Comparison of Container Placement Patterns for Maximizing Greenhouse Space Use

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SUMMARY. A series of equations were developed to provide a convenient means to calculate the number of containers that can be placed into a specified area using three different placement patterns. The calculations require three pieces of information; the container spacing, i.e., distance between the center of one container and the center of the neighboring container, and the length and width of the greenhouse bench or floor area. The solutions allow comparisons of the total number of containers that will fit into that area using three different placement patterns: square, long-staggered, and short-staggered. In general, the closer the container spacing or the larger the production area, the greater the benefit of staggered spacing compared to square spacing. Staggered spacing frequently allows for up to 13% more containers to fit into a given area than square spacing; however, calculations must be made for specific situations to determine the most efficient spacing pattern. Cost analyses were performed on a range of container spacings and greenhouse dimensions. Spacing pattern can affect overhead costs from \$0.02 to \$0.20 per container for a 10-week crop. A spreadsheet, Bench Crop Calculator, is available from the authors for providing assistance in performing the calculations.

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Overhead costs (including equipment, taxes, and utilities) are a significant part of total greenhouse crop-production costs. The overhead cost per square foot per week of bench space has been estimated to be \$0.20 (Brumfield, 1995). Since overhead costs remain constant in a given location regardless of the crop or the number of containers produced, the efficiency with which growing space is used in order to minimize overhead costs per plant is important.

Efficient use of greenhouse space requires knowing how many plants will fit on a bench or floor so that each plant has sufficient space to grow. Containers are spaced by commercial growers on square or staggered spacing. Square spacing is frequently employed since this method is considerably easier for workers to perform accurately. Also, growers usually assume square spacing when planning for the number of containers that will fit in a greenhouse, since the calculation is relatively simple.

We are unaware of an available process through which growers can determine how to place containers on a bench or floor in such a way that the space is used most efficiently. The objective of this project was to develop a decision-support tool to calculate the maximum number of containers that can be placed in a specified area. The equations could be entered in a spreadsheet to allow growers to determine the most efficient spacing pattern for their individual situations or a spreadsheet, named Bench Space Calculator, is available from the authors.

Materials and methods

There are three commonly used patterns of container placement (Fig. 1). Square placement involves placing containers in parallel rows perpendicular to each other in both directions on the growing surface so that any four containers form a square. The other two patterns involve placing containers in staggered arrangements in which any three containers form an equilateral triangle. In the long-staggered pattern, the rows of containers are parallel to the long dimension of the bench or floor space. In the short-staggered pattern, the rows of containers are parallel to the short dimension of the bench or floor space.

We developed a series of equations to calculate the number of containers fitting in a given area in each of the three

Fig. 1. Three possible arrangements of containers: long staggered, short staggered, and square. Rows are numbered sequentially.

arrangements. Equation inputs are the length (feet; 1.0 ft = 0.3048 m) and width (feet) of usable area and the container spacing (inches; 1.0 inch = 2.54 cm), i.e., the distance from the center of one container to the center of the next container.

SHORT-STAGGERED PATTERN. Equations 1 to 6 are used to calculate the total number of rows of containers [Eq. 1] (Fig. 1B), the number of odd-numbered [Eq. 2] and even-numbered rows [Eq. 3], the number of containers fitting in odd-numbered rows [Eq. 4] and in even-numbered rows [Eq. 5], and the total number of containers fitting in the specified area [Eq. 6] using the short-staggered arrangement pattern.

$$\text{Number of rows} = [\text{long dimension} - (0.01083 \times \text{container spacing})] / (0.0725 \times \text{container spacing}) \quad [1]$$

In Eq. [1], the solution is rounded down to the nearest whole number.

$$\text{Number of odd-numbered rows} = \text{number of rows} / 2 \quad [2]$$

Use the rounded solution for number of rows in Eq. 1. The solution for Eq. 2 is rounded up to the nearest whole number.

$$\text{Number of even-numbered rows} = \text{number of rows} / 2 \quad [3]$$

Use the rounded solution for number of rows in Eq. 1. The solution for Eq. 3 is rounded down to the nearest whole number.

$$\text{Number of containers in odd-numbered rows} = (\text{short dimension} \times 12) / \text{container spacing} \quad [4]$$

The solution for Eq. 4 is rounded down to the nearest whole number.

$$\text{Number of containers in even-numbered rows} = [\text{short dimension} - 0.04167 \times \text{container spacing}] / (0.08333 \times \text{container spacing}) \quad [5]$$

The solution for Eq. 5 is rounded down to the nearest whole number.

$$\text{Total number of containers} = (\text{number of odd-numbered rows} \times (\text{number of containers in odd-numbered rows} + \text{number of even-numbered rows} \times \text{number of containers in even-numbered rows})) \quad [6]$$

Use rounded answers to Eqs. 2 to 5 when calculating a solution for Eq. 6.

