Effect of litter decomposition on mowing and plant composition change during *Solidago* stand restoration

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Abstract. Decomposition of organic matter supports important soil ecosystem services. The rate of decomposition depends mostly on the type of plant material being decomposed and the abundance and diversity of organisms that process the organic matter. Consequently, any disturbance to the soil ecosystem will affect the decomposition process. Invasive plants, such as *Solidago* species, pose a serious ecological threat to natural habitats, so effective and environmentally safe methods of controlling their occurrence should be developed. In this study, decomposition rates were used as indicators of soil health during grassland restoration after *Solidago* invasion. Different seed mixtures (grasses, grasses with legumes, seeds collected from a seminatural meadow; use of fresh hay and no seeds) were sown during a field experiment and different mowing frequencies (1, 2 and 3 times per year) were established. Two hypotheses were tested: (1) plant species composition used in the restoration process affects litter decomposition rates, and (2) mowing regimes affect litter decomposition rates. It was found that decomposition rates were higher in plots with the highest species diversity. This indicates that an increase in species diversity has a positive effect on soil processes. Secondly, mowing two and three times per season has a positive effect on the decomposition process. In conclusion, decomposition rates can be used as a tool to identify adequate grassland management.

Keywords: Decomposition rates, goldenrod, ecosystem services, plant invasion, grassland, ecosystem restoration.

1. Introduction

Material characteristics and the environment have a significant impact on the rate of decomposition of organic matter; thus natural ecosystems typically incorporate litter decomposition as a component of the natural cycle (Helsen et al., 2018; Hu et al., 2022a; Pereira et al., 2021). The decomposition rate is typically not substantially affected by species richness (Hu et al., 2022a), but is based on variations in the chemical and functional properties, such as specifically carbon (C), nitrogen (N) and the C: N ratio (Hu et al., 2022a). Furthermore, the rate of decomposition of organic matter and microbial activity is also mediated by the concentrations of nutrients and structural and secondary compounds between the types of litter types (Madureira & Ferreira, 2022). The depth of the soil at which the litter is deposited can also have a substantial impact on the consequences of litter decomposition from an invasive plant on native species and soils (Sun et al., 2022b). However, an exception is cases of severe droughts, where increasing species richness has been shown to slow the rate of litter decomposition (Wang et al., 2022).

Regardless of species diversity, nitrogen-dependent litter decomposition is always present in plant communities (Pereira et al., 2021; Wang et al., 2022). Some species have faster decomposition rates and nutrient release than others. (for example, *Leucaena leucocephala* and *Pithecellobium dulce* showed relatively faster decomposition rates than *Prosopis juliflora*) (Pandey et al., 2022). In the context of Central Europe, the oak-hornbeam forest community saw the fastest rate of decomposition, whereas the drying riparian forest had the slowest rate (Kawałko et al., 2017). Moreover, Pure Scots pine stands showed the slowest rate of decay, whereas mixed and artificially modified pine stands showed notably quicker rates (Breymeyer & Laskowski, 1999). Furthermore, the interaction of species competition and litter type and amount, have a weak relationship, with litter mostly affecting seedling emergence (Loydi et al., 2015). Furthermore, highly positive correlations have been found between soil temperature, soil water content, and litter quality (i.e. litter C, N, phosphorus (P), C: N ratios, and lignin) and the rate of litter decomposition rate (Gong et al., 2015). The decomposition is mainly processed by microbes and invertebrates (Chen et al., 2022b). Regardless of the type of land exploited, elevated temperatures and reduced precipitation patterns constantly slow the decomposition of litter through microbial and faunal impacts (Yin et al., 2019).

