The Slide Hammer Seeder: A Novel Tool for Planting Small Seeds

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Summary. Many important herbs [e.g., mint (*Mentha* sp.), thyme (*Thymus* sp.)], underused and nutritious vegetables [e.g., purslane (*Portulaca oleracea*), *amaranth (Amaranthus tricolor*)], and important biological control plants [e.g., sweet alyssum (*Lobularia maritima*)] have small seeds (≤ 1.5-mm long) that are difficult to plant with raw (i.e., nonpelleted) seed using existing seeders. A novel tool known as the slide hammer (SH) seeder was developed for the precise seeding of raw seeds of small-seeded plants. The SH seeder is a jab-type planter made primarily from electrical conduit tubing and other materials that are inexpensive and readily available in a hardware store or on the Internet. The interchangeable seed hopper is made from a plastic snap cap vial that has one or more holes of varying diameter depending on the desired seeding rate and seed size. Seed forms a "bridge" above the hole in the vial until they are dislodged from the force of the SH that discharges seeds to fall to the soil. Detailed plans are provided for how to make and use the SH seeder. The fabrication time is 2 to 4 hours with a material cost of ≈$32. I determined the seed vial hole specifications for the precise seeding of a variety of small-seeded plants, including chives (*Allium schoenoprasum*), chinese chives (*Allium tuberosum*), basil (*Ocimum basilicum*), grain amaranth (*Amaranthus* sp.), sweet alyssum, purslane, creeping thyme (*Thymus serpyllum*), and spearmint (*Mentha spicata*) that ranged in size from ≈200 to 11,000 seeds per gram. The diameter of the hole that was suitable for discharging the seed from the vial was always larger than the average seed length, and the ratio of hole diameter to seed length ranged from 1.07 to 1.62. Seeding rate uniformity evaluations were conducted for these species using vials with one vs. two holes and showed that the seeding rate was higher by an average of 58% to 173% from a vial with two holes compared with one hole. For most plant species evaluated, the SH seeder was able to dispense as few as one to three seeds consistently. Seed discharge increased somewhat with increasing SH weight for all species evaluated. The SH seeder can be useful for interplanting sweet alyssum as an insectary plant for aphid (Aphidoidea) control between existing plants of organic lettuce (*Lactuca sativa*), and for intercropping cultivars of purslane as a novel vegetable in between transplanted organic broccoli (*Brassica oleracea* Italica group) plants. This novel seeding tool has many potential uses for direct, hand seeding in vegetable and herb production systems and in weed research trials. The seeder could be automated and made with a variety of alternative materials.

Planting seeds by hand has been important since the beginning of agriculture more than 10,000 years ago, and hand seeding is still important for major staple crops like corn (*Zea mays*) in many parts of the developing world (Aikins et al., 2010; Omara et al., 2016). Although jab-style hand seeders were widely used for corn in the United States during the early 1900s (Moore, 2003; Voelker, 2009), their use in the United States today is primarily in research plots for agronomic crops with relatively large seeds (Gonzalez et al., 2018; Leon et al., 2000). However, these seeders are unsuitable for precision planting of small-seeded species that are of interest as cash crop or as "insectary plants" in many horticultural systems. Insectary plants are plants that are grown in high-value vegetable crops, such as lettuce and broccoli, to provide pollen and nectar for beneficial insects [i.e., hoverflies (Syrphidae), parasitoid wasps (Hymenoptera)] that can help to control aphids (Ambrosino et al., 2006; Araj and Wratten, 2015; Brennan, 2013, 2014, 2016; Chaney, 1998; Hogg et al., 2011). One of the most common insectary plants used in regions such as the Salinas Valley of California is sweet alyssum, which has the rather unique ability to flower continuously once flowering commences. Although sweet alyssum and other common insectary plants are often planted as transplants in these vegetable cropping systems to ensure the presence of flowers early in the development of the vegetables, there are situations in which direct seeding of insectary plants may be useful and more cost effective. For example, direct seeding insectary plants may be appropriate where the vegetable is also direct-seeded and therefore present in the field for longer than would occur with transplants. Furthermore, direct seeding may be more cost effective than growing transplants and may encourage the use of insectary plants because it does not require advanced planning; seeds of insectary transplants typically need to be sown 30 to 50 d before they are ready for transplanting. Direct seeding of insectary plants also may be a land-efficient way for farmers to make use of gaps in seed lines resulting from malfunction of the cash

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
3.6967	dram(s)	mL	0.2705
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.1786	lb/inch	$kg\cdot cm^{-1}$	5.5997
28.3495	oz	g	0.0353
0.9144	yard(s)	m	1.0936

crop seeder. To address the need for a seeder that allows the precise planting of small-seeded plants such as sweet alyssum, a simple and effective seeder called the slide hammer (SH) seeder was developed (Fig. 1). The objectives of this article were 1) to describe how to make and use the SH seeder, and 2) to evaluate the accuracy of the seeder for a variety of small-seeded plant species including insectary plants, herbs, and novel vegetables. An online video describing how to make the seeder, a field demonstration of its use, and other features is described at Brennan (2018).

Material and methods

Construction of the SH seeder. Once the materials are obtained, the time to make the SH seeder is 2 to 4 h, and the estimated cost of materials is $32.50 (Table 1). The handle is made of 1/2-inch electrical metallic tube (EMT) conduit that is commonly used to protect and route electrical wiring in buildings (Fig. 1). Table 1 lists the specifications of the EMT and the other materials needed with the typical price from hardware stores in Salinas, CA. The following tools are needed: tape measure, hacksaw or pipe cutter, scissors, utility knife, flat-head screw driver, socket driver for adjusting the hose clamps, pliers with a wire cutter, drill with a range of small bits (i.e., 1/16 inch or smaller depending on the size of the seed to be planted), round file with an outer diameter of ≈0.5 inch, bench vice, hammer, and flat-ended punch. The length of the handle may be varied depending on the height of the operator, but the prototype was cut with a hacksaw to 5 ft long and worked well for the author who is ≈6 ft tall. To form the seeder foot plate, the lower 3.5-inch end of the EMT is compressed in the bench vice until the 90° corner brace can be slipped into the EMT, after which it is compressed further to secure the brace in the EMT. The compressed area can then be hammered against the anvil of the vise to further secure the brace. At ≈39.5 inches from the bottom of the EMT, a 2-inch section of the EMT is compressed in the vice to form a slightly flattened section [≈0.5-inch o.d. at the narrowest point (Fig. 2A)]. The inner stop ridge at the center of the EMT coupler is filed down until the coupler can slide over the top end of the EMT and down to stop at the flattened section. The set screws on the EMT coupler are then tightened to lock the coupler to the handle. The inner hole of the hammer stop washer is filed to increase the diameter until the washer is able to slide over the top of the EMT and down to rest on the EMT coupler. To make the SH, the 3/4-inch metal tees are attached by hand to the threaded polyvinyl chloride (PVC) riser and the 90° elbow is attached to the lower tee. The SH is then placed over the handle to rest on the stop washer and the sliding hose clamp is added above the SH. The compression spring is then secured to the top of the EMT handle using a screw hose clamp (i.e., worm gear) that is tightened with an appropriately sized socket driver. The diameter of the sliding hose clamp just above the SH assembly should then be adjusted so that it can slide with the SH but not slide over the compression spring. This ensures that the SH will engage the spring when the seeder is lifted off the ground.

The extension tube is made from a 2-inch-high by 4-1/8-inch wide piece of clear high-density polyethylene cut from the central wall section

