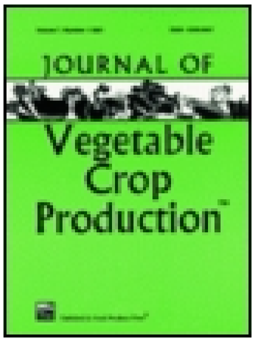

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Mineral Nutrition of Leafy Vegetable Crops Irrigated with Saline Drainage Water

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ABSTRACT. Nine leafy vegetable crops were grown in outdoor sand plots to determine the effects of salinity and the timing of salt stress on leaf-ion concentration. Vegetable species were: radicchio (*Cichorium intybus* L.), curly endive (*C. endivia* L.), pac choi (*Brassica rapa* L., chinensis group), tatsoi (*B. rapa* L., narinosa group), kale (*B. oleracea*, acephala group), cooking greens (*B. rapa* L.), mustard greens (*B. juncea* (L.) Czerniak), spinach (*Spinacia oleracea* L.), and Swiss chard (*Beta vulgaris* L.). All species were planted at the same time and irrigated with a complete nutrient solution. Three weeks after planting, six saline treatments were imposed on half of the plants; the remaining plants were salinized four weeks later. Saline solution compositions were prepared to simulate the high-sodium, high-sulfate drainage waters typically found in the San Joaquin Valley of California. Electrical conductivities of the irrigation waters (EC_i) were 3 (control), 7, 11, 15, 19, and 23 $dS \cdot m^{-1}$. Mineral ion concentrations in leaves were significantly affected by increasing salinity, but not by the stage of growth when salinity was applied. With increasing salinity, Ca^{2+} and K^+ decreased in the leaves of all species, whereas Na^+ and total-S significantly increased. Magnesium in leaves of the composites and the crucifers also increased with salinity, but treatment had no effect on Mg^{2+} con-

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centration in the chenopods. Increases in salinity caused significant increases in Cl^- in leaves of the crucifers and spinach but had no influence on the Cl^- relations in Swiss chard and the composites. The use of moderately saline irrigation waters for the production of these leafy vegetable crops did not adversely affect crop quality as rated by color, texture and the mineral nutrient content available to consumers.

KEYWORDS. Chard, endive, greens, kale, pac choi, radicchio, spinach, tatsoi

INTRODUCTION

In many areas of the world where supplies of good quality water are decreasing, one of the few on-farm water management options available to growers is the reuse of agricultural drainage effluents. This strategy is particularly attractive because significant amounts of good quality water are preserved, and also because the volumes of drainage water that require ultimate disposal are substantially reduced. In the drainage water reuse system proposed for the San Joaquin Valley (SJV) of California, selected crops would be grown and irrigated in sequence, starting with very salt sensitive species (San Joaquin Valley Drainage Program, 1990). Drainage effluents from these crops would be used to irrigate crops of higher salt tolerance. At each step in the sequence, the drainage water becomes progressively more salinized. The composition of the drainage effluents in this region are typically a mixture of salts with Na^+, SO_4^{2-}, Cl^-, Mg^{2+}, and Ca^{2+} predominating in that order.

Some high value leafy vegetable species belong to plant families, e.g., Asteraceae, Brassicaceae, and Chenopodiaceae, whose relatives grow vigorously in saline environments. Shannon et al. (2000) reported that nine specialty vegetables from these taxa, are potentially useful in the drainage water reuse system where only moderate salt tolerance is required. Higher levels of salinity, however, severely limited plant growth. Yield analysis revealed significant differences among the crops in relative salt tolerance as well as in their sensitivity to the growth stage at which salinity was applied.

Leafy vegetables are the primary source of mineral nutrients for human diets (Rubatzky and Yamaguchi, 1997). Numerous food composition tables list major constituents of vegetables and give values for major mineral ions. These values are estimates only, inasmuch as the data are based on a limited number of samples and vary due to factors such as maturity, analytical procedures, and processing (Vaughan and Geissler, 1997). In addition, the availability, uptake, and partitioning of mineral ions within the plant are controlled by numerous environmental factors, including the concentration and composition of solutes in the soil solution. Under saline conditions, mineral ion interactions in the external media may affect the internal requirements of elements essential for plant growth and development (Grattan and Grieve, 1999). These imbalances often influence the growth and nutrition of the crop, which in turn may affect crop quality in terms of color, texture, and nutritive value. The objectives of the present study were to investigate the effects of salinity and the timing of salt application on the ion relations of the nine vegetable species reported by Shannon et al. (2000) and to evaluate the effect of saline drainage water irrigation on the mineral ion content of vegetables provided to consumers.