The process of invasion of plants, from establishment to landscape spread, influences ecological properties such as stand structure, soil nutrient status, biogeochemical cycling, and hydrogeomorphological processes (Rai, 2022). Therefore, the material cycle of an ecosystem has been impacted by invasive plants (Hu et al., 2022a). Invasive plants decompose more quickly than native species and have different effects on the decomposition process (e.g., invasive *Alternanthera philoxeroides*, *Broussonetia papyrifera* and *Celastrus orbiculatus* accelerate the decomposition, and noninvasive *Bidens pilosa* and *Morus alba* not) (Hu et al., 2022a; Leicht-Young et al., 2009; Maan et al., 2022). However, according to research by Incerti et al. (2018), invasive species' litter decomposes at the same pace as native species' litter but releases more nitrogen into the environment. In a pot experiment conducted in China, a positive plant-soil feedback for soil nutrients and a negative plant-soil feedback for growth in native *Sphagneticola calendulacea* resulted from the breakdown of litter from the invasive *Sphagneticola trilobata* (Sun et al., 2022b). However, invasive grass litter has been shown to stunt development and increase disease in native species (LaForgia, 2021; Benitez et al., 2022). Through interactions between microbial and microfauna, invasive plants can accelerate the degradation of organic P (Sun et al., 2022a). In a study by Chen et al. (2022a), invasive *Alternanthera philoxeroides* showed higher invertebrate richness and abundance, microalgae abundance and microbial respiration in a shallow eutrophic lake.

Solidago invasions result in functional and structural changes in grassland plant communities, which are exacerbated by human disturbances. The two invasive species of North American provenance that are found in Central Europe most frequently are *Solidago gigantea* Aiton (Giant goldenrod) and *Solidago canadensis* L. (Canadian goldenrod) (Tokarska-Guzik et al., 2014; Lukash et al., 2021; Meyer 2022; Popay & Parker, 2022). *S. canadensis* may decrease soil respiration, which affects soil carbon cycling through substrates emitted by plants, as well as by competing with native plants and soil microorganisms for the available substrate (Hu et al., 2022b; Xu et al., 2022). *S. canadensis* invasion has been shown to reduce soil organic carbon, total nitrogen, and cation exchange capacity (Xie et al., 2022). Dekanová et al. (2021). Furthermore, Ye et al. (2019) found that *S. canadensis* decomposed faster than *Alnus glutinosa, Phragmites australis*, *Typha angustifolia*, *Phacelurus latifolius*, *Imperata cylindrica* and *Fallopia japonica*. Furthermore, the invasive *S. canadensis* produced larger amounts of litter that decomposed more rapidly compared to the annual graminoid, *Eragrostis pilosa* (Zhang et al., 2016). However, Yu et al. (2022) and Zhong et al. (2022) observed that compared to *Bidens pilosa*, the litter of *S. canadensis* has a lower decomposition rate. The litter decomposition rate is not affected by drought (Yu et al., 2022).

There is a complex correlation between soil health (physicochemical and biological parameters) and plant characteristics, which has important implications for ecosystem restoration (Helsen et al., 2018; Rai, 2022). Furthermore, mowing and raking have been shown to significantly reduce litter accumulation (Huhta et al., 2001). Therefore, when planning management or restoration in locations where plant invasions have occurred, litter decomposition should be considered. Due to the great importance of European grasslands, mechanisms and processes mediated by litter should be taken into account in scenarios of future global change, as well as in the degradation and restoration (Loydi et al., 2015). Therefore, in the present study, of *Solidago* stand restoration methods, we hypothesised that (1) the compositions of plant species used in the reclamation process affect the rate of litter decomposition rate, and (2) the mowing regimes influence litter decomposition.

2. Material and Methods

2.1. Field experiment design for *Solidago* invaded land restoration

The experiment was carried out on former abandoned agricultural land dominated by invasive species North American *Solidago* spp. (*S. gigantea* and *S. canadensis*) in Wrocław, Poland (51°09′42.57″N, 17°06′43.97″E; elevation 116.4 m). The field experiment was established in April 2020 in a 5 × 3 factorial arrangement in a completely randomized design with four replications. The experiment field was cleaned of vegetation and the soil was rototilated before seed introduction. The methods used to control the invasion of *Solidago* species were: 1) application of five types of seed mixtures and 2) three frequency of mowing (Table 1). The seeds were introduced once in 2020, while mowing was repeated each year (Table 1). Two experimental factors were drawn according to a complete randomized block design with 15 treatments in total. Each plot was 2.5 × 2.5 m (See Perera et al. (2022) for further information on the experiment and seed mixtures).

