Agronomic practices

A handheld mechanical plough (0.20 m depth) was used during field preparation. Afterwards, the experimental field was equally amended with 5000 kg ha^{-1} of compost and fertilized with 400 kg ha^{-1} of Burkina phosphate rock (BPR) (26.8% phosphoric anhydride, P_2O_5) (Table 1). To determine the N, P and K concentrations, three and 16 soil samples were collected before sowing and after harvesting, respectively, at both 0-0.20 m and 0.20-0.40 m depth (Figure 2). These samples were collected before sowing and linearly interpolated to estimate the physic-chemical properties of the soil for all 16 plots. The N fertilization was performed twice (at 15 and 30 DAS) by broadcasting urea (46.2% N) at a rate of 217 kg ha^{-1}, corresponding to a total of 100 kg ha^{-1} of N (N1). The total amount of N applied during the growing cycle was equivalent to

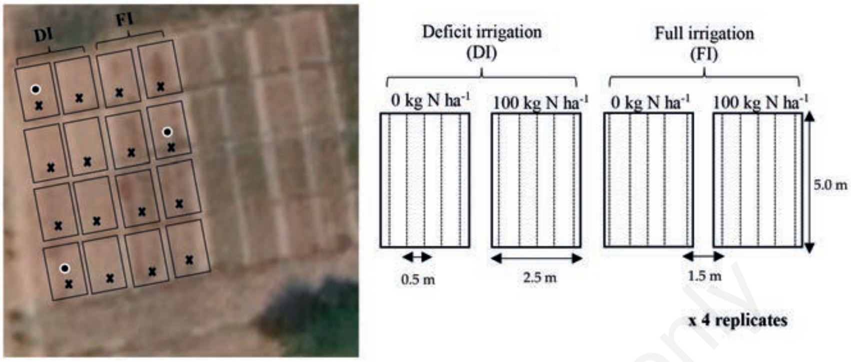

Figure 2. Satellite image (left) showing the experimental field and location of soil samples (o) prior to sowing and plant/soil (x) samples at harvest, as well as the experimental design (right).

Table 1. Chemical characteristics of the different fertilizers used during the experimentation: compost, urea ($CO(NH_2)_2$) and Burkina phosphate rock (BPR).

Parameter	Units	Compost	Urea	Phosphate rock
pH (H_2O)	-	7.3	-	-
C	%	29.1	-	-
Organic matter	%	50.2	-	-
N	%	1.1	46.2	-
C/N	-	27	-	-
P total	%	0.2	-	11.7
K total	%	2.4	-	-
Ca total	%	1.4	-	-

Table 2. Average physic-chemical characteristics of the soil at different depths (0-0.20 and 0.20-0.40 m) before sowing (average of three samples) and after harvesting (average of 16 samples).

Parameter	Units	Before sowing		After harvesting	
		0-0.20 m	0.20-0.40 m	0-0.20 m	0.20-0.40 m
Sand	%	75.1	58.3	-	-
Silt	%	14.2	12.4	-	-
Clay	%	10.7	29.3	-	-
Texture		Loamy-Sandy	Sandy-Clay-Loam	-	-
pH (H_2O)		6.3	6.3	6.7	6.7
C	kg ha^{-1}	7788.0	6634.6	8986.3	7200.3
Organic matter	kg ha^{-1}	13426.5	11438.0	15492.3	12413.4
N total	kg ha^{-1}	814.2	621.9	826.3	659.0
C/N		9.7	10.7	10.9	11.0
P total	kg ha^{-1}	472.8	365.1	545.8	460.4
$P_{Bray\ 1}$	kg ha^{-1}	84.6	51.6	85.6	60.2
K total	kg ha^{-1}	1427.7	2834.9	1542.5	2778.1
K available	kg ha^{-1}	220.1	324.5	322.5	178.9
Bulk density	kg m^{-3}	1120	-	-	-

54.5 kg ha^{-1} of N (from compost in non-N fertilized treatments) and 154.5 kg ha^{-1} of N (from $CO(NH_2)_2$ and compost in N-fertilized treatments). The total P and K application before sowing was 56.1 kg ha^{-1} of P (46.7 kg ha^{-1} of P from BPR and 9.6 kg ha^{-1} of P from compost) and 111.7 kg ha^{-1} of K from compost, respectively. To calculate the total amount of carbon (C), N, P and K content in the top-soil layer (0-0.20 m), the bulk density was measured (1.12 t m^{-3}) and estimated at 2240 t ha^{-1} (Table 2).

