Optimal fertigation for high yield and fruit quality of greenhouse strawberry

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Abstract

Nitrogen (N), phosphorus (P), potassium (K), and water are four crucial factors that have significant effects on strawberry yield and fruit quality. A quadratic regression orthogonal rotation combination experiment that involved 36 treatments with five levels of the four variables (N, P, and K fertilizers and water) was executed to optimize the fertilization and water combination for high yield and quality. SSC/TA ratio (the ratio of soluble solid content to titratable acid) was selected as the index of quality. Results showed that the N fertilizer was the most important factor, followed by water and P fertilizer, and the N fertilizer had a significant effect on yield and SSC/TA ratio. By contrast, the K fertilizer had a significant effect only on yield. N×K fertilizer interaction had a significant effect on yield, whereas the other interactions among the four factors had no significant effects on yield and SSC/TA ratio. The effects of the four factors on the yield and SSC/TA ratio were ranked as N fertilizer > water > K fertilizer > P fertilizer and N fertilizer > P fertilizer > water > K fertilizer, respectively. The yield and SSC/TA ratio increased and then decreased when NPK fertilizer and water increased. The optimal fertilizer and water combination was 22.28–24.61 g/plant $Ca(NO_3)_2 \cdot 4H_2O$, 1.75–2.03 g/plant NaH_2PO_4, 12.41–13.91 g/plant K_2SO_4, and 12.00–13.05 L/plant water for yields of more than 110 g/plant and optimal SSC/TA ratio of 8.5–14.

Introduction

Mineral fertilizers and water have a significant effect on crop yield [1–3]. However, the excessive application of fertilizers may lead to soil and water pollution and become a serious threat to food safety [4,5]. Meanwhile, water scarcity is now a major challenge in China [6]. Therefore, a good management of fertilization and water is increasingly required for agriculture in China.

Strawberry is one of the most profitable fruit cultivars in China, which ranks first in total strawberry production worldwide with a production of 1,801,865 tons in 2016, followed by United States and Mexico among a total of 79 countries [7]. Thus, large amounts of fertilizers and water are needed for strawberry production in China. Consumers prefer strawberries with a sweet taste [8,9]. The strawberry flavor is strongly correlated with the balance between the soluble solid content (SSC) and titratable acid (TA) in ripe fruits [10,11], which are common quality indexes to assess sweetness and sourness [12]. The ratio of SSC/TA is another effective parameter to determine fruit flavor [13,14]. The higher the SSC/TA ratio, the sweeter the fruit [15]. Therefore, increasing strawberry production and enhancing fruit quality with high SSC/TA ratio and without environment pollution are important goals in the field.

Nitrogen (N), phosphorus (P), and potassium (K) are primary mineral fertilizers. N is the most limiting nutrient to crop production because of its important role in cell division [16,17], and N deficiency can decrease crop yield and quality [18,19]. P nutrient is essential for photosynthesis [20], and it is required after emergence [21]. K is the second most abundant element in plant tissues after N [22,23], and it helps enhance water uptake and grain quality [24]. In addition to mineral fertilizers, water greatly contributes to the strawberry fruit content and leaf development [25], and water shortages can lead to large losses of strawberries yield [26].

Although studies have shown that all mineral fertilizers (N, P, and K) and water have effects on the yield and quality of strawberries, most of them only focused on either the effect of water [26–28] or the effect of fertilization [29–33]. The combined application of N, P, and K (NPK) fertilizers and water for high yield and good fruit quality is rarely reported [27,31,34]. Thus, the interaction effect among N, P, and K fertilizers and water on the strawberry yield and fruit quality should be investigated. This study aimed to evaluate the influence of different levels of NPK fertilizers and water on the growth and fruit quality of strawberry and determine the optimal fertilization and water combination for high yield and good quality.

Materials and methods

Experimental site and cultivar

The experiment was conducted for 8 months from November 2016 to June 2017 in an east–west oriented solar greenhouse located in the Zhuozhou Experiment Center, China Agricultural University, China. The Chinese solar greenhouse, as a horticultural facility, is a kind of mono-slope greenhouse that provides effective energy use and is widely used in China, especially in the northern latitudes [35,36]. The structure of this solar greenhouse has a typical width, length, backwall height, and roof height of 8, 50, 2.4, and 3.5 m, respectively (Fig 1).

Fig 1. Solar greenhouse block diagram.

(A) Section view. (B) Top view.

The strawberry cultivar used was 'Hongyan', which has been studied extensively in China [37–40]. It was cultivated on substrate instead of soil in the solar greenhouse with natural light and temperature of 10 °C–26 °C. The substrate, with initial chemical characteristics shown in Table 1, was a mixture with a ratio of 10:2:1 rate of peat, vermiculite, and perlite, respectively. The substrate bags, with dimensions of 100 cm×40 cm×20 cm, were obtained from Beijing Greenovo Agriculture Science and Technology Co., Ltd., and every three strawberry plants were grown on each substrate bag (Fig 2). The strawberries were transplanted on November 3, 2016 and hand-harvested at the mature red stage. Thereafter, the fruits were transported to the laboratory within 2 h by using ice bags for cooling.

Fig 2. Strawberry plants grown on substrate bags.

Table 1. Substrate chemical analysis (%)

Properties	Fertility
Total Nitrogen	0.9705
Total Phosphorus	0.466

Potassium	1.07

Experimental method

To reveal the relationship between the NPK+water combination and the fruit yield and achieve the optimal combination, a quadratic regression orthogonal rotation combination experiment was designed involving four factors at five levels in 36 treatments; this technique is currently the most effective method for multi-factor interaction effect analysis [41]. The four factors were N, P, and K fertilizers and water, which were represented by x_1, x_2, x_3, and x_4, respectively. Calcium nitrate ($Ca(NO_3)_2 \cdot 4H_2O$), sodium dihydrogen phosphate (NaH_2PO_4), and potassium sulfate (K_2SO_4), which were obtained from Shanghai Wintong Chemicals Co., Ltd. with a purity of more than 99%, were used as the sources of N, P, and K, respectively. Tap water was used as the source of water. The arrangement of these factors and the levels of variables chosen are shown in Table 2. All treatments were arranged in a completely randomized block with three replications, and each treatment consisted of six plants. A total of 648 plants grown in the experimental solar greenhouse were studied. All plants were fed with a mixture solution of the NPK fertilizers and water weekly following each treatment arrangement 15 days after the transplant, and additional macronutrients and micronutrients were also applied weekly with the same dosage for each treatment (Table 3). The treatment details are presented in Table 4.

