

Effect of high temperature on mineral uptake, Soluble carbohydrates partitioning and cucumber yield

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Abstract : Plastic film houses are directly associated with increases in plant growth and yield of vegetable crops through a year round cultivation, however, at the same time temperature stresses are one of fates which are difficult to avoid during crop growth. The objective of this study was to examine the translocation and distribution of minerals (N, P, K) and carbohydrates as well as seasonal fluctuation of mineral uptake and carbohydrate production in cucumber plant grown under moderately high temperature. The temperature treatments consisted of 2-layers film houses (optimal temp.) and 3-layers (high temp.). Shoot growth of cucumber plants were linearly increased until 14 weeks after transplanting (WAT) without any significant difference between both temperatures, and the slowdown was observed from 16 WAT. The level of soluble sugar and starch was slightly greater in optimal temperature compared to the high. Cumulative accumulation of soluble sugar was significantly different before and after 12 WAT in both treatments, whereas starch level represented a constant increase. Monthly production of soluble sugar reached the peak between 12 to 16 WAT, and starch peaked between 4 to 8 WAT and 12 to 16 WAT. Total uptake of N, P and K in optimal and high temperature conditions was 18.4g plant⁻¹ and 17.6 for N, 4.7 and 5.1 for P, and 37.7 and 36.2 for K, respectively, and the pattern of monthly N uptake between optimal and high temperatures was greater in early growth stage, whereas was greater in mid growth stage in both P and K. Thus, this study suggests that moderately high temperature influences much greater to photosynthesis and carbohydrate production than plant biomass and mineral uptake. On the basis of the present result, it is required to indentify analysis of respiration rates from plant and soil by constantly increasing temperature conditions and field studies where elevated temperatures are monitored and manipulated.

Key words : Plastic film house, Cucumber, Mineral uptake, Carbohydrates, High temperature

I. Introduction

The production of vegetable crops has shown significant yield increases in South Korea since over the last several decades. The utilization of plastic mulch in combination with drip irrigation has played a major role in the increases in production of many vegetable crops, and the majority of the reports on plastic mulches show that increased RZT is one of the main benefits associated with the use of plastic mulches (Lamont, 1993). The concentration of mineral elements in crop shoot was increased by plastic mulches (Wien and Minotti, 1987), the improvement

of root growth and nutrient uptake led to an increased aboveground growth of crop (Wien et al., 1993). On the other hand of the benefits by enhanced root zone temperature, heat stress due to high ambient temperatures is a serious threat to crop production worldwide (Hall, 2001). Transitory or constantly high temperatures cause a variety of morpho-anatomical, physiological and biochemical changes in plants, which affect plant growth and development and may result in a significant reduction in economic yield. At moderately high temperatures, injuries or death to crop plants may occur only after long-term exposure, and it may be derived from a limited photosynthesis, assimilate partitioning, and water and nutrient use efficiency (Kuiper, 1964; Walker, 1969; Ruter and

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Ingram, 1990). A well-known consequence of elevated temperature in plants is the damage caused by heat-induced imbalance in photosynthesis and respiration; in general, the rate of photosynthesis decreases whereas dark- and photo-respiration rates increase considerably under high temperatures (Nakamoto and Hiyama, 1999). Assimilate partitioning, taking place via apoplastic and symplastic pathways under high temperatures, has significant effects on transport and transfer processes in plants although it strongly depends on genotypes (Yang et al., 2002; Taiz and Zeiger, 2006). Mineral uptake by plants from the rhizosphere is directly influenced by soil temperature, and the lower (chilling) and higher (heat) temperatures compared to the optimum lead to a considerable reduction in mineral uptake (Cumbus and Nye, 1984; Raju et al., 1990; Tindall et al., 1990). Cucumber (*Cucumis sativus*) is one of the most popular vegetable crops cultivated commercially worldwide, and the scale of film house-based cultivation throughout South Korea was approximately 2,836 ha (MAFRA statistics, 2014). Furthermore, a year round cultivation of cucumber often induces the unexpected heat (high in summer season) and chilly (low in winter season) stresses, and thus results in deleterious effects on the growth and yield. Although the literature on plant responses to temperatures is abundant, there are few studies estimating mineral uptake and carbohydrate production during whole growth season. The objective of this study was to examine the translocation and distribution of minerals (N, P, K) and carbohydrates as well as seasonal fluctuation of mineral uptake and carbohydrate production in cucumber plant grown under moderately high temperature.