MATERIALS AND METHODS

Seeds of the following leafy vegetable crops were obtained from Johnny's Selected Seeds, Albion, Maine: curly endive (*Cichorium endivia* L., cv. 'Salad King'); radicchio (*C. intybus* L., cv. 'Red Preco No. 1'); mustard greens (*Brassica juncea* (L.) Czerniak, cv. 'Red Giant'); cooking greens (*B. rapa* L., cv. 'Vitamin Green'); pac choi (*B. rapa* L.); kale (*B. oleracea* L., cv. 'Winterbor'); tatsoi (*B. rapa* L.); spinach (*Spinacia oleracea* L., cv. 'Space'); and Swiss chard (*Beta vulgaris* L., cv. 'Ruby Red'). On 30 January 1997, seeds were sown in 24 outdoor sand tanks at Riverside, California. Each tank contained one row of each species. The rows were spaced 33 cm apart and seedlings were later thinned to 6 to 8 plants per row. The tanks (1.5 by 3.0 by 2.0 m deep) contained washed sand having an average bulk density of 1.2 Mg A m^{-3}. At saturation, the sand had an average volumetric water content of 0.34 m^3 A m^{-3}. Tanks were irrigated once daily with a nutrient solution consisting of (in mM): 3.5 Ca^{2+}, 2.5 Mg^{2+}, 21.5 Na^+, 6.0 K^+, 10.9 $SO_4{}^{2-}$, 7.0 Cl^-, 5.0 $NO_3{}^-$, 0.17 KH_2PO_4, 0.050 Fe (as sodium ferric diethylenetriamine pentaacetate), 0.023 H_3BO_3, 0.005 $MnSO_4$, 0.0004 $ZnSO_4$, 0.0002 $CuSO_4$, and 0.0001 H_2MoO_4 made up with City of Riverside municipal water. This solution, with an electrical conductivity (EC_i) of 3 $dS \cdot m^{-1}$, served as the control treatment. Each sand tank was irrigated daily from its own 3700-L reservoir. Irrigations were of 15 min duration, which allowed the sand to become completely saturated, after which the solution drained to the reservoir for reuse in the next irrigation. Water lost by evapotranspiration was replenished automatically on a daily basis to maintain constant EC_i in the solutions.

Salinization was initiated at two dates to provide information on stage-of-growth × salinity interactions. Emergence of the nine species was, in general, synchronous. When the first true leaves were fully expanded (18 February 1997), salt treatments were initiated on plants in 12 sand tanks. These treatments were designated as 'early salinization.' 'Late salinization' treatments were imposed on plants in the remaining 12 sand tanks on 12 March 1997. Salts were added over a five-day period to avoid osmotic shock to the seedlings. Irrigation waters (EC_i = 3, 7, 11, 15, 19, and 23 $dS \cdot m^{-1}$) were prepared to simulate the high-sulfate, high-sodium saline drainage waters frequently encountered in the San Joaquin Valley of California. Compositions of the salinizing ions are shown in Table 1.

To assure that target ion concentrations were maintained, irrigation waters were analyzed twice during the course of the experiment. Calcium, Mg^{2+}, Na^+, K^+, total-P, and total-S were determined by inductively coupled plasma optical emission spectroscopy (ICPOES) and Cl^- by coulometric-amperometric titration. The pH of the solutions was uncontrolled and ranged from 7.8 to 8.2. This pH range is typical of SJV saline drainage waters, and is also one that is recommended for cole crop production (Rubatzky and Yamaguchi, 1997). The experimental design, a randomized block with 6 salinity treatments and 2 salinization dates with 2 replications, has been previously described (Shannon et al., 2000).

Daytime air temperatures during the experiment ranged from 13.5 to 34.7°C (mean = 22.7°C); nighttime temperatures ranged from 3.7 to 16.1°C (mean = 8.8°C). Relative humidity ranged from 3.4 to 95.4% with a mean of 21.2% during the day and 71.1% during the night.

