x I	ns	ns	ns	ns	ns	ns	***	ns	*	*	**	*	ns	ns	ns	ns
V x F	ns	ns	***	ns	**	ns	ns	ns	*	ns	**	ns	ns	ns	ns	ns
I x F	**	ns	*	ns	***	ns	ns	ns	*	ns	*	ns	ns	ns	ns	ns
V x I x F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
R^2	0.77	0.53	0.82	0.59	0.97	0.95	0.93	0.81	0.77	0.57	0.76	0.65	0.65	0.45	0.71	0.44

Abbreviations: WUE (Water Use Efficiency in kg m^{-3}); GYP (Grain yield per plant in grams); HI (Harvest Index in yield/biomass); TGW (Thousand grain weight in grams); CL_{1-2} (Chlorophyll content); CC (Canopy Cover in %); PH (Plant Height in cm); NOV. (November sowing); DEC. (December sowing).
Note: [a] Variety (V) of *Chenopodium quinoa* Willd. ; [b] Irrigation level (I) (100% PET; 80% PET; 60% PET); [c] Fertilisation (F) (100 kg N ha^{-1}; 50 kg N ha^{-1}; 25 kg N ha^{-1}); *** extremely significant (p<0.001); ** very significant (p<0.01); * significant (p<0.05); ns: not significant (p>0.05); R^2 is the proportion of variance in the dependent variable (crop parameter) which can be explained by the independent variables (V, I, F).

10 weeks, just after flowering. It remained on the plateau phase (ETc = ±6.5 mm day^{-1}) until 18 weeks, then decreased to ±4.5 mm day^{-1} during pasty seed formation and physiological maturity, 19-23 weeks.

Quinoa´s water requirements (Figures 4 and 5) under field conditions varied considerably depending on: cultivar, phenological phase, evapotranspiration rate, type of soil texture and efficiency of the irrigation system. Full irrigation (FI) results have shown that Titicaca´s water demand was 403 mm, whereas for Negra Collana 811 mm (average of both sowing dates). Under progressive drought (PD), the amount of water supplied to Titicaca was 323 mm, whereas for Negra Collana 614 mm. For deficit irrigation (DI), the amount of water supplied was 231 mm and 437 mm to Titicaca and Negra Collana, respectively.

The statistical analysis has shown that water use efficiency (WUE, expressed in kg biomass per m^3 of water applied) was higher under PD and DI, meaning that quinoa was performant under drought-stress conditions (except for Negra Collana sown in December). For the grain yield per plant (GYP), there was significant difference (p<0.001) between the two varieties and for both sowing dates, being up to 10 times higher for Titicaca than for Negra Collana. Moreover, yields have depleted by half between November and December, from

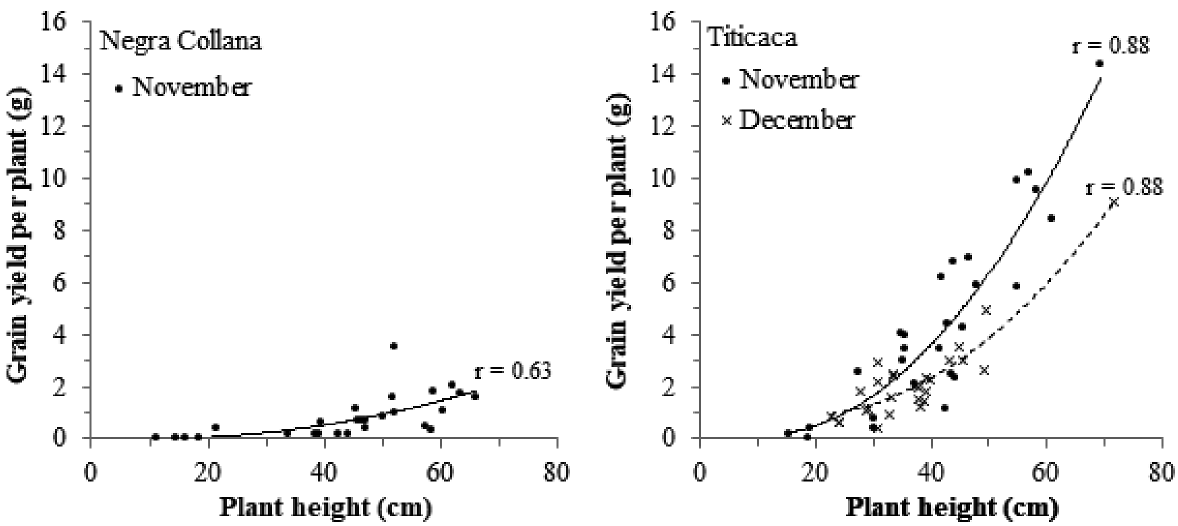

Fig. 6. Relationship (linear regression) between grain yield per plant (g) and plant height (cm) at harvest for Titicaca and Negra Collana.
Fig. 6. Relazione tra resa di granella per pianta (g) e altezza della pianta (cm) alla raccolta per Titicaca e Negra Collana.
Note: r shows Pearson correlation coefficient; Negra Collana (sowing date: December) was removed from the graphs due to high seed abortion in plants.

