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Seasonal and Species-Specific Variation in Weed Seed Predation Across No-Till and Conventional Tillage Systems

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ABSTRACT

Tillage disturbs predator communities and can alter post-dispersal weed seed removal in arable systems. Weed seed predation represents a low-input pathway that may contribute to reductions in seed return, yet variation in predation rates across tillage intensity, seasons and weed species remains incompletely understood in UK cropping systems. Here, we quantified weekly predator-attributable seed losses using seed cards in six fields managed under contrasting tillage systems (three no-till and three conventional) over 2 years, focusing on *Alopecurus myosuroides*, *Bromus secalinus* and *Avena fatua*. Predation was consistently greater in no-till, with weekly removals averaging 76%–79% compared with 46%–52% in conventional tillage, although rates varied markedly among seasons. Losses were consistently highest in spring, while seed losses in autumn and summer varied from year to year, alternating in rank. Inter-annual differences were slight and did not alter the direction or magnitude of the tillage contrast. Species differences were moderate: *B. secalinus* generally showed lower seed removal, while *A. fatua* and *A. myosuroides* were similar and slightly higher. These findings demonstrate that reduced soil disturbance is associated with consistently greater surface seed removal by predators, which represents an important complementary process within integrated weed management. Practices that maintain surface residues and predator habitat may therefore enhance the contribution of biological seed removal in systems that rely on reduced tillage, including those often described as regenerative.

1 | Introduction

The persistence of weed seeds in agricultural landscapes is a critical factor influencing weed population dynamics and the effectiveness of weed management strategies. Weed seed predation, where seeds are consumed by granivores such as insects, birds and small mammals, has emerged as a potential component of integrated weed management (IWM) (Lundgren and Fausti 2015). By removing weed seeds before incorporation into the seedbank, predation can occur alongside conventional weed control practices such as herbicides. Herbicide use, however, can indirectly influence predator communities by altering vegetation structure and resource availability, thereby affecting seed predation dynamics (Holland and Luff 2000; Sarabi 2019). A diversified portfolio of weed control approaches has become increasingly important due to the pressing challenge of herbicide resistance, which threatens the long-term effectiveness of chemical weed control methods (Davies et al. 2019; Heap 2026). The extent to which predation contributes to weed seed losses varies widely and is influenced by farming practices, weed species and predator activity (Westerman, Hofman, et al. 2003).

Among agronomic practices, tillage plays a pivotal role in shaping weed seed predation dynamics (Cromar et al. 1999). Reduced tillage systems, which involve minimal soil disturbance, are often associated with enhanced ecosystem services such as

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biological weed seed removal, partly through increased seed predator abundance and activity (Holland 2004). In contrast, conventional tillage alters soil structure and habitat conditions, with effects on predator populations that are often species-specific (Kladivko 2001; Liebman et al. 2001). While intensive soil disturbance can directly increase the mortality of granivore larvae and pupae, such as carabid beetles, and reduce overall abundance (Müller et al. 2022; Purvis and Fadl 2002), some species may benefit from temporarily loosened soil conditions that facilitate movement or oviposition. The adoption of no-till and minimum tillage practices has been growing globally due to their benefits in conserving soil moisture, reducing erosion and improving soil health, as well as their lower time and cost requirements compared to deeper cultivation (Derpsch et al. 2010; Kassam et al. 2018).

Previous research has shown that no-till fields can exhibit higher seed predation than conventionally tilled systems, often attributed to greater residue cover and improved habitat for granivores (Baraibar et al. 2019; Chauhan et al. 2012; Gallandt et al. 2005). Other studies have examined relationships between predator abundance and seed removal (Bohan et al. 2011; Kulkarni et al. 2015) or the influence of agricultural management intensity on seed predation (Daouti, Feit, and Jonsson 2022). However, these studies have typically focused on single species, single seasons or fields under different management. Reduced soil disturbance is increasingly discussed within sustainability-oriented management frameworks that emphasise ecological processes such as natural predation, although the present study focuses specifically on contrasting tillage intensities rather than comprehensive system-level approaches. Few studies have simultaneously quantified predator-attributable seed losses across tillage systems while accounting for multiple weed species and seasonal variation, limiting understanding of how management, species identity and seasonal dynamics interact to influence predation-driven seed losses.

Annual grassweeds are among the most problematic weeds in European cereal systems, including the United Kingdom (Beckie et al. 2012; Melander et al. 2013; Ribeiro et al. 2023). Their persistence in cropping systems is closely linked to substantial seed return and the accumulation of persistent seedbanks. Understanding whether predation differentially affects these species is therefore agronomically relevant. For example, differences in seed size and physical traits may influence predator selectivity: the smaller seeds of *Alopecurus myosuroides* Huds. (blackgrass) may be more accessible to invertebrate granivores, whereas the larger seeds of *Avena fatua* L. (wild oats) and *Bromus secalinus* L. (rye brome) may be more frequently removed by vertebrates (Hulme 1994; Mittelbach and Gross 1984).

Our study quantified and compared weed seed predation rates across no-till and conventional tillage systems, seasons, weed species and years in UK arable fields. By addressing these factors simultaneously, the study provides a robust assessment of how management intensity, species identity and seasonal dynamics interact to shape predator-mediated seed removal. This contributes to a clearer understanding of the role of biological seed predation within integrated weed management strategies in reduced tillage systems.