Leaves of both 'early' and 'late' salinized spinach, Swiss chard, tatsoi, pac choi, kale, and greens cultivars 'Red Giant' and 'Vitamin Green' were harvested on 21 April 1997; radicchio and endive leaves were harvested on 8 May 1997. Samples were weighed, washed with deionized water, dried in a forced air oven for 1 wk at 70°, reweighed, and ground in a Wiley mill to pass a

TABLE 1. Target ion concentrations in solutions used to irrigate vegetable crops grown in outdoor sand cultures.

EC_i ($dS \cdot m^{-1}$)	Ca^{2+}	Mg^{2+}	Na^+	$SO_4{}^{2-}$	Cl^-
	($mol \cdot m^{-3}$)				
3	3.5	2.5	21.5	10.9	7.0
7	7.3	5.7	50.9	25.9	24.7
11	10.1	9.8	87.0	42.0	42.2
15	13.0	13.9	123.0	58.2	59.6
19	13.5	18.9	168.0	75.2	81.3
23	13.6	24.3	215.6	93.5	98.4

60-mesh screen. Total-S, total-P, Ca^{2+}, Mg^{2+}, Na^+, and K^+ were determined on nitric-perchloric acid digests of the plant material by ICPOES. Chloride was determined on nitric-acetic acid extracts by coulometric-amperometric titration.

Water content (%) was determined from fresh and dry weight measurements of plants from the 11 $dS \cdot m^{-1}$ treatment. Mineral nutrient content of the vegetables (mg per 100 g fresh edible portion) was calculated from the ion concentration ($mmoles \cdot kg^{-1}$ dry wt) and the percent of solids. Statistical analyses of the ion data were performed by analysis of variance with mean comparisons at the 95% level based on Tukey's studentized range test (SAS Institute Inc., 1997).

RESULTS AND DISCUSSION

Analysis of the data revealed that ion concentrations in the vegetable species were significantly affected by salinity but not by the time of salt application. Therefore, ion data from the 'early' and 'late' treatments were combined to give 4 replications at each salinity level. Although the vegetables showed no visible injury symptoms during the course of the experiment that could be attributed to nutrient deficiencies, slight marginal necrosis of the older leaves on a few of the brassicas was observed in the highest salinity treatments (EC_i = 19 and 23 $dS \cdot m^{-1}$). The cause of this disorder was not identified, but the high levels of Na^+ and Cl^- in the tissue indicate that these ions may have been present in toxic levels.

Calcium plays a vital nutritional and physiological role in plant metabolism. Under saline conditions, ion imbalances in the substrate or in the plant may adversely affect Ca^{2+} nutrition (Läuchli, 1990; Grattan and Grieve, 1999). Substrate levels of Ca^{2+} that are adequate for plant requirements under nonsaline conditions may be nutritionally inadequate and growth-limiting when the plant is salt-stressed. The Ca^{2+} status of the plant is strongly influenced by the ionic composition of the external medium in that the presence of other salinizing ions in the substrate may reduce Ca^{2+} activity and limit the availability of Ca^{2+} to the plant (Suarez and Grieve, 1988; Willumsen et al., 1996). Cations such as Na^+ and Mg^{2+} may displace Ca^{2+} from its extracellular binding sites within plant organs to further disrupt Ca^{2+} acquisition, uptake, and transport. Leaf-Ca concentrations in all the vegetables tended to decrease (Tables 2, 3, 4) as salinity increased, despite a four-fold increase in external Ca^{2+}. With the exception of 'Red Giant' greens, the decrease was significant. However, leaf-Ca levels were high enough to prevent physiological disorders that are commonly associated with salinity-induced Ca^{2+} deficiencies in leafy vegetable crops such as internal tipburn, browning, and necrosis of the inner leaves (Grattan and Grieve, 1999). With the exception of

TABLE 2. Effect of increasing salinity on leaf-ion concentrations in selected vegetable species of the Asteraceae. Values are means of 4 replications.