Table 2. Design level of four variables in the quadratic regression orthogonal experiment

Variable X	Changing interval Δ_j	Design level of variables ($m_0 = 12$, $\gamma = 2$)				
		$-\gamma$	−1	0	+1	$+\gamma$
x_1 (g/plant)	13.41	12.57	16.77	20.96	25.15	29.34
x_2 (g/plant)	1.21	1.14	1.52	1.89	2.27	2.65
x_3 (g/plant)	4.78	4.48	5.98	7.48	8.97	10.47
x_4 (L/plant)	7.68	7.20	9.60	12.00	14.40	16.80

Table 3. Additional macronutrients and micronutrients applied to each treatment with the same dosage

Fertilizers	Dosage (g/plant)
$MgSO_4$	4.43
EDTA-2NaFe	3.5461
H_3BO_3	0.3381
$MnSO_4 \cdot 4H_2O$	0.2518
$ZnSO_4 \cdot 7H_2O$	0.0260
$CuSO_4 \cdot 5H_2O$	0.0095
$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	0.0024

Measurement of yield and fruit quality traits

An analytical balance (0.01 g accuracy) was used to measure the fruit weight after the fruits were harvested. Parameters of the fruit quality, namely, soluble solid content (SSC) and titratable acidity (TA), were measured after the fruits were transported to the laboratory. SSC (%) was determined by a digital hand-held pocket refractometer (PAL-1, Atago, Japan), whereas TA (%) was measured by neutralization to pH 7.0 with 0.1 N NaOH. Data were presented as percentages of malic acid.

Table 4. Arrangement of variables in the quadratic regression orthogonal experiment and results of the experiment

Treatments	x_1	x_2	x_3	x_4	x_1x_2	x_1x_3	x_1x_4	x_2x_3	x_2x_4	x_3x_4	x_1x_1	x_2x_2	x_3x_3	x_4x_4	Yield g/plant	SSC %	TA %	SSC/TA
1	1	1	1	1	1	1	1	1	1	1	0.33	0.33	0.33	0.33	134.52	13.25	0.89	14.89
2	1	1	1	−1	1	1	−1	1	−1	−1	0.33	0.33	0.33	0.33	116.59	18.83	1.06	17.76
3	1	1	−1	1	1	−1	1	−1	1	−1	0.33	0.33	0.33	0.33	116.61	9.92	0.81	12.25
4	1	1	−1	−1	1	−1	−1	−1	−1	1	0.33	0.33	0.33	0.33	111.56	12.70	0.67	18.96
5	1	−1	1	1	−1	1	1	−1	−1	1	0.33	0.33	0.33	0.33	142.53	10.72	0.55	19.49
6	1	−1	1	−1	−1	1	−1	−1	1	−1	0.33	0.33	0.33	0.33	126.78	22.92	1.02	22.47
7	1	−1	−1	1	−1	−1	1	1	−1	−1	0.33	0.33	0.33	0.33	120.51	13.02	0.90	14.47
8	1	−1	−1	−1	−1	−1	−1	1	1	1	0.33	0.33	0.33	0.33	96.66	9.91	0.61	16.24
9	−1	1	1	1	−1	−1	−1	1	1	1	0.33	0.33	0.33	0.33	110.23	11.35	1.02	11.13
10	−1	1	1	−1	−1	−1	1	1	−1	−1	0.33	0.33	0.33	0.33	100.67	9.92	0.63	15.74
11	−1	1	−1	1	−1	1	−1	−1	1	−1	0.33	0.33	0.33	0.33	116.62	5.43	0.42	12.92
12	−1	1	−1	−1	−1	1	1	−1	−1	1	0.33	0.33	0.33	0.33	118.36	9.62	0.66	14.58
13	−1	−1	1	1	1	−1	−1	−1	−1	1	0.33	0.33	0.33	0.33	115.25	8.81	0.62	14.21
14	−1	−1	1	−1	1	−1	1	−1	1	−1	0.33	0.33	0.33	0.33	98.93	9.59	0.59	16.26
15	−1	−1	−1	1	1	1	−1	1	−1	−1	0.33	0.33	0.33	0.33	100.02	8.64	0.65	13.29
16	−1	−1	−1	−1	1	1	1	1	1	1	0.33	0.33	0.33	0.33	106.46	13.97	1.11	12.59
17	2	0	0	0	0	0	0	0	0	0	3.33	−0.67	−0.67	−0.67	126.51	11.59	0.85	13.64
18	−2	0	0	0	0	0	0	0	0	0	3.33	−0.67	−0.67	−0.67	96.70	7.79	0.62	12.56

19	0	2	0	0	0	0	0	0	0	0	−0.67	3.33	−0.67	−0.67	117.62	8.05	0.61	13.19
20	0	−2	0	0	0	0	0	0	0	0	−0.67	3.33	−0.67	−0.67	116.46	13.16	0.62	21.23
21	0	0	2	0	0	0	0	0	0	0	−0.67	−0.67	3.33	−0.67	127.43	13.83	0.67	20.64
22	0	0	−2	0	0	0	0	0	0	0	−0.67	−0.67	3.33	−0.67	107.63	9.24	0.47	19.67
23	0	0	0	2	0	0	0	0	0	0	−0.67	−0.67	−0.67	3.33	115.23	7.48	0.46	16.26
24	0	0	0	−2	0	0	0	0	0	0	−0.67	−0.67	−0.67	3.33	103.16	9.75	0.53	18.39
25	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	143.59	10.20	0.52	19.62
26	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	130.25	8.78	0.48	18.29
27	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	137.89	11.38	0.70	16.26
28	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	142.57	10.08	0.39	25.84
29	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	150.26	9.03	0.40	22.57
30	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	162.35	9.06	0.42	21.56
31	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	170.42	8.83	0.50	17.65
32	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	150.21	8.02	0.39	20.56
33	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	149.24	9.50	0.57	16.67
34	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	146.52	8.43	0.41	20.56
35	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	130.52	10.21	0.49	20.83
36	0	0	0	0	0	0	0	0	0	0	−0.67	−0.67	−0.67	−0.67	155.67	10.99	0.56	19.63