II. Materials and Method

1. Plant materials and growth conditions

This study was performed at a farmer's greenhouse located in Byoungcheon-myeon, Cheonan-si, Chung-

cheongnam-do, South Korea in 2013 for cucumber (*Cucumis sativus* cv. Backdadagi). Cucumber seedlings were transplanted on March 1, 2013 with a planting interval of 0.6 m. The mineral sources applied into the soil as a basal fertilizer were as follows; rice straw (2,000 kg), micro-elements (13 kg), bone dust (26 kg), amino acids-containing fertilizer (52 kg) and ash (78 kg) per 1,000 m². An additional fertilizer (12 L per day), liquid manure, was supplied every day for 5 months after 2 weeks of transplanting using a fertigation system. Mineral composition of all fertilizer sources used in this study was described in table 2. In order to elevate air and soil temperatures in greenhouse, we installed 3-layers plastic films compared to 2-layers in conventional cultivation (optimal), and the daily fluctuation of temperature was monitored during growth season (Fig. 1). Cucumber plants were taken to determine the contents of carbohydrates and mineral elements at every two weeks, and the fruit to estimate the yield was harvested as it was fully developed.

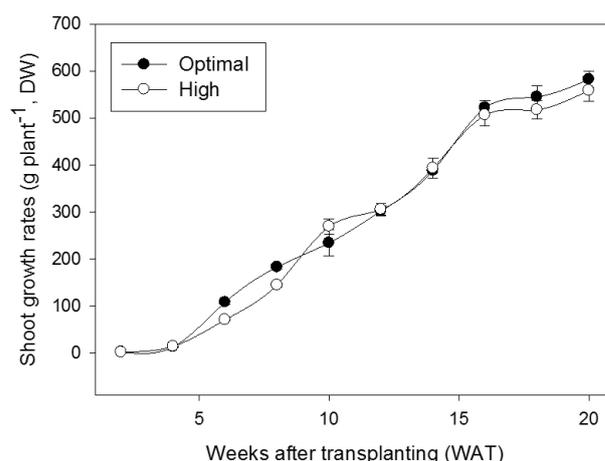


Fig. 1. Time-coursed changes in growth rates of cucumber shoot (leaf + stem + fruit) grown under different temperature conditions (n=5). Cucumber seedlings were transplanted on March 1st, 2013. The symbols indicate optimal (closed) and high (opened) temperatures, respectively.

2. Measurement of soluble carbohydrates

Soluble sugar from fresh leaf, stem and fruit was determined by the reaction of 1.0 mL of the alcoholic extract with 2.0 mL fresh 0.2% anthrone in sulfuric acid (w/v); the absorbance was read at 630 nm. After the extraction of the soluble fractions, the solid fraction was used for starch analysis. Starch was extracted with 9.3 mol L⁻¹ perchloric acid followed by 4.6 N. The extracts were combined and starch concentration was determined after reaction with the anthrone reagent. Glucose was used as the standard for soluble sugar.

3. Measurement of nutrients

Fresh plants were separated into young leaves, fully-expanded leaves, petioles, stems and roots, and then washed with tap water followed by distilled water. One gram of separated fresh samples was ground with 20 mL of dH₂O, passed through a membrane filter (0.45 µm), and used as a sample for measuring water soluble minerals. The oven-dried samples (0.3 g) which were at 80°C for 48 h were soaked in 5 mL of 368 mmol⁻¹ L salicylic acid in 84.7 % sulfuric acid (H₂SO₄) for 24 h then digested in a digestion system, heated to 300°C for 3 h, followed by several drops of hydrogen peroxide (H₂O₂). The extracted solution was transferred to 100 mL volumetric flasks and then diluted to 100 mL with deionized water for mineral assays. The N concentration was colorimetrically determined using the automatic flow injection analyzer (BRAN LUBBE, Germany). The

P concentration was measured using the molybdate–blue colorimetry method (UV–2450, Shimadzu, Japan) and cation concentrations were determined with ICP–OES (INTEGRA XMP, GBC, Australia). The uptake ratio of each N, P, and K of each treatment was calculated as a ratio of each nutrient concentration in each treatment to that in NPK sufficient condition.