EC	Ca	Mg	Na	K	P	S	Cl
(dS/m)	(mmoles/kg dry weight)						
Curly Endive (*Cichorium endivia*)							
3	263a[z]	112b	1092e	2138a	112a	180c	1407a
7	230b	113b	1408de	1657b	97a	169c	1369a
11	192c	117b	1817cd	1506b	102a	210bc	1596a
15	163c	137ab	2213bc	1096c	96a	264bc	1553a
19	122d	155ab	2387b	812d	99a	343b	1472a
23	80.7e	185a	3003a	505e	94a	470a	1684a
Radicchio (*Cichorium intybus*)							
3	340a	108b	487b	1930a	108a	115b	1463a
7	364a	117b	532b	1809a	103a	127b	1433a
11	299ab	114b	650b	1922a	105a	144b	1686a
15	273bc	133b	990b	1822a	106a	160b	1822a
19	233cd	145b	1100b	1494a	106a	188ab	1711a
23	181d	191a	1566a	985b	109a	265a	1551a

[z] Within columns and species, means followed by a different letter are significantly different at the 0.05 probability level according to Tukey's Studentized Range Test.

radicchio, kale, and pac choi, the Ca^{2+} content of the vegetables in the 11 $dS \cdot m^{-1}$ treatment tended to be lower than values reported in typical food composition tables (Table 5).

Leaf-Mg in the crucifers and the composites increased with salinity but not to the extent that might be anticipated from Mg^{2+} concentrations in the irrigation waters (Tables 2, 3, 4). In the highest salinity treatment, leaf-Mg concentrations were 53 to 100% higher than in the control, whereas substrate-Mg concentration increased 10-fold (2.4 to 24.3 $mol \cdot m^{-3}$) as salinity increased from 3 to 23 $dS \cdot m^{-1}$. Leaf-Mg concentrations in spinach and chard were not significantly affected by salinity (Table 4). With the exception of chard, the Mg^{2+}: Ca^{2+} ratio in the vegetable leaves increased consistently and significantly as salinity and the ion ratio in solution increased. Chard contained twice as much Mg^{2+} as Ca^{2+} over the range of treatments. The Mg^{2+} content in vegetables irrigated with saline drainage water (11 $dS \cdot m^{-1}$) ranged from ~20 (endive, radicchio, mustard greens, pac choi) to 135 mg (spinach) per 100 g fresh edible portion (Table 5).

Although Na^+ is not an essential nutrient for glycophytic plants, it can enhance plant growth. Chard, and other types of *Beta vulgaris*, are natrophilic plants whose growth is stimulated by low concentrations of NaCl, and in which a high percentage of K^+ may be replaced by Na^+ (Marschner, 1995). For most plants, however, the presence of high concentrations of Na^+ limits growth and can severely depress acquisition of K^+, Ca^{2+}, and Mg^{2+}. In our

TABLE 3. Effect of increasing salinity on leaf ion concentrations in selected vegetable species of the Brassicaeae. Values are means of 4 replications.

EC (dS/m)	Ca	Mg	Na	K	P	S	Cl
	(mmoles/kg dry weight)						
Tatsoi (*Brassica rapa*, narinosa group)							
3	531a[z]	131b	829d	2080a	138a	207c	610b
7	492a	156 ab	1410c	1722a	133a	245c	797b
11	488a	172ab	1627c	1311b	125a	321b	930b
15	405a	185ab	2323b	969bc	139a	308b	988b
19	290b	174ab	2749a	1005bc	136a	378ab	1378a
23	215b	200a	2891a	740c	135a	398a	1353a
Vitamin Green (*Brassica rapa*, narinosa group)							
3	551a	124c	1082c	1998a	158a	216c	609c
7	561a	155bc	1637bc	1533b	143a	224c	883b
11	527a	165bc	1919ab	1338bc	147a	302bc	980b
15	433ab	181abc	2301ab	1057c	134a	326b	1080b
19	376bc	208ab	2479ab	1150bc	130a	360ab	1294a
23	296c	234a	2697a	1049c	138a	437a	1385a
Kale (*Brassica oleraceae*, acephala group)							
3	714a	296b	485c	1767a	162a	416b	364c
7	790a	344ab	713bc	1330b	162a	505a	598b
11	694a	339ab	878b	1106bc	156a	498a	631b
15	589a	350ab	1058ab	1283b	138a	410b	807a
19	490b	417a	1152ab	1024c	139a	458a	751a
23	388b	397a	1374a	820c	138a	515a	839a
Red Giant (*Brassica juncea*)							
3	493a	129c	299b	1922a	120a	230b	538c
7	498a	161bc	397b	1818a	133a	266b	814b
11	489a	166bc	473b	1817a	128a	276b	900b
15	465a	201b	598b	1677ab	127a	293b	1044b
19	429a	252a	1033a	1390b	121a	379a	1370a
23	346a	274a	1066a	1445b	127a	371a	1362a
Pac choi (*Brassica rapa*, chinensis group)							
3	432a	108c	859e	2402a	141a	258c	914c
7	438a	140c	1303d	1845b	139a	269c	1093bc
11	380a	131c	1795c	1406c	125ab	308bc	1252bc
15	340ab	174b	2051bc	1128cd	125ab	407bc	1362ab
19	279bc	179b	2378b	1128cd	123ab	329bc	1444ab
23	211c	213a	3143a	781d	102b	565a	1684a