Results

Yield respond to N, P, and K fertilizers and water

After a significance test on regression coefficients and regression formulas, the equation that governs the effect of N (x_1), P (x_2), K (x_3), and water (x_4) on yield (y_1) is formulated as follows:

$$y_1 = 125.35 + 6.62x_1 + 0.85x_2 + 4.10x_3 + 4.35x_4 - 2.03x_1x_2 + 5.72x_1x_3 + 2.80x_1x_4 - 3.81x_2x_3 - 1.17x_2x_4 + 2.43x_3x_4 - 8.85x_1^2 - 7.49x_2^2 - 7.37x_3^2 - 9.45x_4^2 \quad (R^2 = 0.87). \tag{1}$$

ANOVA results are shown in Table 5. The regression was significant at the 0.01 probability ($F = 10.29 > F_{0.01}(14, 21) = 3.07$), indicating that the regression model was a good fit for the experimental data. The F-value for the lack-of-fit test was 0.13. This value was less than the significant value at the 0.05 probability ($F_{0.05}(10, 11) = 2.85$), which was insignificant; the regression model was relatively suitable. Therefore, this regression model could be used to evaluate the effects of N, P, and K fertilizers on the 'Hongyan' strawberry yield.

Table 5. ANOVA table of effects of N (x1), P (x2), K (x3), and water (x4) on yield (y1).

Source of variance	*df*	*SS*	*MS*	*F-value*	*Significance*
x_1	1.00	1051.26	1051.26	12.74	**
x_2	1.00	17.24	17.24	0.21	ns
x_3	1.00	402.62	402.62	4.88	*
x_4	1.00	454.31	454.31	5.51	*
x_1x_2	1.00	65.69	65.69	0.80	ns
x_1x_3	1.00	522.81	522.81	6.34	*
x_1x_4	1.00	125.89	125.89	1.53	ns
x_2x_3	1.00	232.41	232.41	2.82	ns
x_2x_4	1.00	21.81	21.81	0.26	ns
x_3x_4	1.00	94.28	94.28	1.14	ns
x_1^2	1.00	2506.56	2506.56	30.38	**
x_2^2	1.00	1796.00	1796.00	21.77	**
x_3^2	1.00	1737.75	1737.75	21.06	**
x_4^2	1.00	2859.44	2859.44	34.66	**
Regression	14.00	11888.07	849.15	10.29	**
Residual	21.00	1732.65	82.51		
Lack of fit	10.00	183.29	18.33	0.13	ns
Error	11.00	1549.35	140.85		
Total	35.00	13620.72			

$F_{0.05}$ (1, 21) = 4.32, $F_{0.01}$ (1, 21) = 8.02, $F_{0.05}$ (14, 21) = 2.20, $F_{0.01}$(14, 21) = 3.07, $F_{0.05}$ (14, 21) = 2.20, $F_{0.05}$ (10, 11) = 2.85, $F_{0.01}$ (10, 11) = 4.54.

* and ** are significant at the 0.05 and 0.01 probability levels, respectively.

ns: non-significant differences.

As shown in Table 5, N, K, and water had a significant effect on strawberry yield, but P had no significant effect. The relative magnitude of the effects of N, P, K, and water on yield was N>water>K>P in accordance with the absolute value of the standardized regression coefficient. No significant interaction occurred between N×P, N×water, P×K, P×water, and K×water. Thus, an ideal fit equation could be obtained as follows:

$$y_1 = 125.35 + 6.62x_1 + 4.10x_3 + 4.35x_4 + 5.72x_1x_3 - 8.85{x_1}^2 - 7.49{x_2}^2 - 7.37{x_3}^2 - 9.45{x_4}^2. \quad (2)$$

From the equation above, the partial regression equations were as follows:

$$y_1(x_1) = 125.35 + 6.62x_1 - 8.85{x_1}^2, \quad (3)$$

$$y_1(x_2) = 125.35 - 7.49{x_2}^2, \quad (4)$$

$$y_1(x_3) = 125.35 + 4.10x_3 - 7.37{x_3}^2, \quad (5)$$

$$y_1(x_4) = 125.35 + 4.35x_4 - 9.45{x_4}^2, \quad (6)$$

The partial regression equation results showed that yield rapidly increased with an increase in N and P fertilizers at levels below 0.37 (22.51 g/plant) and 0 (1.89 g/plant), respectively, and rapidly decreased at levels above them (Fig 3). With increasing K fertilizer, the yield rapidly increased and then slowly decreased, and it peaked at the 0.28 (7.90 g/plant) level of K fertilizer. When increasing water, the yield rapidly increased and then gradually decreased, and the maximum value was at the 0.23 (12.55 L/plant) level of water.

Fig 3. Effects of N, P, and K fertilizers and water on the yield.

The interaction effect of every two factors on yield and SSC/TA ratio are shown in Fig 4. Interaction analysis showed that yield rapidly increased and then slowly decreased as the N fertilizer increased but slowly increased and then slowly decreased as the P fertilizer increased. Furthermore, the maximum yield was 126.59 g/plant at 22.51 g/plant $Ca(NO_3)_2 \cdot 4H_2O$ and 1.89 g/plant NaH_2PO_4 (Fig 4(a)). Yield rapidly increased and then slowly decreased with increasing levels of N and K fertilizers, and the maximum yield was 127.16 g/plant at 22.51 g/plant $Ca(NO_3)_2 \cdot 4H_2O$ and 7.90 g/plant K_2SO_4 (Fig 4(b)). The same trends were obtained for N×water interaction, that is, the yield rapidly increased, slowly decreased, and reached the maximum yield of 127.09 g/plant at 22.51 g/plant $Ca(NO_3)_2 \cdot 4H_2O$ and 12.55 L/plant water (Fig 4(c)). Similarly, for the P×K (Fig 4(d)), P×water (Fig 4(e)), and K×water (Fig 4(f)) interactions, the yield increased and then decreased, and the maximum yields were 125.92 g/plant at 1.89 g/plant NaH_2PO_4 and 7.90 g/plant K_2SO_4 (Fig 4(d)), 125.85 g/plant at 1.89 g/plant NaH_2PO_4 and 12.55 L/plant water (Fig 4(e)), and 126.42 g/plant at 7.90 g/plant K_2SO_4 and 12.55 L/plant water (Fig 4(f)), respectively.

