Weed Science 2016 64:285–293

WSSA WEED SCIENCE SOCIETY OF AMERICA

Effects of Water on Recovery of Weed Seedlings Following Burial

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Recovery of common agricultural weeds after burial by soil was studied in four greenhouse and three field experiments. Species studied included velvetleaf, Powell amaranth, common lambsquarters, barnyardgrass, and giant foxtail. Seedlings were bent over before burial to simulate the effect of the impact of soil thrown by a cultivator. Altogether, more than 35,000 seedlings were marked and observed for recovery. No seedlings recovered from 4 cm of burial. Recovery from complete burial under 2 cm of soil ranged from 0 to 24% depending on the experiment, species, and watering treatment, but recovery greater than 5% was rare. Large-seeded species tended to recover from complete burial under 2 cm of soil better than small-seeded species. The study did not reveal a difference in recovery of grasses relative to broadleaf weeds. Overall, seedlings tended to recover best when water was applied daily after burial, worst when water was applied once on the day of burial, and to an intermediate extent when no water was applied. However, difference in recovery between the no-water and watering-once treatments were usually small. Also, many experiment by species combinations showed no significant differences among watering treatments. When even a small portion of the seedling was left exposed, recovery generally exceeded 50%. Organic weed management systems commonly use burial of weed seedlings with tine weeders and soil thrown by sweeps and hilling disks to control weeds in crop rows. Recovery from burial could pose a substantial weed management problem in some circumstances, particularly for large-seeded weed species. Maximizing burial depth is important for limiting recovery. Recovery from burial can be minimized by withholding irrigation for several days after hilling-up operations.

Nomenclature: Barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG; common lambsquarters, *Chenopodium album* L. CHEAL; giant foxtail, *Setaria faberi* Herrm. SETFA; Powell amaranth, *Amaranthus powellii* S. Wats. AMAPO; velvetleaf, *Abutilon theophrasti* Medik. ABUTH.
Key words: Cultivation, irrigation, mechanical weed management, rainfall, soil cover.

Despite the importance of herbicides in modern agriculture, cultivation remains an important weed management method. Many crop fields are cultivated, even when herbicides are also applied, and in some specialty crops, cultivation is essential because availability of appropriate herbicides is limited (van der Schans and Bleeker 2006). In organic production systems, cultivation plays an even greater role in weed management and forms the final defense of the crop after cultural practices are applied (Bond and Grundy 2001; Melander et al. 2005). Finally, cultivation, often with hand hoes or animal-drawn implements, is important for weed management in some regions of the world where herbicides are too expensive or too limited in availability for extensive use (Vissoh et al. 2004).

Cultivators kill weeds by three mechanisms (Mohler 2001). First, they uproot weeds leading to desiccation. Second, they fragment weeds and, in particular, separate the roots from the shoot, leading to starvation of the roots and desiccation of the shoot. Third, they kill weeds by burying the shoot, leading to starvation and decay of the whole plant. A few studies have investigated the relative importance of these three factors (Fogelberg and Dock Gustavsson 1999; Kurstiens and Kropff 2001), but little attention has been given to the biology of weed response to uprooting, dismemberment, or burial. Notable exceptions include studies by Cavers and Kane (1990) and Jones et al. (1995), who investigated the response of weed seedlings to various forms of damage, including burial. The closest study to the work reported here is that of Baerveldt and Ascard (1999) which focused on response of weed seedlings of various sizes to burial under different depths of soil. Kurstiens and Perdok (2000) studied soil and plant properties that led to greater or lesser covering of weeds and crops during harrowing. Other than these agricultural studies, investigations of response of seedlings to burial have

DOI: 10.1614/WS-D-15-00130.1
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Table 1. Growth stage and size (in parentheses) of seedlings at burial. Growth stage is indicated by the presence of cotyledons only (Cotyl.) or the number of true leaves. Size was measured as distance from the base to the growing point of a broadleaf and from the base to the tip of the longest leaf for grasses. Plant size is the mean over replications of the mean of 10 randomly selected plants per flat or plot.