Table 1: Description of treatments. Seed mixtures composition and mowing were used to control the *Solidago* invasion. The number of plant species that were introduced as seed mixtures in 2020 and the average number of species observed in 2022 are shown. (See Perera et al. (2022) for further information on the experiment and seed mixtures).

Factor 1: Seed mixtures	Abbreviation	Number of species in the	Average number	Average *Solidago*

		seed mixture composition in 2020	of plant species in 2022	coverage in 2022 (%)
Grasses	G	04	17	12
Grasses with legumes	L	06	12	6
Seeds collected from the seminatural meadow	M	37	28	17
Application of fresh hay from seminatural meadow	F	47	22	28
Without seed (only Solidago)	C	00	24	38
Factor 2: Frequencies of mowing				
Once	X			
Two	Y			
Three	Z			

2.3. Litterbag experiment

Decomposition rates were estimated using the litterbag method (Seastedt, 1984). Two types of litterbags were prepared. The coarse mesh litterbags were prepared using fibreglass mesh LUX 165 160g/m^2 10 mb PROXIM (15 × 20 cm, aperture 5 mm) to allow free microbes and small soil animals and fine mesh nylon litterbags of nylon (15 × 20 cm, aperture 0.02 mm) to allow free microbes. The hay was collected from semi-natural grasslands in Wrocław, Poland, Central Europe (51°9'41.5"N, 17°6'41.5"E). Before the experiment, the hay was air dried and chopped into small pieces (approximately 10 cm). Each decomposition bag was filled with a total of 12 g of chopped hay; 60 litterbags of each type.

The litter bags were placed in three terms: June 2021 (summer), August 2021 (autumn), and April 2022 (spring). All litter bags were covered with topsoil and kept in the field for two months each time. After removal of the litterbags in two months, soil particles, roots, and other nontarget plant material adhering to the remaining litter were removed. The cleaned litter residues were dried at 70°C for three days to achieve a constant weight. Finally, the weight of the remaining litter was recorded to quantify the decomposition rates and compare the drivers of soil microbial versus invertebrate-mediated decomposition.

The decomposition rates (K_t) were calculated according to the formula:

$$K_t = ln\ ln\ \frac{x_0}{x_t} \quad ,$$

where X_0 – initial weight, X_t – weight decreases after time *t*, *t* - incubation time (days) (Seastedt, 1984).

2.4. Statistical analysis

The decomposition rates (k) were calculated for each plot. The data was normalised using the Shapiro-Wilk test, which confirmed normality. The decomposition rates were compared between treatments using a mixed model. In the model, the explanatory variables listed in Table 1 were used, as well as their interaction effects (seed × mowing; seed × season; mowing × season). Additionally, the block effect was used as a random effect. Differences between treatments were further compared using the Tukey test. The analyses were conducted in SAS University Edition Software.

3. Results

Seed source, mowing, season, and the interaction effects of seed source and season significantly affect decomposition rates. In addition, there is a significant difference between the decomposition rates measured in two mesh sizes (Table 2).

Table 2. The summary table of statistics on mixed models in comparison of the fine-meshed and coarse-meshed between experimental factors. Statistically significant results at $p \leq 0.05$ are in bold. The variables are explained in Table 1. DF = degree of freedom.

Effect	Fine-meshed litterbags			Coarse-meshed litterbags		
	DF	F	p	DF	F	p
Seed	4	8.52	**<0.0001**	4	4.73	**0.002**
Mowing	2	6.86	**0.001**	2	2.87	**0.03**
Seed × mowing	8	0.70	0.7	8	0.51	0.8
Season	2	19.96	**<0.0001**	2	8.14	**0.0006**
Mowing × season	4	0.62	0.7	4	0.92	0.4
Seed × season	8	4.33	**0.0001**	8	2,10	**0.04**
Mesh size	DF = 1, F = 43.18, p = <**0.0001**					

The decomposition rates were higher in coarse-meshed litterbags compared to fine-meshed (Fig 1).