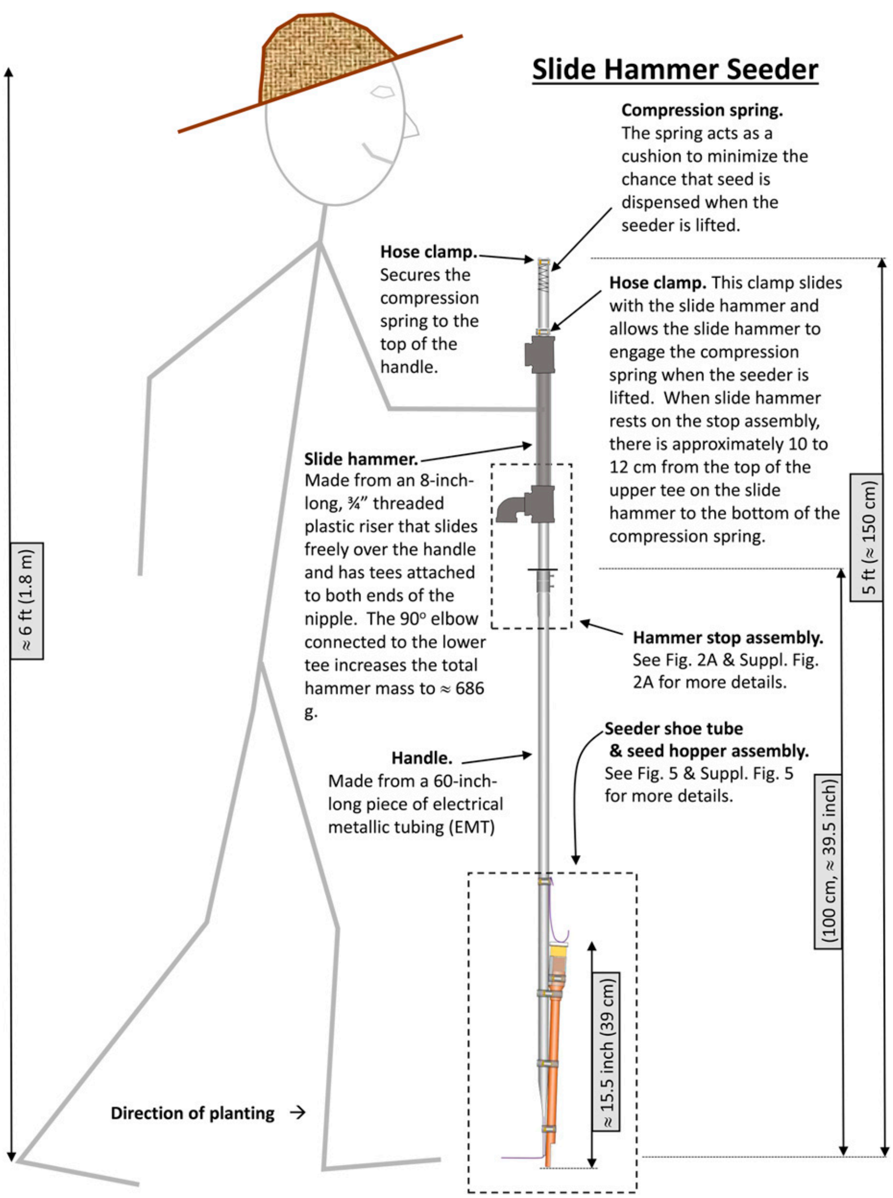


Fig. 1. The slide hammer seeder illustrating the various components that are about to scale; 1 inch = 2.54 cm, 1 ft = 0.3048 m. See Supplemental Fig. 1 for enlarged, color version.

Table 1. Materials needed for making the various components of the slide hammer (SH) seeder in order from the top of the seeder to the bottom, and the estimated cost.

Quantity or length	Component and description[z]	Cost ($)
	Handle	
5 ft	1/2-inch electrical metallic tubing (EMT) × 10 ft (0.62 inch i.d., 0.71 inch o.d.). Typically sold in 10-ft lengths for ≈$3.30 each. Thus, a single length can make two seeders.	1.65
1	-3 to 4-inch-long steel compression spring with an i.d. of about 0.72 to 0.75 inch and o.d. of about 0.83 inch. This should slide freely on the EMT. The ideal spring rate is about 0.93 lb/inch. A suitable spring is one where the spaces between spring coils compress about half way when the SH seeder is lifted up by the slide hammer. For example, see compression spring no. 3185 (Century Spring Corp., Commerce, CA) with the following specifications: made from 0.042 inch diameter steel wire with a zinc finish with 12 coils, 3.53 inches long (free length), 0.744 inch i.d., 0.828 o.d., spring rate of 0.93 lb per inch.	4.55
1	Hose clamp SAE #8, effective range: 1/2 to 29/32 inch, 13 to 23 mm.	1.00
	Slide hammer and hammer stop	
1	Hose clamp SAE #6, effective range: 7/16 to 25/32 inch, 11 to 20 mm. Adjusted to slide between the bottom of the compression spring and the upper slide hammer coupler.	1.00
1	3/4-inch × 8-inch-long threaded PVC riser [PVC (1 inch o.d., 0.82 inch i.d.)] that will slide freely over the EMT. These risers are typically sold with threads (14 threads/inch) that match the threads on the iron tees noted below.	1.69
2	3/4-inch threaded, black, iron tees. These attach to both ends of the PVC riser.	5.78
1	3/4-inch threaded 90° iron elbow.	2.39
1	1–1/2-inch o.d. steel washer, with ≈0.69 inch i.d. The i.d. will need to be filed slightly so that it can slide down over the EMT. Washer thickness should be ≈0.15 inch.	0.15
1	1/2-inch EMT screw coupling. The inner stop in the center of the coupler will need be filed down so that the coupler can slide over the EMT.	0.38
	Seeder shoe tube and seed hopper assembly	
1	Irrigation flag with 0.06-inch o.d., steel wire. This is used to make the J-shaped wire that secures the seed vial in the extension tube.	0.10
1	Hose clamp #6, effective range 7/16 to 25/32 inch, 11 to 20 mm. Clamps the J-shaped wire to the handle.	1.00
1 or more	Seed vial, 7 drams, clear, polystyrene snap cap vial. Approximately 1.09 inch o.d. at the base, 1 inch i.d., 2 inches tall with cap on. A suitable vial is one where the outer diameter at the vial base is about the same or slightly smaller than the outer diameter of the larger end of the copper reducing coupler that the vial rests on in the SH seeder (Fig. 5). Vials are often sold in cases of 144 vials for ≈$40 per case; for example see item no. PLC-03732 (Qorpak, Bridgeville, PA).	0.28
1	Smooth, clear, rectangular piece of high-density polyethylene [HDPE (2 inches high × 4-1/8 inches wide, 0.01-inch thick)] cut from the wall of a single-use bottle for water or soda. This is used to make the extension tube.	0.00y
3/4 × 3/4 inch	Cellophane tape, 3/4-inch wide.	0.00x
5 × 1 inch	Duct tape. This can be made by cutting or tearing a 1-inch-wide strip from a 5-inch-long strip of duct tape that is commonly sold in 1.89-inch-wide rolls.	0.00x
1	1 × 1/2-inch copper reducing coupler	4.59
1 ft	1/2-inch type L copper pipe. Typically sold in 10-ft lengths for ≈$14 each.	1.40
3	Hose clamp SAE #12, effective range: 11/16 to 1-1/4 inch, 17 to 32 mm. One of these clamps the extension tube to the copper reducing coupler. The other two connect the seeder shoe to the base of the handle.	3.00
1	Hose clamp SAE #16, effective range: 13/16 to 1-1/2 inch, 21 to 38 mm. This clamps the reducing coupler to the EMT.	1.19
1	Seeder foot. 3.5 × 3/4 inch 90° corner brace. Both arms of the brace are 3.5 inches long.	1.49
Total		31.64

[z]1 ft = 0.3048 m, 1 inch = 2.54 cm, 1 inch = 25.4 mm, 1 lb/inch = 0.1786 kg·cm^{-1}, 1 thread/inch = 0.3937 thread/cm, 1 dram = 3.6967 mL.

[y]No estimated price is listed for the piece of HDPE because this will be free from a bottle that was to be recycled.

[x]No estimated price is listed because of the small amount of tape required. A 50-yard (45.7 m) roll of duct tape 1.89 inch wide typically costs ≈$5, and a 300-ft-long roll of 3/4-inch-wide cellophane tape typically costs ≈$3.