LONG-STAGGERED PATTERN. Equations 7 to 12 are used to calculate the total number of rows of containers [Eq. 7] (Fig. 1A), the number of odd-numbered [Eq. 8] and even-numbered rows [Eq. 9], the number of containers fitting in odd-numbered rows [Eq. 10] and in even-numbered rows [Eq. 11], and the total number of containers fitting in the specified area [Eq. 12] using the long-staggered arrangement pattern.

$$\text{Number of rows} = [\text{short dimension} - (0.01083 \times \text{container spacing})] / (0.0725 \times \text{container spacing}) \quad [7]$$

In Eq. [7], the solution is rounded down to the nearest whole number.

$$\text{Number of odd-numbered rows} = \text{number of rows} / 2 \quad [8]$$

Use the rounded solution for number of rows in Eq. 7. The solution for Eq. 8 is rounded up to the nearest whole number.

$$\text{Number of even-numbered rows} = \text{number of rows} / 2 \quad [9]$$

Use the rounded solution for number of rows in Eq. 7. The solution for Eq. 9 is rounded down to the nearest whole number.

$$\text{Number of containers in odd-numbered rows} = (\text{long dimension} \times 12) / \text{container spacing} \quad [10]$$

The solution for Eq. 10 is rounded down to the nearest whole number.

$$\text{Number of containers in even-numbered rows} = [\text{long dimension} - 0.04167 \times \text{container spacing}] / (0.08333 \times \text{container spacing}) \quad [11]$$

The solution for Eq. 11 is rounded down to the nearest whole number.

$$\text{Total number of containers} = (\text{number of odd-numbered rows} \times \text{number of containers in odd-numbered rows}) + (\text{number of even-numbered rows} \times \text{number of containers in even-numbered rows}) \quad [12]$$

Use rounded answers to Eqs. 8 to 11 when calculating a solution for Eq. 12.

SQUARE PATTERN. Equations 13 to 15 are used to calculate the number of rows of containers using the short dimension of the area [Eq. 13] (Fig. 1C), the number of containers fitting in each row [Eq. 14] and the total number of containers fitting into the given area using the square spacing arrangement [Eq. 15].

$$\text{Number of rows} = \text{short dimension} / \text{container spacing} \quad [13]$$

The solution for Eq. 13 is rounded down to the nearest whole number.

$$\text{Number of containers per row} = \text{long dimension} / \text{container} \quad [14]$$

The solution for Eq. 14 is rounded down to the nearest whole number.

$$\text{Total number of containers} = \text{number of rows} \times \text{number of containers per row} \quad [15]$$

Use rounded answers to Eqs. 13 to 14 when calculating a solution for Eq. 15.

The number of containers placed at various spacings that fit in different sized areas were compared to illustrate the application of the model for maximizing space use (Table 1). Cost analyses were also conducted to illustrate the potential economic impact of the different spacing patterns.

Results and discussion

The most common means of estimating the number of containers fitting into a specific area entails calculating the bench or floor area (length $\times$ width) and dividing this value by the container area, calculated as the square of the container spacing. For example, using a 6-ft (1.83-m) $\times$ 10-ft (3.05-m) bench [60 ft² (5.57 m²)] and 14-inch (35.6-cm) spacing on the crop [1.36 ft² (0.126 m²) per container], the number of containers calculated to fit in this area is 44 (60/1.36). This answer is incorrect. Using a square spacing pattern, only five rows of containers placed on 14-inch (35.6 cm) spacing will fit along the short (6 ft)

dimension of the bench resulting in a loss of two inches [70 inches (177.8 cm) used while 72 inches (182.9 cm) are available]. Only eight rows will fit along the long (10 ft) dimension resulting in wasting 8 inches [112 inches (2.85 m) used while 120 inches (3.05 m) are available]. Thus, only 40 plants can actually fit on this bench using the square pattern. The error results from assuming that the plants will occupy every square inch of space available. Therefore, the most common means for growers to estimate container numbers fitting in a given area is inaccurate.

A staggered arrangement frequently allows a significant increase in the number of containers fitting in a given area, as compared to square placement (Table 1). For example, the num-

ber of 6-inch (15.2 cm) containers fitting pot-to-pot in a 6 × 20-ft (1.83 × 6.10-m) area is 7.1% and 7.9% greater when arranged in long-staggered and short-staggered patterns compared to the square pattern. In fact, the only examples in which the square spacing was more efficient than the staggered spacing were when the containers were placed on relatively small bench or floor areas at 12-inch (30.5-cm) spacing.