Experiment	Size[a]	Velvetleaf	Common lambsquarters	Powell amaranth	Giant foxtail	Barnyardgrass
		mm				
G1	S	Cotyl.	2	Cotyl.–1	—	—
G1	L	1	—	2–3	2–3	Cotyl (30–60)[b]
G2	S	(65)	(16)	—	(38)	—
G2	L	(81)	(35)	—	(103)	Cotyl. (67)
G3	S	1	2 (small)	—	Cotyl.	—
G3	L	3	4	—	1	Cotyl.
G4	—	2 (38)	2–3 (23)	2–3 (26)	2 (62)	2–3 (57)
F1	—	2–3 (39)	4–5 (45)	3–4 (36)	2–3 (55)	2–3 (59)
F2	—	4–5 (132)	3–4 (21)	3–4 (17)	3 (137)	2–3 (53)
F3	—	2–3 (41)	2–3 (27)	3 (29)	2–3 (65)	2–3 (58)

[a] S, small; L, large; —, only one size seedling used in the experiment. "Small" and "large" are relative and actual size is specified by the height and growth stage.
[b] Size was visually estimated rather than computed from multiple measurements.

involved species of dune systems (Harris and Davy 1987; Martinez and Moreno-Casasolai 1996; Maun et al. 1996), and wetlands with sediment deposition (Thampanya et al. 2002).

The objective of this study was to determine how well seedlings of several common agricultural weed species recover from burial. We hypothesized that grasses would recover better than broadleaf species because, as seedlings, their apical meristems are already below ground before burial. We further hypothesized that species with relatively large seeds would recover better than those with relatively small seeds, because energy reserves remaining in a large seed might aid recovery. Based on early experiments and grower observations, we also hypothesized (1) that recovery would be worst if a single rainfall or irrigation event followed burial because the soil would be settled and hard; (2) that recovery would be better if no rain fell after burial because the soil would remain loose and more easily pushed aside; and (3) that recovery would be best if the soil remained continuously moist and therefore soft. Our study differs from the previous work reviewed above in its focus on complete rather than partial burial and on the effects of soil moisture on seedling recovery from burial.

Materials and Methods

Seven experiments were performed, and the design of the later experiments evolved based on results of the earlier ones. The first greenhouse experiment, G1, was intended to determine whether any of the study species had sufficient recovery from burial to make further investigations worth pursuing. Accordingly, variables in the study included seedling size and burial depth. Subsequently, an organic farmer widely recognized as an expert in cultivation suggested that a single rainfall event following cultivation settled the soil, thereby increasing the difficulty of recovery from burial (Klaas Martens, personal communication). Experiments G2 and G3 were intended to test this hypothesis. Additionally, they explored the effects of seedling size and, in G2, effects of burial depth. The substantially greater overall recovery observed in G1, which was watered daily, relative to G2 and G3 suggested that perhaps continuously damp soil facilitated seedling recovery. The four subsequent experiments therefore focused on comparison of watering treatments: none, once, or daily. Because no seedlings recovered from burial under 4 cm of soil in G1 and G2, the later experiments used only a 2-cm burial depth, except the second field experiment, F2, in which burial depth was not controlled. The desire to increase statistical power by increasing the number of replications and number of seedlings buried in each replication precluded further investigation of effects of seedling size. The later experiments thus focused on seedlings in the size range commonly observed when cultivation is used to throw soil around the base of corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] plants (Table 1).

Greenhouse Studies. All greenhouse experiments used a randomized complete block design. Flat positions were not rerandomized periodically, as is sometimes done in greenhouse experiments, because moving the flats would have cracked the soil, which potentially could have affected seedling recovery. In experiment G1, the focus was on comparison of species, developmental stages, and burial depths (2 and 4 cm), all with daily watering after burial. Experiment G2 compared species, burial depth, and a single watering compared with no watering. Experiment G3 was similar to G2, but burials were all to 2 cm depth. Experiment G4 compared species and three watering treatments: no watering after burial, a single watering on the day of burial, and daily watering.

The species used in the experiments were velvetleaf, common lambsquarters, Powell amaranth (except G2 and G3), barnyardgrass, and giant foxtail. Seeds were collected from agricultural populations near Ithaca, NY (42.43°N, 76.48°W), air dried for a few weeks and stored at 4 C until use. Seeds were sown on 4 cm of a soil mixture consisting of two parts silt loam topsoil screened through a 1.3-cm mesh and one part peat–vermiculite–perlite potting media (Cornell mix), except experiment G4, which used a similar mixture of four parts topsoil : one part peat : one part vermiculite. Seeds were covered with another 1 cm of the soil mixture and watered daily until seedlings were ready to bury.