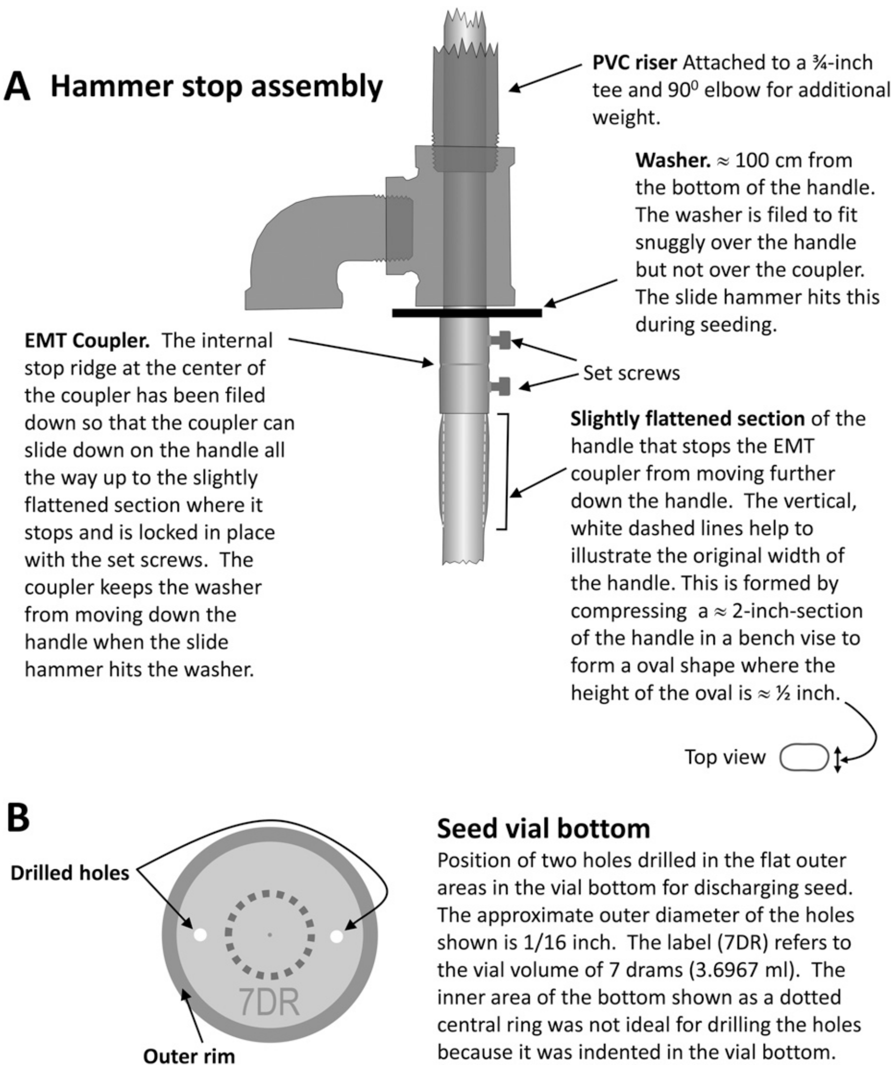


Fig. 2. Detailed illustrations of the hammer stop assembly (A), and the position of the holes in seed vials of the slide hammer seeder (B); 1 inch = 2.54 cm, 1 dram = 3.6967 mL. EMT = electrical metallic tube; PVC = polyvinyl chloride. See Supplemental Fig. 2 for enlarged, color version.

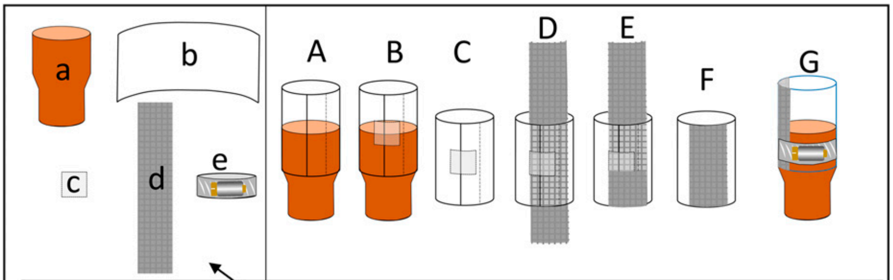
of a 2-L plastic soda or water bottle following the steps in Fig. 3. The seeder shoe is fabricated from a 1-ft-long section of 0.5-inch type L copper tubing as described in Fig. 4. The extension tube and attached copper reducing coupler (Fig. 3G) is then slipped over the top of the seeder shoe, and three hose clamps are used to attach the seeder shoe and seed hopper assembly to the lower end of the handle by the seed foot plate (Fig. 5). The union of the seeder shoe and coupler can be secured as needed with duct tape, but normally this is unnecessary. The J-shaped wire that holds the seeding vial in the extension tube is made from a 6-inch-long piece of wire cut from an irrigation flag and bent into the J shape using pliers. The J-shaped wire is then secured to the handle with a hose clamp so that it touches the top of the seed vial sitting in the extension tube (Fig. 5). The position of the seeder shoe and seed hopper assembly relative to the seeder foot plate is adjusted up or down on the handle as needed, depending on the desired seeding depth.

Seed vials for dispensing seed are made by drilling one or more holes in the bottom of the vial depending on seed size and desired seeding rate. The holes should be drilled in the flat bottom area of the vial ≈3 to 5 mm away from the outer edge of the vial (Fig. 2B). If multiple holes are used in a vial, it is best to position these on opposite sides of the vial bottom so that they function independently (i.e., if a piece of debris in the seed clogs one hole, the other hole is far enough away that it will remain open).

Seed vial hole diameter selection, calibration, and use of the SH seeder. The easiest way to determine an appropriate hole diameter that will consistently discharge seed is to use a drill bit with a diameter that is at least as large as the longest dimension of the seed. Standard drill sets available in hardware stores typically range from a minimum of 1/16-inch diameter (1.59 mm or ≈#52 to #53 wire gauge size) to 0.5-inch diameter, but may be available as individual bits in smaller wire gauge sizes or in jewelry drill bit sets that typically range from #80 (0.34 mm) to #60 (1.02 mm). Multiple holes can be added to opposite sides of the vial bottom to achieve higher seeding rates and can be plugged as needed by covering them with adhesive tape.

To determine the minimum appropriate hole diameter, it is helpful to place a representative seed sample inside a folded piece of transparent adhesive tape so that it can be compared with the diameter of available drill bits or seed of another species where the appropriate hole diameter has already been chosen. A hand lens or dissecting microscope can help to compare seed size with drill bit diameter. A good starting point is to test holes that are slightly larger than the seed length.

Once a candidate hole diameter has been selected and the hole has been made, the vial can be tested in the seeder. To do this, add seed to the vial so that it is ≈1/4 to 3/4 full, and load the vial into the extension tube. If the vial has insufficient seed, the seeds may not be dispersed evenly enough over the holes to allow for a uniform seeding rate. With one hand, hold the seeder handle perpendicular to the ground with the seeder foot plate resting on a block of wood so that the seeder shoe is just above the rim of a glass or plastic jar (e.g., 16 fl oz, ≈4 to 5 inches tall) that will catch discharged seed. With the other hand, raise the SH up to the spring on the top of the handle, and then release the SH so that it drops and hits the hammer stop washer. Alternatively, the seeder can be attached temporarily with screws through the seeder



Materials needed

a. ½ x 1 inch copper reducing coupler.
b. Smooth, clear, rectangular piece of high-density polyethylene (HDPE, 2 inch high x 4 1/8 inch wide) cut from the wall of a single used bottle for water or soda.
c. Piece of cellophane tape (≈ ¾ x ¾ inch)
d. Strip of duct tape (5 inch long x 1 inch wide).
e. Hose clamp (11/16 to 1 ¼ inch, 17 to 32 mm effective range)

Extension tube fabrication steps

1. The rectangular piece of HDPE should be cut from the bottle using a utility knife and scissors so that the long dimension is oriented around the circumference of the bottle (**b**).
2. Wrap the piece of HDPE tightly and evenly around the larger end of the coupler (**A**) into a tubular shape that overlaps by ≈ ½ inch as indicated by the outer seam (solid, vertical line) and inner seam (dashed, vertical line).
3. Holding the HPDE tightly around the coupler, temporarily secure the outer seam with the piece of cellophane tape (**B**).
4. Slide the tube off of the coupler (**C**).
5. Align the strip of the duct tape on the inside of the tube with the adhesive side facing out towards the inner seam and so that the tape is evenly aligned with the inner and outer seam (**D**); there should be approximately 2 inches of tape extending out of the top of the tube and 1 inch out of the bottom of the tube. Stick the tape along the inner wall so that it covers the inner seam, and then bend the bottom section of tape up so that it sticks to the lower section of the outer wall covering the outer seam (**E**).
6. Bend the upper section of tape down to cover the remainder of the outer wall seam (**F**). The end of the tape will therefore be at or near the lower rim of the tube.
7. Slide the tube back over the coupler (**G**) and add the hose clamp to secure the tube and the coupler. Note that the position of the extension tube on coupler has been rotated to show the front of the tube facing right as in Fig. 5 & Suppl. Fig. 5.

Fig. 3. Materials needed and steps for fabricating the extension tube that holds the seed vial on top of the seeder shoe tube; 1 inch = 25.4 mm. See Supplemental Fig. 3 for enlarged, color version.

foot plate to a large wooden block or shipping pallet, so that the seeder is secured in an upright position and does not need to be held vertically by hand during testing. Count the number of seeds discharged with each hit of the SH and repeat at least 10 times as needed to test for seeding rate uniformity with a single hole open in the seed vial. For some species, a vial with two or more smaller holes may provide a more uniform minimum seeding rate than a vial with a single larger hole.

Once an appropriate hole diameter has been determined that consistently delivers a minimum number of seeds with each hit, and relatively few or no hits with no seed discharged, additional holes can be added to the vial to achieve the desired seeding rate. If one has a limited selection of drill bit diameters, a round needle file can be used to gradually increase the diameter of a hole, but this may not be ideal because it may be difficult to replicate. As noted in the following Practical Implications section, the seeding rate also can be adjusted by "diluting" the target seed with inexpensive seed of another species that has been killed.