[z] Within columns and species, means followed by a different letter are significantly different at the 0.05 probability level according to Tukey's Studentized Range Test.

TABLE 4. Effect of increasing salinity on leaf-ion concentrations in selected vegetable species of the Chenopodiaceae. Values are means of 4 replications.

EC (dS/m)	Ca	Mg	Na	K	P	S	Cl
	(mmoles/kg dry weight)						
Swiss Chard (*Beta vulgaris*)							
3	181a[z]	390a	2409d	1522a	118a	126d	1041a
7	182a	374a	2651cd	1544a	117a	141cd	1236a
11	143ab	368a	2958bc	1457a	122a	153bcd	1328a
15	136b	370a	3144ab	1263ab	121a	179abc	1224a
9	121b	332a	3289ab	1249ab	125a	190ab	1407a
23	123b	333a	3514a	1034b	101a	207a	1451a
Spinach (*Spinacia oleracea*)							
3	145a	539a	257d	2447a	125a	116c	357c
7	118b	509a	323d	2363ab	120a	115c	483c
11	123b	554a	614c	2301ab	111a	147b	732b
15	114b	562a	840c	2067bc	112a	158b	824b
19	112b	557a	1191b	1873cd	124a	193a	1041a
23	82c	496a	1480a	1666d	108a	217a	1110a

[z] Within columns and species, means followed by a different letter are significantly different at the 0.05 probability level according to Tukey's Studentized Range Test.

study, leaf-Na in the vegetables increased significantly as Na^+ in the irrigation water increased from 20 to 200 mol · m^{-3} (Tables 2, 3, 4). Even between closely related species, there were wide differences in leaf-Na concentrations. The composite, endive, contained about twice as much Na^+ as radicchio in all salt treatments. 'Red Giant' was a weaker Na^+ accumulator than the other four crucifers. Chard accumulated nearly 10 times as much Na^+ as spinach at the lowest salinity level. The relatively high concentration of Na^+ in moderately saline irrigation waters (11 dSm^{-1}) resulted in substantially higher Na^+ content for these vegetables than values given in food composition tables (Table 5).

Under salinity stress, maintenance of adequate levels of K^+ is essential for plant survival. High levels of external Na^+ not only interfere with K^+ acquisition by the roots but also may disrupt the integrity of root membranes and alter the selectivity of the root system for K^+ over Na^+ (Grattan and Grieve, 1999). External K^+ concentration was constant in this study, whereas Na^+ increased across salinity treatments. As a result, K^+ in the vegetable leaves decreased significantly as salinity increased (Tables 2, 3, 4). The K^+ content per 100 g edible portions of the leafy vegetables generally equaled or exceeded published values (Table 5).

Irrigation with saline waters had little effect on total-P in the vegetable leaves. Only pac choi showed a significant decrease in total-P in response to

TABLE 5. Water content and mineral ion concentration per 100 g edible portion of selected vegetables irrigated with moderately saline water (11 $dS \cdot m^{-1}$). Published values are given for comparison.

