






Germination response of invasive plants to soil burial depth and litter accumulation is species-specific

Judit Sonkoly^{1,2}  | Orsolya Valkó^{2,3}  | Nóra Balogh^{2,4} | Laura Godó^{2,4} |
 András Kelemen³  | Réka Kiss³ | Tamás Migléc² | Edina Tóth^{1,2} | Katalin Tóth² |
 Béla Tóthmérész⁵  | Péter Török^{1,2} 

¹MTA-DE Lendület Functional and Restoration Ecology Research Group, Debrecen, Hungary

²Department of Ecology, University of Debrecen, Debrecen, Hungary

³MTA-ÖK Lendület Seed Ecology Research Group, Institute of Ecology and Botany, Centre for Ecological Research, Vácrátót, Hungary

⁴Juhász-Nagy Pál Doctoral School, University of Debrecen, Debrecen, Hungary

⁵MTA-DE Biodiversity and Ecosystem Services Research Group, Debrecen, Hungary

Correspondence

Orsolya Valkó, University of Debrecen, Faculty of Science and Technology, Department of Ecology, Egyetem tér 1, Debrecen, H-4032 Hungary.
 Email: valkoorsi@gmail.com

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Abstract

Questions: Plant invasions are considered among the biggest threats to biodiversity worldwide. In a full-factorial greenhouse experiment we analysed the effect of soil burial depth and litter cover on the germination of invasive plants. We hypothesised that: (a) burial depth and litter cover affect the germination of the studied species; (b) the effects of burial and litter cover interact with each other, and (c) the effects are species-specific, but dependent on seed size.

Methods: We tested the germination and seedling growth of 11 herbaceous invasive species in a full-factorial experiment using four levels of seed burial depths and litter cover. We analysed the effect of burial, litter cover, and their interactions on germination, seedling length and biomass across species and at the species level.

Results: Soil burial depth and litter cover had a significant effect on the germination of the studied species, but there were considerable differences between species. We observed a general trend of species with bigger seeds being not or less seriously affected by soil burial and litter cover than smaller-seeded species. Correlations between seed weight and effect sizes mostly confirmed this general trend, but not in the case of soil burial.

Conclusions: Our findings confirmed that seed size is a major driver of species' response to litter cover and to the combined effects of litter cover and soil burial, but there is no general trend regarding the response to soil burial depth. Despite its very small seeds, the germination of *Cynodon dactylon* was not affected by soil burial. The germination of *Ambrosia artemisiifolia* was hampered by both soil burial and litter cover despite its relatively large seeds. Thus, specific information on species' response to burial depth and litter accumulation is crucial when planning management or restoration in areas threatened by plant invasions.

KEYWORDS

establishment, germination, greenhouse experiment, invasive species, litter accumulation, plant invasions, seed burial, seed size, seedling emergence, soil burial

1 | INTRODUCTION

The spread of invasive species is considered among the biggest threats to biodiversity worldwide (Early et al., 2016; Mollot et al., 2017). Invasive plants regularly colonize habitats like old-fields (Cramer et al., 2008; Kelemen et al., 2016), whose area is increasing in several parts of the world due to the cessation of agricultural use and management (Ramunkutty and Foley, 1999; Prach et al., 2017). Perennial invasives can also persist until the later stages of succession, so they can even disrupt natural vegetation assembly and the recovery of old-fields (Cramer et al., 2008). The pathway of succession and species assembly can be ameliorated by restoration, but the presence of invasive plants can seriously hamper these projects as well (Cramer et al., 2008). Thus, where invasive species are a problem for the successful restoration of native communities, the most effective mode of management can be the eradication of the viable propagules of invasive species from the sites, for example by limiting their germination and establishment using adequate management regimes (Regan et al., 2006).