At burial, seedlings were marked with toothpicks, bent horizontal and buried to the specified depth with screened topsoil (not the soil–potting medium mixture). In all experiments, care was taken to insure that all seedlings were completely buried, with no tissue showing. Some details varied between experiments as noted below. Greenhouse temperature was maintained at 29/21 C day/night, except in G2, when the greenhouse temperature control system was overwhelmed by hot sunny weather in early June and temperatures exceeded 35 C for 4 d during and following seedling burial. Experiments G1, G2, and G4 were conducted during winter, and 1,000W metal halide lights were used between 8 A.M. and 6 P.M. to prevent etiolation of the seedlings before burial.

G1. Seedling recovery as affected by burial depth and growth stage. The experiment was conducted February to April 2006. Treatments were replicated four times. One hundred seeds of each weed species were sown in a 2.5 by 2.5-cm grid in 36 by 51-cm by 10-cm-deep flats. The soil continued to be watered daily to field capacity after burial. When possible, seedlings were buried at two different growth stages (Table 1). Seedlings were buried with either 2 or 4 cm of soil. Seedlings were scored as recovered after approximately 2 wk. At the time of scoring, all plants that had not re-emerged were dead and badly decomposed.

G2. Seedling recovery as affected by burial depth and watering treatment. The experiment was conducted from late April to June 2007. Treatments were replicated four times. The flats used were as in G1. Enough seeds of each species were sown to produce an expected 50 seedlings per flat based on prior germination tests. When more than 50 seedlings were present, seedlings were thinned to 50 relatively uniformly spaced individuals. Seedlings of most species were buried at two sizes (Table 1) and buried with either 2 or 4 cm of soil. Flats were either not watered or watered with approximately 25 mm of water applied over the space of several hours on the day of burial.

G3. Seedling recovery as affected by seedling size and watering treatment. The experiment was conducted February to April 2009. Treatments were replicated four times. Experiment G3 was similar to G2, except that seedlings were grown in one-half of flats that were 51 by 66 cm by 15 cm deep. These were divided in half with a polystyrene divider, and the half that was not planted was filled with gravel to hold the divider in place. Plants were grown to two sizes (Table 1), and all seedlings were buried with 2 cm of soil. After burial, either the flats were not watered or were given approximately 25 mm of water on the day of burial.

G4. Seedling recovery as affected by watering treatment. The experiment was conducted in January and February 2014. Treatments were replicated five times. Enough seeds were planted in 51 cm by 66 cm by 15-cm-deep flats to produce an expected 140 seedlings. When seedlings were at the two to three leaf stage, they were thinned to approximately 100 well-spaced seedlings of uniform size per flat. Seedlings were buried with 2 cm of topsoil. After burial, flats were either (1) not watered, (2) given 20 mm of water on the day of burial, or (3) given 20 mm of water daily. Seedlings were scored as recovered 12 d after burial.

Field Studies. All field experiments were conducted near Aurora, NY (42°73′N, 76°63′W) on a Lima silt loam soil (fine-loamy, mixed, mesic glossoboric halpludalfs). The same five species used in G1 and G4 were used in the three field experiments. The experiments used a randomized complete block split plot design with five replications, in which species was the main plot factor and watering treatment was the subplot factor. Watering treatments in the field experiments were as in G4: no water, water on day of seedling burial, and daily watering after burial, except that natural rainfall was allowed to disrupt these treatments. At each watering, 20 mm of water was applied with a watering can, but no water was applied if rainfall had visually wetted the soil by noon. Rainfall was recorded at a nearby (< 0.5 km) weather station. Seedling recovery was evaluated 7 d after burial. Details of the individual experiments are given below.

F1. Seedling recovery as affected by watering treatment. This experiment essentially repeated G4 under field conditions. Each main plot consisted of two 3-m rows of a given weed species, with rows separated by 30 cm. Subplots (each 1 m long) received the three watering treatments. When seedlings were at the designated growth stage (see Table 1), they were thinned to a maximum of 100 individuals of uniform size and marked with toothpicks. A wooden frame (40 by 100 cm) was placed around each subplot, seedlings were bent prostrate, and 8,000 ml of topsoil was used to bury the seedlings to a depth of 2 cm. The soil used for burying seedlings was taken from an area adjacent to the plots and screened through 0.6-cm mesh. Care was taken to insure that all seedlings were completely buried.