The advantage of a staggered compared to square arrangement frequently increases with increasing area (Table 1). For example, when comparing containers placed at 6-inch (15.2-cm) spacing, the percent increase in container number of the short-staggered pattern versus the square pattern ranges from 3.1% on the 4 × 10-ft (1.22 × 3.05 m) bench

to 13.1% on the 20 × 100-ft (6.10 × 30.5 m) area. In general, the dimensions used in Table 1 that reflect typical greenhouse floor sizes often display greater percentage increases in container number using staggered versus square spacing compared to the dimensions typical of benches. Application of these calculations to overwintering of containerized perennials and woody plants calculated 15% to 20% increases in containers accommodated in typical cold frame polyhouses using staggered patterns compared to square patterns (Will and Faust, 1996).

Relatively small differences in total container number were observed between long- and short-staggered patterns. Typically, the difference in container number between short-staggered and long-staggered arrangements was

Table 1. Number of containers fitting on benches or floors of various dimensions in square (S), short-staggered (SS), and long-staggered (LS) arrangements (Eqs. [6], [12], and [15]). Numbers in parentheses indicate the percentage change in the number of containers compared to square placement. The cost analyses use overhead costs of \$0.20/ft² per week and a 10-week crop.^z

Container diam or spacing (inch)	Bench or floor dimensions (ft)		Total containers/ bench (% change compared to S arrangement)			Cost/ container (\$)			Savings (\$ loss)/ bench compared to S arrangement)	
	Width	Length	S	SS	LS	S	SS	LS	SS	LS
4	4	10	360	391 (8.6)	384 (6.7)	0.22	0.20	0.21	6.89	5.33
4	6	10	540	595 (10.2)	590 (9.3)	0.22	0.20	0.20	12.22	11.11
4	6	20	1080	1190 (10.2)	1190 (10.2)	0.22	0.20	0.20	24.44	24.44
4	6	50	2700	3010 (11.5)	2990 (10.7)	0.22	0.20	0.20	68.89	64.44
4	10	100	9000	10148 (12.8)	10183 (13.1)	0.22	0.20	0.20	255.11	262.89
4	15	100	13500	15308 (13.4)	15275 (13.2)	0.22	0.20	0.20	401.78	394.44
4	20	100	18000	20468 (13.7)	20366 (13.1)	0.22	0.20	0.20	548.44	525.78
6	4	10	160	165 (3.1)	176 (10.0)	0.50	0.48	0.45	2.50	8.00
6	6	10	240	253 (5.4)	254 (5.8)	0.50	0.47	0.47	6.50	7.00
6	6	20	480	518 (7.9)	514 (7.1)	0.50	0.46	0.47	19.00	17.00
6	6	50	1200	1311 (9.3)	1294 (7.8)	0.50	0.46	0.46	55.50	47.00
6	10	100	4000	4466 (11.7)	4389 (9.7)	0.50	0.45	0.46	233.00	194.50
6	15	100	6000	6756 (12.6)	6783 (13.1)	0.50	0.44	0.44	378.00	391.50
6	20	100	8000	9046 (13.1)	8978 (12.2)	0.50	0.44	0.45	523.00	489.00
10	4	10	48	52 (8.3)	58 (20.8)	1.67	1.54	1.38	6.67	16.67
10	6	10	84	85 (1.2)	92 (9.5)	1.43	1.41	1.30	1.43	11.43
10	6	20	168	176 (4.8)	188 (11.9)	1.43	1.36	1.28	11.43	28.57
10	6	50	420	442 (5.2)	476 (13.3)	1.43	1.36	1.26	31.43	80.00
10	10	100	1440	1576 (9.4)	1554 (7.9)	1.39	1.27	1.29	188.89	158.33
10	15	100	2160	2398 (11.0)	2390 (10.7)	1.39	1.25	1.26	330.56	319.44
10	20	100	2880	3220 (11.8)	3227 (12.1)	1.39	1.24	1.24	472.22	481.94
12	4	10	40	39 (-2.5)	38 (-5.0)	2.00	2.05	2.11	(2.00)	(4.00)
12	6	10	60	61 (1.7)	57 (-5.0)	2.00	1.97	2.11	2.00	(6.00)
12	6	20	120	121 (0.8)	117 (-2.5)	2.00	1.98	2.05	2.00	(6.00)
12	6	50	300	314 (4.7)	297 (-1.0)	2.00	1.91	2.02	28.00	(6.00)
12	10	100	1000	1083 (8.3)	1095 (9.5)	2.00	1.85	1.83	166.00	190.00
12	15	100	1500	1653 (10.2)	1692 (12.8)	2.00	1.81	1.77	306.00	384.00
12	20	100	2000	2223 (11.2)	2189 (9.5)	2.00	1.80	1.83	446.00	378.00

^zThe numbers in this table indicate the final rounded solutions; however, rounding errors can occur if the rounded solutions are inappropriately used for further calculations. See text for discussion concerning rounding errors.

