replenish storage carbohydrates used in spear and fern production (Scott et al., 1939).

Optimizing soil moisture levels resulted in significantly increased fern dry weight (Table 2), which agrees with Wilcox-Lee (1987). The interaction indicated that the treatment effect was not the same for all cutting treatments. The high soil moisture level was significant for only the FERN treatment.

The results indicated that the motherstalk method of asparagus culture may be a productive alternative to traditional cutting methods. Since crown dry weights in the motherstalk treatments remain high during the cutting season, it may be possible to extend the cutting season into early summer. These studies indicated that increased attention must be given to soil moisture levels if optimum yields are to be achieved with this technique. Further research is necessary to monitor and evaluate its usefulness and potential under field conditions in a temperate climate.

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Precision Seeder Uniformity Varies with Theoretical Spacing

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ADDITIONAL INDEX WORDS. **seeding, seed metering, seeding uniformity, planters, planting**

SUMMARY. Precision vegetable seeders were found to have unexpected variation in seed spacing uniformity. A belt seeder and vacuum seeder were evaluated using cabbage (*Brassica oleracea* L. *capitata* group) seeded at different seed spacings to determine if seeder uniformity improved with increasing seed spacing. Seeding uniformity of the belt seeder was not affected by seed spacing, but uniformity of the vacuum seeder was. Variation in seed spacing with the vacuum seeder was consistent in absolute units, thus seed spacing nonuniformity (expressed as a percentage of theoretical spacing) decreased with increasing seed spacing. Operating the vacuum seeder with the air pressure seed release mechanism disengaged improved seeder precision. Uniformity and precision of the belt seeder were better than that of the vacuum seeder.

An important feature of a precision seeder's performance is its ability to place seeds singularly a given distance apart. Recent studies evaluating seeding uni-

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formity of vacuum and belt precision vegetable seeders (Bracy and Parish, 1998; Parish and Bracy, 1998) detected inconsistencies in the metering uniformity of precision seeders previously assumed to be very uniform (Parish et al., 1991). Bracy and Parish (1998) determined a belt seeder was as effective at singulating spherical seeds [cabbage (*Brassica oleracea* var. *capitata* L.)] and nearly spherical seeds [onion (*Allium cepa* L. var. *cepa* L.)] as the most precise vacuum seeder, but seeding uniformity of all seeders with elongated [carrot (*Daucus carota* L.)] and cucumber (*Cucumis sativus* L.)] or angular [spinach (*Spinacia oleracea* L.)] seeds was inadequate for precision seeding. The belt seeder was also more effective than the vacuum seeders at spacing the seeds uniformly within the target area when outliers were removed.

Parish and Bracy (1998) assessed the uniformity of metering size-graded and ungraded turnip (*Brassica rapa* L. var. *rapifera* L.) seed with precision belt and vacuum seeders. They hypothesized that a vacuum seeder should meter a wider range of seed sizes more uniformly than a belt seeder, since the holes in the seed plate must only be smaller than the smallest seeds in the lot. They concluded, however, that neither the belt nor the vacuum seeder gave the singulation and uniformity a grower would expect from a precision seeder.

Visual observations of the vacuum plates during operation of the vacuum seeders indicated that the seed was being singulated with few misses and multiples (Bracy and Parish, 1998; Parish and Bracy, 1998). Distribution of the seeds on the test surface, however, was not uniform. They speculated that the loss in uniformity must have occurred as the plate rotated down to the release point, with seed not being released or being released erratically, thus introducing variability into the seed spacing.

Wanjura and Hudspeth (1969) found that a 3-inch (8-mm) seed drop height consistently produced a better seed pattern than a 6-inch (15-mm) drop height with a cotton (*Gossypium hirsutum* L.) vacuum seeder. They recommended that the metering device on a planter should be located as low as practicable, and seed should fall freely to the bottom of the soil trench.

Breece et al. (1981), however, stated that irregular seed placement in

the row is often blamed on the seed metering mechanism when it is actually caused by the seed placement mechanism. They also speculated that the effect of seed bounce in a seed tube caused what appears to be skips and doubles but is really poor seed-to-seed spacing.