4. Statistical analysis

The analysis of variance (ANOVA) was conducted to find effects of treatments. Least significant difference (LSD) was performed to determine the significance of the difference between the means of treatments. *Pearson's* correlation coefficient analysis was performed to determine the relationship between minerals. An α value of 0.05 was chosen to indicate statistical significance. All statistical analysis was performed using version 9.01 of SAS (SAS Institute Inc, Cary, NC).

III. Results and Discussion

Soil chemical properties during whole growth period were examined and compared between both temperature conditions (Table 1). All chemical indices were not significantly different between both temperatures, but were greater than those of the recommended optimal range except soil pH. Mineral composition of fertilizer sources applied into the soil as basal and additional fertilizers were described in table 2. As a result of mineral composition, rice straw, amino acids-containing fertilizer, bone dust

Table 1. Comparison of soil chemical properties between temperature treatments during whole growth period.

Temperature	pH (1:5)	EC (dS m ⁻¹)	OM (g kg ⁻¹)	T-N (%)	Av. P ₂ O ₅ (mg kg ⁻¹)	Exch. cations (cmolc+kg ⁻¹)			
						K	Ca	Mg	Na
Optimal	7.2 - 7.5	1.76 - 3.83	29 - 31	0.12 - 0.14	717 - 805	0.96 - 1.08	9.7 - 11.0	3.9 - 4.4	0.49 - 0.63
High	7.2 - 7.4	2.37 - 4.26	31 - 33	0.12 - 0.14	780 - 848	0.93 - 1.27	10.1 - 11.0	3.8 - 4.7	0.42 - 0.58
Optimal range of soil chemistry	6.0 - 6.5	< 2.0	20 - 30	-	400 - 500	0.70 - 0.80	5.0 - 6.0	1.5 - 2.0	-

Table 2. Mineral composition of fertilizer sources applied into the soil as basal and additional fertilizers.

Time	Fertilizer source	N	P	K	Ca	Mg	Na	Fe	Cu	Mn	Zn
		%						mg kg ⁻¹			
Basal	Rice straw	1.22	0.14	0.14	0.70	0.31	nd	3,145	54	75	nd
	Micro-elements	0.04	0.22	0.68	0.86	0.60	0.45	8,213	16	145	nd
	Bone dust	0.11	2.35	0.19	8.99	0.80	0.86	1,724	20	nd	30
	Amino acids-containing fertilizer	9.00	0.31	1.93	0.33	0.17	1.78	1,596	9	nd	nd
	Ash	0.14	0.41	3.43	3.04	1.00	0.91	8,756	38	54	nd
Additional	Liquid manure	0.20	nd	0.15	0.02	0.01	0.08	9	nd	nd	nd

Table 3. Concentration of macro elements in leaf, stem and fruit of cucumber plants subjected to high temperature during whole growth period.

Temperature	Tissue	N	P	K	Ca	Mg
		%, DW				
Optimal	Leaf	2.59 - 3.52	0.23 - 0.49	2.35 - 4.63	2.40 - 4.90	0.80 - 1.59
	Stem	1.32 - 2.24	0.50 - 0.78	4.73 - 6.87	0.73 - 1.12	0.48 - 0.72
	Fruit	2.85 - 5.15	0.62 - 1.13	4.93 - 7.02	0.51 - 0.83	0.36 - 0.47
High	Leaf	2.29 - 3.29	0.36 - 0.61	4.09 - 5.37	2.73 - 4.34	1.10 - 1.65
	Stem	1.25 - 2.21	0.56 - 0.94	3.45 - 7.30	1.03 - 2.69	0.52 - 0.96
	Fruit	2.78 - 4.98	0.82 - 1.26	5.48 - 7.40	0.65 - 1.13	0.43 - 0.68

and ash were used as a soil physical amendment, N source, P source and K source, respectively. In addition, all basal fertilizer sources contained huge amount of iron (Fe). The temperature of air and soil in greenhouse was not different between both treatments (data not shown), but, on the average, 3-layers plastic film-covered treatment (high temperature) was approximately 2°C higher during whole growth season.