Fig4. Effects of interaction among N, P, and K fertilizers and water on the yield.

(A) N-P interaction effect on yield with K fertilizer and water at 0 level. (B) N-K interaction effect on yield with P fertilizer and water at 0 level. (C) N-water interaction effect on yield with P fertilizer and K fertilizer at 0 level. (D) P-K interaction effect on yield with N fertilizer and water at 0 level. (E) P-water interaction effect on yield with N fertilizer and K fertilizer at 0 level. (F) K-water interaction effect on yield with N fertilizer and P fertilizer at 0 level

Frequency analysis was conducted to obtain the optimal fertilization combination for high yield (Table 6). Among 625 kinds of fertilization combinations, 27 combinations of the four factors had a yield of more than 110 g/plant. The 99% confidence interval for N, P, and K fertilizers and water levels were 0.314–0.871, −0.357–0.357, 0.169–0.794, and 0.000–0.592, respectively. Therefore, when applying 22.28–24.61 g/plant $Ca(NO_3)_2 \cdot 4H_2O$, 1.75–2.03 g/plant NaH_2PO_4, 12.41–13.91 g/plant K_2SO_4, and 12.00–13.42 L/plant water, fruit yield will reach more than 110 g/plant with a probability of 99%.

Table 6. Frequency analysis of N, P, and K fertilizers and water for strawberry yield of more than 110 g/plant.

Levels	N fertilizer		P fertilizer		K fertilizer		Water	
	Sets Times	Frequency	Sets Times	Frequency	Sets Times	Frequency	Sets Times	Frequency
−2	0	0.00	0	0.00	0	0.00	0	0.00
−1	0	0.00	7	0.26	1	0.04	2	0.07
0	12	0.44	13	0.48	13	0.48	15	0.56

1	14	0.52	7	0.26	12	0.44	10	0.37
2	1	0.04	0	0.00	1	0.04	0	0.00
Total	27	1	27	1	27	1	27	1
Average	0.593		0.000		0.481		0.296	
Standard error	0.108		0.139		0.121		0.115	
99% confidence interval	0.314–0.871		−0.357–0.357		0.169–0.794		0.000–0.592	
Optimal Fertilization (g/plant)	22.28–24.61		1.75–2.03		12.41–13.91		12.00–13.42	

SSC/TA ratio responds to N, P, and K fertilizers and water

The regression equation that governs the effect on the SSC/TA ratio (y_2) by N (x_1), P (x_2), K (x_3), and water (x_4) is formulated as follows:

$$y_2 = 17.30 + 1.17x_1 - 1.12x_2 + 0.77x_3 - 1.09x_4 - 0.43x_1x_2 + 0.55x_1x_3 - 0.42x_1x_4 - 0.94x_2x_3 - 0.61x_2x_4 - 0.19x_3x_4 - 1.97{x_1}^2 - 0.95{x_2}^2 - 0.21{x_3}^2 - 0.92{x_4}^2 \quad (R^2 = 0.72). \tag{7}$$

ANOVA results are shown in Table 7. The F-value for the regression model was 3.82, which was larger than $F_{0.01}$ (14, 21) = 3.07. Thus, the regression model was a good fit for the experimental data. The F-value for the lack-of-fit test was 0.66. This value was less than the significant value at the 0.05 probability ($F_{0.05}$ (10, 11) = 2.85), which was insignificant. Thus, the regression model was relatively suitable. This regression model could be used to evaluate the effects of N, P, and K fertilizers on the SSC/TA ratio of 'Hongyan' strawberry fruits.

Table 7. ANOVA table of effect of N, P, and K fertilizers and water on the SSC/TA ratio.

Source of variance	*df*	*SS*	*MS*	*F-value*	*Significance*
x_1	1.00	32.60	32.60	5.46	*
x_2	1.00	30.08	30.08	5.04	*
x_3	1.00	14.40	14.40	2.41	ns
x_4	1.00	28.62	28.62	4.80	*
x_1x_2	1.00	2.92	2.92	0.49	ns
x_1x_3	1.00	4.76	4.76	0.80	ns
x_1x_4	1.00	2.81	2.81	0.47	ns
x_2x_3	1.00	14.12	14.12	2.37	ns
x_2x_4	1.00	5.94	5.94	1.00	ns
x_3x_4	1.00	0.59	0.59	0.10	ns
${x_1}^2$	1.00	124.81	124.81	20.92	**
${x_2}^2$	1.00	28.72	28.72	4.81	**

x_3^2	1.00	1.43	1.43	0.24	ns
x_4^2	1.00	27.01	27.01	4.53	*
Regression	14.00	318.81	22.77	3.82	**
Residual	21.00	125.31	5.97		
Lack of fit	10.00	47.05	4.70	0.66	ns
Error	11.00	78.26	7.11		
Total	35.00	456.55			

$F_{0.05}(1, 21) = 4.32$, $F_{0.01}(1, 21) = 8.02$, $F_{0.05}(14, 21) = 2.20$, $F_{0.01}(14, 21) = 3.07$, $F_{0.05}(14, 21) = 2.20$, $F_{0.05}(10, 11) = 2.85$, $F_{0.01}(10, 11) = 4.54$.

* and ** are significant at the 0.05 and 0.01 probability levels, respectively.

ns: non-significant differences.