2 | Materials and Methods

2.1 | Study Sites

Weed seed predation was assessed between August 2023 and July 2025 to quantify variations across species, tillage systems, and seasons in six fields managed by Niab in Cambridge, UK. The fields were identified as Field 1, Field 2, Field 3, Field 4, Field 5 and Field 6. Fields 1, 2, 5 and 6 were located within a 5 km radius, while Fields 3 and 4 were within a 1 km radius and approximately 25 km from the other fields (Figure 1). All fields were separated or surrounded by hedgerows, mainly *Crataegus monogyna* (hawthorn), *Prunus spinosa* (blackthorn) and *Corylus avellana* (hazel), providing consistent edge environments. Fields 1–3 had been under continuous inversion tillage at a minimum depth of 20 cm for at least 10 years at the start of predation assessment. Fields 4–6 were under a regenerative cropping system, where repeated direct drilling into crop stubble with minimal soil disturbance has been practised for 5–8 years (including fallow breaks) prior to the start of this study. The soil types varied among the fields: Fields 3 and 4 were on Hanslope series clay soils, and Fields 1, 2, 5 and 6 were on chalky, silty-loam soils (British Geological Survey 2023).

All trials were carried out over six 5-week periods to capture seasonal variations: autumn 2023 (August–September), spring 2024 (February–March), summer 2024 (June–July), autumn 2024 (September–October), spring 2025 (February–March) and summer 2025 (June–July). The experimental year 2023/24 received 740 mm of precipitation, substantially more than in 2024/25 (449.2 mm). Monthly mean temperatures were comparable at 15.6°C and 15.5°C for the 2023/24 and 2024/25 seasons, respectively. Temperature and rainfall data during the experimental period are shown in Figure 2. A detailed description of the management of the selected fields is provided in Table 1.

2.2 | Weed Species

The species assessed were *A. myosuroides*, *B. secalinus* and *A. fatua*. *A. myosuroides* is highly competitive in winter crops like wheat and winter oilseed rape, with a lifecycle that includes germination in autumn and spring, flowering from late spring to early summer (May to June), and seed shedding in summer (June to August) (Moss 1985). Its seeds have a 1- to 5-year longevity, with an annual decline rate in the seedbank of about 80%. Although this can suggest a relatively rapid seedbank turnover, population persistence remains highly dependent on annual seed input, and losses occurring before or during seed incorporation can substantially influence recruitment dynamics. Each seed weighs approximately 1.8 mg, and a single plant can produce around 800 seeds, with about 100 seeds per head (Moss 1983). *Bromus secalinus* primarily competes with winter wheat. It has autumn germination, flowering in early summer, and seed shedding in late summer and autumn. The species produces up to 100 seeds per plant, each weighing approximately 5 mg. Seeds of *A. fatua* are shed in late summer and autumn (Beckie et al. 2012). Each plant can produce up to 500 seeds, each weighing around 30 mg, with a longevity exceeding 5 years (Agriculture and Horticulture Development Board 2018). Unlike the other two species, the thin seed coat



FIGURE 1 | Map showing the locations of the experimental sites in the United Kingdom (a). (b) shows the locations of Fields 3 and 4, while (c) shows the locations of Fields 1, 2, 5 and 6. *Source:* Google Earth.

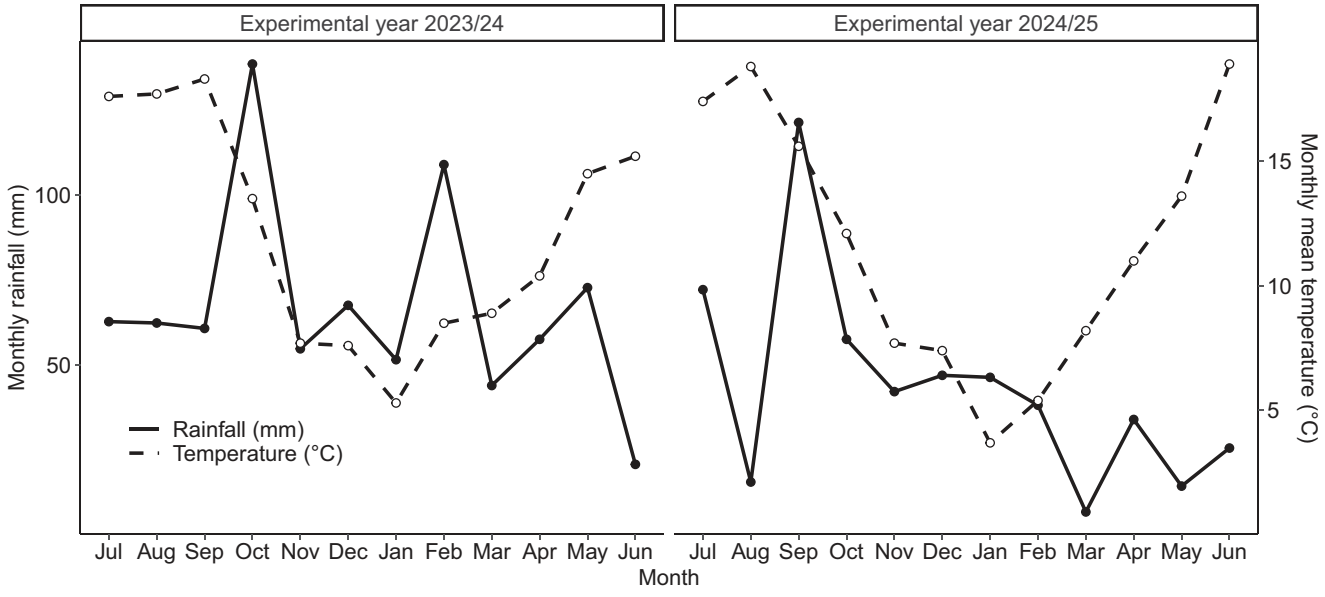


FIGURE 2 | Monthly rainfall and mean temperature data during the experimental period, obtained from Niab Weather Station, Cambridge, UK.

TABLE 1 | Field management history and characteristics of experimental sites before and during the study period.