1. Growth and yield of cucumber

The shoot growth rates were linearly increased until 14 weeks after transplanting (WAT) without any significant difference between both temperatures (Fig. 1), and the slowdown of cucumber growth was observed from 16 WAT. Total shoot weight grown for 20 weeks was 581.9 g plant⁻¹ (leaf + stem + fruit) for optimal and 558.4 for high. Fruit fresh weight and total yield of fruit per 10 a for whole growth season was not significant between both temperature conditions

(Table 3). The fresh weight of each fruit was between 180 to 190 g, and total yield was 18 to 20 Mg 10a⁻¹.

2. Carbohydrates production

Temporal changes in the contents of soluble sugar and starch from leaf, stem and fruit of cucumber plant were monitored at every two weeks during the whole growth season (Fig. 2). Overall, the level of soluble sugar and starch was slightly greater in optimal temperature compared to the high. Soluble sugar was the greatest in leaf, and followed fruit and stem until early growth stage (6 WAT), after that time point, the level in fruit was kept the highest, which ranged from 4.2 to 7.3 mg g⁻¹ in optimal and from 3.7 to 6.2 in high, on the other hand, the level in leaf was sharply declined at 8 WAT and constantly maintained low until the end of growth season (from 1.1 to 2.1 mg g⁻¹ in optimal and from 0.7 to 1.4 in high). Soluble sugar in stem showed similarly with leaf, which represented a drastic decline. A tendency of starch level was

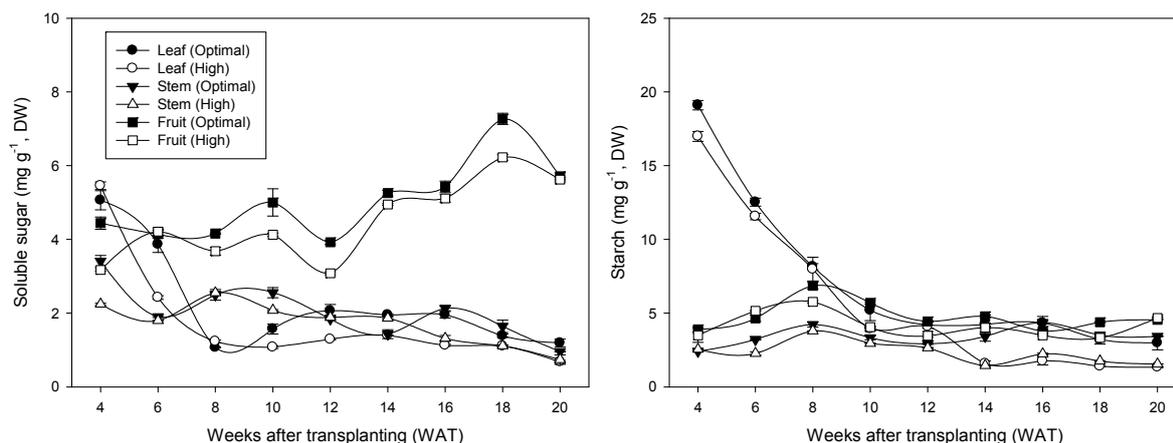


Fig. 2. Time-coursed changes in soluble sugars and starch contents in leaf, stem and fruit of cucumber plants grown under different temperature conditions (n=5). Cucumber seedlings were transplanted on March 1st, 2013. The symbols indicate optimal (closed) and high (opened) temperatures, and leaf (circle), stem (triangle) and fruit (rectangular), respectively.