Nitrogen, phosphorus and potassium mass balances and surpluses

The removal of N, P and K per experimental plot was calculated using 12 seed samples and three stem and leaf samples. The entire N cycle, including values of atmospheric N deposition (wet and dry) and N emissions, was determined using the data provided by Delon *et al*. (2010). The latter experiment was conducted under similar agroclimatic conditions to those of this study (Katibougou-Mali at 12° 54'N and 7° 31'W; 307 m.a.s.l). The amount of N deposition (both wet and dry) between November-January was estimated at 2.8 kg ha^{-1} of N and the N emissions at 9.7 kg ha^{-1} of N. As our experiment was conducted during the dry season using a drip-irrigation system, losses from leaching were not considered.

The gross N balance (NB) was computed as follows:

$$NB = (N_{soil\ before\ sowing} + N_{urea} + N_{compost} + N_{atmospheric\ deposition\ (wet\ \&\ dry)}) - (N_{uptake\ plant} + N_{uptake\ seeds} + N_{soil\ emissions}) \tag{2}$$

The gross P balance (PB) was computed as follows:

$$PB = (P_{soil\ before\ sowing} + P_{phosphate} + P_{compost}) - (P_{uptake\ plant} + P_{uptake\ seeds}) \tag{3}$$

The gross K balance (KB) was computed as follows:

$$KB = (K_{soil\ before\ sowing} + K_{phosphate} + K_{compost}) - (K_{uptake\ plant} + K_{uptake\ seeds}) \tag{4}$$

The N surplus (NS) was computed as follows:

$$NS = (N_{urea} + N_{compost} + N_{atmospheric\ deposition\ (wet\ \&\ dry)}) - (N_{uptake\ plant} + N_{uptake\ seed}) \tag{5}$$

The P surplus (PS) was computed as follows:

$$PS = (P_{phosphate} + P_{compost}) - (P_{uptake\ plant} + P_{uptake\ seeds}) \tag{6}$$

The K surplus (KB) was computed as follows:

$$KS = (K_{phosphate} + K_{compost}) - (K_{uptake\ plant} + K_{uptake\ seeds}) \tag{7}$$

The N, P, K requirements per one ton of seeds and one ton of stems and leaves were computed as follows (as reported by Gebrelibanos and Dereje, 2015):

$$N\ uptake = \frac{Seed\ yield\ \left(\frac{kg}{ha}\right) x\ Seed\ total\ N\ \left(\frac{kg}{ha}\right)}{100} \tag{8}$$

The total N, P, K requirements per one ton of total dry biomass (seeds, stems and leaves) was calculated from the harvest index (HI) as follows:

$$Weighted\ sum = \frac{\left(\frac{N,P,K\ seeds\ x\ HI\ seeds}{2}\right) + \left(\frac{N,P,K\ stems\ and\ leaves\ x\ HI\ stems\ and\ leaves}{2}\right)}{1000} \tag{9}$$

Statistical analysis

Data were examined by analysis of variance (ANOVA) and by pairwise comparison of means using the Tukey HSD test with critical value $P<0.05$. All the statistics were conducted using the R software (version 5.3.3). To estimate the differences between observed and simulated values, the mean absolute percentage error (MAPE) was used and computed as follows:

$$MAPE = \frac{1}{N} \sum_{i=1}^{i=N} \frac{|Oi - Pi|}{(Oi)} x\ 100 \tag{10}$$

Where: O_i is the observed value, P_i is the simulated value.