Field	Location	Tillage type	Description	Crop rotation (2019–2025)
Field 1	Hinxton, Cambridge	Conventional	Conventional tillage for > 10 years, less weedy	Winter beans—winter wheat—potatoes—winter beans—winter wheat—**winter wheat—winter beans**
Field 2	Hinxton, Cambridge	Conventional	Conventional tillage for > 10 years, dominated by *A. myosuroides*	Winter beans—winter wheat—winter wheat—winter wheat—winter wheat—**winter beans—winter beans**
Field 3	Childerley, Cambridge	Conventional	Conventional tillage for 8 years, less weedy	Winter wheat—winter wheat—spring barley—winter wheat—winter wheat—**winter beans—winter wheat**
Field 4	Childerley, Cambridge	No-till	Direct drilling for 8 years, less weedy	Winter wheat—winter wheat—spring barley—winter wheat—winter wheat—**fallow—winter wheat**
Field 5	Hinxton, Cambridge	No-till	Direct drilling for 5 years, dominated by brome species and broadleaf weeds	Fallow—fallow—spring barley—winter wheat—winter wheat—**winter wheat—fallow**
Field 6	Hinxton, Cambridge	No-till	Direct drilling for 5 years, dominated by grasses and broadleaf weeds	Winter wheat—spring wheat winter wheat—winter wheat—winter wheat—**winter wheat—winter beans**

Note: Farm-standard weed control was practised in Fields 1–4, including pre- and post-emergence herbicide application. Fields 5 and 6 were under a regenerative cropping system and mechanical weed control; thus, no herbicides were applied. Bold font in the crop rotation column highlights the crops present during the spring and summer of this study. Autumn assessments were conducted soon after crop harvest.

provides little to no protection against seed predators; however, the seeds are partially shielded by the lemma and palea (Westerman, Wes, et al. 2003).

2.3 | Weed Seed Predation Assessment

Predation was assessed using a 'seed card' method adapted from Westerman, Wes, et al. (2003). Seeds were scattered on cards made of firm, high-quality sandpaper (10 × 8 cm, KWB grain size 120) sprayed with repositionable glue (3 M repositionable spray mount). Treatment cards were left exposed to predators and placed directly on the soil surface and secured with steel U-pins to prevent bending, curling, or displacement by predators. Similarly, 'control cards' were placed in cages made of strong nylon-mesh bags (each measuring 25 × 15 cm) and pinned to the soil surface to ensure stability (Figure 3a). The control cards accounted for seed losses due to non-predator factors such as rain, wind or adhesive degradation. Seeds did not germinate during the experimental periods. The glue provided sufficient adhesion under all weather conditions while allowing predators to remove the seed. Exposed glue areas were covered with fine sand to prevent small predators from sticking to the cards. The number of seeds per card was scaled to seed mass (fewer larger seeds and more smaller seeds), with 50 *A. myosuroides* (~0.12 g), 30 *B. secalinus* (~0.3 g) and 20 *A. fatua* (~0.4 g) per card.

Daytime visual observations and nighttime infrared trail camera recordings showed that larger seed predators, such as birds, rabbits, mice and ground beetles, could easily remove seeds from the cards (see Figure S1). However, because no behavioural control treatment was included, potential effects of the sandpaper or glue on predator attraction or avoidance cannot be ruled out. It was assumed that any missing seeds were either consumed immediately or stored in seed caches for later consumption by the predators (Westerman, Wes, et al. 2003). However, some seeds may have been removed without being consumed, or they might have remained viable after passing through the digestive systems of larger predators. Piles of *A. fatua* husks were frequently observed on or near the seed cards, indicating seed consumption by ground beetles and small rodents (Kjellsson 1985).

A systematic grid sampling design was employed in each field to assess predation rates. Each field was divided into five transects, starting at least 20 m from the edge to minimise potential edge effects, such as variations in predator abundance or activity near field boundaries (Rand et al. 2006). Transects were spaced at least 10 m apart to prevent overlap in predator activity. To minimise potential edge-driven predator effects and capture representative variations in microhabitats, soil cover and predator activity, transects were strategically arranged parallel to the field edges. Along each transect, cards were placed at three positions spaced 10 m apart. One treatment seed card and one control card were placed at each position, spaced ~1 m apart. Weed species were randomly assigned to each transect, and their positions were maintained throughout the 5-week experimental period to ensure consistency in assessing predation rates through each season. In total, 30 seed cards per field and 10 per species were randomly placed along transects (Figure 3b). Transects and positions were strategically placed to capture representative field variations, including microhabitats and soil cover. Predator

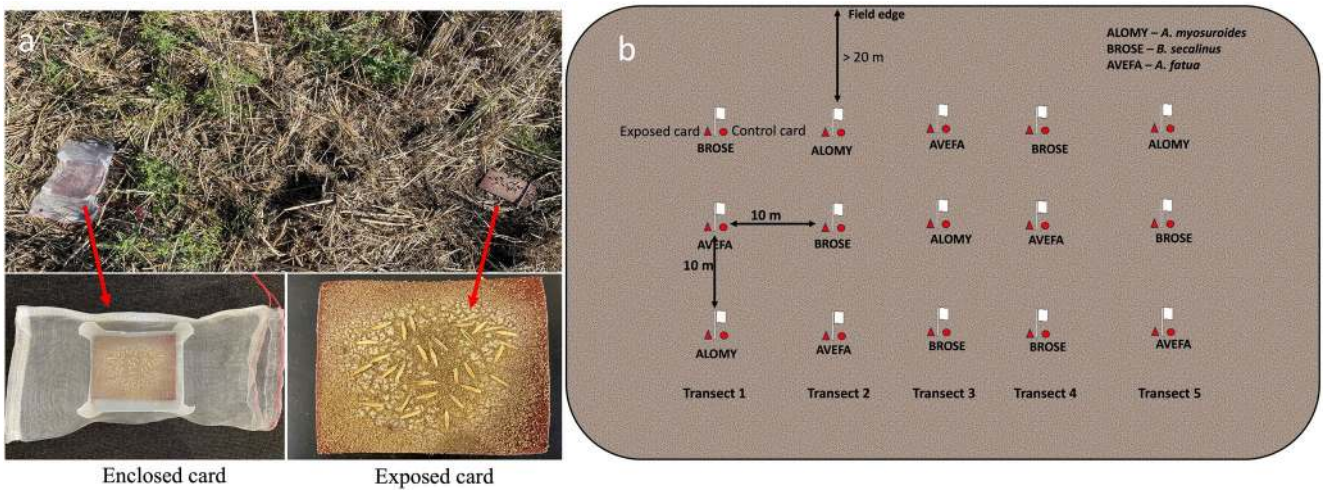


FIGURE 3 | Seed card placement (a) and field layout of the seed cards (b) during the predation assessment.

identity and activity density were not quantified, as the focus was on comparative seed removal across management systems.