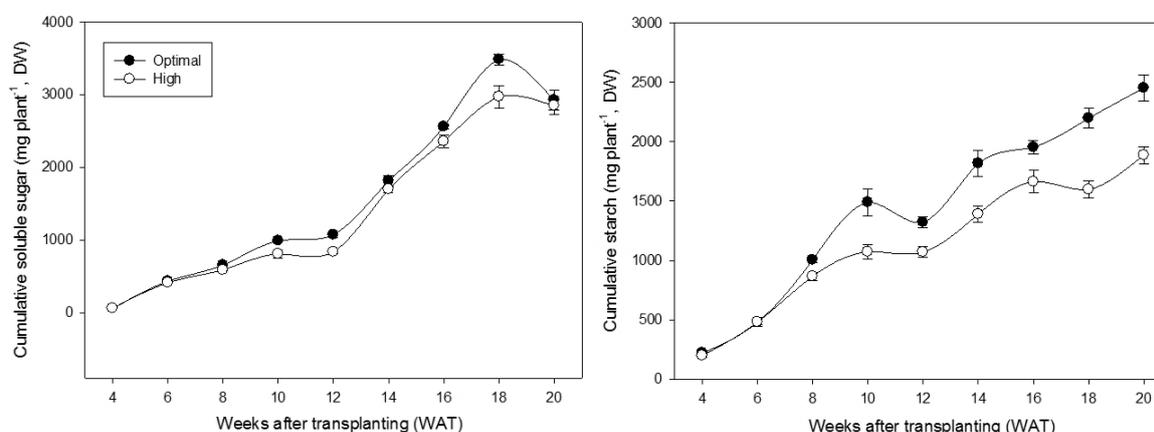


Fig. 3. Cumulative levels of soluble sugars and starch in cucumber plants grown under different temperature conditions (n=5). Cucumber seedlings were transplanted on March 1st, 2013. The symbols indicate optimal (closed) and high (opened) temperatures, respectively.

extremely different with soluble sugar. The starch in leaf was significantly greater (2.0 to 9.0 fold) at early growth stage (until 8 WAT) than that in stem and fruit, but the level was greatly declined to the similar level to stem and fruit. Furthermore, the starch level in leaf and stem subjected to high temperature (1.3 to 2.2 mg g⁻¹) represented significantly lower than optimal (3.2 to 4.3 mg g⁻¹) after 14 WAT. We estimated the production of cumulative (Fig. 3) and monthly (Fig. 4) soluble sugar and starch during the whole growth season based on the data from leaf, stem and fruit of cucumber plant. The difference in cumulative soluble sugar and starch levels between both tem-

perature conditions revealed obviously after 8 WAT. The accumulation of soluble sugar was significantly different before and after 12 WAT in both treatments, and it showed 127 mg g⁻¹ per week in optimal and 97 mg g⁻¹ in high from 4 to 12 WAT whereas 402 mg g⁻¹ per week in optimal and 356 mg g⁻¹ in high from 12 to 18 WAT, which means about 2.0 to 2.5 fold greater in late growth season compared to the early season. On the other hand, starch level represented a constant increase, which indicates 140 mg g⁻¹ per week in optimal and 106 mg g⁻¹ in high. Monthly production of soluble sugar reached the peak between 12 to 16 WAT (1489 mg g⁻¹ in optimal and 1523 mg g⁻¹

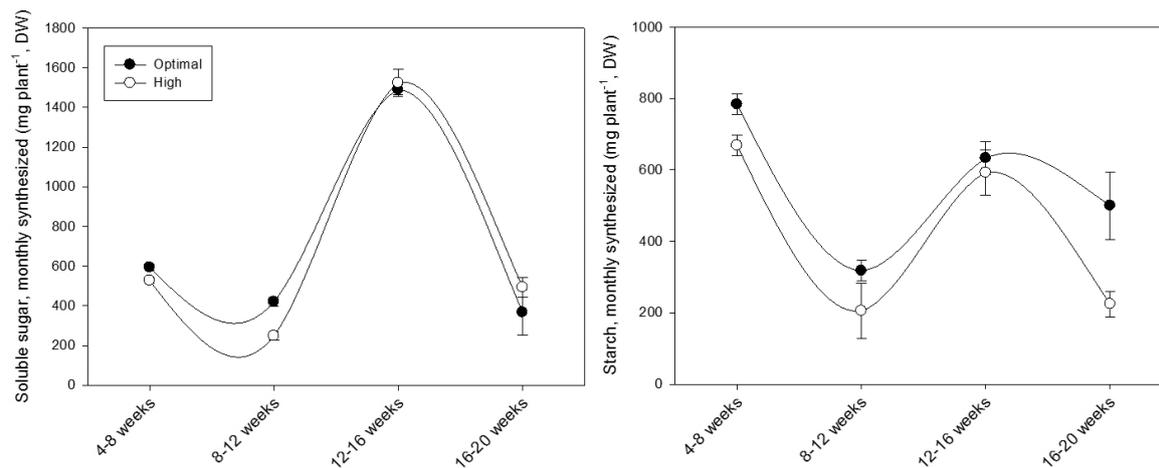


Fig. 4. Monthly synthesis of soluble sugars and starch in cucumber plants grown under different temperature conditions ($n=5$). Cucumber seedlings were transplanted on March 1st, 2013. The symbols indicate optimal (closed) and high (opened) temperatures, respectively.