Seed germination requires specific environmental conditions, so that the developing seedling has a higher chance of survival and establishment (Vandelook et al., 2008). Environmental factors like temperature, light and water availability, and the chemical environment affect seed germination (Baskin and Baskin, 1998), all of which substantially vary with soil depth (Benvenuti et al., 2001; Burmeier et al., 2010). The depth from which a seedling can emerge depends on the amount of its seed reserves, which is mostly determined by the size of the seed (Humphries et al., 2018). Thus, the depth from which a seedling can emerge strongly depends on the size of the seed (Grundy et al., 2003; Nandula et al., 2006). Smaller seeds need to precisely track whether they are on or near the soil surface, for which their germination is most usually light-dependent (Milberg et al., 2000; Burmeier et al., 2010). Seedlings of large-seeded species can emerge from greater depths, so their germination is typically not light-dependent (Milberg et al., 2000; Jankowska-Blaszczuk and Daws, 2007). Experimental studies demonstrated that germination and/or emergence rates generally decline with seed burial depth (Benvenuti et al., 2001; Traba et al., 2004; Burmeier et al., 2010) and that this relationship is often seed size-dependent (Bond et al., 1999; Grundy et al., 2003; Limón and Peco, 2016). In turn, seed size and shape can strongly influence how easily seeds can be incorporated into deeper soil layers (Bekker et al., 1998), and also predict persistence in the soil (Thompson et al., 1993).

Besides soil burial depth, litter cover (i.e., the cover of dead plant material) is also a factor that can strongly affect seed germination and seedling establishment (Facelli and Pickett, 1991). The effects of litter on seedling establishment are mainly due to: (a) the formation of a mechanical barrier (Donath and Eckstein, 2010); (b) ameliorated water conditions (Eckstein and Donath, 2005); (c) decreased temperature fluctuations (Facelli and Pickett, 1991); (d) decreased solar irradiation (Jensen and Gutekunst, 2003); (e) the changed red/far-red ratio of light (Jankowska-Blaszczuk and Daws, 2007); (f) the altered chemical environment by leached nutrients and

allelochemicals (Ruprecht et al., 2010); and (g) protection from seed predators (Hölzel, 2005; Donath and Eckstein, 2012). Moreover, direct litter effects can also influence the outcome of plant-plant interactions, thus further altering the structure and composition of plant communities (Facelli and Pickett, 1991). Although the effects of litter on germination and establishment are mostly considered to be inhibitory (Jensen and Gutekunst, 2003; Eckstein and Donath, 2005), it can also have neutral and even facilitative effects depending on the amount of litter, the environmental conditions, and the species in question (Xiong and Nilsson, 1999; Loydi et al., 2013). Several experimental results have confirmed the assumption that litter can have neutral or positive effects on seedling establishment, especially in the case of larger seeds (Hölzel, 2005; Myster, 2006; Miglécz et al., 2013), when litter is present only in a small amount (Xiong and Nilsson, 1999; Loydi et al., 2013), or when water availability is suboptimal (Eckstein and Donath, 2005; Ruprecht et al., 2010).

Seedling establishment can be limited by the availability of seeds, the availability of suitable microsites, or both (Moore and Elmendorf, 2006). Therefore, if a site is already infested with the seeds of invasive species, the limitation of suitable microsites and ultimately the depletion of their viable seed bank can be an effective control method (Regan et al., 2006). Thus, to assess the risks posed by invasives and to plan management and restoration accordingly, information on their germination requirements is essential. There have been several studies dealing with their separate effects, but there are hardly any studies that have simultaneously manipulated burial depth and litter cover. Rotundo and Aguiar (2005) found that litter had a positive effect on seedling establishment and growth when seeds were sown on the soil surface, but not when the seeds were buried to half the seed length. This suggests that the effects of litter cover and soil burial interact with each other, but more detailed studies are needed to unravel these effects. To fill this knowledge gap, our aim was to assess both the separate and the combined effects of soil burial and litter cover on the germination and establishment of invasive species. We set up a greenhouse experiment where 11 invasive species were sown at different soil burial depths and litter covers in a full-factorial design. We hypothesised that: (a) soil burial and litter cover affect the germination and establishment of the studied species; (b) the effects of soil burial and litter cover interact with each other; and (c) that the effects are species-specific, but dependent on seed size.