The N and P fertilizers and water had a significant effect on strawberry fruit's SSC/TA ratio, but the K fertilizer had no significant effect. The relative magnitude of the effects of N, P, and K fertilizers and water on the SSC/TA ratio was N>P>water>K, which was in accordance with the absolute value of the standardized regression coefficient. No significant interaction occurred among N, P, K, and water in terms of the SSC/TA ratio (Table 7). Therefore, an ideal fit equation could be obtained as follows:

$$y_2 = 17.30 + 1.17x_1 - 1.12x_2 - 1.09x_4 - 1.97{x_1}^2 - 0.95{x_2}^2 - 0.92{x_4}^2. \quad (8)$$

From the equation above, the partial regression equations were as follows:

$$y_2(x_1) = 17.30 + 1.17x_1 - 1.97{x_1}^2, \quad (9)$$

$$y_2(x_2) = 17.30 - 1.12x_2 - 0.95{x_2}^2, \quad (10)$$

$$y_2(x_4) = 17.30 - 1.09x_4 - 0.92{x_4}^2. \quad (11)$$

The partial regression equation results showed that the SSC/TA ratio rapidly increased with an increase in P and water at levels below −0.59 (1.67 g/plant) and −0.59 (10.58 g/plant), respectively, and slowly decreased at levels above them (Fig 5). With increasing N, the SSC/TA ratio gradually increased and then gradually decreased, with a maximum value at the 0.30 (22.22 g/plant) level of N.

Fig 5. Effects of N, P, and K fertilizers and water on the SSC/TA ratio.

The SSC/TA ratio rapidly increased and then rapidly decreased with increasing levels of N, whereas it slowly increased and then rapidly decreased with increasing P; meanwhile, the maximum SSC/TA ratio was 17.80 at 22.22 g/plant Ca $(NO_3)_2 \cdot 4H_2O$ and 1.67 g/plant NaH_2PO_4 (Fig 6(a)). The same trend in Fig 6(a) was obtained in Fig 6(b) for the N×water interaction, and the maximum SSC/TA ratio was 17.80 at 22.22 g/plant Ca $(NO_3)_2 \cdot 4H_2O$ and 10.58 L/plant water (Fig 6(b)). For the P×water interaction, the SSC/TA ratio slowly increased and then rapidly decreased with increasing P fertilizer and water, and the maximum SSC/TA ratio was 17.64 at 1.67 g/plant NaH_2PO_4 and 10.58 L/plant water (Fig 6(c)).

Fig 6. Effects of the interaction among N, P, and K fertilizers and water on the SSC/TA ratio.

(A) N-P interaction effect on SSC/TA ratio with water at 0 level. (B) N-water interaction effect on SSC/TA ratio with P fertilizer at 0 level. (C) P-water interaction effect on SSC/TA ratio with P fertilizer at 0 level.

Frequency analysis was performed to obtain the optimal fertilization combination for preferable SSC/TA ratio (Table 8). Among 625 kinds of fertilization combinations, 47 combinations of the three factors were available with strawberry fruit's SSC/TA ratio varying between 8.5 and 14. The 99% confidence interval for N, P, and water levels were 0.101–0.962, −0.663–0.407, and −0.650–0.437, respectively. Thus, when applying 21.38–24.99 g/plant $Ca(NO_3)_2 \cdot 4H_2O$, 1.64–2.04 g/plant NaH_2PO_4, and 10.44–13.05 L/plant water, the fruit SSC/TA ratio will reach 8.5–14 with a probability of 99%.

Table 8. Frequency analysis of N, P, and water for strawberry fruit's SSC/TA ratio of 8.5–14.

Levels	N fertilizer		P fertilizer		Water	
	Sets Times	Frequency	Sets Times	Frequency	Sets Times	Frequency
−2	0	0.00	12	0.26	12	0.26
−1	12	0.26	8	0.17	8	0.17
0	11	0.23	8	0.17	8	0.17
1	11	0.23	12	0.26	11	0.23
2	13	0.28	7	0.15	8	0.17
Total	47	1	47	1	47	1
Average	0.532		−0.128		−0.106	
Standard error	0.167		0.208		0.211	
99% confidence interval	0.101–0.962		−0.663–0.407		−0.650–0.437	
Optimal Fertilization (g/plant)	21.38–24.99		1.64–2.04		10.44–13.05	

Optimal fertilization combination for both high yield and best quality

In accordance with the intersection calculation of the optimal fertilization combination for high yield and best quality, the best fertilization combinations for high yield (more than 110 g/plant) and best fruit SSC/TA ratio (8.5–14) were 22.28–24.61 g/plant $Ca(NO_3)_2 \cdot 4H_2O$, 1.75–2.03 g/plant NaH_2PO_4, 12.41–13.91 g/plant K_2SO_4, and 12.00–13.05 L/plant water.

Discussion

Currently, market intermediaries pay considerable attention to fruit quality to enhance profits by meeting consumers' preferences of sweetness [11,42], and the SSC/TA ratio has been widely used as a reliable predictor to evaluate the strawberry flavor of sweetness and sourness. Strawberries are sweeter if their SSC/TA ratio is high than if their SSC/TA ratio is low [12,15,28,43,44]. The minimum SSC/TA ratio for acceptable flavor is 8.75 [45], and people prefer the taste of cultivars 'Clery' and 'Daroyal', which have high SSC/TA ratios of 9.66 and 9.26, respectively [46]. The cultivar 'NCS 10-156' has an SSC/TA ratio of 11.6, and it is believed to be more suitable for sale than other cultivars [47]; all these SSC/TA ratios are consistent with the typical range (8.5–14) for strawberries with optimal fruit quality [48,49]. In general, the SSC/TA ratio is an important parameter to evaluate fruit quality for strawberry production [50,51]. Therefore, the SSC/TA ratio was the focus of this study.

Previous studies have shown that N, P, K, and water have significant effects on the yield and fruit quality of strawberry [27,52–55]. A quadratic regression orthogonal rotation combination experimental design was used to investigate the optimal fertilization and water combination for high strawberry yield and best fruit quality with optimal SSC/TA ratio. In the present work, N, P, and water had a significant effect on yield and SSC/TA ratio, whereas K had a significant on yield only. Except for the interaction between N and K having a significant effect on yield, the other interactions among the four factors had no significant effect on yield and SSC/TA ratio. The effects of the four factors on yield and SSC/TA ratio were ranked as N>water>K>P and N>P>water>K, respectively. N was the most important factor among the four factors that had a significant effect on yield and SSC/TA ratio. Thus, N was the key factor in determining the fruit yield and quality. By contrast, when application levels were above 0, P and water had a significant negative effect on the SSC/TA ratio; this result was consistent with findings of previous studies [27,56]. Excessive P suppresses SSC production and promotes TA formation, and excessive water reduces the fruits' sweetness perception.