Data were collected weekly over 5 weeks in each season by recording the number of remaining seeds from treatment and control cards. After each assessment, all cards were replaced weekly with new cards with fresh seeds to maintain consistent adhesive strength and ensure accurate results.

2.4 | Statistical Analysis

We analysed seed-loss counts with a binomial Bayesian generalised linear mixed-effects model (GLMM) using the '*brms*' package (Bürkner 2017). A GLMM was chosen because the response is a count of seed removed by predators (successes) out of the total seeds placed per card (trials), and observations are not independent: cards belong to replicates within field–season combinations, and fields can differ in their baseline removal and in how tillage/species effects manifest. The mixed-effects structure, therefore, models the binomial mean while partially pooling information across fields/replicates to avoid pseudoreplication and overfitting. Weakly informative priors were set to stabilise estimation while remaining conservative. Convergence and fit were assessed by *Rhat* ($\widehat{R}$), effective sample sizes, posterior predictive checks, Bayesian R^2 and visual checks. Posterior marginal means and contrasts were derived on the response scale and summarised as posterior means with 95% Bayesian credible intervals (CrIs). The model structure is shown below:

$$\begin{aligned} y_i &\sim \text{Binomial}\left(n_i, p_i\right) \\ \text{logit}\left(p_i\right) &= \alpha + X_i\beta + b_{0,\text{Field}[i]} + \text{Tillage}\, b_{1,\text{Field}[i]} \\ &\quad + \text{Species}\, b_{2,\text{Field}[i]} + b_{0,\text{Field}\times\text{Season}\times\text{Rep}[i]} \end{aligned} \tag{1}$$

where

$$\begin{aligned} b_{0,\text{Field}} &\sim \mathcal{N}\left(0, \sigma^2_{\text{field}}\right) \\ b_{1,\text{Field}} &\sim \mathcal{N}\left(0, \sigma^2_{\text{tillage}}\right) \\ b_{2,\text{Field}} &\sim \mathcal{N}\left(0, \sigma^2_{\text{species}}\right) \\ b_{0,\text{Field}\times\text{Season}\times\text{Rep}[i]} &\sim \mathcal{N}\left(0, \sigma^2_{\text{rep}}\right) \end{aligned}$$

Here, y_i is the number of seeds removed from card i out of n_i seeds. α is an intercept, $X_i\beta$ are the fixed effects for Species, Treatment (exposed vs. enclosed cards), Tillage, Season, Year and Week, and all two-way interactions. To capture unexplained heterogeneity, we include four random-effect terms: $b_{0,\text{Field}} \sim \mathcal{N}\left(0, \sigma^2_{\text{field}}\right)$, a field-specific random intercept; $b_{1,\text{Field}} \sim \mathcal{N}\left(0, \sigma^2_{\text{tillage}}\right)$, a random slope allowing the effect of Tillage to vary by field; $b_{2,\text{Field}} \sim \mathcal{N}\left(0, \sigma^2_{\text{species}}\right)$, a random slope allowing the effect of Species to vary by field; and $b_{0,\text{Field}\times\text{Season}\times\text{Rep}[i]} \sim \mathcal{N}\left(0, \sigma^2_{\text{rep}}\right)$, a random intercept for each unique combination of Field, Season and $\text{Rep}_{[i]}$ (replicate/seed card position), accounting for the nested structure of replicates within fields and seasons, capturing small-scale spatial variation. All analyses were performed in R v4.2.3 (R Core Team 2025).

3 | Results

3.1 | The Effects of Tillage System, Season and Species on Weed Seed Predation

Overall, mean weekly seed predation after 1 week exposure was consistently higher in no-till fields (79% in 2023/24; 76% in 2024/25) than in conventional-till fields (51% in 2023/24; 46% in 2024/25; Figure 3a), with no-till exceeding conventional by ~13–39 percentage points in 2023/24 and ~19–38 percentage points in 2024/25 (Conditioned on Field and Rep). This pattern held across all combinations of weed species and seasons (Figure 4a). The largest tillage differences occurred for *B. secalinus* during the summer of 2023/24 (~38.9 percentage points; 95% CrI: 19.3, 53.9) and the autumn of 2024/25 (~37.6 percentage points; 95% CrI: **19.6**, **52.0**).

A strong and repeatable seasonal pattern in predation rates was evident across both tillage systems and species (Figure 4b). Predation was consistently highest in spring, with means averaged across fields and replicates spanning ~62%–84% under conventional tillage and ~89%–94% under no-till in 1 week. Autumn means were ~20%–51% (conventional) and ~60%–82% (no-till), while summer was ~15%–65% (conventional) and ~46%–87%