Kachman and Smith (1995) compared alternative measures of accuracy in seed placement for planters and, based on the theoretical seed spacing, recommended using four measures for evaluating seeding uniformity. Their recommended measures (based on a seeder standard issued by the International Organization for Standardization, 1984) included multiple index, miss index, quality of feed index, and precision. Multiple index (MULT) indicated multiple seed drops and was the percentage of seed spacings that were less than or equal to one-half of the theoretical seed spacing. Miss index (MISS) indicated missed seed locations or skips and was the percentage of spacings >1.5 times the theoretical spacing. Quality of feed index (QFI) indicated single seed drops and was the percentage of spacings that were more than half but no more than 1.5 times the theoretical spacing. QFI was an alternative way of presenting the information contained in MISS and MULT. Precision (PREC) was the coefficient of variation of the spacings after omitting the missed and multiple seed drops (outliers). PREC was a measure of the uniformity of spacings classified as singles, whereas MULT, MISS, and QFI were measures of singulation or lack thereof. A more complete discussion of these terms and examples of calculations was given by Kachman and Smith (1995).

Although mean (MEAN) and coefficient of variation (cv) have been used in research publications to describe spacing uniformity (Hudspeth and Wanjura, 1970; Parish, 1972; Parish et al., 1991; Wilkins et al., 1992), Kachman and Smith (1995) judged MEAN and cv as inappropriate measures of seeder accuracy. MEAN does not reflect variation in spacing, and cv does not identify the types of nonuniformity (e.g., misses, multiples, or nonuniform basic spacing).

If loss in uniformity in vacuum seeders occurs at the seed release point or as an effect of seed bounce in the seed tube, absolute variability would be relatively constant over seed spac-

ing, but uniformity would be better at the wider spacings. Consequently, if seed were dropped 0.5 inch (13 mm) off target at all seed spacings, uniformity would be expected to be greater at a 12-inch (30-mm) spacing than at a 3-inch (8-mm) spacing. The objective of the current study was to evaluate if seeding uniformity of belt and vacuum seeders improved with increasing theoretical seed spacing. Seeding uniformity of the vacuum seeder was also evaluated with the pressure seed release mechanism engaged and disengaged to determine if seed release contributed to nonuniformity.

Materials and methods

Spacing measurements of cabbage seed from two seeders (belt-type Stanhay model S870, Hestair Farm Equipment, Suffolk, England; and vacuum-type Gaspardo SV255, Gaspardo, Pordenone, Italy) were used in this study. The seeders were operated over a 20-ft (6-m) greased board at a ground speed of 1.5 mph (2.4 km·h⁻¹) with seed spacing measurements recorded over a center distance of 10 ft (3 m). The board was coated with grease to prevent seed from bouncing and to retain exact placement of the seed.

Six theoretical seed spacings of 1.5, 3.0, 4.5, 6.0, 9.0, and 11.2 inches (38, 77, 114, 153, 229, and 284 mm) were achieved with the Gaspardo seeder using the same metering plate (10 holes, each 1.0 mm in diameter) but different chain drive ratios. The Gaspardo seeder was also operated with a theoretical spacing of 3.0 inch (77 mm) in which the air pressure seed release tube was disengaged and plugged. Seed belts with 10 or 32 holes, 9/64 inch (3.6 mm) in diameter, were used in the Stanhay seeder to obtain theoretical spacings of 2.8, 5.6, 9.0, and 18.0 inches (71, 142, 229, and 457 mm). Six replications of seed spacing measurements from each seeder and corresponding theoretical seed spacings were recorded.

The seed spacings were analyzed using the methods (MULT, MISS, QFI, and PREC) described by Kachman and Smith (1995). Acceptable QFI values with precision seeders were established at ≥85%, indicating that ≥85 of every 100 drops were singulated seed. Researchers have indicated >95% accuracy with agronomic planters, indicating the metering accuracy (ACCU) to be within 5% of the

Table 1. Seeding uniformity of Stanhay belt seeder at different seed spacings.

Theoretical spacing inches (mm)	Measures ^z					
	MEAN inches (mm)	MEAN/theoretical	MISS (%)	MULT (%)	QFI (%)	PREC (%)
2.8 (71)	2.8 (71)	1.0	7	2	91	14 a ^y
5.6 (142)	5.0 (128)	0.9	4	6	90	12 ab
9.0 (229)	8.5 (216)	0.9	4	4	91	6 c
18.0 (457)	15.2 (385)	0.8	0	9	91	7 bc
Significance			NS	NS	NS	*

^zMEAN = mean seed spacing, MEAN/theoretical = ratio of MEAN to theoretical spacing, MISS = missed seed locations (skips), MULT = multiple seed drops, QFI = quality of feed index (single seed drops), PREC = precision (variation of the spacings within target range).