Results

Physic-chemical characteristics of the experimental site

The experimental field was characterized for having a loam-sandy texture at 0-0.20 m, and a sandy-clay-loam texture at 0.20-0.40 m, respectively (Table 2). The total amount of N found in the top layer was 814.2 and 826.3 kg ha^{-1} before sowing and after harvesting, respectively. The total amount of organic matter (OM), C, P and K found in the soil at sowing was significantly lower to that observed at harvest (Table 2). The reported increase in OM, C, P, K, and, to a lesser extent, of N between sowing and harvesting was due to compost (5000 kg ha^{-1}), urea (100 kg ha^{-1} of N) and BPR application (400 kg ha^{-1} of N). The $P_{Bray\ 1}$ (method displaying the P availability in the soil) and K availability at 0-0.20 m was 84.6 and 85.6 kg ha^{-1} of P and 220.1 and 322.5 kg ha^{-1} of K before sowing and after harvesting, respectively.

Nitrogen, phosphorus and potassium uptake

The ANOVA and Tukey HSD post-hoc test for N, P, K uptake showed significant differences between treatments and for different parts of the plant (Table 3). N was the macronutrient of greatest interest, as P and K fertilization was only provided at the time of sowing and not throughout the experiment as in the case of N. For the treatment FI-N1, the total N uptake (seeds, stems and leaves) was of 50.6 kg ha^{-1} of N, and for the opposite treatment, DI-N0, 10.2 kg ha^{-1} of N (Table 3). The main effect between factors showed that quinoa was more reactive to irrigation than to N fertilization. However, for both factors significant differences were reported ($P<0.05$). Differences in the response of plants to N fertilization and irrigation was reflected in the dry biomass at harvest (seeds, stems and leaves). For instance, the seed yields from the FI-N1 treatment were significantly ($P<0.05$) higher than those found in DI-N0 (Table 3). Although significant differences were observed when irrigation and N fertilization acted as a main factor effect, larger differences in terms of yield were reported between irrigation treatments (1127.7 and 276.3 kg ha^{-1} of seed under FI and DI, respectively) when compared to N fertilization treatments (838.5 and 565.4 kg ha^{-1} of N under N1 and N0, respectively).

Furthermore, statistical differences ($P<0.05$) were also depicted when testing the ANOVA for P and K. The total P uptake was strongly influenced by changes in irrigation and N fertilization, with a positive relationship between higher water inputs and increasing N fertilization rates (FI-N1). For instance, for the FI-N1 treatment the total P uptake was of 6.3 kg ha^{-1} of P; whereas for the treatment DI-N0, the P uptake was as low as 1.2 kg ha^{-1} of P (Table 3). For P, both irrigation and N fertilization had a similar main effect on total P uptake, displaying significant differences ($P<0.05$) in both cases. Nonetheless, greater differences ($P<0.05$) were observed under FI, with a P uptake of 4.8 kg ha^{-1} of P than under DI, 1.4 kg ha^{-1} of P. A similar trend was reported for total K uptake of seeds, stems and leaves, with a positive relationship between higher irrigation and increasing N fertilization. As for P, total K uptake was also significantly higher under the FI-N1 treatment ($P<0.05$) than for the DI-N0 treatment (Table 3). However, no significant differences were noted when DI interacted either with N1 and N0, or between FI-N0. Regarding the effect of main factors, the largest differences ($P<0.05$) on total K uptake were displayed under irrigation (total K uptake of 99.7 and 42.4 kg ha^{-1} of K for FI and DI, respectively) when compared to N fertilization (total K uptake of 91.0 and 51.1 kg ha^{-1} of K for N1 and N0, respectively).