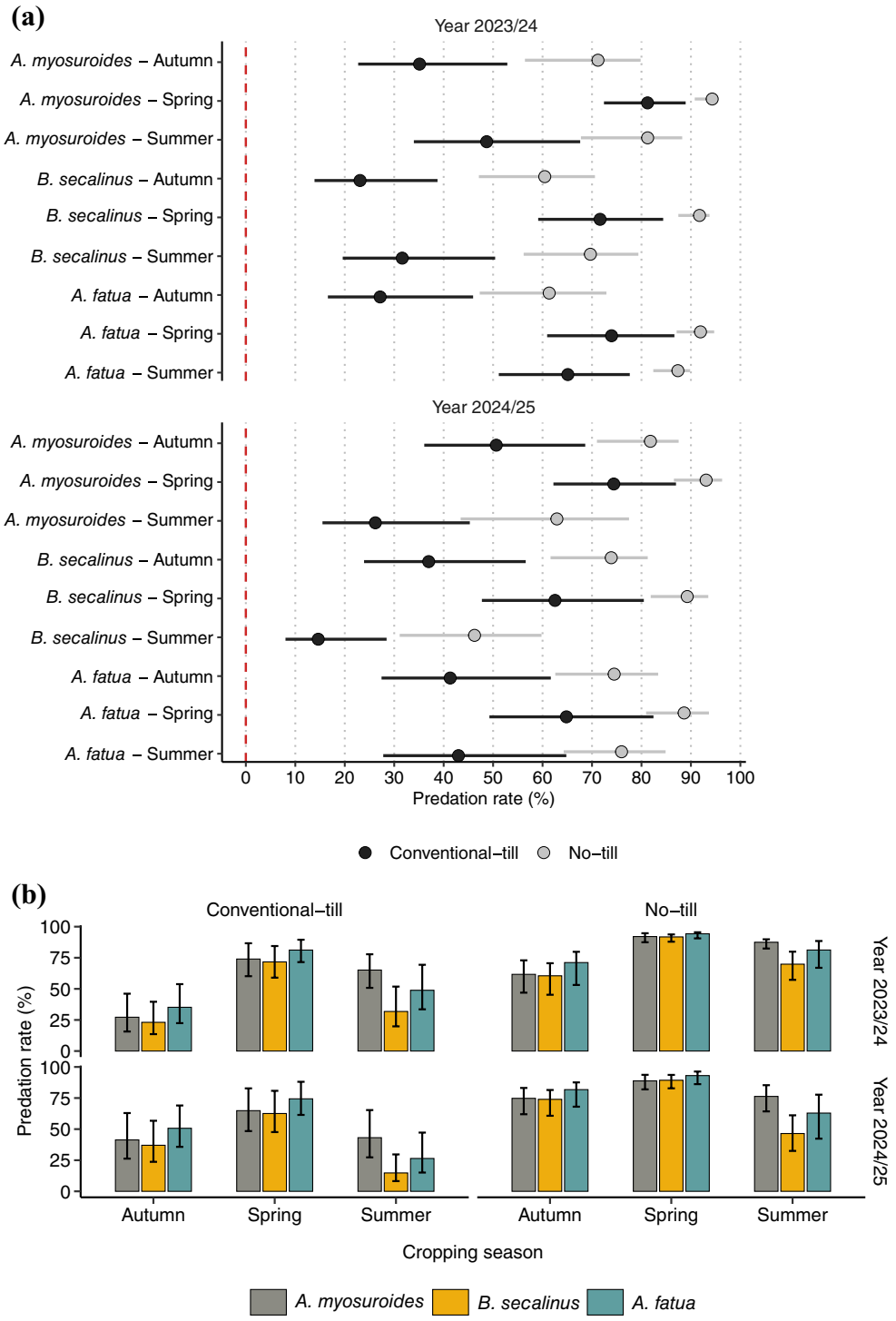


FIGURE 4 | Weed seed predation rates as influenced by tillage system, season and species. (a) shows predation rates for three weed species under no-till and conventional tillage systems, while (b) shows predation rates across three cropping seasons. Points represent posterior means, and horizontal (a) and vertical (b) lines indicate 95% credible intervals (CrIs). The vertical dashed red line in (a) marks 0% predation.

(no-till). Across tillage systems, seed removal ranged from ~62% to 95% in spring, ~20% to 82% in autumn and ~15% to 87% in summer per week. Spring consistently peaked, but the difference between summer and autumn varied by year; summer was higher in wetter 2023/24, whereas autumn was higher in drier 2024/25.

Although the tillage effect dominated, species also differed in predation rates (Figure 4b). *B. secalinus* was consistently lowest, whereas *A. fatua* and *A. myosuroides* were slightly higher and similar across tillage systems, seasons and years. Across all combinations of tillage, season, and year, *A. myosuroides* and *A. fatua* were predated about ~10–20 percentage points higher than *B. secalinus* (although these differences are consistently inside the 95% CrI; Figure 4b), while differences between *A. myosuroides* and *A. fatua* were minor and not consistent across years.