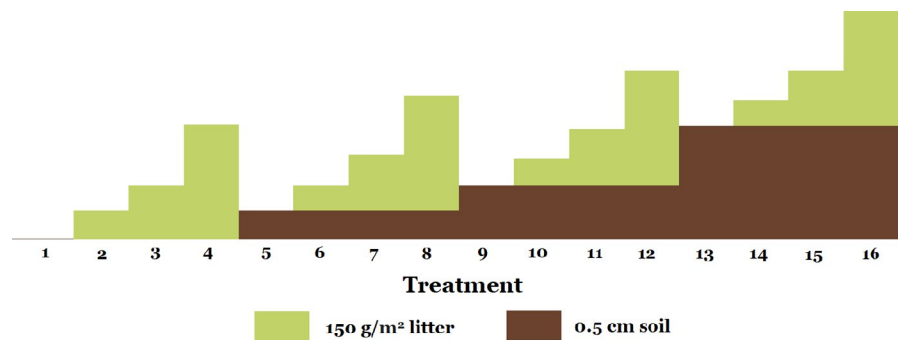
2 | METHODS

For the experiment, we selected 11 species originating from different continents and acting as invasives in other regions of the world (Table 1). The species were selected to cover a high proportion of the seed size range of herbaceous invasive species. The studied species are mainly from the Asteraceae and Poaceae families, which corresponds to the fact that species from these families are disproportionately represented among the invasive plants for example in China (Weber et al., 2008) and in the Mediterranean region (Andreu

TABLE 1 Characteristics of the 11 species studied

Species	Family	TSW	Native to	Alien invasive in
<i>Conyza canadensis</i>	Asteraceae	0.060	North America	Europe
<i>Cynodon dactylon</i>	Poaceae	0.114	Africa	America, Oceania, Asia
<i>Solidago canadensis</i>	Asteraceae	0.230	North America	Europe, Asia, Oceania
<i>Lactuca serriola</i>	Asteraceae	0.482	Europe, Asia, North Africa	North America
<i>Cirsium arvense</i>	Asteraceae	0.945	Europe, Asia	North America
<i>Centaurea solstitialis</i>	Asteraceae	1.366	Europe, Asia, North Africa	North America
<i>Bromus tectorum</i>	Poaceae	3.696	Europe, Asia	North America
<i>Bromus inermis</i>	Poaceae	4.574	Europe, Asia	North America
<i>Ambrosia artemisiifolia</i>	Asteraceae	5.656	Central and North America	Africa, Asia, Australia, Europe
<i>Asclepias syriaca</i>	Asclepiadaceae	6.063	North America	Europe, Asia
<i>Tragopogon dubius</i>	Asteraceae	6.529	Europe, West Asia	North America

Note: TSW, Thousand-seed weight (g). Native and invasive alien ranges are given according to CABI Invasive Species Compendium (CABI, 2019) and the Invasive Plant Atlas of the United States (www.invasiveplantatlas.org). TSW values are based on Török et al. (2013).

FIGURE 1 Soil burial depth and litter cover in the 16 treatments demonstrating the experimental design

and Vilá, 2010), and that the Asteraceae and Poaceae families have the highest number of species in the global naturalised alien flora (Pyšek et al., 2017). In addition, we selected *Asclepias syriaca*, as it is also colonising large areas of Europe and is especially widespread in Hungary (Tokarska-Guzik and Pisarczyk, 2015), representing a major threat in old-fields and degraded sand grasslands (Kelemen et al., 2016). Seeds were collected from natural populations in the Great Hungarian Plain (East Hungary, Central Europe) during 2016. Note that all seeds were collected in the same region where some of them are native and others are invasive aliens. We tested whether results differ between locally native and locally invasive species, and we found that there was no significant difference between the results of locally native and locally invasive species (Welch's two-sample *t* tests for differences in the effect sizes of litter cover, soil burial and the two combined, $p = 0.399$, $p = 0.526$ and $p = 0.738$, respectively). Henceforth we refer to the studied species as invasive species.

We set up a greenhouse experiment in which we tested the effects of increasing seed burial depths (0, 0.5, 1 and 2 cm soil) and increasing levels of litter cover (0, 150, 300 and 600 g/m²) and their interaction in a full-factorial design (altogether 16 treatments; Figure 1). We filled pots with steam-sterilised potting soil and placed 25 seeds of a species on each of them, then applied soil burial and litter cover according to the treatment. We used the same potting soil for burying the seeds; litter was collected in a seminatural grassland

dominated by the narrow-leaf grasses *Festuca rupicola* and *Poa angustifolia*. All 16 treatments were applied on all 11 species with five replications, meaning altogether 880 pots and 22,000 seeds. The pots were placed randomly in a greenhouse, frequently rearranged and watered daily with tap water to provide optimal conditions for germination. Germination lasted six weeks from the beginning of April 2017. At the end of the germination tests, we counted and removed all seedlings, measured the length of the shoot on 10 randomly chosen seedlings per pot (altogether 5,484 measurements) and weighed the aboveground biomass in each pot with an accuracy of 0.0001 g. Only those seedlings were counted that emerged above the soil surface, and thus had germinated successfully. Fatal germination events have not been counted.