Vegetable	Water (%)	Ca	Mg	Na	K	P	S	Cl	Source[z]
		mg/100 g							
Endive	**92.8**	**55**	**20**	**300**	**424**	**23**	**48**	**408**	**1**
	93.8	66	13	50	304	41	--	--	2
	93.1	81	10	14	234	51	--	--	3
Radicchio	**93.1**	**116**	**24**	**61**	**419**	**23**	**52**	**188**	**1**
	92.0	93	22	45	420	43	--	--	2
Tatsoi	**93.7**	**123**	**26**	**236**	**323**	**24**	**63**	**208**	**1**
Mustard Greens									
Vitamin	**95.0**	**106**	**20**	**220**	**262**	**23**	**48**	**490**	**1**
Red Giant	**94.1**	**116**	**24**	**61**	**419**	**23**	**52**	**118**	**1**
	89.3	181	29	33	374	46	--	--	2
	92.6	138	--	18	220	32	--	--	3
Kale	**89.0**	**306**	**91**	**222**	**476**	**53**	**175**	**246**	**1**
	89.7	202	45	43	420	55	--	--	2
	91.2	134	--	43	221	46	--	--	3
Pac choi	**94.0**	**118**	**24**	**248**	**426**	**24**	**53**	**192**	**1**
	93.8	118	19	71	234	39	--	--	2
Chard	**93.8**	**36**	**55**	**421**	**353**	**23**	**30**	**292**	**1**
	92.3	93	73	205	380	39	--	--	2
	92.7	73	--	86	321	24	--	--	3
Spinach	**90.1**	**49**	**135**	**141**	**900**	**34**	**47**	**260**	**1**
	91.5	107	92	110	605	57	--	--	2
	90.7	93	88	71	470	51	--	--	3

[z] Source: **(1)** Data from this study; (2) Rubatatzky and Yamaguchi (1997); (3) Ensminger et al. (1995)

salinity. Phosphorus content ranged from about 23 (endive, radicchio, tatsoi, greens, pac choi, chard) to 53 (kale) mg per 100 g edible portion (Table 5).

Total-sulfur in the leaves of all the vegetables increased as substrate-sulfate increased from 11 to 94 $mol \cdot m^{-3}$ (Tables 2, 3, 4). The crucifers were particularly active S-accumulators. Members of the Brassicaceae are among the 15 plant families that biosynthesize significant quantities of sulfur-rich plant products, i.e., the glucosinolates (Rodman, 1991). Hydrolysis of these compounds yields ‘mustard oils’ that impart the characteristic spicy taste to these vegetables (Marschner, 1995). Increases in total-S accumulation in response to irrigation with moderately saline, sulfate-dominated waters may enhance the flavor and consumer-acceptability of the cruciferous vegetables evaluated in this study. Although Asteraceae is not listed among the taxa of glucosinolate-producing plants, endive also contained relatively high concentrations of total-S. Total-S ranged from 30 (chard) to 175 (kale) mg per 100 g edible portion (Table 5).

Shoot-Cl of all species increased as the Cl^- concentration in the irrigation waters increased from 8 to 95 $mol \cdot m^{-3}$, but this increase was not significant for the composites and chard. Kale was a relatively weak Cl^- accumulator, although shoot-Cl increased over two-fold as salinity increased. Under control conditions, the composites accumulated higher concentrations of Cl^- than did the other vegetables tested. Chloride content per 100 g fresh edible portion ranged from 118 mg (mustard greens) to 408 mg (endive) (Table 5).

Shoot fresh weights of these selected vegetables was reduced by 50% when the EC_i of the irrigation water reached ~15 $dS \cdot m^{-1}$ (Shannon et al., 2000). However, crop quality in terms of color, texture, and flavor of plants irrigated with waters ranging from 3 to 15 $dS \cdot m^{-1}$ was rated as highly acceptable (USSL Staff, personal evaluations). Small plant size may have little effect on market acceptability, particularly for shredded salad mixes and other convenience-food items. With the exception of Na^+, mineral ion content of the vegetables irrigated with saline water (11 $dS \cdot m^{-1}$) was generally consistent with concentrations reported in food composition tables, particularly in view of the acknowledged discrepancies and variability in published values (Vaughan and Geissler, 1997).

The use of moderately saline irrigation waters for the production of leafy vegetable crops appears to be a viable option for growers in areas where supplies of high quality waters are limited. Crop yields can undoubtedly be maximized under field conditions by refinements in cultural practices, such as, adjusting planting and/or harvesting dates, increasing planting density, improving fertilization regimes or timing.

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