F2. Seedling recovery as affected by watering treatment after burial during interrow cultivation. A groove about 1 cm deep was scratched between corn plants in corn rows 11 d after planting. Seeds were sown in the grooves and then covered with fine soil. Plots were 6 m long, with 2-m-long subplots for the watering treatments. The corn rows were part of the Cornell Organic Grain Cropping Systems Experiment (Caldwell et al. 2014), and operations followed cultural practices for that experiment. On July 9, 2014, 29 d after sowing of the weed seeds, the field was cultivated with a Brillion high-residue row-crop cultivator (Landoll Corporation, Marysville, KS) equipped with hilling disks to throw soil into the crop rows. After cultivation, seedlings that had not been completely covered were marked with colored toothpicks to avoid confusing them later with seedlings that had been fully buried but which recovered. To determine the depth of soil thrown into the crop row during cultivation, two bamboo sticks per plot were marked with colored tape 5 cm from the end and inserted in soil to the lower edge of the tape before cultivation. When seedling recovery was evaluated, the sticks were marked at the new soil level and the depth of soil moved into the row recorded as the distance between the mark and the bottom of the tape.

F3. Seedling recovery as affected by watering treatment after partial and complete burial. This experiment was similar to F1, except that one of the two rows in each subplot was selected at random, and the seedlings in that row were only partially buried. Seedlings in the other row were completely buried as usual. This resulted in a randomized complete block split-split plot design. In the partial burial treatment, one cotyledon of velvetleaf was left exposed. For common lambsquarters and Powell amaranth, which have small cotyledons, one lower true leaf was left exposed. For giant foxtail and barnyardgrass, 1 to 2 cm of the tip of the longest leaf was left exposed. In all cases, the remainder of the plant was buried as close to 2 cm as possible.

Statistical Analysis. All analyses of seedling recovery after burial were performed by logistic regression using SAS Proc Genmod (Statistical Analysis System 9.2, Cary, NC). Because no seedlings recovered from 4-cm burials, burial depth was not included in the models. In the greenhouse experiments, low recovery rates resulted in many cells with zero recovery. Moreover, in G1, G2, and G3, structurally zero cells were present because some species were only studied at one seedling size (Table 1). Consequently, the Genmod algorithm failed to converge for the full models, which included replication and all treatment factors for these experiments. In these cases, reduced models were tried until a model was obtained that converged and preserved the maximum amount of information on species and treatment comparisons. The nature of the models used is specified in the tables of results. Probability estimates for various treatment combinations were obtained by back-transforming logit least squares means. Genmod uses a small number to represent zero, and when the least squares mean logit was less than −25, the back-transformed estimate is reported as zero.

Significance of pairwise comparisons were determined at the $P < 0.05$ level. Where treatment by species interactions were significant, the number of comparisons was sufficiently large to make Type 1 errors likely. To minimize this problem, when interactions were present, we only examined and reported comparisons among treatments within species. In G4, the logistic regression model with species and treatment failed to converge, so individual models were run for each species. Although all of these converged on a solution, some of the pairwise treatment

Table 2. Seed mass of species used in experiments G4, F1, F2, and F3. Seed lots used in the other experiments were similar.

Species	Mass of 100 seeds (SE)
	g
Velvetleaf	0.950 (0.008)
Powell amaranth	0.047 (< 0.001)
Common lambsquarters	0.058 (0.001)
Barnyardgrass[a]	0.250 (0.038)
Giant foxtail[a]	0.150 (0.001)

[a] Mass of the achene plus palea and lemma.

comparisons could not be estimated. In these cases, significance of pairwise comparisons was estimated by assessing 2 by 2 contingency tables with chi-square tests. Similarly, the species comparison model for G1 converged but failed to produce some pairwise comparisons, and chi-square tests of 2 by 2 contingency tables were used to obtain significance of missing comparisons.

When interactions occur and zero cells are present, estimates of main effect probabilities can be unrealistically low. Although significance of main effects is uninterpretable when interactions are present, main effect values are still of qualitative interest. To obtain main effect estimates, in all cases we used reduced models with only the single effect and no replication. This led to the minimum possible number of zero cells for that main effect.

Results and Discussion

When soil is thrown into the crop row by cultivator sweeps or hilling disks, impact of the leading edge of the wave bends weed seedlings over and they are then buried under the crest of the wave. Thus, our bending the seedlings over before burying them reflects the reality of field conditions, in addition to providing uniformity of burial depth in the experiments. Baerveldt and Ascard (1999), however, found that recovery was less when seedlings were bent rather than upright, so our estimates of recovery are probably lower than would occur in a cultivated field, where some seedlings are only partially bent over by soil movement.