The effects of soil burial depth, litter cover, species identity, and their interactions on the germination rate, seedling length and seedling biomass across species were analysed using three-way ANOVAs. We used two-way ANOVAs to analyse the effects of soil burial depth, litter cover and their interactions on the species level.

To test if the effect sizes correlate with seed size, we calculated Cohen's *d* (standardised mean difference, calculated as the difference of the means of control and treated groups divided by the weighted pooled standard deviations of these groups) for soil burial, litter cover and for the two combined for each species, and then used Spearman's rank correlation tests. Thus, the

standardised mean difference of treatment 1 (control) and treatment 4 was the effect size for litter cover; the standardised mean difference of treatment 1 and treatment 13 was the effect size for soil burial; and the standardised mean difference of treatment 1 and treatment 16 was the effect size for soil burial and litter cover combined (see Figure 1).

Conyza canadensis and *Solidago canadensis* were excluded from the analyses of seedling length and biomass because of their very low (often 0%) germination rate in treatments other than the control. Germination rate values were arcsine-transformed and seedling biomass values were square-root-transformed to obtain normally distributed residuals, which was verified by residual plots. Homogeneity of variances was confirmed by Bartlett's test. As we allocated seeds to treatments randomly and the replicates were also arranged randomly in the greenhouse, the error terms can be considered additive (Sileshi, 2012). All statistical analyses were carried out in the R statistical environment (R Core Team, R Foundation for Statistical Computing, Vienna, Austria).

3 | RESULTS

From the 22,000 seeds sown 9,480 seeds (43.1%) germinated. The mean germination rate of the studied species in the control treatment ranged from 0.11 (*Cynodon dactylon*) to 0.94 (*Bromus tectorum*), but the highest germination rate was not found in the control treatment in most species (except for *Centaurea solstitialis*, *Conyza canadensis* and *Solidago canadensis*) (Appendix S1).

Germination rate was significantly affected by both soil burial depth, litter cover, species identity and their interactions, but most factors explained only a very small fraction of the total variation, while species identity explained 71% of it (Table 2, Figure 2). When analysed at the species level, the effects of both soil burial and litter cover were significant for most of the species, excluding some of the large-seeded ones (Table 3). The variance explained by soil burial was relatively high for the small-seeded species except for *Cynodon dactylon*. For the large-seeded species, the effect of seed burial depth was either not significant or explained only a small amount of the total variation, except for *Ambrosia artemisiifolia*. The amount of variance explained by litter cover was rather low for all the species (Table 3). The interaction term was significant for only a few species, and the variance explained by it was low for most species, except for *Solidago canadensis*. The unexplained variance was more than 50% for most of the large-seeded species and *Cynodon dactylon* (Table 3).

Seedling length was significantly affected by both soil burial depth, litter cover, species identity and their interactions, but most factors explained only a very small fraction of the total variation, while species identity explained 89% of it (Appendices S2 and S3). When analysed at the species level, the effect of litter cover on seedling length was significantly positive for all species, and it explained a relatively high amount (>40%) of the variance for several species (Appendix S4).

TABLE 2 The effect of soil burial depth, litter cover, species identity and their interactions on the germination rate across the studied species (three-way ANOVA)

	df	p	VC
Soil burial depth	3	<0.001	0.078
Litter cover	3	<0.001	0.020
Species identity	10	<0.001	0.712
Soil × Litter	9	0.001	0.003
Soil × Species	30	<0.001	0.057
Litter × Species	30	<0.001	0.014
Soil × Litter × Species	30	<0.001	0.032
Residual	704		0.084

Note: VC = variance component, i.e., the relative contribution of factors and their interactions to the total variation (expressed as the ratio of the sum of squares of the factor to the total sum of squares).