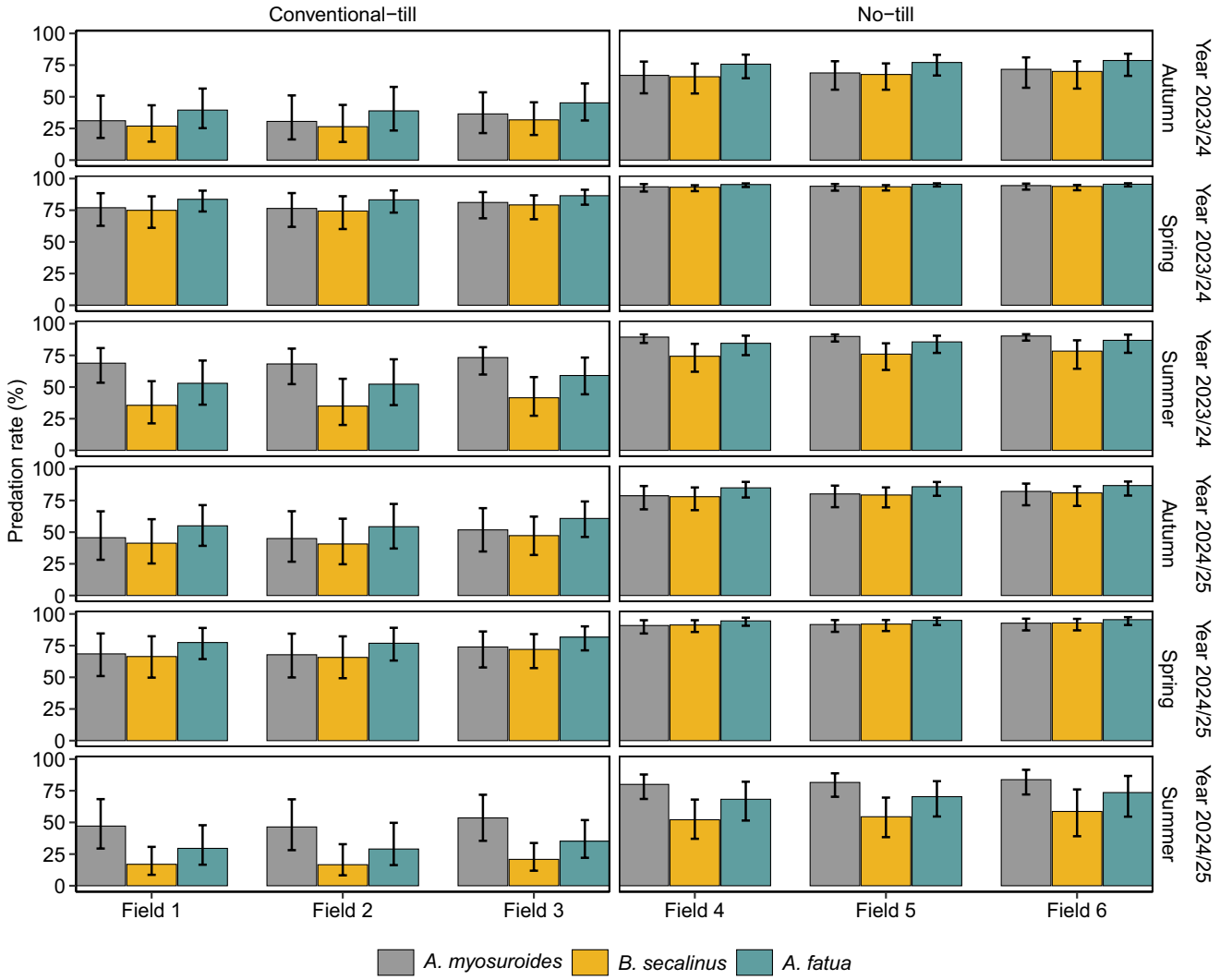


FIGURE 5 | Field-level weekly seed predation rates for *A. myosuroides*, *B. secalinus* and *A. fatua*. Bars show the posterior mean predation rate, and error bars represent the 95% CrI for each field.

Between-year variation was moderate. Predator-attributable seed removal was higher in wetter 2023/24 than in drier 2024/25 across all species and seasons (Figure 4b). The difference between years was about ~4–6 percentage points under conventional tillage and about ~3–5 percentage points under no-till. However, the relative magnitude of the no-till effect remained consistent between years, indicating a stable tillage effect over time. Tables S1–S3 show complete pairwise contrasts for season, species and year.

3.2 | Between-Field Predation Variation

Predation rates were highly consistent among fields within the same tillage system, demonstrating the robustness of the tillage effect across different locations (Figure 5). Fields under no-till management exhibited uniformly high predation rates with minimal variability, whereas conventional-till fields showed consistently lower rates. This pattern was maintained across all seasons, with the most pronounced differences occurring in spring and autumn. The limited variation observed during summer was attributable to differences between weed species rather than field location within a tillage system. In all season and year combinations, the predation rate in the lowest-performing no-till field was comparable to or greater than that in the highest-performing conventional-till field.

3.3 | Weekly Predation Rates and the Effectiveness of the Control Cards

Enclosed control cards (nylon-mesh caged) showed markedly lower to no seed removal than exposed cards across weeks and years, confirming that the observed removals on exposed cards were predominantly due to predators rather than other factors like rain, wind, or adhesive failure (Figure 6). Overall, the results show that seed removal rates were mostly stable across the 5-week assessment period in each season, though species, field, and seasonal differences persisted.

4 | Discussion

Predation rates varied strongly by species and season, ranging from 76% to 79% under no-till and 46% to 52% under conventional tillage. These results align with previous studies reporting