Table 3. Probability of recovery for seedlings buried in greenhouse experiment G1, seedling recovery as affected by seedling size and burial depth. Because no seedlings recovered from burial by 4 cm of soil, only data for the 2-cm burial depth are shown. Logistic regression model included plant size and species for velvetleaf and Powell amaranth but because recovery was not affected by size for either species, only results from the model for species means are shown.

Species	Mean[a]
Velvetleaf	0.060 b
Powell amaranth	0.017 c
Common lambsquarters	0 c
Barnyardgrass	0.146 a
Giant foxtail	0 c
Mean	0.027

[a] Numbers followed by the same letters are not significantly different at P < 0.05.

Table 4. Probability of recovery for seedlings buried in greenhouse experiment G2, seedling recovery as affected by burial depth, seedling size, and no watering (None) vs. one watering (Once). Because no seedlings recovered from burial by 4 cm of soil, only data for the 2-cm burial depth are shown. The logistic regression model included species and watering treatment; interactions between species and watering were significant.

	Watering treatment[a]		
Species	None	Once	Mean
Velvetleaf	0.003 a	0 b	0.001
Common lambsquarters	0 a	0 a	0
Barnyardgrass	0.009 a	0.005 a	0.007
Giant foxtail	0.010 a	0 b	0.005
Mean	0.005	0.001	

[a] Numbers within a row followed by the same letters are not significantly different at P < 0.05.

The species chosen for investigation in this study are major weeds of the northeastern United States and many other regions of the world. They also allow comparison of the relative ability of grass and broadleaf species to recover from burial. Additionally, they represent a range of seed mass (Table 2). Tolerance of other stresses is correlated with seed mass (Grime and Jefferey 1965; Mohler and Teasdale 1993), so we hypothesized that seed mass might also affect the ability to recover from burial. Because interactions between species identity and other factors occurred in most experiments, statistical comparison of species within experiments is not appropriate. However, the significant difference among species in G1 and comparison across the other experiments shows that velvetleaf and barnyardgrass, which have the greatest seed mass, usually also had higher overall recovery from burial than the smaller seeded species (Tables 3–9). In experiment F1, however, Powell amaranth showed the greatest overall recovery (Table 7), so the pattern does not hold universally. Our finding that large-seeded species often recover from burial better than small-seeded species agrees with the results of Habel (1954, discussed in Baerveldt and Ascard 1999). Yanful and Maun (1996) found that seedlings from large seeds of the perennial broadleaf amberique-bean (*Strophostyles helvola* (L.) Ell.), which is common on dunes of the Lake Erie shore, recovered from burial by sand better than

Table 5. Probability of recovery for seedlings buried in greenhouse experiment G3, seedling recovery as affected by seedling size and no watering (None) vs. one watering (Once). The logistic regression model included replication, species, and watering treatment: interactions between species and watering were significant.

Species	Watering treatment[a]		
	None	Once	Mean
Velvetleaf	0 a	0 a	0
Common lambsquarters	0.002 a	0.002 a	0.002
Barnyardgrass	0.005 a	0 b	0.002
Giant foxtail	0.032 a	0.030 a	0.031
Mean	0.011	0.009	

[a] Numbers within a row followed by the same letters are not significantly different at $P < 0.05$.

seedlings from smaller seeds. No effect on recovery from burial of the difference in growth form between grasses and broadleaf species could be detected in this study.