The total amount of N, P and K requirements was calculated to assess the macronutrient uptake by the plant per unit of biomass (Eq. 8-9, Table 4). The N requirements were of 20.4 and 7.6 kg ha^{-1} of N per ton of seeds and per ton of stems and leaves produced, respectively. Additionally, the total amount of N required to produce one ton of total dry biomass was of 12.7 kg of N (weighted sum of seeds, stems and leaves). In addition, in order to produce one ton of seeds and one ton of stems and leaves, the K requirements were of 16.0 and 42.9 kg of K, respectively. These findings implied that for producing one ton of total dry biomass, quinoa required a total amount of 35.5 kg ha^{-1} of K (weighted sum of seeds, stems and leaves). Of all macronutrients in study, quinoa demonstrated a lower requirement of P. In order to produce one ton of seeds and one ton of stems and leaves, the P requirements were of 2.8 and 0.8 kg ha^{-1} of P, respectively. Overall, quinoa required 1.6 kg ha^{-1} of P (weighted sum of seeds, stems and leaves) to produce one ton of total dry biomass.

Nitrogen, phosphorus and potassium mass balances and surpluses in the soil at harvest

The effect of the different management strategies, including quinoa genotype, fertilization and irrigation, was evaluated using the N, P and K mass balances (Eq. 2-4) as well as through macronutrient surpluses (Eq. 5-7) found in the soil at harvest (Table 5). In general, much of the differences in mass balances

Table 3. ANOVA Tukey HSD post-hoc test for N, P and K uptake (kg ha^{-1}) for different irrigation schedules (100 and 50% ETc) and N fertilization levels (100 and 0 kg N ha^{-1}).

Treatment		Nitrogen (N) (kg ha^{-1})			Phosphorus (P) (kg ha^{-1})			Potassium (K) (kg ha^{-1})			Dry biomass (kg ha^{-1})	
Irrigation	Nitrogen	Seed uptake	Stem and leaf uptake	Total uptake	Seed uptake	Stem and leaf uptake	Total uptake	Seed uptake	Stem and leaf uptake	Total uptake	Yield	Stems and leaves
FI	N1	29.0±4.0^{a}	21.6±12.3^{a}	50.6±12.8^{a}	3.9±0.9^{a}	2.3±1.3^{a}	6.3±1.8^{a}	20.6±3.7^{a}	112.7±70.7^{a}	133.3±72.0^{a}	1380.0±251.4^{a}	3096.7±1893.6^{a}
DI	N1	6.1±4.0^{c}	7.7±4.2^{b}	13.9±5.9^{c}	0.8±0.6^{c}	0.8±0.3^{b}	1.7±0.4^{cc}	4.8±2.7^{c}	43.9±24.8^{b}	48.7±25.7^{b}	297.1±207.2^{c}	982.9±632.8^{b}
FI	N0	18.1±2.9^{b}	9.1±1.0^{b}	27.2±3.0^{b}	2.4±0.3^{b}	1.0±0.3^{b}	3.4±0.1^{b}	13.8±3.3^{b}	52.3±10.5^{b}	66.1±12.6^{b}	875.4±98.6^{b}	1129.6±79.2^{b}
DI	N0	4.9±2.8^{c}	5.3±1.5^{b}	10.2±4.2^{c}	0.7±0.4^{c}	0.5±0.2^{b}	1.2±0.6^{c}	4.3±2.8^{c}	31.9±12.1^{b}	36.2±149^{b}	255.4±153.3^{c}	717.9±186.5^{b}
Main effect: Nitrogen												
N1		17.6±12.1^{a}	14.7±11.5	32.3±20.9^{a}	2.4±1.7	1.6±1.2	4.0±2.7^{a}	12.7±8.5^{a}	78.3±63.2	91.0±68.6	838.5±588.4^{a}	2039.8±1763.5
N0		11.5±7.2^{b}	7.2±2.3	18.7±9.3^{b}	1.6±0.9	0.7±0.3	2.3±1.1^{b}	9.0±5.6^{b}	42.1±15.3	51.1±20.3	565.4±335.7^{b}	923.8±250.8
Main effect: Irrigation												
FI		23.5±6.5^{a}	15.4±10.7^{a}	38.9±15.0^{a}	3.2±1.0^{a}	1.7±1.2^{a}	4.8±1.9^{a}	17.2±4.9^{a}	82.5±58.9^{a}	99.7±61.6^{a}	1127.7±316.4^{a}	2113.1±1662.3^{a}
DI		5.5±3.5^{b}	6.5±3.4^{b}	12.0±5.4^{b}	0.8±0.5^{b}	0.7±0.3^{b}	1.4±0.5^{b}	4.6±2.8^{b}	37.9±20.4^{b}	42.4±22.0^{b}	276.3±183.4^{b}	850.4±484.9^{b}

$^{a-c}$Means that do not share a letter were significant different at 5 % probability level using Tukey HSD post-hoc test.