^yMeans within a group followed by same letter are not significantly different at $P = 0.05$, by Duncan's multiple range test.

NS, * Nonsignificant or significant at $P \leq 0.05$, respectively.

theoretical seeding population (Bateman, 1972; Halderson, 1983; Synder and Hummel, 1985). ACCU, like MEAN, gives an indication of total seed metering but does not measure singulation. Precision seeders for vegetables should have at least as much, if not more, accuracy as typical agronomic planters (Parish, 1972).

Kachman and Smith (1995) reported a practical upper limit of 29% for the value of PREC, since a 29% value would be obtained with any random scattering of seeds within the target range. An acceptable PREC for seed measurements taken in the lab should fall below 10%, which would mean that the standard deviation of spacings within the target region would be $\leq 10\%$ of the theoretical spacing.

Although not considered a valid measure of uniformity by Kachman and Smith (1995), MEAN is the only measure that a grower can readily use to determine seeder performance. It was included to illustrate fallibility of the typical seeder calibration checks (catching the seed while the drive tire is rotated) for determining seeding uniformity of the seeder.

Data were analyzed using the GLM statistical procedure (SAS, 1995). MEAN was calculated using PROC MEAN procedure (SAS, 1995).

Results and discussion

Seed spacing did not have a significant effect on seed singulation with the belt seeder (Table 1). MEAN of the belt seeder was close to theoretical spacing at all seed spacings as MEAN/theoretical ratios were close to or equal to 1.0. Few skips ($\leq 7\%$) or multiple seed drops ($\leq 9\%$) occurred at any seed spacing with the belt seeder. Seed singulation with the belt seeder was excellent as indicated by QFI's $\geq 90\%$.

PREC (uniformity of spacings within the target area) of the belt seeder was affected by seed spacing as precision increased (lower PREC) with increasing seed spacing (Table 1). Best PREC was obtained at the 9.0- and 18.0-inch (229- and 457-mm) spacings. PREC at the 2.8- and 5.6-inch (71- and 142-mm) spacings were $>10\%$ and were not considered acceptable precision for a precision seeder. Since MISS, MULT, and QFI were not affected by variation in seed spacing,

holes in the belt were assumed to be filled and, therefore, not associated with loss of PREC at the narrower seed spacings. These data support the theory that, if loss in uniformity is at the seed release point or is an effect of seed bounce, absolute variability would be relatively constant over seed spacing and precision would be greater at the wider spacings. Wanjura and Hudspeth (1969) reported that trajectories of falling seed varied and caused the intended impact point to vary by ± 1 inch (25 mm).

All measures of seeding uniformity and precision of the vacuum seeder were affected by seed spacing (Table 2). MEAN exceeded theoretical spacing at all seed spacings but was only 10% greater than theoretical at the widest seed spacing. At the smallest seed spacing of 1.5 inches (38 mm), MEAN was three times greater than the theoretical.

MISS ranged from 60% for the smallest spacing to 18% for the widest theoretical spacing. Multiple seed drops (MULT) were significantly lower at the four widest spacings than at the 3.0-inch (77-mm) spacing. Although

Table 2. Seeding uniformity of Gaspardo vacuum seeder at different seed spacings.

Theoretical spacing inches (mm)	Measures ^z					
	MEAN inches (mm)	MEAN/theoretical	MISS (%)	MULT (%)	QFI (%)	PREC (%)
1.5 (38)	4.5 (115)	3.0	60 a ^y	19 ab	21 d	27 a
3.0 (77)	4.2 (107)	1.4	35 b	24 a	41 c	25 ab
4.5 (114)	6.0 (153)	1.3	38 b	12 bc	49 bc	24 ab
6.0 (153)	7.0 (178)	1.2	26 bc	7 c	68 a	13 c
9.0 (229)	11.3 (287)	1.3	32 bc	10 bc	58 ab	17 bc
11.2 (284)	12.4 (315)	1.1	18 c	10 bc	73 a	19 bc
Significance			***	*	***	**

^zMEAN = mean seed spacing, MEAN/theoretical = ratio of MEAN to theoretical spacing, MISS = missed seed locations (skips), MULT = multiple seed drops, QFI = quality of feed index (single seed drops), PREC = precision (variation of the spacings within target range).