The combined application of fertilizer and water should be optimized based on the interaction analysis in the present study. The yield and SSC/TA ratio increased and then decreased as two factors increased but the two other factors were fixed at 0. These trends indicated maximum or optimal values of yield and SSC/TA ratio.

The optimal fertilizer and water combination for high yield (>110 g/plant) and best fruit quality (SSC/TA ratio of 8.5–14) was achieved by using a quadratic regression orthogonal rotation combination experimental design and variance analysis. The optimal fertilizer and water combination was found to be 22.28–24.61 g/plant $Ca(NO_3)_2{\cdot}4H_2O$, 1.75–2.03 g/plant NaH_2PO_4, 12.41–13.91 g/plant K_2SO_4, and 12.00–13.05 L/plant water.

Conclusion

N was the most important factor on yield and SSC/TA, followed by water and P. N, P, and water significantly influenced yield and SSC/TA, whereas K had a significant effect only on yield. The N×K interaction had a significant effect on yield. However, the other interactions among the four factors showed no significant effects on the yield and SSC/TA. The effects of the four factors on the yield and SSC/TA ratio were ranked as N>water>K>P and N>P>water>K, respectively. The yield and SSC/TA ratio increased and then decreased when NPK fertilizers and water increased. The optimal fertilizer and water combination for high yield (>110 g/plant) and best fruit quality (SSC/TA ratio of 8.5–14) was 22.28–24.61 g/plant $Ca(NO_3)_2{\cdot}4H_2O$, 1.75–2.03 g/plant NaH_2PO_4, 12.41–13.91 g/plant K_2SO_4, and 12.00–13.05 L/plant water. The results obtained in this study are believed to be useful for further research on fertilization and water application in crops.

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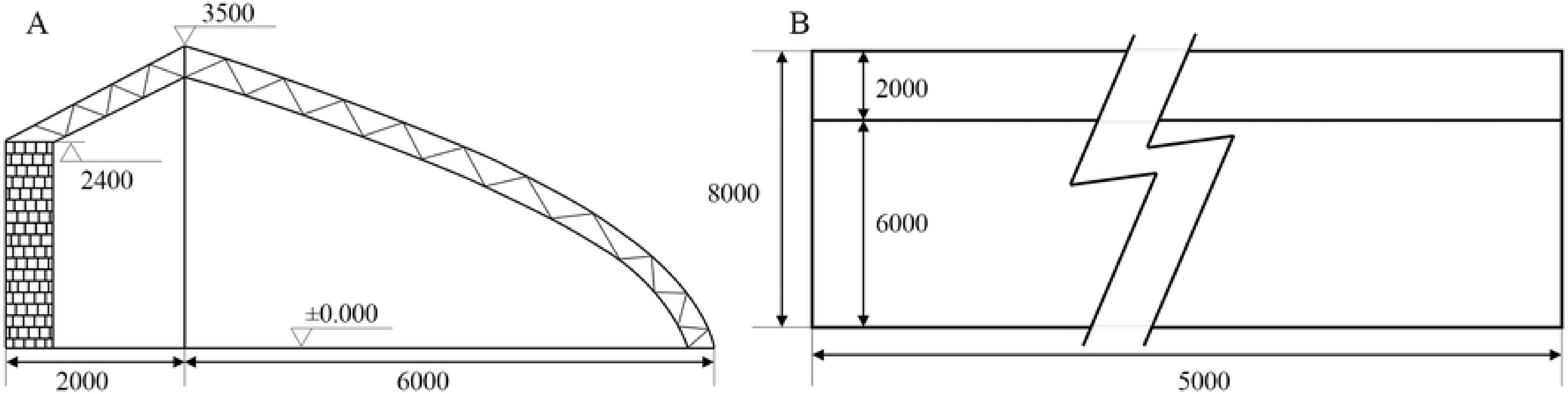
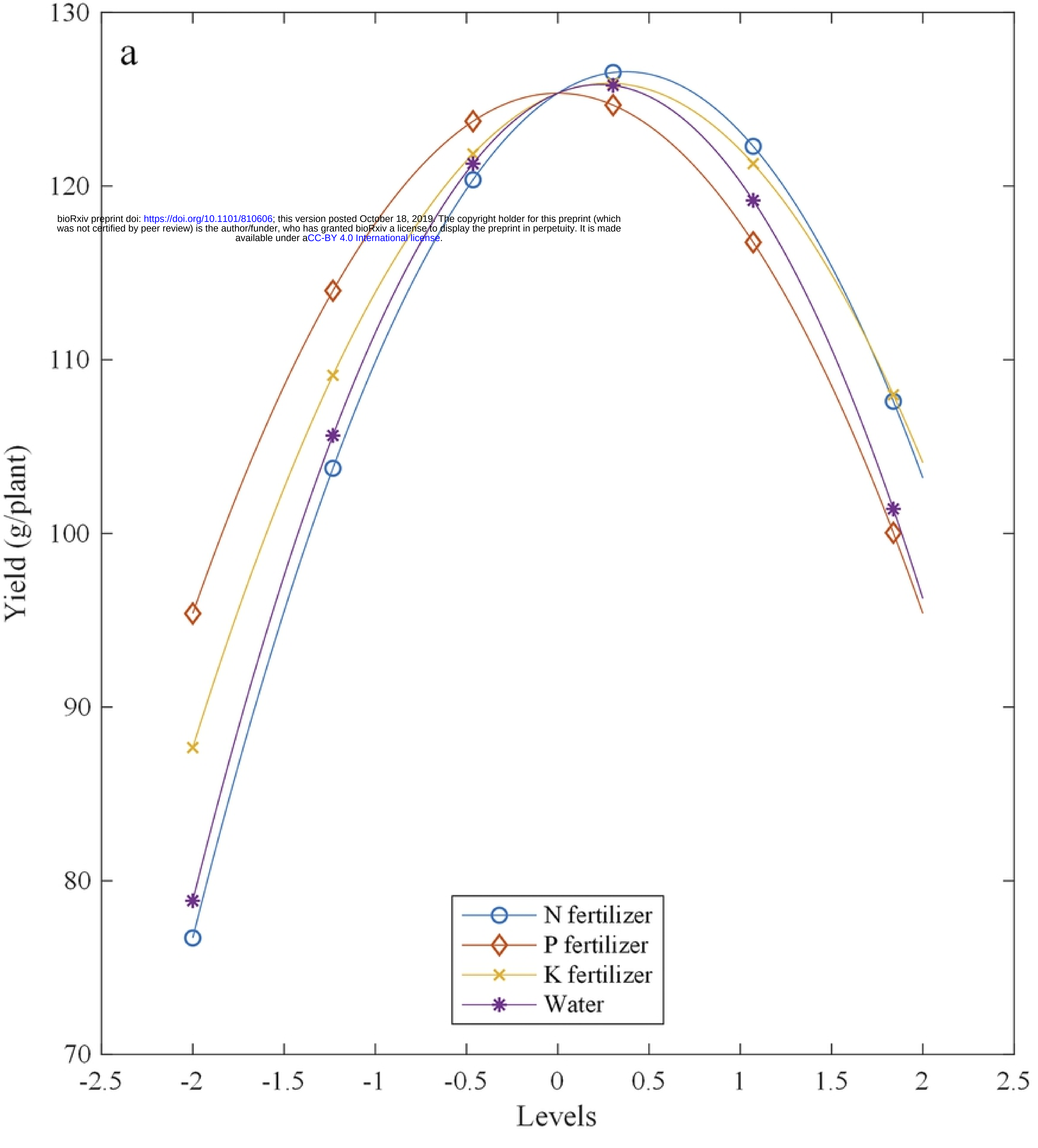