Table 4. N, P and K (kg ha^{-1}) requirements to produce one ton of quinoa seeds, one ton of aboveground biomass (stems and leaves) and sum of dry biomass (seeds, stems and leaves) for different irrigation schedules (100 and 50% ETc) and N fertilization levels (100 and 0 kg ha^{-1} of N).

Treatment		Seeds			Stems and leaves			Harvest index of (seeds)	Harvest index of stems and leaves	Total requirements to produce one ton of seeds, stems and leaves		
Irrigation	Fertilizer	N	P	K	N	P	K	%	%	N	P	K
FI	N1	21.0±2.9	2.9±0.6	14.9±2.7	7.0±4.0	0.8±0.4	36.4±22.8	30.8	69.2	25.3	3.1	66.7
DI	N1	20.7±13.6	2.8±1.9	16.2±9.1	7.9±4.3	0.8±1.0	44.6±25.2	43.7	56.3	13.6	1.7	33.0
FI	N0	20.7±3.3	2.7±0.3	15.7±3.7	8.1±0.8	0.9±0.3	46.3±9.3	23.2	76.8	6.9	0.8	24.3
DI	N0	19.1±11.0	2.9±1.8	16.9±11.0	7.4±2.1	0.7±0.2	44.4±16.9	26.2	73.8	5.1	0.6	18.1
	Mean	20.4±0.8	2.8±0.1	16.0±0.7	7.6±0.4	0.8±0.1	42.9±3.8	-	-	12.7	1.6	35.5

were displayed for K, implying that K was more influenced by irrigation and N fertilization than when compared to N and P. In regards to the K mass balance (KB), there was a negative relationship ($P<0.05$) with lower and higher values under the FI-N1 and DI-N0 treatments, respectively. However, no significant differences were reported when N fertilization nor irrigation were the main factor effect. Additionally, K surpluses (KS) showed a similar behaviour to that of KB, with negative surpluses under the FI-N1 treatment ($P<0.05$). This was explained by the fact that quinoa required more K (133.3 kg ha^{-1} of K under FI-N1 as reported in Table 3) to that provided by compost (111.7 kg ha^{-1} of K). These results confirmed that quinoa removed K previously found in the soil, and therefore mass balances were negative. The opposite trend occurred for the DI-N0 treatments, with a K surplus of 81.5 kg ha^{-1} ($P<0.05$). These values were in harmony to those reported in Table 3, where K uptake (36.2 kg ha^{-1} of K) was lower under DI-N0.

For the N mass balance (NB), no significant differences ($P>0.05$) were described for the interactions between irrigation and N fertilization. Even though the highest values were observed under FI-N1 (911.1 kg ha^{-1} of N) than under DI-N0 (823.0 kg ha^{-1} of N), these differences were too low to render the treatments statistically different. However, there were significant differences ($P<0.05$) between treatments in terms of N surpluses (NS) in the soil at harvest. For instance, NS were higher under DI-N1. Under DI-N1, the lack of water inhibited the N from dissolving and, therefore, diminished the N uptake by the plant (as reported in Table 3 for DI-N1 and N0). On the contrary, treatments with higher irrigation and lower N fertilization (FI-N0) had a minor effect on N surpluses in the soil at harvest (30.1 kg ha^{-1} of N). The analysis of the main factor effect showed significant differences ($P<0.05$) among N fertilization rates, with NS of 125.0 and 38.6 kg ha^{-1} of N under N1 and N0, respectively. However, no differences were reported when irrigation was the main factor. For the P mass balance (PB), there were no significant differences either between the main factors or amongst treatments. The results showed that when N fertilizer was the main factor, PB was higher under N0 (Table 5). On the contrary, higher PB values were reported under FI. As P uptake was similar among treatments, P surpluses at harvest showed no significant differences.