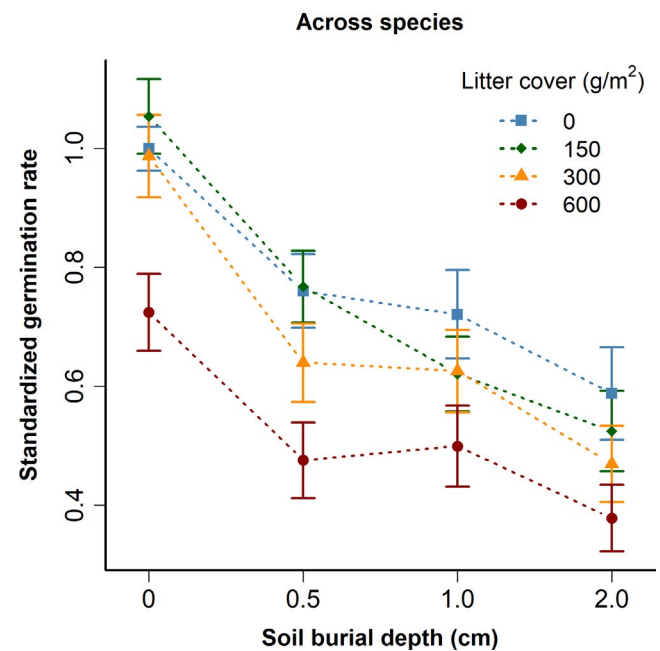


FIGURE 2 The effect of soil burial depth and litter cover on the germination rate across the studied species (mean ± SE)

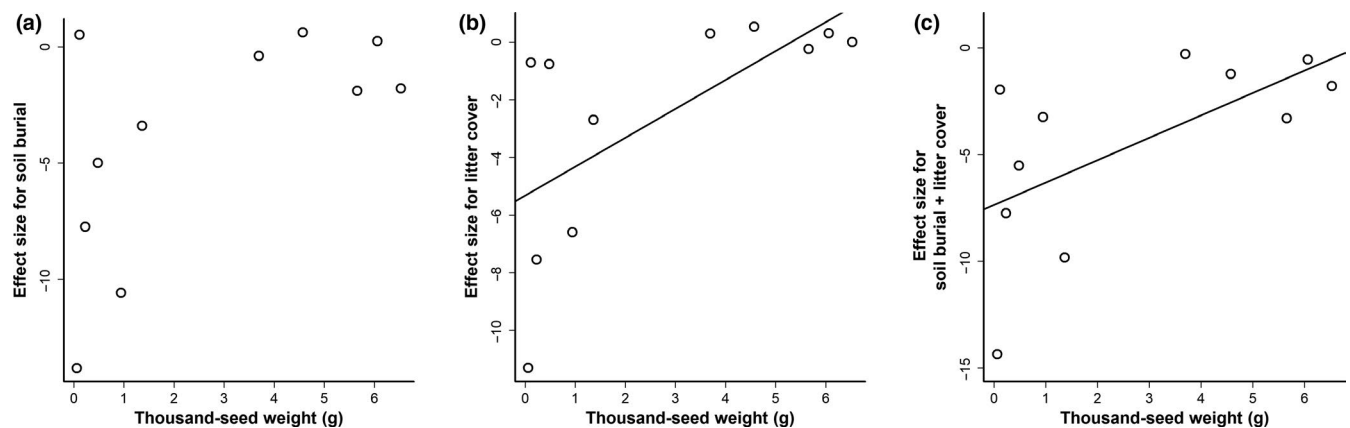
Seedling biomass was significantly affected by both soil burial depth, litter cover, species identity and their interactions, but most factors explained only a very small fraction of the total variation, while species identity explained 84% of it (Appendices S5 and S6). When analysed at the species level, seedling biomass was significantly affected by soil burial depth, litter cover or their interaction in only some of the species, and the unexplained variance was relatively high for all the species (Appendix S7).

The correlation between seed weight and the effect size of seed burial on the germination rate of species was not significant (Figure 3a), but seed weight was strongly correlated to both the effect size of litter cover (Figure 3b) and to the effect size of the combined effect of soil burial and litter cover (Figure 3c).

TABLE 3 The effect of soil burial depth, litter cover and their interaction on the germination rate of the studied species (two-way ANOVAs)

Species	Soil		Litter		Soil × Litter		Resid.
	<i>p</i>	VC	<i>p</i>	VC	<i>p</i>	VC	VC
<i>Ambrosia artemisiifolia</i>	<0.001	0.434	<0.001	0.165	0.065	0.085	0.316
<i>Asclepias syriaca</i>	0.584	0.027	0.573	0.028	0.925	0.052	0.893
<i>Bromus inermis</i>	0.391	0.039	0.610	0.023	0.373	0.126	0.812
<i>Bromus tectorum</i>	0.119	0.065	0.308	0.039	0.028	0.217	0.679
<i>Centaurea solstitialis</i>	<0.001	0.561	<0.001	0.222	0.134	0.040	0.177
<i>Cirsium arvense</i>	<0.001	0.445	0.012	0.077	0.391	0.063	0.415
<i>Conyza canadensis</i>	<0.001	0.617	<0.001	0.153	<0.001	0.182	0.048
<i>Cynodon dactylon</i>	0.006	0.112	<0.001	0.277	0.337	0.086	0.526
<i>Lactuca serriola</i>	<0.001	0.653	0.022	0.036	0.006	0.090	0.221
<i>Solidago canadensis</i>	<0.001	0.476	<0.001	0.144	<0.001	0.312	0.067
<i>Tragopogon dubius</i>	0.001	0.177	0.045	0.079	0.085	0.150	0.593