Essentially all seedlings were either growing vigorously at the time of evaluation or failed to re-emerge after burial. Excavations showed that seedlings that failed to recover were dead and usually in some state of decay. In the experiments reported here, recovery rates from complete burial usually ranged from no recovery to a few percent recovery, although some species in some experimental conditions had greater than 10% recovery. Similarly, Jones et al. (1995) demonstrated low recovery of common chickweed [*Stellaria media* (L.) Vill.], corn poppy (*Papaver rhoeas* L.), annual bluegrass (*Poa annua* L.), and roughstalk bluegrass (*Poa trivialis* L.) after complete burial under 1 or 2 cm of potting media. Wild-proso millet (*Panicum miliaceum* L.) recovery from shallow burial by soil turning was about 55% (Cavers and Kane 1990). The relatively high recovery in this case may have been related to the small size of the seedlings, which were buried immediately upon emergence and therefore probably still had substantial seed reserves to assist recovery. Studies of dune species generally report low recovery from complete burial (Maun 2004; Maun et al. 1996; Shi et al. 2004; Zhang and Maun 1990). However, amberique-bean had high rates of recovery, even when buried to 150% of the seedling's height (Yanful and Maun 1996). This species, however, has much heavier seeds than the species investigated in the experiments reported here. In dune systems, recovery of seedlings from complete burial probably has little consequence, because most dune species have vegetative reproduction and many seedlings will escape complete burial. Agricultural systems can have thousands of seedlings per hectare in the crop row, and recovery of a few percent of those potentially can have a substantial competitive effect on the crop. In contrast, recovery of a few tenths of a percent, as was commonly observed for some treatments and species in our experiments, would have little agronomic effect unless weed populations were unusually dense.

The continuously moist soil provided by daily watering frequently promoted recovery relative to the dryer soil in the no-water or watering-once after burial treatments. This pattern is seen most clearly in experiment G4, in which velvetleaf, barnyardgrass, and giant foxtail all had greater recovery with daily watering than with either no watering or watering once (Table 6) and in F1, in which common lambsquarters and barnyardgrass had greater recovery with daily watering than with one or both of the other treatments (Table 7). The only reversal of this pattern in the entire study was Powell amaranth in F1, for which recovery was greater with no watering than with daily watering or watering once (Table 7). Although no statistical comparison can be made between experiments, the difference in overall recovery in G1 vs. G2 and G3 is suggestive. Recovery of velvetleaf and barnyardgrass, in G1, which was watered daily, was sufficiently high to have had agronomic consequences if it occurred in a crop field

Table 6. Probability of recovery for seedlings buried in greenhouse experiment G4, seedling recovery as affected by watering treatment. Because of the frequency of zero cells, probability of recovery estimates were made using separate logistic regression analyses for each species, and data were combined over replications.

Species	Watering treatment[a]			
	None	Once	Daily	Mean
Velvetleaf	0.014 b	0.004 b	0.146 a	0.055
Powell amaranth[b]	0.006 a	0 a	0 a	0.002
Common lambsquarters[b]	0 a	0 a	0.002 a	0.001
Barnyardgrass[b]	0 b	0 b	0.056 a	0.018
Giant foxtail[b]	0.010 ab	0 b	0.014 a	0.008
Mean	0.006	0.001	0.044	

[a] Numbers within a row followed by the same letters are not significantly different at $P < 0.05$.
[b] Comparisons based on chi-square tests of 2 by 2 contingency tables because of the presence of cells with zero recovery.

Table 7. Probability of recovery for seedlings buried in field experiment F1, seedling recovery as affected by watering treatment. The logistic regression model included replication, species, watering treatment, and the interaction between species and watering treatment.

Species	Watering treatment[a]			Mean	Days with rain[b]
	None	Once	Daily		
Velvetleaf	0.056 a	0.042 a	0.081 a	0.060	2
Powell amaranth	0.241 a	0.163 ab	0.143 b	0.183	1
Common lambsquarters	0.045 b	0.038 b	0.151 a	0.077	1
Barnyardgrass	0.139 ab	0.101 b	0.185 a	0.143	1
Giant foxtail	0.048 a	0.024 a	0.064 a	0.045	1
Mean	0.107	0.074	0.125		

[a] Numbers within a row followed by the same letters are not significantly different at $P < 0.05$.
[b] Days with rainfall > 5 mm between burial and evaluation.

(Table 3). In contrast, these species had negligible recovery in G2 and G3, where water was applied only once after burial or not at all (Tables 4 and 5). Finally, despite rainfall events after burial in F2 and F3, barnyardgrass still had greater recovery with daily watering than with the other treatments.

Moist soil offers less resistance to seedlings emerging from germinating seeds than dry soil (Morton and Buchele 1960), and the continuously moist soil with daily watering probably offered less resistance to recovery of buried seedlings than the drier soil of the other treatments. We ensured that the soil in which the seedlings were rooted was always moist at the time of burial, and the loose soil of the no-water treatment would have acted as a barrier to capillary evaporation. Consequently, the buried seedlings in the no-water treatment should have had sufficient moisture in the rooting zone for maintaining turgor pressure during recovery. Nevertheless, contact with dry soil may have dried the shoots of buried seedlings in the no-water treatment, thereby reducing their vigor. Although softer soil with daily watering and shoot desiccation in the other treatments might explain the lower recovery with dryer soil, the result was not a foregone conclusion. The continuously moist soil in the daily watering treatment could have promoted attack on the shoots by microorganisms, thereby decreasing rather than increasing recovery. Plants deprived of light are prone to infestation by fungi (Grime and Jeffrey 1965), and mortality of seedlings in the soil due to microbial attack is common (Davis and Renner 2007; Mohler et al. 2012).