Fig1

Fig2


a
Yield (g/plant)
130
120
110
100
90
80
70
-2.5
-2
-1.5
-1
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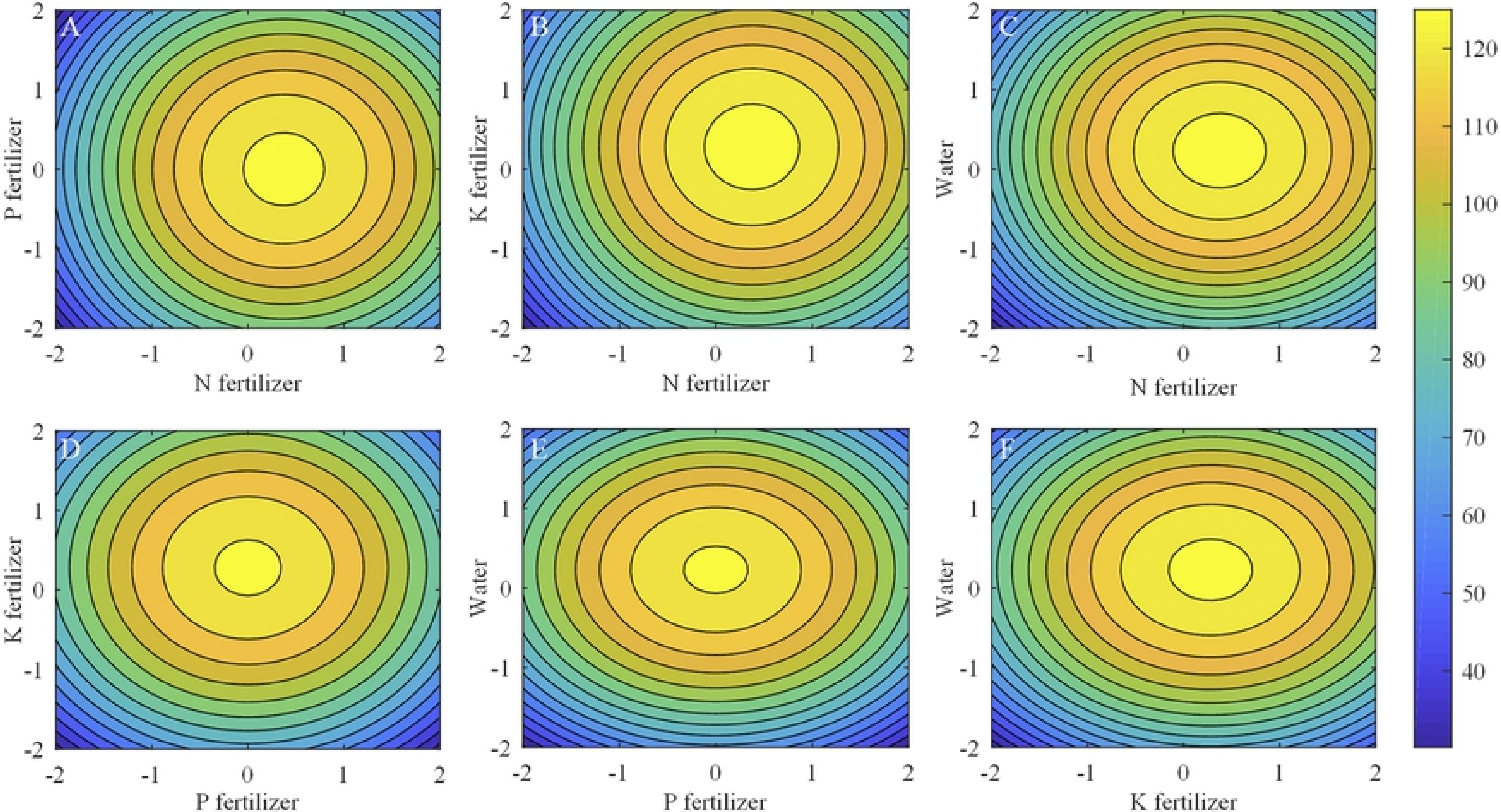
0
0.5
1
1.5
2
2.5
Levels
N fertilizer
P fertilizer
K fertilizer
Water

Fig3


A
B
C
D
E
F
P fertilizer
K fertilizer
Water
N fertilizer
P fertilizer
K fertilizer
-2
-1
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1
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90
100
110
120