To adjust the seeder to the appropriate seeding depth, it is helpful to use a light-colored test seed, such as grain amaranth, that is relatively easy to see in dark-colored soil. The seeder shoe tube can then be moved up or down on the seeder handle to adjust the seeding depth for the site-specific soil conditions. After the appropriate seeding depth has been determined with the test seed, the vial can be replaced with the appropriate vial of the desired seed species. It may be helpful to try using several seeding depth and seed vial settings in a small area of a field, and count seedling emergence to help to select the best seeder settings.

The procedure for using the SH seeder for field planting involves holding the seeder in one hand, placing the seeder foot plate on the soil surface, striking the SH against the hammer stop washer, and then lifting the seeder to the next planting location. It is important to stress that the primary force striking the SH stop washer comes from the weight of the SH that is held relatively loosely in the hand of the operator as the SH falls to the stop washer. If an appropriate vial hole was chosen, the SH does not need to be struck hard against the hammer stop to discharge seed. After the hit, the seeder can be left to rest on the soil and leaned forward as the operator steps forward as if the seeder is a walking stick that is then lifted and moved to the soil surface at the next planting location. Using this motion, it is relatively easy to sow seeds in 30 to 40 target locations in 1 min as is shown in the online video (Brennan, 2018). The compression spring on the top of the handle acts as a cushion to minimize the chance of dispensing seed when moving from one target seeding location to the next. The seed vial hole may be too large if the vial consistently discharges seed when the seeder is lifted between planting locations.

HOW THE SH SEEDER WORKS. Seed is discharged in small quantities from the seeder when the force of the SH hits the hammer stop washer and the force is transmitted down the handle to dislodge seed in the vial (Brennan, 2018). This jarring force temporarily disrupts the "bridge" or "arch" of seed directly above the hole in the vial (Fig. 6) and allows a small amount of seed to flow through the vial hole and down through the seeder shoe to the soil. After the seed has been discharged, the seed directly above the vial hole reforms a bridge that prevents additional seed from being discharged until the next hit of the SH. Although bridging or arching is a common problem that

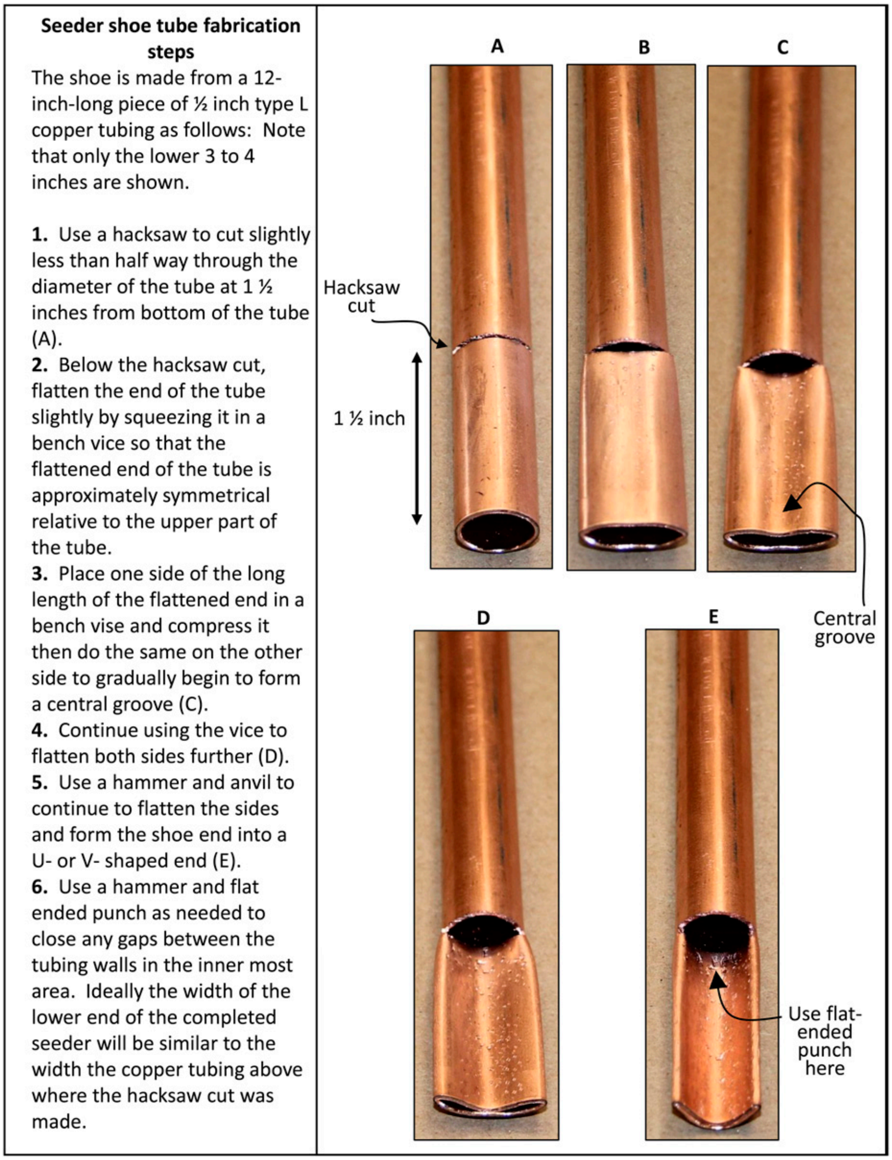


Fig. 4. Photographs of the steps to fabricate the seeder shoe of the slide hammer seeder; 1 inch = 2.54 cm. See Supplemental Fig. 4 for enlarged, color version.

can hamper the flow of dry materials, such as seed and granular fertilizers, from hoppers or silos, bridging with the SH seeder is advantageous because it prevents seed discharge until the bridge is disrupted by the force of the SH striking the hammer stop washer.

Expt. 1: Seeding rate uniformity evaluation. Seeding rate uniformity of the SH seeder with each hit of the SH was tested with plant species with a range of seed sizes (Table 2) using vials with one and two holes. Grain amaranth seed was obtained from the bulk food section of a grocery store in Monterey, CA (Whole Foods Market, Austin, TX). Sweet alyssum seed was produced by Kamprath Seeds Inc. (Manteca, CA). All other seeds were purchased from Johnny's Selected Seeds (Winslow, ME). Grain amaranth is produced by three species with light-colored seeds [foxtail amaranth (*Amaranthus caudatus*), blood amaranth (*Amaranthus cruentus*), prince's-feather (*Amaranthus hypochondracus*)], but it is not known which species produced the seed described in this article.

For the eight species tested, the average seed length was determined by randomly selecting four seeds and measuring the seed length with the eyepiece graticule on a dissecting microscope that was calibrated with a stage micrometer. The SH seeder calibration procedure noted previously was used to determine the minimum, appropriate vial hole diameter for seed of each species with the seeder temporarily attached to a large wooden block that held the seeder vertically. The weight of the SH used in this evaluation was 642 g and it dropped 10 to 11 cm before striking the hammer stop washer. Two holes of the selected diameter for each species were drilled into the vial bottom on opposite sides and approximately one-fourth of the distance from the vial side (Fig. 2B). With one hole in the vial bottom closed with adhesive tape, the vial was loaded with seeds and the number of seeds discharged into a glass jar for each of 20 consecutive hits was recorded; the vial was approximately one-half full for all species except for the smallest-seeded species (spearmint and creeping thyme), where it was approximately one-quarter full. The seed vial was then emptied, the tape was removed to open both holes, and the vial was reloaded to test it with two holes with 20 consecutive hits. Exploratory Software for Confidence Intervals [ESCI (Cumming and Calin-Jageman, 2017)] was used to calculate 95% confidence intervals (CIs) for number of seeds discharged from one vs. two holes, and the mean and 95% CI of the difference assuming that the one- and two-hole comparisons were independent groups. The one- vs. two-hole measurements were considered different if the 95% CI of the difference did not include zero.