^yMeans within a group followed by same letter are not significantly different at $P = 0.05$, by Duncan's multiple range test.

***, ***, * Significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

Table 3. Seeding uniformity of Gaspardo vacuum seeder at 3.0-inch (77-mm) seed spacing with air pressure seed release engaged or disengaged.

Air pressure seed release	Measures ²					
	MEAN inches (mm)	MEAN/ theoretical	MISS (%)	MULT (%)	QFI (%)	PREC (%)
Engaged	4.2 (107) a	1.4	35 a ^y	24	41	25
Disengaged	3.0 (77) b	1.0	20 b	24	56	21

²MEAN = mean seed spacing, MEAN/theoretical = ratio of MEAN to theoretical spacing, MISS = missed seed locations (skips), MULT = multiple seed drops, QFI = quality of feed index (single seed drops), PREC = precision (variation of the spacings within target range).

^yMeans within a group followed by same letter are not significantly different at $P = 0.05$, by Duncan's multiple range test.

QFI was greatest at the three widest spacings, QFI at none of the theoretical spacings was adequate for precision seeding.

Precision increased as seed spacing with the vacuum seeder increased, but differences were only significant between the 1.5-inch (38-mm) spacing and the three widest spacings and between the three narrowest spacings and the 6.0-inch (153-mm) spacing. PREC at all seed spacings was >10% and unacceptable for precision seeding.

Operating the vacuum seeder with the air pressure seed release disengaged improved seeding uniformity (Table 3). MEAN was equivalent to theoretical seed spacing when the seed release was disengaged, but was 40% greater than theoretical when the seed release was engaged. Significantly fewer skips (MISS) were noted when the seed release was disengaged. MULT were not affected by the operation of the seed release. Although QFI and PREC improved with the seed release disengaged, values were still not satisfactory for precision seeding. Results from this experiment indicated no improvements in seeding uniformity were obtained from using the seed release mechanism.

Loss of uniformity of the vacuum seeder was probably a combination of several factors. Although not obvious when viewing the vacuum plate during testing, the high plate speed required to achieve the narrower seed spacings could have resulted in greater misses and multiples. Wanjura and Hudspeth (1969) found that pattern efficiency of vacuum wheels differed most at lower vacuum pressures and faster wheel speeds. Since PREC of the vacuum seeder and belt seeder were poorer at the narrower seed spacing, the effect of seed drop should also be considered a factor. Breece et al. (1981) reported that the effect of cottonseed bounce in a seed tube caused what appeared to be skips and doubles but was really poor

seed-to-seed spacing. They also indicated that irregular seed placement is often blamed on the seed metering mechanism when the seed placement mechanism is at fault. The better PREC with the belt seeder might be attributed to a much shorter seed drop [1.5 inch (38 mm)] than with the vacuum seeder [7 inch (178 mm)], as variation in seed placement will be multiplied with greater release-to-surface distance (Wanjura and Hudspeth, 1969).

Overall, seeding uniformity of the belt seeder was better than that of the vacuum seeder. Our results support reports from Parish et al. (1991) and Bracy and Parish (1998) who found that seeding uniformity of the Stanhay belt seeder (especially with spherical seed) was greater than that of a vacuum seeder.

Conclusions

Seeding uniformity of the belt seeder was not affected by seed spacing, but the uniformity of the vacuum seeder was affected. Seeding uniformity of the vacuum seeder increased as seed spacing increased from 1.5 inches (38 mm) to 11.2 inches (284 mm). These results support our hypothesis that absolute variation in seed spacing with the vacuum seeder is consistent, thus uniformity (expressed as a percentage of theoretical seed spacing) increases with increasing seed spacing. Nonuniformity probably occurred due to the higher plate speeds at the narrower seed spacing and as a result of the additional random variation from the longer seed drop. Disengaging the air pressure seed release on the vacuum seeder increased seeding uniformity and precision, indicating that positive pressure release of the seed is not essential nor helpful. Uniformity and precision of the belt seeder was better than that of the vacuum seeder with the spherical cabbage seed used in this experiment.

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