Table 4. Yield of cucumber fruits under different growth temperature conditions.

Temperature	Fresh weight (g fruit ⁻¹)	No. of fruit per plant	Yield per plant (kg)	Yield (Mg 10a ⁻¹)
Optimal	188.2 ± 6.6 ^{ns}	67.4 ± 1.5 ^{ns}	12.0 ± 0.7 ^{ns}	19.2 ± 1.2 ^{ns}
High	183.9 ± 5.2	66.0 ± 1.0	11.7 ± 0.4	18.7 ± 0.7

in high, respectively), whereas starch peaked between 4 to 8 WAT and 12 to 16 WAT. More carbon losses due to increased respiration and the shortage of non-structural carbohydrate have been considered as a factor responsible for plant growth by high temperature (Younger and Nudge, 1968; Canmore-Neumann and Kafkafi, 1983), and this observation is consistent with our results. On the other hand, other researchers (Sattelmacher et al., 1990b; Du and Tachibana, 1994) suggested that sugar increased as the result of both growth cessation and the changes in carbohydrate metabolism. Therefore, it is considered that moderately enhanced temperature like our study led to much more consumption of soluble carbohydrates to maintain cellular respiration than modified carbohydrate metabolism.

3. Concentration and uptake of minerals

The concentration of macro elements from leaf, stem and fruit of cucumber plant exposed to optimal

and high temperature conditions was measured during the whole growth season (Table 3). All elements measured from each tissue were not significant between both temperature conditions, and the concentration of each element was strongly dependent upon tissue. Nitrogen (N), phosphorus (P) and potassium (K) were the greatest in fruit, which means 2.85 to 5.15, 0.62 to 1.13 and 4.93 to 7.02% (dry weight based) in optimal and 2.78 to 4.98, 0.82 to 1.26 and 5.48 to 7.40% in high, respectively, and followed by stem and leaf. On the other hand, calcium (Ca) and magnesium (Mg) were the greatest in leaf, which indicates 2.40 to 4.90 and 0.80 to 1.59 in optimal and 2.73 to 4.34 to 1.10 to 1.65 in high, respectively. The trend of minerals (N, P and K) concentration in both temperature conditions was increased in leaf whereas decreased in stem and fruit with an increase in growth stage (data not shown). We also examined growth stage-based (Fig. 5) and monthly (Fig. 6) uptake of minerals, N, P and K, in optimal and high temperature conditions based on the data of dry weight and mineral con-

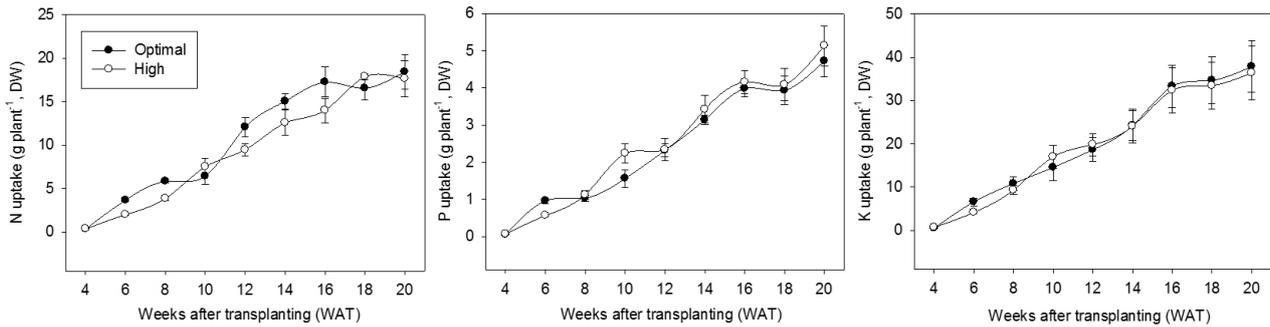


Fig. 5. Cumulative uptake of nitrogen (N), phosphorus (P) and potassium (K) in cucumber plants grown under different temperature conditions (n=5). Cucumber seedlings were transplanted on March 1st, 2013. The symbols indicate optimal (closed) and high (opened) temperatures, respectively.