Expt. 2: SH weight evaluation. With spearmint, basil, and chinese chives, the effect of SH weight on seeding rate was evaluated using hammers with the following weights: 532, 686, 816, 946, 1082, and 1217 g. Thus, the percentage increase from the lowest-weight hammer was 29%, 54%, 78%, 103%, and 129%, respectively. These weight increments were achieved by adding 3/4-inch fittings to the lower tee of the SH where the lowest-weight hammer only had the PVC riser and the upper and lower tees attached, the 686-g hammer had the 90° elbow added (as in Fig. 1), and the subsequent increments had one, two, or three 3/4-inch PVC risers (1-1/2 inches long) each added with a 3/4-inch black, iron coupling. Within each species these hammer weight increments were evaluated in a randomized complete block experiment with six replicates using vials with two holes of the diameter

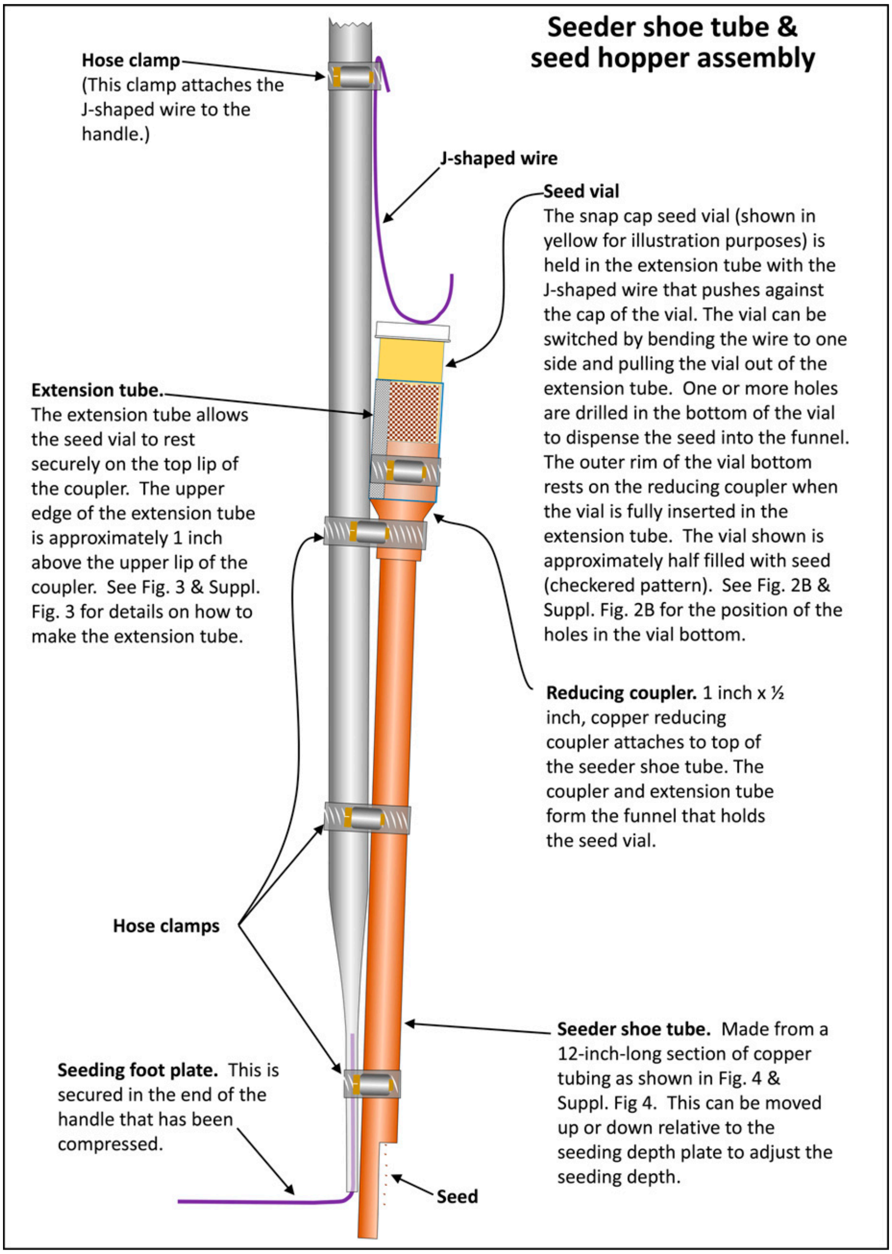


Fig. 5. Detailed illustration of the seeder shoe tube and seed hopper assembly of the slide hammer seeder; 1 inch = 2.54 cm. See Supplemental Fig. 5 for enlarged, color version.

used in Expt. 1. For each hammer weight and replicate, the seed discharged from each of four hits of the hammer was counted and used to calculate the average seed discharge count. The seed vial was emptied and refilled for each replicate and the vial was inverted between treatments within each replicate to remove any potential seed settling effect. SigmaPlot (version 13; Systat Software, San Jose, CA) and PROC REG in SAS (SAS Institute, Cary, NC) were used to determine and plot the best-fit regression relationships between seeding rate and SH weight. Regression model selection was done to maximize the adjusted R^2 for the best-fit first-, second-, or third-order model using the Selection=ADJRSQ option in PROC REG.

Results and discussion

SEED VIAL HOLE DIAMETER SELECTION, CALIBRATION, AND USE OF THE SEEDER. The selected, minimum hole diameter for dispensing seed from the vials was always larger than the average seed length, although this relationship differed considerably by species (Fig. 7; Table 2). For example, the selected hole diameter for spearmint (0.71 mm) was similar to the average seed length (0.67 mm) with a ratio of 1.07, whereas the hole diameter for chinese chives (5.16 mm) was nearly 2 mm larger than the average seed length (3.18 mm) with a ratio of 1.62. Consequently, vial hole diameter needed to be much larger than the seed length for chinese chives than spearmint, because chinese chives seeds are angular whereas spearmint seeds are almost spherical. Angular seeds discharge less readily through the holes than round seed; therefore, attempts to use smaller vial holes for chinese chives often resulted in more hits with no seed dispensed.

EXPT. 1: SEEDING RATE UNIFORMITY EVALUATION. As expected, with all species evaluated, the average number of seeds dispensed with each hit of the SH was greater with two holes in the vial bottom than with one hole (Figs. 8 and 9). With four of the eight evaluated species, the selected hole diameter resulted in some hits with no seed discharged with a single hole (spearmint, purslane, sweet alyssum, chinese chives), although among these four species this usually represented 15% or less of the hits; purslane was the exception, with 30% of the single-hole hits resulting in zero discharge. The general trend of wider CI in the two-hole than one-hole seeding rate indicates more variability with the two holes. With the smallest species evaluated (spearmint), the single hole discharged a single seed in 13 of 20 hits, and two holes discharged two seeds in 10 of the 20 hits. Seed singulation is desirable where seed is limited or expensive, or where the market demands harvested products of a uniform size, such as with lettuce that is sold by the head.

EXPT. 2: SH WEIGHT EVALUATION. SH weight influenced seed discharge from the SH seeder for the three species evaluated and overall tended to increase gradually as SH weight increased (Fig. 10). For example, the average increase in seed discharge (seeds per hit) from the lightest (532 g) to the heaviest SH (1217 g) was 1.5 (mint), 2.7 (basil), and 1.5 (chinese chives). Thus, although the SH weight had increased by 129% from the lightest to heaviest