Note: VC, variance component, i.e., the relative contribution of factors and their interactions to the total variation (expressed as the ratio of the sum of squares of the factor to the total sum of squares).

**FIGURE 3** The correlation of seed weight and the effect size (Cohen's *d*) for: (a) soil burial (Spearman rank correlation, $\rho = 0.121$); (b) litter cover (Spearman rank correlation, $\rho = 0.764$, $p = 0.009$); and (c) litter cover and soil burial combined (Spearman rank correlation, $\rho = 0.618$, $p = 0.048$) for the germination rate of species

4 | DISCUSSION

We hypothesised that soil burial and litter cover negatively affect the germination and establishment of the studied species. The novelty of our study is that we simultaneously manipulated soil burial depth and litter cover, and that we also tested whether the effects of soil burial and litter cover interact with each other. The main result of our study is that although soil burial and litter cover generally negatively affect the germination of the studied invasives, the results are highly species-specific.

Previous studies have also analysed the separate effects of soil burial and litter cover on the germination of seeds including some invasive species as well (Reader, 1993; Guillemin and Chauvel, 2011), but there are hardly any results on their combined effects. Rotundo and Aguiar (2005) analysed the effects of litter on the seed germination of *Bromus pictus* in a greenhouse experiment, where seeds

were positioned on the soil surface or buried in it to half the seed length. Their results indicated that litter increases the germination and emergence rates of surface-lying seeds, but not the emergence of buried seeds. When analysed on the species level, the effect of the seed burial depth × litter cover interaction on the germination was significant for some of the species. This was probably due to deep soil burial masking the potential effects of litter cover, resulting in smaller or no effect of litter cover in treatments with deeper soil burial for the species *Cynodon dactylon*, *Lactuca serriola* and *Solidago canadensis* (see Appendix S1). The effect of the interaction term was significant for the length and the biomass of seedlings in even fewer of the studied species. These findings suggest that the effects of soil burial and litter cover interact with each other in some species, but this is not a general phenomenon.

We also hypothesised that the effects are species-specific, but dependent on seed size. When analysed across species, the effects

of soil burial and litter cover on germination rate were significant, but their interaction was not, and species identity explained most of the variance. This is in good accordance with the notion that the germination response to litter is dependent on species identity (Eckstein and Donath, 2005). At the species level, soil burial was significant for most of the species and it explained a relatively high amount of the variance in germination for several species. In the case of smaller-seeded species, variance explained by soil burial depth was relatively high, except for *Cynodon dactylon*, while in the case of larger-seeded species soil burial depth was either not significant or explained little variance, except for *Ambrosia artemisiifolia*, where soil burial explained a relatively large amount of the variance.

Our species-level results were mostly in line with former results on these species. Regarding *Asclepias syriaca*, Yenish et al. (1996) found that soil burial up to 2 cm did not affect its emergence, which is in accordance with our results. Our findings for the two *Bromus* species were quite similar; neither soil burial nor litter cover had a significant effect on their germination success. Probst et al. (1997) observed no decline in the emergence of *Bromus tectorum* seeds from soil burial depths less than 5 cm, which corresponds to our results. Wicks et al. (1971) also stated that *Bromus tectorum* seeds germinated well under up to 2.5 cm (1 inch) of soil burial. In agreement with our findings, the field germination rate of *Centaurea solstitialis* was also found to be higher at a depth of 1 cm than at 2 cm (Larson and Kiemec, 1997). We found that the germination of *Cirsium arvense* was strongly inhibited by soil burial, which was in accordance with the former findings that a burial of 1.5 cm (Tiley, 2010) and 2–3 cm (Laubhan and Shaffer, 2006) can inhibit its germination. By contrast, others indicate that *Cirsium arvense* can emerge even from a depth of 6 cm (Wilson, 1979). Our results regarding *Conyza canadensis* were in accordance with those of Weaver (2001) and Nandula et al. (2006), who both reported that its emergence is maximum on the soil surface and decreases quickly with burial depth. In case of *Solidago canadensis*, we found that both soil burial and litter cover significantly reduce germination, and the inhibiting effect of litter cover for the germination of this species was also demonstrated by Goldberg and Werner (1983) and by Reader (1993). Our result that *Tragopogon dubius* was significantly negatively affected by soil burial depths up to 2 cm disagrees with Qi and Upadhyaya (1993), who found a high emergence rate of *Tragopogon dubius* at 2 cm burial depth.