Fine-meshed litterbags: The decomposition rate was significantly higher in summer compared to spring and autumn (Fig. 1). Seed significantly affected decomposition rates, showing the highest decomposition rates in plots covered with semi-natural meadow (M). This trend was confirmed by the seasonal analysis: in summer and spring, the rate of decomposition increased in the seminatural meadow (M), and in autumn, there were no differences between treatments. Additionally, mowing frequency changed the decomposition rates. Moderate mowing frequency (2 times a year) positively affected the decomposition process; however, it does not differ significantly from mowing 3 times a year.

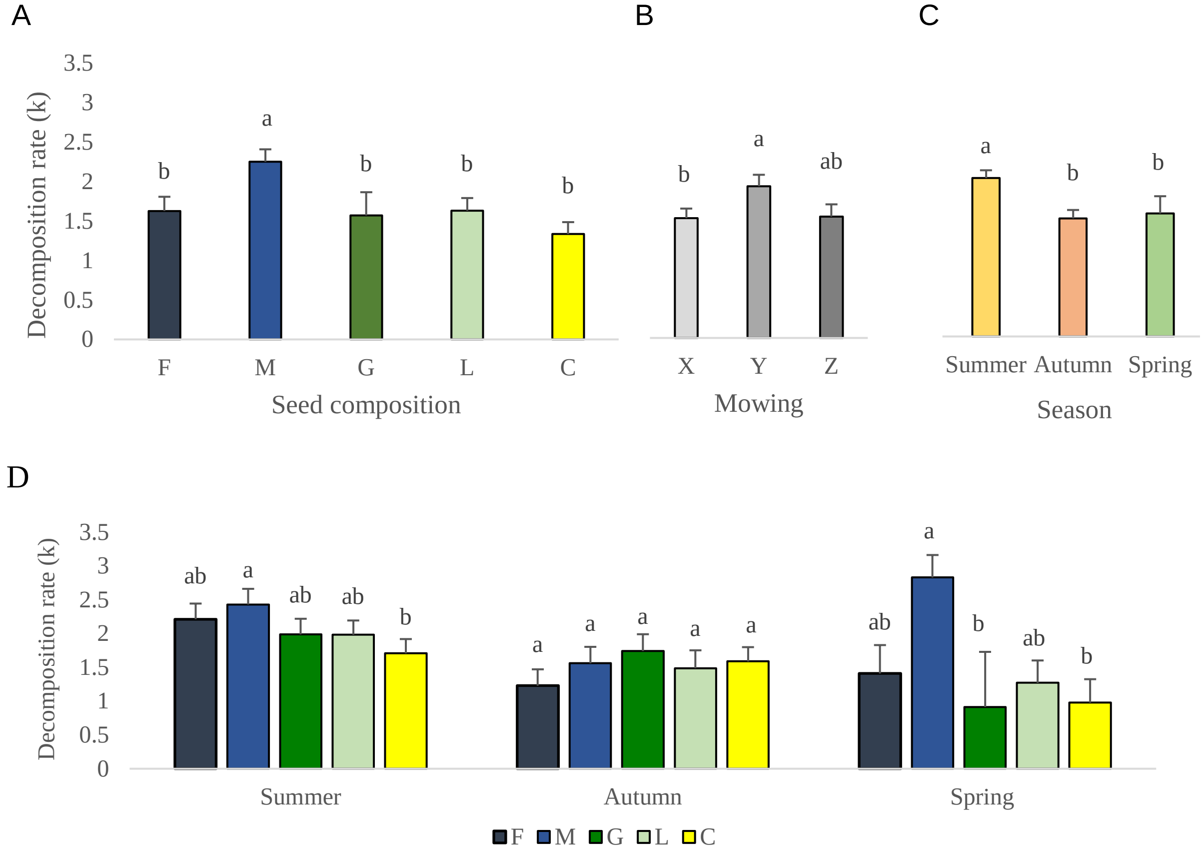

Figure 1. Decomposition rates in the fine-meshed litterbags in 5 variants of seed composition (A), 3 variants of mowing (B), 3 seasons (C) and interactive effects of seed mixture and season (D).