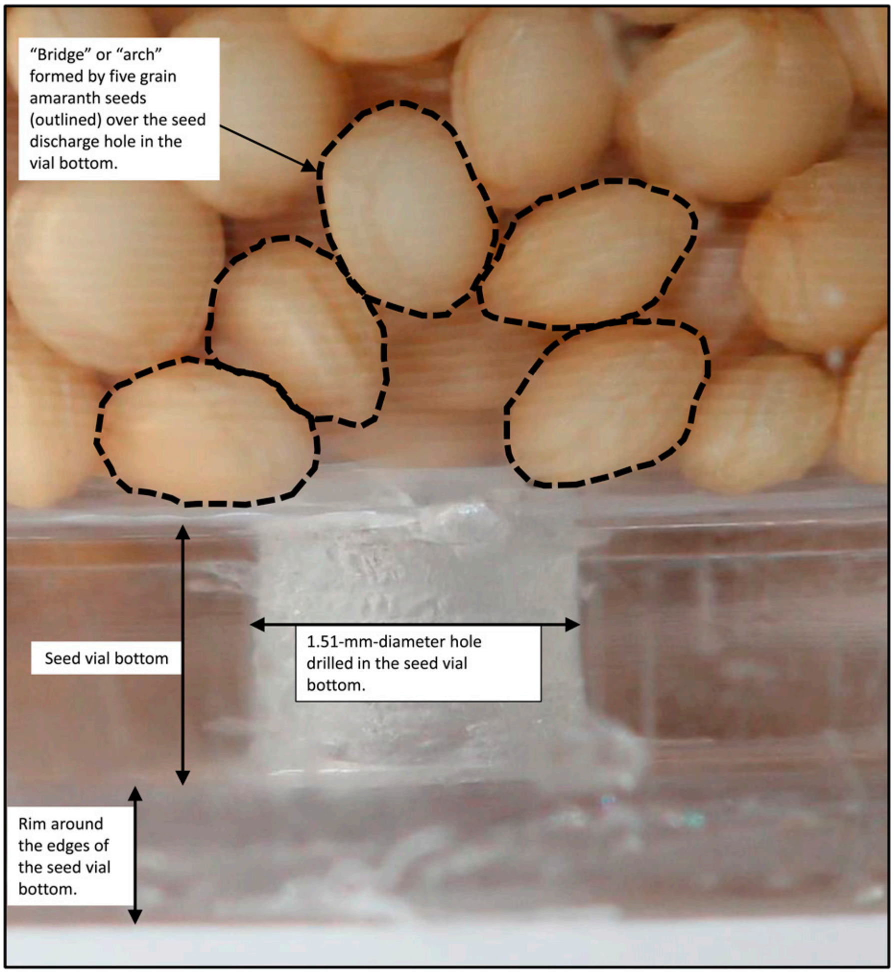


Fig. 6. Photograph of the "bridge" or "arch" of grain amaranth seeds formed over the 1.51-mm (0.06-inch) diameter seed discharge hole drilled in the bottom of the seed vial using a #53-gauge drill bit. The five seeds that form the bridge are outlined and prevent seed from moving through the hole until the bridge is broken by the force of the slide hammer striking the slide hammer stop washer (Fig. 2A). For purposes of illustration, the hole in the vial bottom was made at the outer edge of the vial bottom adjacent to the tubular wall of the vial and rim that goes around the edges of the vial bottom, but normally the hole would be made away from vial wall (Fig. 2B). See Supplemental Fig. 6 for enlarged, color version.

SH, the average increase in seed discharge per hit was 80% (spearmint), 44% (basil), and 17% (chinese chives). It is important to note that although the average number of seeds discharged per hit was always greater from the 1217-g than 532-g SH for all three species evaluated, the 95% CI of the paired difference between the lightest and heaviest SH, shown in [ ] was positive for spearmint [0.3, 2.8] and basil [1.1, 4.2] but not for chinese chives [–3.5, 6.5]. This indicates more variability in the effect of SH weight on seed discharge with chinese chives than for spearmint and basil.

Practical implications and potential modification of the SH seeder. The SH seeder is a novel seeder design that in its current form or modification may be useful in a variety of settings from the home garden to transplant nurseries and large-scale vegetable operations where one wants to plant small amounts of seed at a fairly uniform seeding rate. For example, in the home garden or small-scale nursery where a limited amount of seed needs to be planted in a flat for transplanting, a seed vial could be held by hand and moved slowly over the soil, while tapping the vial cap with the other hand to dispense the seed on the soil's surface. The seed could then be covered with a shallow layer of soil. This vial tapping method of dispensing seed results in more accurate and even seeding than if the vial was shaken like a salt or pepper shaker over the soil surface (no data presented).

In large-scale vegetable operations in the Salinas Valley of California, I have found the SH seeder to be a rapid and efficient way to interseed raw sweet alyssum seeds as insectary plants at specific locations between lettuce seedlings. This interseeding can be done after lettuce emergence or thinning, so that the interplanted sweet alyssum can be placed at specific locations relative to the lettuce (i.e., equally spaced between the lettuce, or where there are gaps due to unintended skips by the lettuce seeder). A 5/64-inch-diameter drill (1.98 mm) was used to make the holes in the seed vial for the interplanting of sweet alyssum in lettuce field trials (E.B. Brennan, unpublished data); this hole diameter is slightly larger than what was used for the one- vs. two-hole comparison [1.85 mm (Fig. 8A)] and worked well particularly where the vial had two holes. To ensure at least one or more vigorous plants of the insectary species like sweet alyssum, it is best to use a vial with multiple holes even if this results in several emerged seedlings at each seeding location. More vigorous plants typically will compete successfully with others.

The SH seeder has also worked well for interseeding cultivars of purslane as a novel and potential earlier maturing cash crop between transplanted broccoli (E.B. Brennan, unpublished data). Furthermore, in weed research, the SH seeder could be a useful tool for seeding small amounts of weed seed at specific locations within a cash crop. In any of these cases, an additional way to control the seeding rate other than varying the number or diameter of the seed vial holes is to "dilute" the seed of interest by mixing it with killed seed of an inexpensive species such as grain amaranth. The diluting seed can be killed by heating it for several minutes in a microwave. Grain amaranth may be ideal for diluting other seeds because it is readily available, inexpensive, and has relatively round seeds that flow well through holes that can be made with a commonly available, thin drill bit [1/16 inch (1.59 mm)]. This drill bit diameter is slightly larger than

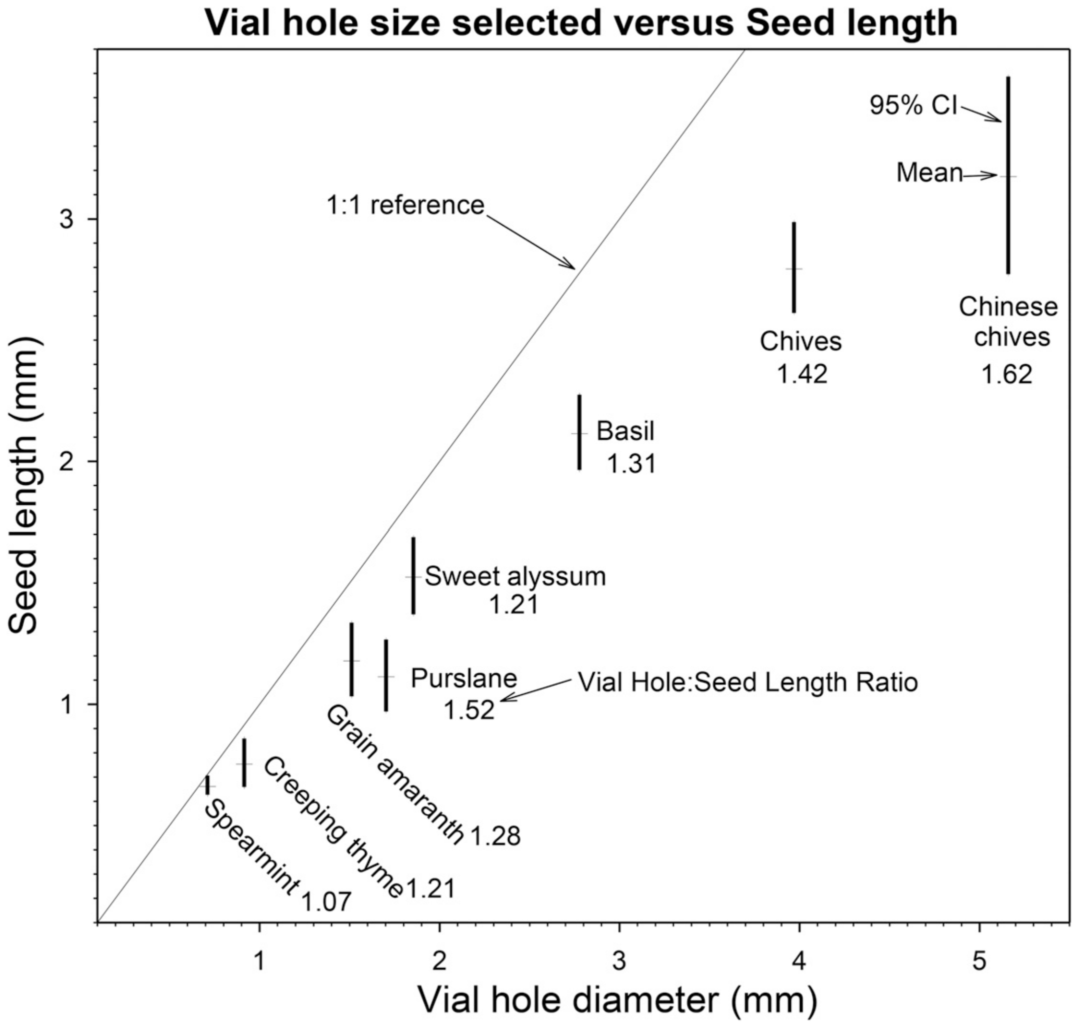


Fig. 7. Relationship between the selected seed vial hole diameter vs. seed length. Seed length refers to the longest dimension of the seed and is shown for each species as a 95% confidence interval (CI) error bar with the mean at the horizontal line on the CI (n = 4). The reference line shows where there is a 1:1 relationship between seed length and vial hole diameter. Means and 95% CIs that are further to the right from the reference line indicate species in which the selected hole diameter was proportionally larger than the average seed length and thus have a larger hole:seed length ratio. See Table 2 for the vial hole diameters in inches, millimeters, and wire gauge size; 1 mm = 0.0394 inch.