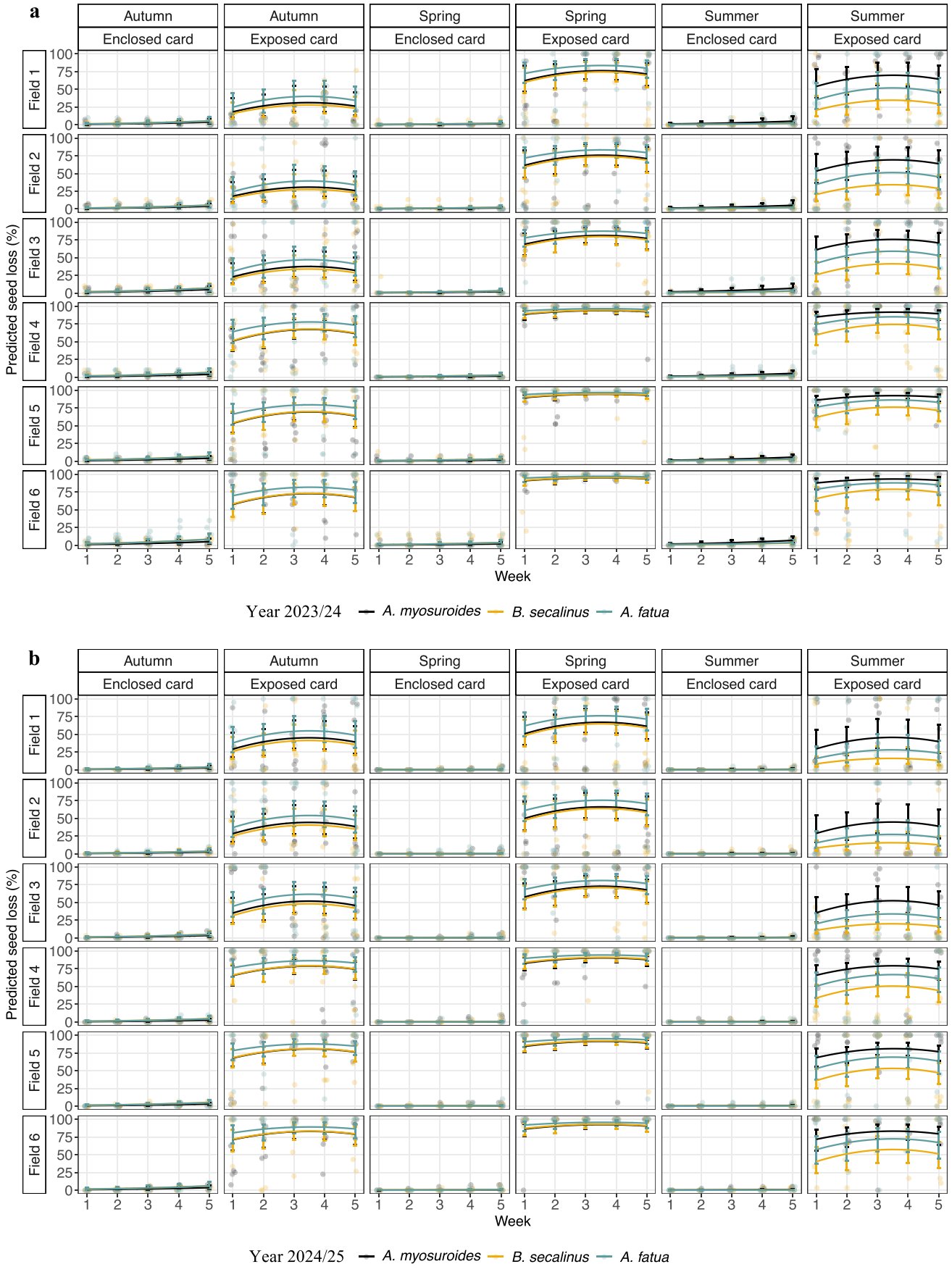


FIGURE 6 | Weekly trajectories of seed loss in (a) 2023/24 and (b) 2024/25 cropping years. Points represent the posterior mean seed loss for exposed and enclosed seed cards, while error bars show 95% CrIs. Jittered points show raw proportions (lost/total). Lines depict fitted smooths over weeks.

higher predation rates in no-till systems than in conventionally tilled fields, often attributed to greater predator activity and diversity resulting from improved habitat complexity (Cromar et al. 1999; Jacobsen et al. 2022). Building on previous work, the present study employed weekly seed card assessments across three species, three seasons and 2 years within each tillage system, allowing us to assess whether tillage effects on seed removal varied across weed species, seasons and years. Although spatial replication per treatment was limited, the intensive temporal sampling design provides complementary insight to studies that prioritise broader landscape-level replication. Reduced soil disturbance in no-till systems provides a more stable environment for seed predators such as ground beetles and small mammals (Clements et al. 1996; Daouti, Feit, and Jonsson 2022). No-till also ensures more seeds remain on the soil surface, exposed to predators, compared with conventional tillage, which buries seeds, limiting predator access (Kulkarni et al. 2015). The rates reported in this study are based on one-week seed exposures recorded for five consecutive weeks per season. However, because predation can accumulate with longer exposure times (Westerman, Wes, et al. 2003), the 1-week assessments used here likely reflect short-term removal rates rather than cumulative seasonal losses, although some studies report limited sensitivity of removal rates to exposure duration (Pannwitt et al. 2017).

Predation varied among weed species, suggesting that seed traits strongly mediate predator selectivity (Honek et al. 2003; Kulkarni et al. 2017). *Avena fatua* experienced the highest predation rates in spring, followed by *A. myosuroides*, which exhibited similar losses to *A. fatua* during summer, whereas *B. secalinus* consistently showed the lowest losses across all seasons and tillage systems. Differences in physical traits, nutritional content and palatability may influence predator selectivity (Borchert and Jain 1978; Jørgensen and Toft 1997; Tschumi et al. 2018a). The lower predation of *B. secalinus* seeds could be linked, in part, to a harder seed coat, which may deter some generalist predators (Schutte et al. 2008).

Seasonal variation in predation rates was evident: predation increased from autumn to spring, peaked in spring and then declined in summer. This is consistent with other studies reporting increased granivore activity during warmer months following winter when food demands are higher (Blubaugh and Kaplan 2016). In addition, this may be due to an increased energy demand and limited availability of alternative food sources. Importantly, the spring assessments were conducted before the main seed-shedding period of the studied species, indicating that the observed peak was unlikely to be driven by fresh seed rain but rather by predator activity dynamics and background resource availability. The decline in summer predation rates compared to spring may reflect multiple interacting mechanisms. Higher temperatures and lower humidity can reduce predator activity in some contexts (Saska et al. 2010). In addition, the increased availability of naturally shed weed seeds during summer may reduce the relative attractiveness of experimental seed cards, leading to lower proportional removal due to predator satiation (Heggenstaller et al. 2006; Honek et al. 2003). This observed seasonal dynamic, however, is characteristic of systems with minimal soil disturbance, where a large proportion of seeds remains exposed on the surface and accessible to granivorous predators, a stark contrast to conventional tillage, where seed burial significantly reduces such predation opportunities.