Furthermore, the differences between total N, P and K mass balance estimations and actual values at harvest were calculated using the MAPE (Eq. 10, Figure 3). The MAPE showed that estimated NB underestimated actual N values (–7.5 %); whereas the PB and KB were slightly overestimating actual values (+4.3 and +3.3%, respectively). Nevertheless, these differences between observed and estimated values were generally low, implying that mass balance equations for N, P and K performed well.

Discussion

The sections of this study on macronutrient requirements and mass balances were crucial to better understand the needs of quinoa under a tropical savannah (wet and hot) climate and to minimize N, P, K losses into the environment.

The first objective of this study was to fill the gap in literature by examining macronutrient requirements of different parts of the plant. Our research reported an average of 2.08 and 1.63% of N and K in seeds, respectively; hence corroborating the results of Gómez-Ramírez *et al*. (2017) who reported similar concentrations

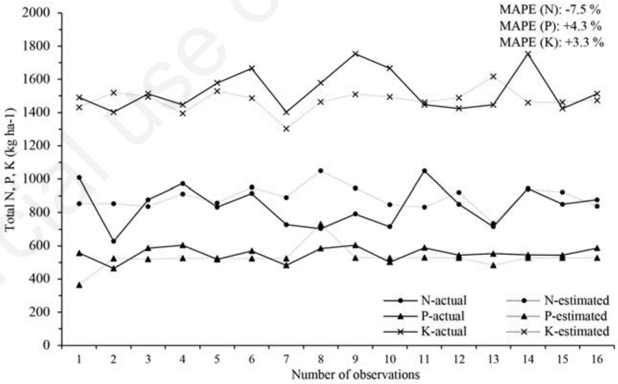

Figure 3. Differences (using MAPE) between observed N, P and K (kg ha^{-1}) soil content at harvest and estimated values from N, P and K mass balance equations (NB, PB, KB).

Table 5. ANOVA and Tukey HSD test for N, P, K mass balances and N, P, K surpluses in the soil for different irrigation schedules (100 and 50% ETc) and N fertilization levels (100 and 0 kg ha^{-1} of N). While N values refer to the concentration in the soil, P and K refer to its availability in the soil.

Treatment		Nitrogen (N) (kg ha^{-1})		Phosphorus (P) (kg ha^{-1})		Potassium (K) (kg ha^{-1})	
Irrigation	Nitrogen	N balance (NB)	N surplus (NS)	P balance (PB)	P surplus (PS)	K balance (KB)	K surplus (KS)
FI	N1	911.1±12.8	106.7±12.8^{b}	526.1±1.3	53.4±1.3	1412.1±72.0b	–15.6±72.0^{b}
DI	N1	922.3±40.3	143.4±5.9^{a}	485.7±69.9	53.2±1.7	1472.4±29.3ab	69.0±25.7^{ab}
FI	N0	888.8±92.5	30.1±3.0^{c}	576.3±89.0	52.3±3.4	1473.3±13.1ab	51.6±12.6^{ab}
DI	N0	823.0±51.6	47.1±4.2^{c}	514.8±18.6	53.0±1.8	1539.6±46.5a	81.5±14.9^{a}
Main effect: Nitrogen							
	N1	916.7±30.4	125.0±20.9^{a}	505.9±53.4	53.3±1.5	1442.2±62.7	26.7±68.6
	N0	855.9±81.8	38.6±9.3^{b}	545.5±71.3	52.7±2.7	1506.5±47.6	66.6±20.3
Main effect: Irrigation							
	FI	900.0±66.9	68.4±39.4	551.2±67.8	52.8±2.6	1442.7±60.1	18.0±61.6
	DI	872.6±67.9	95.3±48.4	500.2±53.1	53.1±1.7	1506.0±51.4	75.3±22.0

$^{a\text{-}c}$Means that do not share a letter were significant different at 5% probability level using the Tukey HSD post-hoc test.