Coarse-meshed litterbags: Similarly, for fine-meshed litterbags, the decomposition rate increased in summer compared to other seasons (Fig. 2). Furthermore, the increased plant diversity introduced by the seminatural meadow seeds (M) positively affected decomposition, specifically in summer and spring. Additionally, mowing twice was more effective than mowing once a year.

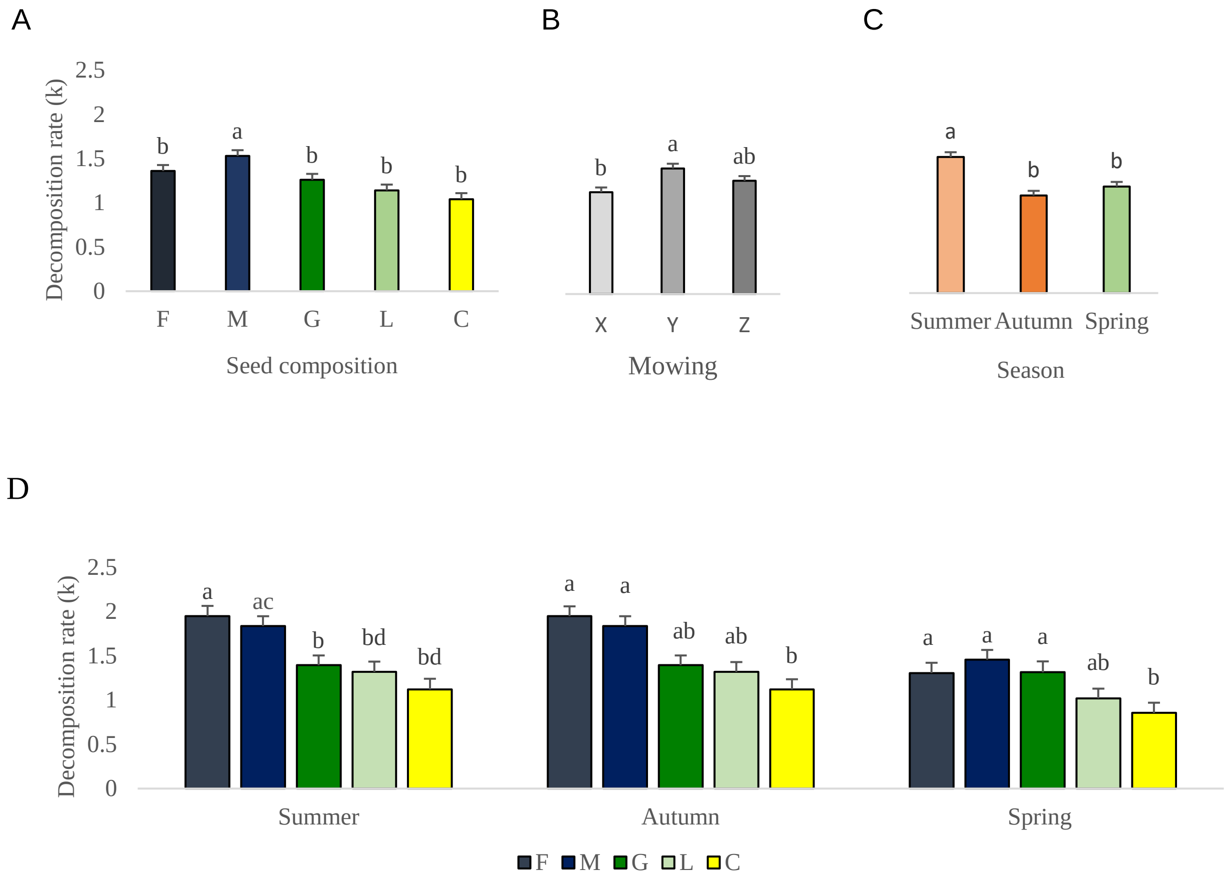

Figure 2. Decomposition rates determined in the coarse-meshed litterbags in 5 variants of seed introduction method (A), 3 variants of mowing (B), 3 seasons (C) and interactive effects of seed and season (D).