Bench Space Calculator

Shaded cells represent required input locations
(four significant figures are recommended)

Spacing Arrangement Comparison				
Inputs				
Feet	Inches			
6	10.00	Container Spacing (inch)		
20	0.000	Short Dimension (ft & inch)		
	0.000	Long Dimension (inch)		
Results		Total Container Number	%Change from Square Pattern	
Short Staggered Arrangement		176	4.8	
Long Staggered Arrangement		188	11.9	
Square Arrangement		168		

Cost/Savings Analysis		
Inputs		
0.2000	Overhead Expenses per square foot per week (\$)	
10.00	Crop Time (weeks)	
Results	Cost per Container (\$)	Savings/Loss per Bench (\$) (compared to Square)
Short Staggered Arrangement	1.364	11.43
Long Staggered Arrangement	1.277	28.57
Square Arrangement	1.429	

Fig. 2. A view of the Bench Crop Calculator spreadsheet developed to assist users with container-spacing and cost-analysis calculations (1 inch = 2.54 cm, 1 ft = 0.3048 m). This Microsoft Excel spreadsheet is available from the authors.

<3%. The most efficient staggered pattern varies with the bench dimensions, i.e., no consistent pattern was observed.

While performing the calculations, keep in mind that calculations may not always reflect reality. For example, if one extra row of containers can not fit onto a bench because it is just 1 mm (0.0394 inch) too wide, then dozens of containers can be lost. While in reality, one could easily bend a plastic container 1 mm to force an extra row onto a bench. Therefore, accurate measurements of container diameters or spacings is important, since small changes in container diameter can have a relatively large impact on the number of containers fitting on a specific bench. Similarly, accuracy can be lost when an insufficient number of significant figures are used when converting the length measurement to or from metric units. For example, a 10-cm container is often considered to be a 4-inch container; however, the unit conversion results in a calculated 3.937-inch container. Using 4.000 versus 3.937 results in slightly different solutions. Consequently, four significant figures are recommended, although three are acceptable in most circumstances.

Increase in the number of contain-

ers fitting on a bench in a staggered arrangement as compared to square placement results in a 13% reduction in growing area per plant. This reduction in area per plant is independent of container size. It is based on the ratio of the polygonal growing space in staggered placement to the square growing space in square placement. The area of the square growing space of a plant placed pot-to-pot in square placement is equal to the diameter of the container squared ($A = d^2$). The area of the hexagonal growing space of a plant placed pot-to-pot in staggered placement is equal to 0.87 times the diameter of the container squared ($A = 0.87 d^2$). Because the additional space in the square pattern is in the corners of the growing area of each plant, losing this space is not important to the development of a well-shaped plant. Light interception by plants in the staggered patterns is more efficient than in the square pattern where leaf overlapping would begin before the corners of the square were filled in.

Cost analyses were performed to demonstrate the potential savings from different spacing situations (Table 1). These analyses examine the effect of the spacing pattern on three different bench or floor dimensions where the overhead

square foot cost per week is \$0.20 and a 10-week crop is grown at 12-inch (30.5-cm) spacing. The cost per container at the 4-inch (10.2-cm) spacing was mostly affected by the container spacing, not the bench or floor dimensions. For example, cost per container at the 4-inch (10.2-cm) spacing was typically less than or equal to \$0.02 difference between spacing patterns regardless on bench dimensions. While, the cost per container for the 12-inch (30.5-cm) spacing was greatly affected by spacing patterns and bench dimensions, ranging from a \$0.02 to \$0.23 difference between the different combinations.

The savings or loss per bench as a result of the spacing pattern is also demonstrated in Table 1. Savings per bench was as high as \$548 when comparing short-staggered to square spacing in the 20 × 100 ft (6.10 × 30.5 m) growing area. These savings estimates indicate that spacing pattern can have a significant economic impact.

Equations 1 to 15 can be entered into a spreadsheet to allow for comparisons between different greenhouse bench and crop situations. A Microsoft Excel spreadsheet has been developed and is available from the authors (Fig. 2). The user must provide three measurements including container spacing (inches) and the short and long dimensions of the bench or floor area (feet and inches). The spreadsheet will calculate the total container number and percent change comparing the staggered patterns to the square pattern. Cost and savings analysis can be calculated by inputting the estimated overhead expenses per square foot per week and the crop time, i.e., the number of weeks on the bench. The spreadsheet then calculates the cost per container and the savings or loss per bench comparing the staggered patterns to the square pattern. Space is provided in the spreadsheet cells for four significant figures to be entered. Significant rounding errors can occur if fewer figures are used. This is especially the case when converting units from metric measurements.

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