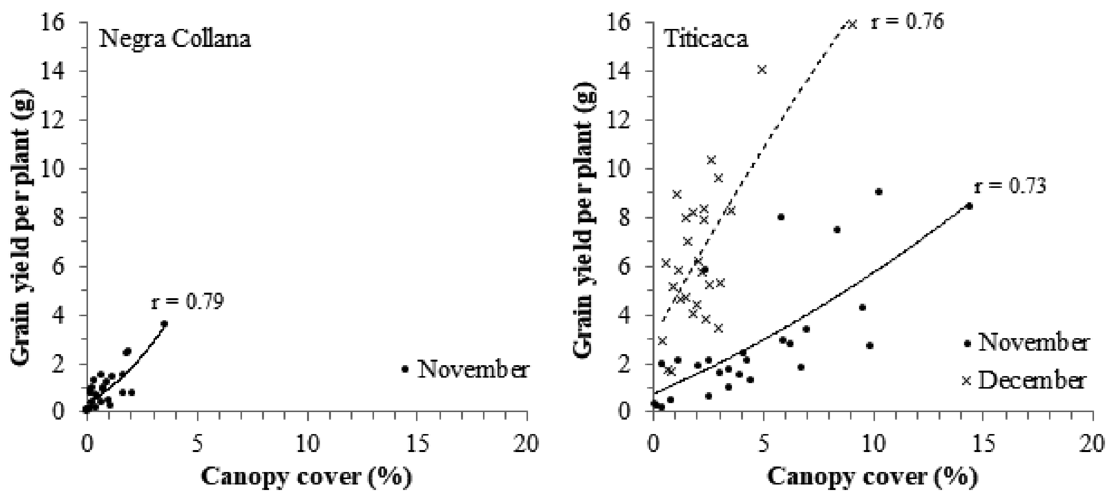

Fig. 7. Relationship (linear regression) between grain yield per plant (g) and canopy cover (%) for Titicaca and Negra Collana.
Fig. 7. Relazione tra resa di granella per pianta (g) e canopy cover (%) per Titicaca e Negra Collana.
Note: r shows Pearson correlation coefficient; Negra Collana (sowing date: December) was removed from the graphs due to high seed abortion in plants.

2.69 to 1.22 g plant^{-1} (average of both varieties). In fact, extreme temperatures during flowering, higher than 39 °C, have resulted in high seed abortion in plants. For Titicaca sown in November under DI and 25 kg N ha^{-1} fertilisation was the most performant, with yields of 9.5 g plant^{-1} (equivalent to 1.9 t ha^{-1}). However, for the sowing in December, higher yields (4.05 g plant^{-1}, equivalent to 0.8 t ha^{-1}) were observed under PD and 50 kg N ha^{-1}. Harvest index (HI, as a ratio of harvested grain to total dry matter) have shown statistical significant differences ($p<0.001$) between the two varieties, 0.38 and 0.05 HI for Titicaca and Negra Collana (average of both sowing dates), respectively. In addition, statistical significant differences ($p<0.001$) between quinoa varieties were observed when analysing the weight of thousand grains (TGW) for both sowing dates; having Titicaca seeds doubled the weight of Negra Collana seeds, 1.94 and 1.00 g, respectively.

Chlorophyll content (CL), N in the leaf, has shown statistical significant differences ($p<0.001$) amongst quinoa varieties, with higher N values for Titicaca sown in November. This was probably the consequence of N redistribution from leaf to storage organs, hence leading to leaf senescence and fostering seed filling. Canopy cover (CC) had varied between quinoa varieties, with 3 times more vegetation coverage for Titicaca than for Negra Collana. Quinoa sown in December has shown statistical significant differences ($p<0.05$) among the heights of the two varieties, 44 and 39 cm for Negra Collana and Titicaca, respectively (average of both sowing dates). Strong relationships, using Pearson correlation coefficient (r), were observed between plant height and GYP (Figure 6), with values of 0.88 and of 0.63 for Titicaca and Negra Collana, respectively. Figures 6 and 7 show the notable enhancement of GYP (5 g per plant^{-1}, equivalent to 1 t ha^{-1}) once the plant exceeded 50 cm height. On the other hand, the relationship between GYP and CC (Figure 7) was robust, showing a correlation coefficient higher than 0.7 for both varieties and sowing dates. In fact, greater canopy was responsible of an increase in light interception, enhancing assimilation and plant growth.