The observed trends highlight the potential contribution of reduced tillage systems to enhancing predator-mediated seed losses within broader sustainability-oriented approaches to weed management (Gallandt et al. 2018). Post-dispersal seed losses of 40%–63% have been shown to substantially influence population trajectories in some species and reduce the herbicide efficacy required to prevent population growth (Westerman et al. 2005). In that context, the levels of predation observed here, particularly under no-till, fall within a range that could meaningfully contribute to population regulation when integrated with other management strategies. The magnitude of this contribution will depend on factors such as predator diversity, landscape complexity and crop rotations (Jacobsen et al. 2022). Predation, therefore, represents a complementary process that can reduce overall seed return and potentially lower the intensity of chemical or mechanical control (Westerman et al. 2005). Integration with additional tactics, including herbicides, cover crops, timely cultivation and weed seed capture approaches such as harvest weed seed control and top-cutting (Kanomanyanga et al. 2026), is essential to achieve resilient integrated weed management.

Although identifying and quantifying the predators responsible for seed losses from the seed cards was beyond the scope of this study, seasonal differences in the relative contribution of vertebrate and invertebrate granivores to weed seed removal have been documented in arable systems. Invertebrate seed predators often contribute substantially to post-dispersal regulation following seed rain, whereas vertebrate granivores such as rodents can dominate predation services at other times of the season (Blubaugh and Kaplan 2016; Tschumi et al. 2018a). Such temporal variation in predator communities has been shown to influence both the magnitude and timing of weed seed losses (Bohan et al. 2011; Tschumi et al. 2018b). These variations can also be associated with other factors such as temperature, field management and crop type, which can influence predator populations and activity (Bohan et al. 2011; Kulkarni et al. 2017). Future research should build on approaches such as molecular gut content analysis, which have been used to identify predator-seed trophic interactions and quantify weed seed consumption by granivores in arable systems (Guenay-Greunke et al. 2024; Daouti et al. 2024), to further resolve how predator communities mediate seed losses under different management practices.

4.1 | Interpretation and Methodological Limitations

Seed card assays quantify the proportion of seeds removed from the soil surface under standardised exposure conditions and therefore represent potential predation pressure rather than realised impacts on the seedbank. Several processes occurring in fields are not captured by this approach, including the magnitude and timing of seed rain and natural densities, secondary dispersal, seed burial by machinery or rainfall and variation in the duration of seed accessibility to predators. Seed residence time on the surface may be influenced by rainfall or field operations (Baraibar et al. 2019; Peco et al. 2014), potentially reducing the window during which predation can occur. Moreover, predation occurs predominantly after seed shedding from late summer to autumn, when its demographic influence is expected

to be greatest, because predation that coincides with peak seed availability has been shown to play a disproportionate role in regulating population growth in annual grass weeds (Daouti, Jonsson, et al. 2022). The seasonal patterns reported here, therefore, reflect differences in predator activity under standardised exposure conditions rather than actual variation in the residence time of naturally shed seeds. We also lack information on how natural background seed availability may alter predator responses to experimental seeds and, consequently, estimated removal rates.

High proportional losses measured with seed cards can still occur alongside persistent weed populations if total seed production is large or if only a fraction of the shed seeds is accessible to predators. Translating short-term removal rates into population-level outcomes, therefore, requires integration with demographic information such as seed production, dispersal pathways, burial dynamics and seed survival. Such data were beyond the scope of this study, which instead aimed to provide a comparison of relative predation intensity across contrasting tillage systems and seasons.

Despite these constraints, seed card approaches remain valuable because they allow standardised, repeatable comparisons of predator activity in working agricultural landscapes. Multi-season datasets of this type remain limited for intensively managed UK arable systems, and they help identify when and where predation pressure is most likely to contribute to integrated weed management.

5 | Conclusions

Our results show that across the assessed six fields, rates of seed removal by predators were consistently higher under no-till than under conventional tillage, and this difference remained robust across species, seasons and years. Averaged across factors, weekly seed removals ranged from ~76% to 79% in no-till compared to ~46% to 52% in conventional fields. Spring recorded the highest predation rates, whereas the difference between summer and autumn was year-dependent. Species differences were moderate, with *B. secalinus* consistently showing the lowest seed losses, while *A. fatua* and *A. myosuroides* were higher than *B. secalinus* and varied by season. Between-year variation did not change the direction or magnitude of the tillage contrast. These findings demonstrate that reduced soil disturbance was associated with consistently greater predator-mediated seed loss at the soil surface in arable systems that are widely used in the United Kingdom. While we did not directly measure seedbank dynamics, the magnitude of seed removal observed suggests that predation may contribute to reducing seed return, particularly when integrated with other management practices. Coupling no-till with practices that maintain predator habitat, such as crop residue retention, cover crops and diverse rotations, may enhance the reliability of predator-mediated seed removal within integrated weed management systems.

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Conflicts of Interest

J.K. was funded by Syngenta, Jealott's Hill International Research Centre, UK, and supported through research facilities provided by Niab, Cambridge, United Kingdom. C.L. is employed by Syngenta, Jealott's Hill International Research Centre, UK. Other authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Nighttime and daytime captured pictures of a rabbit (a) and a carabid beetle feeding on weed seeds. **Table S1:** Pairwise seasonal contrasts in predation rates across species, tillage and year, expressed as posterior mean percentage differences with 95% credible intervals (CrIs). Values are absolute differences in percentage points between seasons. Positive estimates indicate higher predation in the first season listed. Significant = Yes, credible interval excludes 0 (evidence of a significant difference); Significant = No, credible interval overlaps 0 (no significant difference). **Table S2:** Pairwise species contrasts in predation rates across tillage, season and year, expressed as posterior mean percentage differences with 95% CrIs. Values are absolute differences in percentage points between seasons. Positive estimates indicate higher predation in the first species listed. Significant = Yes, credible interval excludes 0 (evidence of a significant difference); Significant = No, credible interval overlaps 0 (no significant difference). **Table S3:** Pairwise year contrasts in predation rates across species, tillage and season, expressed as posterior mean percentage differences with 95% CrIs. Values are absolute differences in percentage points between seasons. Positive estimates indicate higher predation in the first species listed.