Fig4

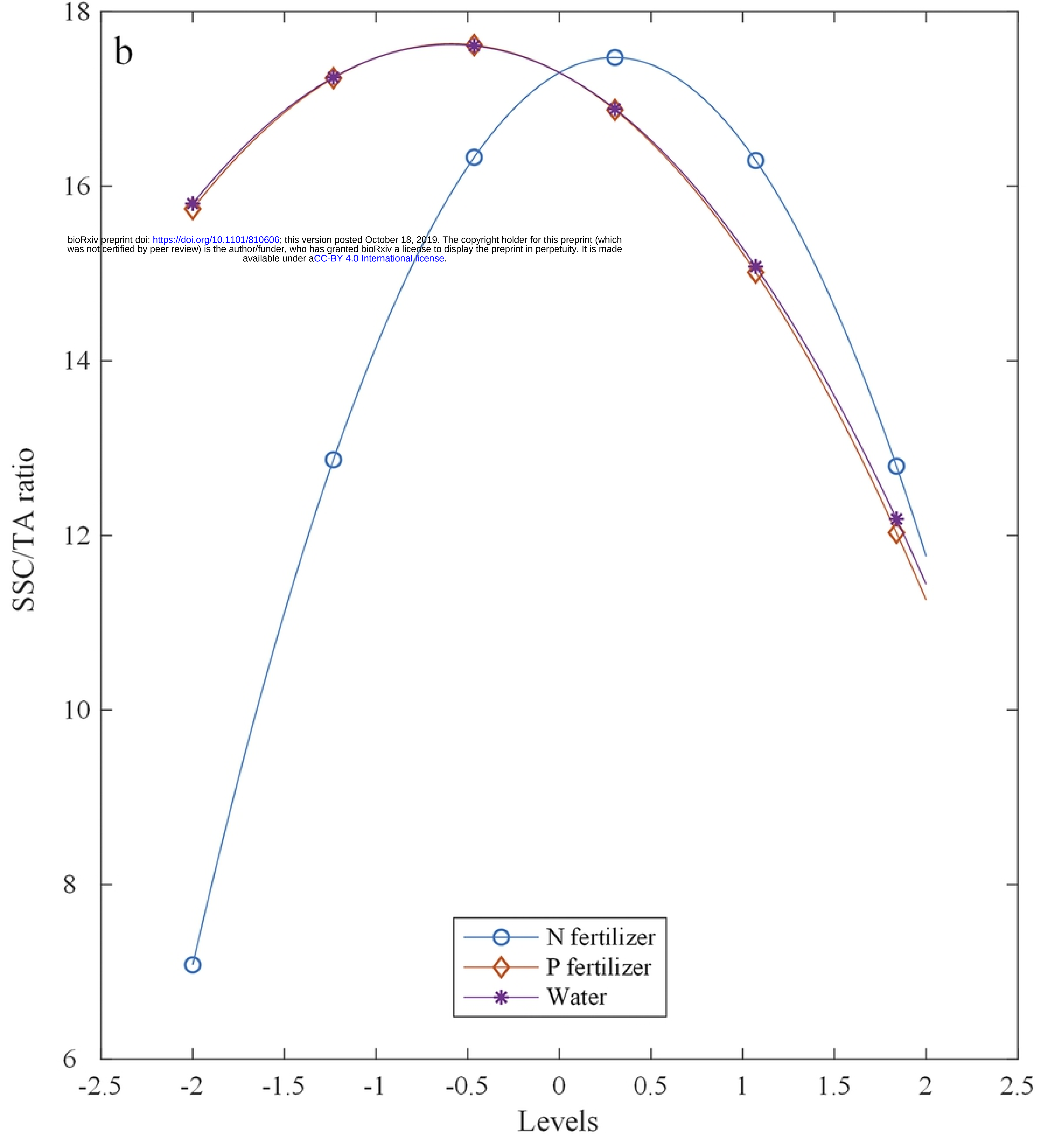
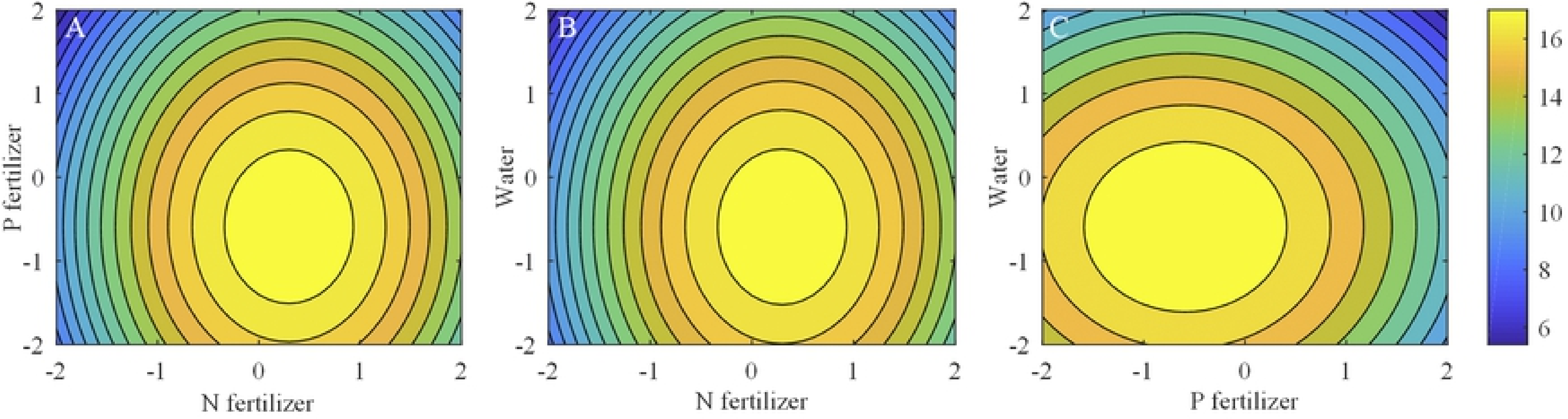

b
18
16
14
12
10
8
6
SSC/TA ratio
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Levels
N fertilizer
P fertilizer
Water

Fig5



A
B
C
P fertilizer
N fertilizer
Water
N fertilizer
Water
P fertilizer
2
1
0
-1
-2
16
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12
10
8
6

Fig6