(2.36 and 1.79% of N and K content in seeds, respectively) in treatments subjected to low pressure radiofrequency plasma-LPRF (RF 10 s). In addition, the average N seed content measured in our research (2.08%) was slightly lower to that measured by Kakabouki *et al*. (2018), ranging from 2.6-2.8%. In respects to K and P seed content, our work measured 16352 mg kg^{-1} of K and 2845 mg kg^{-1} of P (equivalent to 1.63% K and 0.28% P, average of all treatments). The latter were in harmony to those reported in literature, with a P concentration in quinoa seeds of 0.22% (Blanco, 2016). In comparison with other crops, the K content in seeds were in line to those observed in soybean (15,800 mg kg^{-1} of K) (Parvej, 2015); but differed, were higher for K (16,352 mg kg^{-1} of K) and lower for P (2845 mg kg^{-1} of P), to those observed in quinoa by Fuentes and Paredes-González (2015), reporting 5630 mg kg^{-1} of K and 4570 mg kg^{-1} of P. These differences on P concentrations were explained by a downregulation of phosphorylated protein in crops exposed to water deficits, as reported by Luo *et al*. (2018) for maize. It was likely that phosphorylated protein played a key role on regulating the photosystem and metabolism of plants (Cheng *et al.,* 2014). Other studies suggested similar responses on quinoa, where the phosphorylated protein modified key physiological processes such as photosynthesis, respiration, and water relations, among others (Zurita-Silva, 2015). Other authors affirm that protein and lipid (in the form of phospholipids) content in cv. Titicaca was higher after the abrasion of the pericarp, particularly of the linoleic omega fatty acid (Troisi *et al.,* 2015). All of these possible physiological responses support the differences on P concentrations between our study and those conducted under different agroclimatic conditions.

The second main objective of this study on N, P, K mass balances and its responses to the combined effect of irrigation and fertilizer application was successfully addressed and the gap in literature fulfilled. Regarding N, P, K uptake and mass balances, we observed that irrigation was the main factor determining seed yield and biomass at harvest. Increasing N fertilization had a minimal effect on seed yields and dry biomass. This was observed when comparing different N fertilization rates; for instance, DI-N1 and DI-N0 (297 and 255 kg ha^{-1} of seed, respectively). Various studies suggest that the low effectiveness of N fertilization in maize was due to a nutrient imbalance caused by the application of high rates of P and K (Adediran and Banjoko, 1995). Hence, the high PO_4^{3-} application rates of this study, from BPR and compost, might have resulted in a nutrient imbalance and consequently the vain effect of N on crop growth and development. Another reason supporting the low effect of N on yields at harvest was the competition between bacterial community and the crop for N in the soil, thus reducing the efficiency of increasing N fertilization rates (N1). The previous statement supports the idea that quinoa yields did not significantly increase with higher N fertilization rates, unlike other experiments (Jacobsen *et al.,* 1994; Kaul *et al.,* 2005).