The experiments reported here provide some evidence for lower recovery after a single watering relative to no watering, but the effect is weak. A single watering significantly lowered recovery of velvetleaf and giant foxtail relative to no watering in G2 (Table 4), barnyardgrass in G3 (Table 5), and barnyardgrass with complete burial in F3 (Table 9). The reverse pattern was never significant. Moreover, the no-watering treatment had numerically (though not necessarily significantly) greater recovery than the watering-once treatment in 20 species–experiment cases, whereas the reverse held in only three cases. Although the effect of a single watering inhibiting recovery is apparently real, it probably only occasionally affects weed management.

Recovery after the typical hilling-up operation in experiment F2 was generally similar to recovery for the same species in other experiments. That is, a few percent to less than 1% of the seedlings

Table 8. Probability of recovery for seedlings buried in field experiment F2, seedling recovery as affected by watering treatment after burial during interrow cultivation. The logistic regression model included replication, species, watering treatment, and interaction between species and watering.

Species	Watering treatment[a]			Mean	Days with rain[b]
	None	Once	Daily		
Velvetleaf	0.185 a	0.130 a	0.219 a	0.160	2
Powell amaranth	0.017 a	0.011 a	0.009 a	0.011	2
Common lambsquarters	0.011 a	0.008 a	0.020 a	0.012	2
Barnyardgrass	0.019 ab	0.005 b	0.053 a	0.027	2
Giant foxtail	0.031 a	0.005 a	0.056 a	0.032	2
Mean	0.045	0.027	0.061		

[a] Numbers within a row followed by the same letters are not significantly different at $P < 0.05$.
[b] Days with rainfall > 5 mm between burial and evaluation.

https://doi.org/10.1614/WS-D-15-00130.1 Published online by Cambridge University Press

Table 9. Probability of recovery for seedlings buried in field experiment F3, seedling recovery as affected by watering treatment after either partial or complete burial. The logistic regression model included replication, species, watering treatment, degree of burial, and the two- and three-way interactions between the main effects.

	Watering and burial treatments[a]							
	None		Once		Daily			
Species	Complete	Partial	Complete	Partial	Complete	Partial	Mean	Days with rain[b]
Velvetleaf	0.031 c	0.834 a	0.012 c	0.676 b	0.040 c	0.784 ab	0.386	4
Powell amaranth	0.033 b	0.487 a	0.014 b	0.597 a	0.044 b	0.480 a	0.283	2
Common lambsquarters	0 b	0.669 a	0.009 b	0.567 a	0.009 b	0.572 a	0.283	1
Barnyardgrass	0.009 d	0.373 b	0 e	0.401 b	0.100 c	0.686 a	0.269	2
Giant foxtail	0.043 b	0.766 a	0.051 b	0.734 a	0.051 b	0.710 a	0.392	2
Mean	0.028	0.629	0.019	0.606	0.053	0.646		

[a] Numbers within a row followed by the same letters are not significantly different at $P < 0.05$.
[b] Days with rainfall > 5 mm between burial and evaluation

recovered for all species except velvetleaf (Table 8). Although some seedlings were buried by less than 2 cm of soil, most of those that were completely buried were covered by 2 cm or more (Figure 1). Very low recovery rates for individuals buried by more than 3 cm of soil probably compensated for the relatively higher recovery for seedlings buried by less than 2 cm of soil. The higher recovery of velvetleaf can be attributed to the exceptionally large size of the velvetleaf seedlings at the time of cultivation (Table 1). Unlike the other experiments, in which seedlings of a species were buried when they reached the target size, in F2, all species were buried simultaneously during the final corn cultivation. Velvetleaf was consistently the first species to emerge in all experiments, including F2 (data not shown). The relatively high recovery of velvetleaf in F2 illustrates the difficulty of controlling rapid emerging, fast-growing species like velvetleaf by burial during cultivation.