4. DISCUSSION

Despite of the amount of research examining quinoa's water requirements under water-stress conditions, there were no studies displaying such low water inputs than those observed in this research (231 mm Titicaca and 437 mm Negra Collana, average of both sowing dates under DI). Furthermore, this study's average WUE results (0.53 kg m^{-3} Titicaca and 0.34 kg m^{-3} Negra Collana) were similar to those recorded in Bolivia (0.21-0.45 kg m^{-3}) (Geerts *et al.,* 2008), but lower to those observed in Italy and Morocco (0.6 and 1.7 kg m^{-3}, respectively) (Hirich *et al.,* 2014a; Hirich *et al.,* 2014c; Riccardi *et al.,* 2014). In fact, drought stress conditions at key phenological stages (pre-flowering, flowering and pasty grain formation) have had a negative effect both on grain yield per plant and WUE (Geerts *et al.,* 2008). GYP results were in harmony with those modelled in AquaCrop showing that quinoa can be highly performant under DI (Geerts *et al.,* 2009; Cusicanqui *et al.,* 2013). Titicaca's harvest index (HI) results (0.38, average of both sowing dates) were lower to those observed in Morocco (0.57-0.67), but higher than those of Iraq (0.28) (Hirich *et al.,* 2014c; Hassan, 2015).

Moreover, recent research in Algeria, Lebanon, Mauritania, Yemen and Iraq have suggested that 35 °C was the critical threshold at flowering, if exceeded quinoa plants would become sterile (Breidy, 2015; CNRADA, 2015; Djamal, 2015; Hassan, 2015; Saeed, 2015). Nonetheless, this research has proven that Titicaca can stand temperatures above 35 °C during flowering and still be highly performant (up to 1.9 t ha^{-1}). In regards to Negra Collana, long cycle variety, the effect of temperatures above 39 °C has resulted in a very low number of plants with seeds. This is because pollen viability is a function of pollen moisture content which is strongly dependent on vapour pressure deficit (Hatfield and Prueger, 2015). At high temperatures, vapour pressure deficits were highest resulting in pollen desiccation and low pollen viability. In this line, further research would be required to better understand the effect of temperature on plant fertility.

In contrast with other studies, this research did not bring to light any relevant information on yield enhancement with increasing nitrogen fertilisation (Kaul *et al.,* 2005; Shams, 2012). But was in harmony with other investigations (Moreale, 1993), showing that N-fertilisation does not play a crucial role on crop growth nor seed yield, and that quinoa's N uptake was of 25 kg N ton^{-1} of seed produced (1:40 ratio). In addition, the combination of high temperatures and soil moisture in sandy-loam soils during fertilisation could have resulted in urea volatilization (ammonia losses) and hydrolysis. Overall, this investigation has shown that quinoa can adapt and be highly performant in poor structured (sandy-loam texture) and low fertility soils (<0.5 % organic matter and 0.03 % N), typically of the Sahel.

5. CONCLUSIONS

This research confirms that quinoa is a climate resilient crop that can cope with high temperatures and drought-stress conditions. It has a good adaptation to slightly acidic, poor structured and low fertile soils, besides of having low N-requirements. Moreover, Titicaca yields could attain 900 kg ha^{-1} if sown in November (average of all treatments), and could be exceeded if appropriate agronomic practices are followed. For the time being, it will be important to prioritize the use of short-cycle varieties (Titicaca, 85 days), rather than long cycle varieties (Negra Collana, 150 days). By sowing short cycle varieties in November, the effect of extreme temperatures occurring in mid-February until the onset of the rainy season will be diminished. In fact, quinoa's sowing could be advanced by several weeks towards northern parts of the country. Moreover, organic amendment is highly recommended at the rate of 1 t ha^{-1}

or higher prior to sowing; besides of a two-time mineral fertilisation in the form of ammonium nitrate, rather than urea, at the rate of 50 kg N ha^{-1}. Mechanised tilling, at 10-20 cm depth, would be advised, and if irrigated frequent soil aeration would be recommended to avoid soil adhesion that allows effective root development. For that, sowing in furrows would also be supported. Furthermore, research on plant-breeding should target higher-temperature and wind tolerant varieties capable of standing the warmest months and winds occurring during the Harmattan. This could potentially broaden the spatial distribution and sowing time across the country, as well as to other hot-spot regions to climate change. Overall, this research has allowed settling a provisional quinoa crop-calendar, besides of describing ideotype cultivars and suitable agro-meteorological zones for quinoa production in Burkina Faso. For that, quinoa regional programmes implemented by FAO, TCP/SFW/3404 and TCP/RAF/3602 (Burkina Faso, Cameroun, Niger, Senegal, Chad, Togo and Ghana), need to be further supported and its production scaled-up.

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