Thirdly, sustainable farming systems in SSA are now better understood for this crop thanks to a comprehensive evaluation of surpluses from fertilizer application. The N, P, K applications, in the form of $CO(NH_2)_2$, compost and BPR, were higher to those required by quinoa and consequently in the results of mass balances and macronutrient surpluses found in the soil. In particular, N and P, and to a lesser extent K, received higher macronutrient inputs to those required by quinoa (surpluses of 81.8, 53.0 and 46.0 kg ha^{-1} of N, P, K, respectively, average of all treatments). Additionally, in all treatments, similar N, P, K uptake values (20.4, 2.8 and 16.0 kg N, P, K per ton of seed produced, respectively) were observed to those reported in literature (18.7, 5.0 and 13.8 kg N, P, K per ton of seed produced, respectively) under optimal growing conditions in The Netherlands and Denmark (Moreale, 1993). While the present study measured 7.6, 0.8 and 42.9 kg N, P, K per ton of stems and leaves produced, Moreale's (1993) study recorded 5.0, 1.8 and 32.5 kg N, P, K per ton of stems and leaves produced. Regarding the N, P and K requirements per ton of total biomass, including seeds, stems and leaves, few differences were depicted between these two studies; particularly, under optimal irrigation and N fertilization conditions. For instance, under FI-N1, an agreement was observed between our study and Moreale's (1993) in terms of N, P and K requirements, respectively with 25.3 and 23.8 kg ha^{-1} of N, 3.1 and 6.8 kg ha^{-1} of P, 66.7 and 46.3 kg ha^{-1} of K for one ton of total biomass produced. However, the present findings on P requirements (3.1 kg ha^{-1} of P per one ton of total biomass) were slightly lower to those (120 kg ha^{-1} of P_2O_5) cited in literature for a production of 4.0-7.0 ton ha^{-1} (equivalent to 4.8-8.4 kg ha^{-1} of P per one ton of total biomass) (Mujica, 2015). Others (Sephar and Rocha, 2010) suggest a P application rate of 80 kg ha^{-1} of P_2O_5 for seed yields over 2.0 ton ha^{-1} (equivalent to 10.8 kg ha^{-1} of P per ton of seeds produced). In contrast, the present showed that only 2.8 kg of P were required to produce one ton of seeds. Also, this study demonstrated that the most required macronutrient was K (35.5 kg of K per one ton of total biomass produced, average of all treatments), with very similar K application rates observed by González *et al*. (2015) and Spehar *et al*. (2015) (100 kg of K_2O for yields over 2.0 ton ha^{-1}, equivalent to 41.5 kg of K per one ton of total biomass produced). Finally, the emerging findings support the sustainable management of quinoa in other regions with similar agroclimatic conditions, *e.g.* Mediterranean region, where quinoa is rapidly expanding (Pulvento *et al.,* 2010; De Santis *et al.,* 2016*,* 2018; Alvar-Beltrán *et al.,* 2020).

Conclusions

The N, P, K mass balances of quinoa were useful for determining both the input requirements and outputs from crop removal and losses. Overall, the N and K requirements of quinoa were moderate to high (35.5 and 12.7 kg of K and N per one ton of total biomass produced, average of all treatments). The N, P and K mass balances were positive, notably for N and P, and to a minor extent for K. This confirmed that crop N, P, K requirements were lower to those estimated during the experimental design. For this reason, macronutrient surpluses were found in the field at harvest. For the optimal observed yields (1380 kg ha^{-1} under FI-N1, with a fertilization of 56.1 kg ha^{-1} of P and 111.7 kg ha^{-1} of K in the form of compost and BPR), the N and P surpluses were considerably high at 106.7 kg ha^{-1} of N and 53.4 kg ha^{-1} of P, respectively, but low for K (–15.6 kg ha^{-1} of K). In order to attain the highest yields while maintaining nutrient balance, the present results indicate that P needs to be applied at lower rates, and therefore 5000 kg ha^{-1} of compost (10 kg ha^{-1} of) should suffice quinoa's P demand. Hence, it is not necessary to provide additional P in the form of phosphate (BPR). Also, reducing P fertilization rates could be beneficial in terms of yield besides of increasing N efficacy. In this experiment, 5000 kg ha^{-1} of compost provided the field with 111.7 kg ha^{-1} of K, which was lower to that required by the crop under optimal growing conditions, FI-N1 (–15.6 kg ha^{-1} of K). A recommendation for providing the field with the necessary macronutrients is to fertilize with chemical compounds that have higher concentration of K and N, *e.g.* potassium nitrate (KNO_3) with 13% N and 37% K, respectively. Combined fertilizers can be cost-effective and approximately 400 kg of KNO_3 are sufficient for satisfying quinoa's N and K requirements for producing one ton of total biomass (including seeds, stems and leaves). Considering the typical sandy-loam texture of the experimental field, the use of organic matter can be promoted for increasing the water holding capacity of the soil. Overall, agronomic efficiency through fertilizer management practices, including those related with planting density, time of sowing, weeding, split of fertilizer and application rates need to be further explored. We then therefore expect higher yields besides minimizing the environmental costs associated with fertilizer misuse in SSA.

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