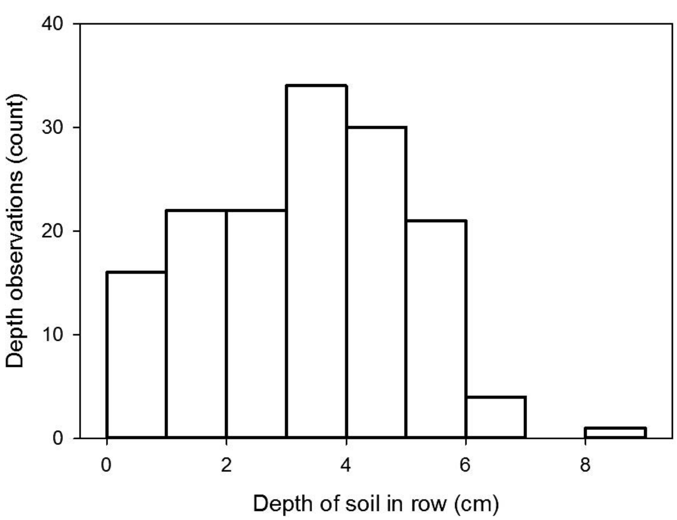

Figure 1. Frequency distribution of the depth of soil thrown into the crop row during interrow cultivation in experiment F2. The *y* axis shows the number of observations having the soil depth shown on the *x* axis.

Biological principles, farmer anecdotes, and our own field observations indicated that partial burial of seedlings should lead to much lower mortality than complete burial. These observations were confirmed by experiment F3. The intent in F3 was to leave only a small but consistent fraction of the leaf surface area of the plant exposed while burying the rest of the plant, and in particular, the shoot growing point, as close to 2 cm deep as possible. Despite this thorough, though partial, burial, over 35% of seedlings recovered in every species by treatment case, and in most cases, recovery was substantially greater than 50% (Table 9). For all species by treatment combinations, partial burial led to greater recovery than complete burial (Table 9). The difference is particularly notable for common lambsquarters, which had almost no recovery with complete burial but 57 to 67% recovery when part of a single leaf was left exposed. Studies on agricultural weeds (Baerveldt and Ascard 1999; Jones et al. 1995) and dune species (Martinez and Moreno-Casasolai 1996; Shi et al. 2004; Zhang and Maun 1990) have shown similar high recovery when burial is slightly short of complete. Results of F3 emphasize the importance of throwing as much soil into the row as the crop will tolerate to maximize the proportion of seedlings that are completely buried.

This study demonstrates that even relatively shallow burial (e.g., 2 cm) can be an effective control measure for a wide range of weed species, provided the seedlings are no more than a few centimeters tall and coverage with soil is complete. Weed species with relatively large seeds (e.g., > 2 mg) appear to recover from burial more readily than species with small seeds (< 1 mg). Under some conditions, a relatively small but still agronomically consequential proportion of seedlings can recover from complete burial. Conditions that favor recovery after seedling burial include loose, dry soil and continuously moist soil. Soil that is settled by a single watering and then dried quickly appears to provide the poorest conditions for seedling recovery. In many circumstances, controlling soil moisture conditions after cultivation is impossible. In irrigated systems, however, either a modest sprinkle irrigation followed by hot, dry weather or no irrigation for several days is likely to allow less recovery of weeds after a hilling-up operation than irrigation that results in several days of moist soil.

Acknowledgments

We thank Scott Morris and the several student assistants who helped with seedling burials: Min Park, Shaun Hall, Rachel Schell-Lambert, Rumi Sologuren, Feng Zhong, John Orlowski, Daniel Demeree, Steve Pietruszka, Kathleen C. Alvey, Elizabeth Kennedy, Kendra Ellis, Xiana Garcia Friere, and Kathleen Bitter. We thank Jay Barry of the Cornell Department of Biological Statistics and Computational Biology for advice on statistical analysis and Vanessa Wikel for help checking calculations. Support for the project was provided by funds from the Post-Doctoral Fellowship Program of the Higher Education Commission of Pakistan and by funds from the Cornell Agricultural Experiment Station (Multi-State Hatch Projects NE-1000, NE-1026, and NE-1047 Project numbers 125450, 3120006036 NYC-145843 NE1026, and 231327 NYC-125800 NE1047).

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Received July 29, 2015, and approved October 15, 2015.

Associate Editor for this paper: Martin M. Williams, III, USDA-ARS.