Table 2. Seed characteristics and vial hole diameters used to evaluate the slide hammer is of the handle is made out of electrical conduit tubing discusses the different components to the handles made of electrical conduit was used for a half-inch electrical conduit seeder.

Common name, cultivar[z]	Seed size (no./oz)[y]	Avg seed length (mm)[x]	Vial hole diam (mm)	Drill bit diam to make vial hole [gauge (#) or inches][w]
Spearmint	311,700	0.67	0.71	#70
Creeping thyme	210,000	0.76	0.91	#64
Sweet alyssum	71,000	1.53	1.85	#49
Purslane, 'Gruner Red'	61,088	1.12	1.70	#51
Grain amaranth	37,500	1.18	1.51	#53
Chives, 'Staro'	20,100	2.12	2.78	7/64 inch
Basil, 'Genovese'	17,900	2.80	3.97	5/32 inch
Chinese chives	5,900	3.18	5.16	13/64 inch

[z]Cultivar name is shown in single quotes where available. Listed in order of seed size.
[y]Seeds reported at the Johnny's Selected Seeds (Winslow, ME) website for all plants except for grain amaranth that was calculated from the approximate number per pound (600,000) reported in Putnam et al., (1989); these are provided as a rough guide because seed size is often thought of in seeds per unit of weight; 1 seed/oz = 0.0353 seed/g.
[x]Mean of four seeds; 1 mm = 0.0394 inch.
[w]Wire gauge size (no.) was the original unit of drill bit diameter measurement for many of plants but can be converted to inches where needed from the vial hole diameter column; 1 inch = 25.4 mm.

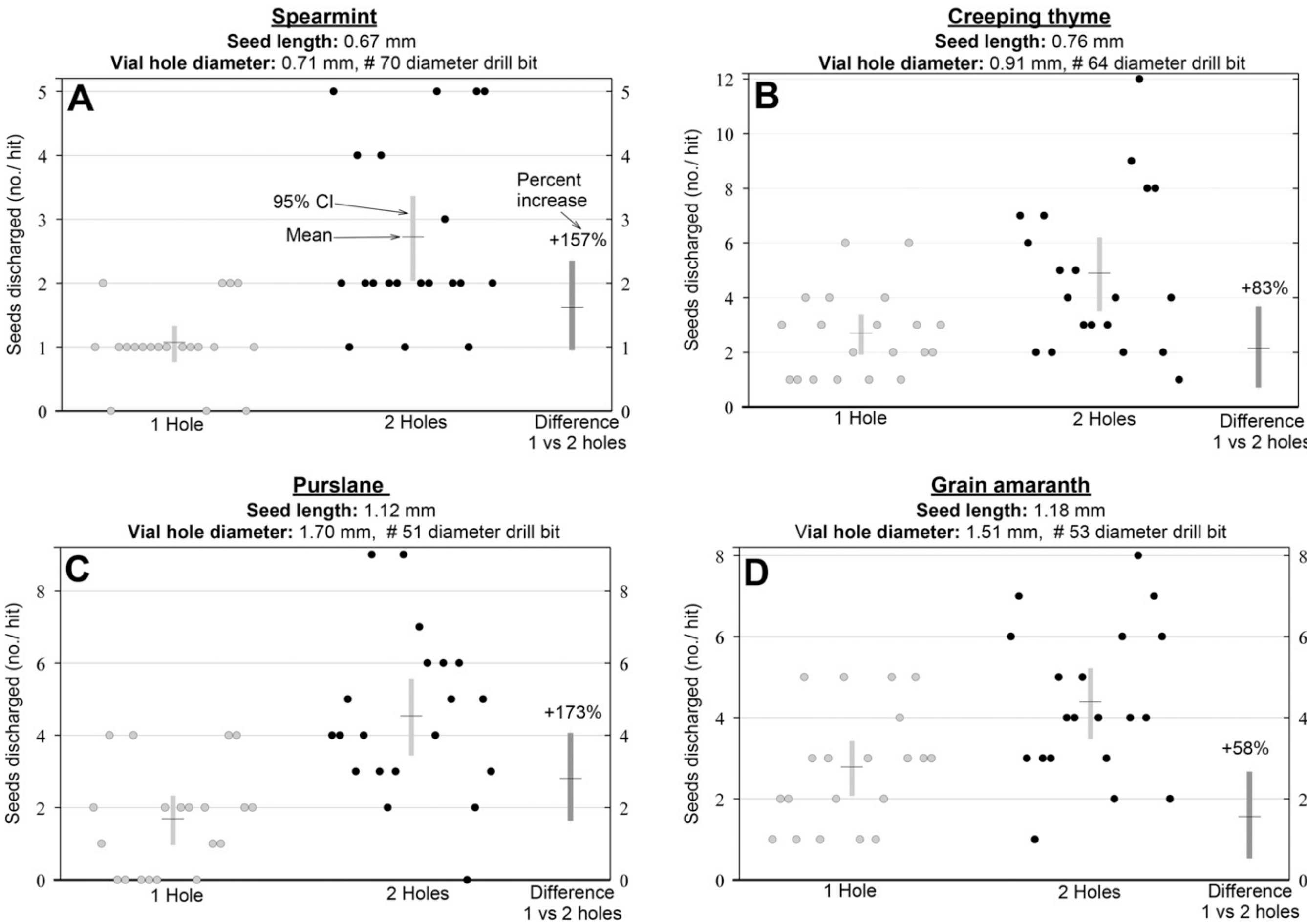


Fig. 8. The number of seeds discharged from vials with one or two holes in the vial bottom with each hit of the slide hammer seeder for spearmint (A), creeping thyme (B), purslane (C), and grain amaranth (D). Plots A to D are in order of increasing vial hole diameter. Seed length refers to the longest dimension of the seed. The drill bit diameter in wire gauge size (#) or inches that was used to make the holes is included with each plot label; the vial hole diameter in millimeters can be used to convert the drill bit diameter to inches if needed. The dots are the raw data (gray for one hole, black for two holes) of 20 consecutive hits (from left to right) that are clustered around a vertical error bar that is 95% confidence interval (CI) with the mean at the central horizontal line on the bar. The mean difference between the one- vs. two-hole measurements and the 95% CI of the difference are shown on the right of each plot with the percentage change from one to two holes noted above the difference; 1 mm = 0.0394 inch.

the 1.51-mm hole used for the one- vs. two-hole comparison with grain amaranth (Fig. 7D), but has worked well for seeding purslane mixed with killed grain amaranth seed. Grain amaranth may even work to dilute smaller seed as long as the small seed does not segregate to the bottom of the vial over time. Other inert materials (i.e., sand) may also work as a diluting material for some species if the seed does segregate in the mixture and the mixture discharges from the seeder only when the SH is hit.

The force that discharges seed from the vial when the SH hits the hammer stop washer potentially comes from the weight of the SH and how fast and hard the hammer is hit against the stop washer. To achieve the greatest uniformity in seeding, the person operating the SH seeder should rely primarily on the weight of the SH to discharge the seed. In my experience using the SH seeder, a SH with a weight of 500 to 700 g provides adequate force to discharge seed and is not overly heavy.

Although the SH seeder described here is hand-operated, there are several ways that an automated version of it could be developed for dispensing small amounts of seed or other granular material at specific locations in agricultural settings. For example, an automated SH seeder could be added to a precision vegetable seeder to allow growers to interplant small amounts of raw seed of sweet alyssum as insectary plants at specific locations along with the vegetable seed. Potentially, this technique would be more cost effective than using pelleted sweet alyssum seed as described in Brennan (2015). A similar approach also could be used to integrate an SH seeder into a mechanical vegetable transplanter or a grain drill for cover crop seeding.