4. Discussion

Litter decomposition allows the release of nutrients from organic materials for plant growth. It is also crucial for soil functioning. Because the litter decomposition process depends directly and indirectly on many environmental, biological, and anthropogenic factors, it can be used as an indicator of soil health (Fugère et al., 2020; Bärlocher et al., 2020; Wang et al. 2020a,b). Organisms such as microbes and soil invertebrates lead to decomposition, so population variations will change this process (Chen et al., 2022b). In coarse mesh bags, decomposition is the result of three main processes such as microbial breakdown, macroinvertebrate consumption, and physical abrasion, in which microbial breakdown accounts for the majority of decomposition in fine mesh bags (Fugère et al., 2020; Bärlocher et al., 2020). Decomposition rates increased as the size increased in litterbags (Chen et al., 2022b). This was similar to the case when comparing coarse to fine mesh litter bags; decomposition rates were higher in coarse mesh litter bags in our experiment.

A global biodiversity meta-analysis by Mori et al. (2020) has shown that increasing plant diversity positively affects the decomposition process. In the current study, a higher cover of *Solidago* species resulted in a lower rate of decomposition in the three seasons studied. Before litter decomposition, *S. canadensis* litter exhibited a stronger allelopathic effect than native litter on lettuce (*Lactuca sativa*) (He et al., 2022). Our previous study on the response of native grassland species to allelopathic species revealed that leaves and flowers of *Solidago* species have stronger inhibition effects than stems, roots, and rhizomes (Perera et al., 2023). Therefore, Solidago allelopathy will alter the neighbouring species which may change the decomposition of litter. It was also found that the decomposition rates were greater in plots with higher plant diversity.

Furthermore, according to our previous study on the impact of soil invertebrates, conducted in the same experimental field, it was observed that the season is significant concerning the abundance and number of taxa present (Perera et al., 2022). However, Ustinova et al. (2022) found that *S. gigantea* does not favour any particular arthropod species over others for litter decomposition of the litter and does not accelerate decomposition. However, several microbiological characteristics of soil can be influenced by *S. gigantea* as well as *S. canadensis* (Bobulská et al., 2019; Li, Zhang & Peng, 2012). Potthoff et al. (2006) concluded that although microbial communities can withstand the process of grassland restoration process, they do not reflect the change in the composition of plant species that followed the introduction of native grasses. During the management of grasslands, lower soil layers' microbial populations were barely impacted, except for fungal organisms associated with plants and litter (Potthoff et al., 2006). Furthermore, the basal respiration rate and arbuscular mycorrhizal fungi in root colonisation were higher in the soil in meadows (Chmolowska et al., 2017). Furthermore, the land restoration in our experiment was environmentally friendly, did not disturb the soil after seed establishment, and did not use any herbicides.

In steppe-like grasslands, the removal of dead and even living biomass, combined with vegetation cutting such as mowing or grazing, increased seedling survival, and excellent nature conservation (Ruprecht et al., 2010). Furthermore, lawn maintenance and litter removal had positive effects on the number of germinated seeds in *Silene flos-cuculi* and *Lotus pedunculatus* (Rasran et al.,, 2007). According to Li et al. (2021), the effects of removal of the aboveground litter of both *Phragmites australis* and *Spartina alterniflora* on nitrification and denitrification are species-specific. During the mowing treatment, above-ground biomass was removed in our experiment and therefore may have helped the emergence of late-emerging species, affecting the species composition. Furthermore, variations in soil moisture during mowing likely affected litter decomposition, as has been shown to occur in grasslands (Wang et al., 2020b).

5. Conclusions

In this experiment, two methods were used to control the invasion of the *Solidago* spp. The decomposition rates were used as an indicator of soil health after differentiated mowing frequency and the introduction of five variants of seed composition. After a 30-day incubation of litterbags in three seasons, it was found that higher plant biodiversity promotes the decomposition process in the grassland ecosystem. The mowing regimes change the litter decomposition. Furthermore, two and three mowings per year increase the decomposition rate. It was also found that mowing and the introduction of seeds to suppress the invasion of *Solidago* spp. is beneficial for the soil ecosystem.

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Author contributions

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Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

Data supporting the findings of this study are available from the corresponding author on request.

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