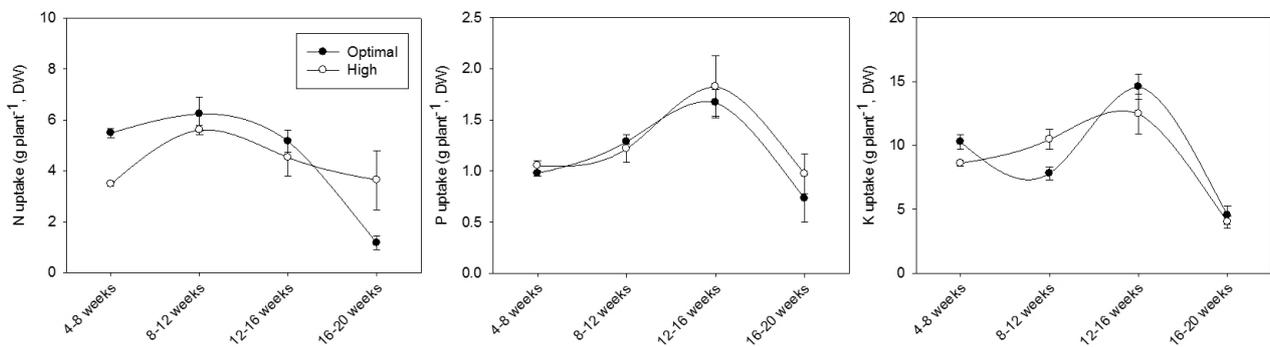


Fig. 6. Monthly uptake of nitrogen (N), phosphorus (P) and potassium (K) in cucumber plants grown under different temperature conditions (n=5). Cucumber seedlings were transplanted on March 1st, 2013. The symbols indicate optimal (closed) and high (opened) temperatures, respectively.

centration, and the significant difference in mineral uptake between both conditions was not revealed. Total uptake of N, P and K in optimal and high temperature conditions was 18.4 g plant⁻¹ and 17.6 for N, 4.7 and 5.1 for P, and 37.7 and 36.2 for K, respectively, and, furthermore, the uptake of fruit to whole plant occupied from 85 to 90%. The pattern of monthly N uptake between optimal and high temperature conditions was significant greater in optimal at early stage (4 to 8 WAT), not significant at mid stage (8 to 16 WAT), and remarkably reduced in optimal at late stage (16 to 20 WAT). The trend in P and K uptake was similar to between both temperature conditions, which mean a constant increase from 4 to 16 WAT and a sharply decrease at late stage, although K uptake in optimal was temporarily declined at 8 to 12 WAT. High temperature affects the rates of uptake of mineral nutrients (Tindall et al., 1990; Baghour et

al., 2002; Baghour et al., 2003). In this study, however, the concentrations and uptake of mineral nutrients in whole plants (leaf, stem and fruit) were little affected by temperature. Possibly the temperature stress during experiment season were not a limiting factor for nutrient uptake, as suggested by the small differences in cucumber plant growth (Fig. 1) and yield (Table 4) between optimal and moderately high temperature treatments. Results from this study with cucumber plant suggest that moderately high temperature doesn't have any effect on the production of plant biomass and the uptake of mineral nutrients. On the other hand, the production and partitioning of soluble carbohydrates decreased in the presence of high temperature, and was distinct in starch. Thus, the physiology of cucumber plants may be more effective in photosynthesis and carbohydrate metabolism than mineral uptake and

plant growth when air and soil temperatures are high. Further research should include analysis of respiration rates from plant and soil by constantly increasing temperature conditions to fully understand the shoot:root ratio, the uptake and distribution of mineral nutrients and the production, partitioning and losses as a energy of soluble carbohydrates. Moreover, there is a need for future field studies where elevated temperatures are monitored and manipulated.

Acknowledgement

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