Although the SH seeder described here is made with materials that are readily available in hardware stores in developed countries or through the Internet, alternative materials could be used to make the seeder in less-developed regions of the world. For example, a straight, strong, thin-culmed

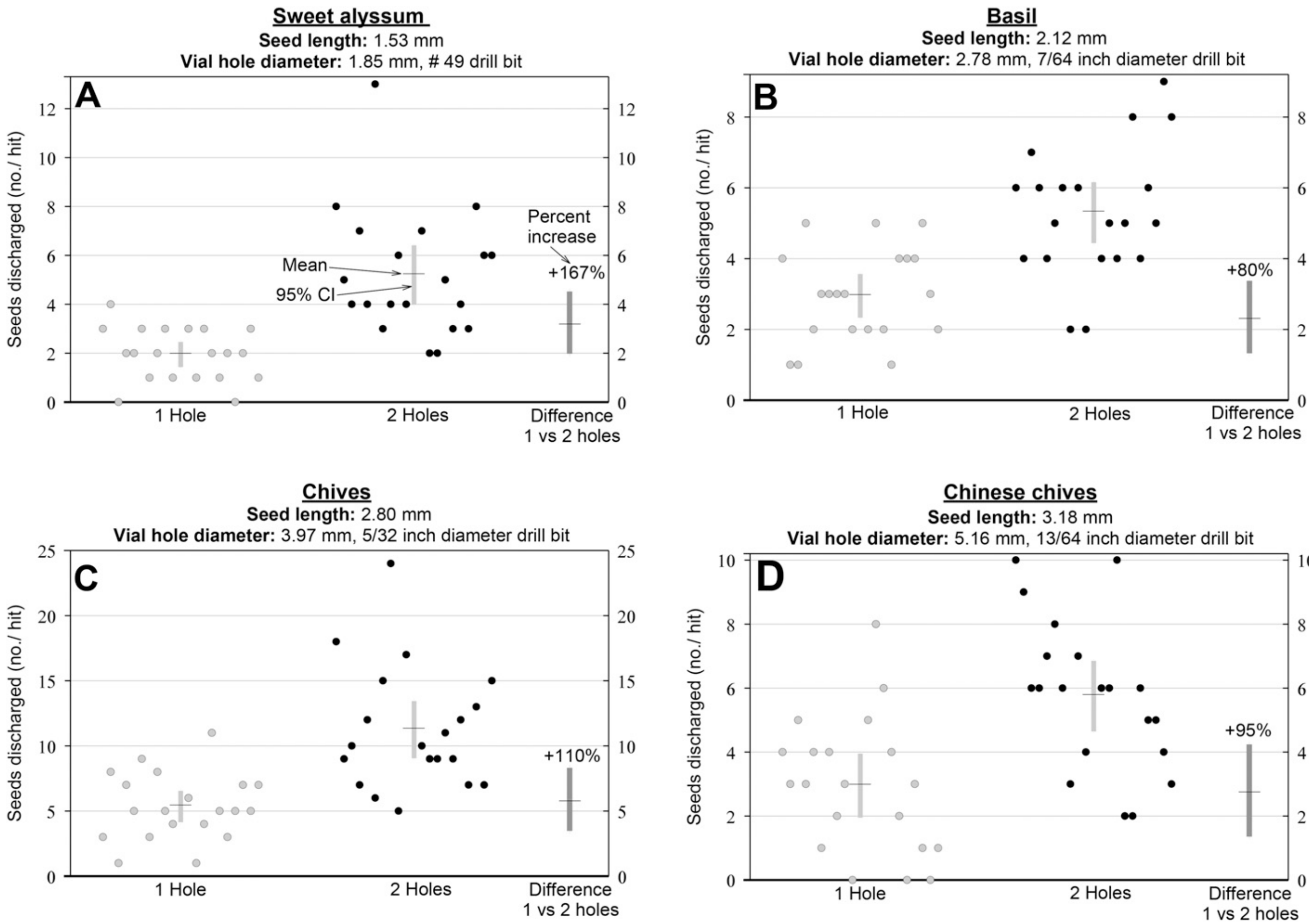


Fig. 9. The number of seeds discharged from vials with one or two holes in the vial bottom with each hit of the slide hammer seeder for sweet alyssum (A), basil (B), chives (C), and chinese chives (D). Plots A to D are in order of increasing vial hole diameter. Seed length refers to the longest dimension of the seed. The drill bit diameter in wire gauge size (#) or inch that was used to make the holes is included with each plot label. The dots are the raw data (gray for one hole, black for two holes) of 20 consecutive hits (from left to right) that are clustered around a vertical error bar that is 95% confidence interval (CI) with the mean at the central horizontal line on the bar. The mean difference between the one- vs. two-hole measurements and the 95% CI of the difference are shown on the right of each plot with the percentage change from one to two holes noted above the difference; 1 mm = 0.0394 inch.

bamboo [e.g., golden bamboo (*Phyllostachys aurea*), black bamboo (*Phyllostachys nigra*), or weaver's bamboo (*Bambosa textilis*)] may work well for many of the components (handle, seeder shoe, and SH). In addition, wire or strips of tire inner tube or other wrapping material could be used instead of the hose clamps to attach the various components. Even the spring on the top of the seeder could be made by hand with wire or with some other cushioning material (Brennan, 2018). Furthermore, a plastic pill vial with holes drilled in the bottom may work well as the seed vial.

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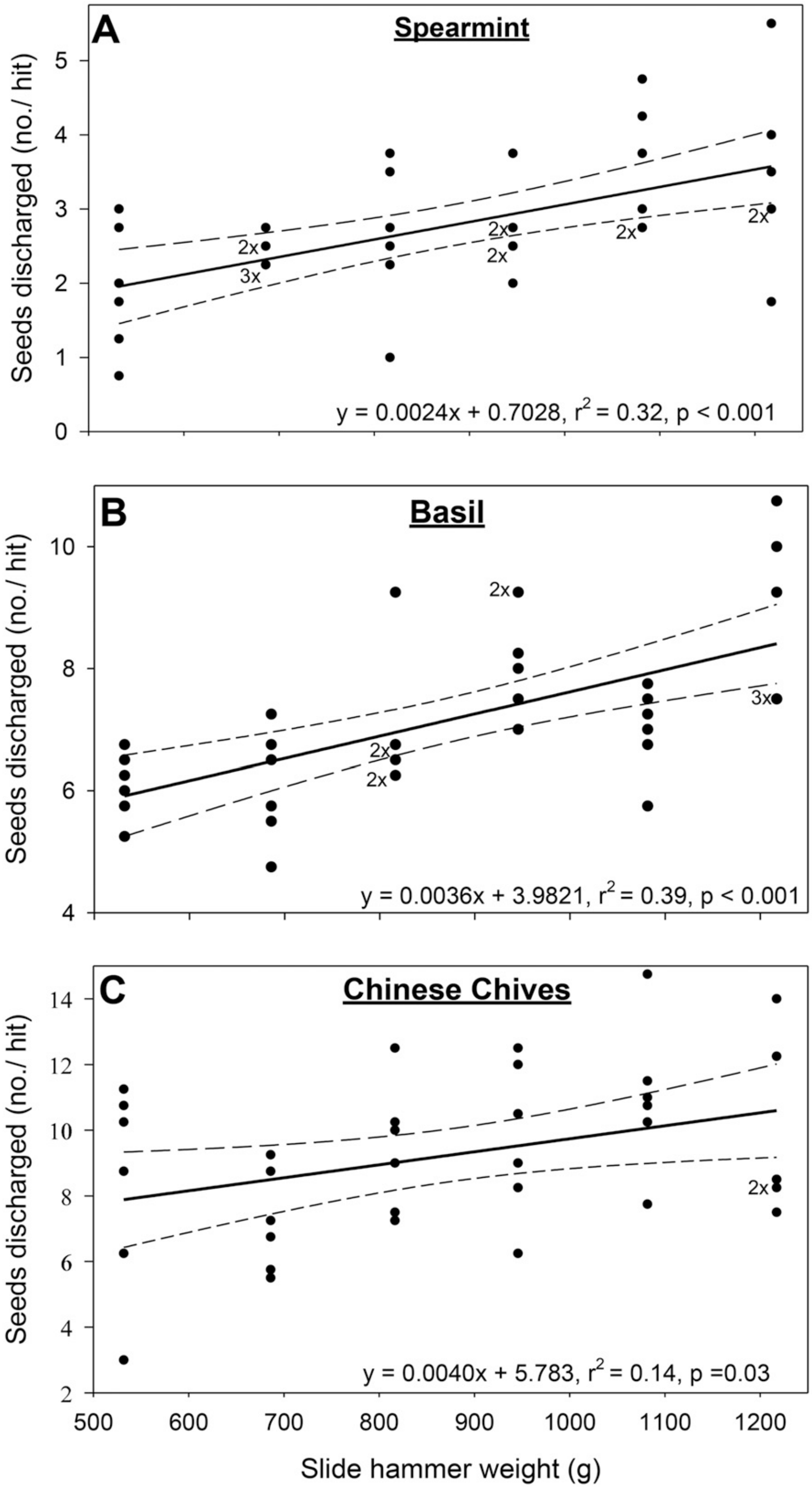

Fig. 10. Relationship between slide hammer weight and the number of seeds discharged from vials with two holes for spearmint (A), basil (B), and chinese chives (C). The weights of the slide hammers evaluated were 532, 686, 816, 946, 1082, and 1217 g representing a 29%, 54%, 78%, 103%, and 129% increase, respectively, relative to the lightest hammer (532 g). Dots are the average number of seeds discharged from four hits with the slide hammer for six replications of each slide hammer weight. The numbers to the left of a dot indicate the number of replicates (i.e., 3x = 3 replicates) where more than one replicate had the same value; 1 g = 0.0353 oz.

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