We also analysed whether the separate and combined effects of soil burial and litter cover depend on seed size by testing the correlation of the effect size and the seed weight of each species. The effect sizes for the combined effects and for the separate effect of litter were strongly correlated with seed weight. Species with larger seeds had effect sizes close to zero, while the effect sizes for the small-seeded species were more variable, but in general larger (in the negative range). Our finding that the germination of smaller seeds is hampered by a litter layer of 600 g/m² corresponds to the notion that smaller seeds absorb the amount of water needed for germination more rapidly than larger seeds (Kikuzawa and Koyama, 1999), so the positive effect of litter on moisture conditions is more

pronounced in case of larger seeds, while small seeds, whose germination is usually light-dependent, are hampered by a thick litter layer (Milberg et al., 2000). In case of the separate effects of soil burial, the correlation of effect size with seed weight was not significant. Large-seeded species had effect sizes close to zero in this case as well, but for small-seeded species the effect sizes had an even broader range. Among the small-seeded species, the response of *Cynodon dactylon* markedly differed from that of the others, having a positive effect size for soil burial. Having species whose germination behaviour deviates from the general trend corroborates the assumption that the light dependence of germination is not simply determined by seed size, as it can also be species-specific and altered by adaptations to specific habitat conditions (Milberg et al., 2000; Eckstein and Donath, 2005).

There were two species that considerably deviated from the general trends that we identified. For other large-seeded species the effect of soil burial depth was either not significant or explained only a small amount of the variance in germination, but the germination of *Ambrosia artemisiifolia* was significantly affected by soil burial, and it also explained a relatively high proportion of the variation (see also Appendix S1). Former studies have also found that the germination of *Ambrosia artemisiifolia* seeds decreases with burial depth, being the highest on the soil surface (Guillemin and Chauvel, 2011; Essl et al., 2015). On this basis, soil tillage after high seed production is a feasible control option for *Ambrosia artemisiifolia* if it is not followed by deep soil tillage in the following year (Guillemin and Chauvel, 2011). Our results indicated that litter cover may also decrease the establishment of this species, but it is much less effective compared to soil burial. The germination of *Ambrosia artemisiifolia* being hampered by both soil burial and litter cover besides its relatively large seeds is most probably an adaptation to establishment on disturbed sites (Milberg et al., 2000).

The other species that refuted the expectations was *Cynodon dactylon*, as its germination was basically not affected by soil burial depth (see Appendix S1 and Table 3), despite having the second smallest seeds among the studied species. We suggest that the reason behind this germination behaviour may be that *Cynodon dactylon* is a highly drought-tolerant species that regularly grows in very dry habitats (Shi et al., 2012), but its germination and/or seedlings may not be drought-tolerant. Thus, its seeds need to be able to germinate from greater depths where soil moisture conditions are more favourable. This assumption is in accordance with the finding of Mahmood et al. (1996) that an increase in soil moisture content significantly increases the germination of *Cynodon dactylon* seeds.

Another important notion is that the type of litter may also influence the results, as different types of litter may affect germination and establishment differently (Myser, 2006), but previous results suggest that these differential effects are probably due to physical rather than chemical processes (Peterson and Facelli, 1992). In our experiment the physical and chemical effects of litter could not be differentiated, but as these effects are not separated under real-life field conditions either, we aimed to analyse their net effects. Apart from seed size, seed shape is another seed trait which may influence



the germination response to soil and litter cover (Facelli and Pickett, 1991), but the relationship seems to be complex, and it is possibly species-specific (Grundy et al., 2003). However, in case of the studied species the effect of seed shape could not be meaningfully tested, because seed size and shape (seed shape index, Thompson et al., 1993) were not independent in the studied species (bigger seeds were in general more elongated, except for *Ambrosia artemisiifolia*). Results indicate that seedling geometry may also influence whether a seedling can penetrate the litter layer (Facelli and Pickett, 1991). Soil burial and litter cover may also affect the temporal dynamics of germination, ultimately affecting vegetation dynamics and succession (Facelli and Pickett, 1991; Facelli and Facelli, 1993); thus, how the timing of germination can be altered is probably another important aspect to test.

Understanding the germination behaviour and control options of invasive species is even more crucial in the light of climate change and land use changes, which is expected to facilitate their further spread and the rise of new invasive species as well (Cunze et al., 2013; Hellmann et al., 2008). Information on the cropping system used before abandonment may also be essential (Cardina et al., 2002; Guglielmini and Satorre, 2004). The use of reduced tillage cropping systems is rapidly spreading, and in such cases weed seeds accumulate on the soil surface or in the uppermost layers, enabling rapid germination of most species (Mohler, 1993). In order to identify if (and what kind of) tillage could be recommended for the control of invasives after abandonment, it is essential to know the soil depth from which seedlings of the locally problematic species can emerge (Humphries et al., 2018). Litter can also have an important role in the control of invasives, as it has already been demonstrated that it can hamper the establishment of weeds in old-fields (Deák et al., 2011) and decrease the emergence of invasives such as *Solidago canadensis* (Goldberg and Werner, 1983) or *Flaveria bidentis* (Li et al., 2016). Thus, a deeper insight into the effects of litter on the germination of invasives can be valuable in practical nature conservation. Another practical consideration is the effect of hay transfer as a restoration measure (Eckstein and Donath, 2005), as different amounts and types of litter can have differential effects on target species as well. Whether these effects differ between invasive and non-invasive species cannot be assessed based on our study. Contrary to our results on invasive plants, the germination response of non-invasive species to soil burial was found to be correlated with seed size in previous studies (Bond et al., 1999; Limón and Peco, 2016). The combined effects of soil burial and litter cover have only been studied on a non-invasive species previously, in which case their effects strongly interacted with each other (Rotundo and Aguiar, 2005).

Based on our results, the germination of most invasive plants can be strongly affected by soil burial and litter cover, which limits their ability to establish on undisturbed natural or semi-natural communities. We can conclude that seed size is a major driver of the germination response to litter cover and to the combined effect of litter and soil burial, but there is no general trend regarding the response to soil burial depth. Among the studied species the

germination of the small-seeded *Cynodon dactylon* was practically not affected by soil burial, while the much bigger seeds of *Ambrosia artemisiifolia* were significantly inhibited, which may be attributed to the influence of their habitat preferences and strategy. Thus, to effectively deal with the ever-increasing threat of invasive plants, species-specific information on their germination response to litter cover and soil burial is essential. Such species-specific information would not only aid restoration but could also improve our ability to assess the risks posed to natural and semi-natural habitats. Furthermore, a more general implication is that although seed size is an important driver of plants' response to several factors and it is associated with many plant attributes, other effects such as that of habitat preference or plant strategy can mask the influence of seed size.

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AUTHOR CONTRIBUTIONS

BT, OV and PT designed the study; JS, OV, NB, LG, AK, RK, TM, ET and KT carried out the experiments and collected the data; JS analysed the data; JS led the writing of the manuscript and all authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

All primary data are available as Supplementary Material (Appendix S8).

ORCID

Judit Sonkoly  <https://orcid.org/0000-0002-4301-5240>

Orsolya Valkó  <https://orcid.org/0000-0001-7919-6293>

András Kelemen  <https://orcid.org/0000-0002-2480-5669>

Béla Tóthmérész  <https://orcid.org/0000-0002-4766-7668>

Péter Török  <https://orcid.org/0000-0002-4428-3327>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

Appendix S1. The germination rate of each species in the treatments.

Appendix S2. The effect of soil burial depth, litter cover, species identity and their interactions on seedling length across the studied species (three-way ANOVA).

Appendix S3. The effect of soil burial depth and litter cover on seedling length across the studied species (mean \pm SE).

Appendix S4. The effect of seed burial, litter cover and their interaction on the seedling length of each species.

Appendix S5. The effect of soil burial depth, litter cover, species identity and their interactions on seedling biomass across the studied species (three-way ANOVA).

Appendix S6. The effect of soil burial depth and litter cover on seedling biomass across the studied species (mean \pm SE).

Appendix S7. The effect of seed burial, litter cover and their interaction on the seedling biomass of each species.

Appendix S8. All primary data generated during the study.

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