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Abstract

Conservation status of hay meadows highly depends on their management. The main goal of this study was to assess the efficiency of different mowing regimes in maintenance of plant species richness and diversity of mesic hay meadows. The field experiment was carried out on a species rich, mesic hay meadow in Western Hungary. We evaluated the effects of four alternative types of management on the plant community after 7 years of continuous treatment: (1) mowing twice a year, typical traditional management, (2) mowing once a year in May, most practised currently by local farmers, (3) mowing once a year in September, often proposed for conservation management and (4) abandonment of mowing. Both cutting frequency and timing had significant effects on species richness and diversity of vegetation. Traditional mowing resulted in significantly higher number and higher diversity of vascular plant species than other mowing regimes. Mowing twice a year was the only efficient way to control the spread of the invasive *Solidago gigantea,* and mowing in September was more successful in it than mowing in May. We conclude that the traditional mowing regime is the most suitable to maintain botanical diversity of mesic hay meadows, however other regimes should also be considered if certain priority species are targeted by conservation.

Keywords: *plant species richness, plant diversity, meadow management, plant invasion,* Solidago gigantea*, temperate mesic grasslands*

Introduction

Although the majority of recent mesic hay meadows have been formed by human deforestation and classified as semi-natural habitats, they harbour an outstanding diversity of plant and animal species (Veen et al. 2009; Hejcman et al. 2013). The maintenance of biodiversity in these secondary grasslands depends on their appropriate management and thus holds a high interest in conservation planning. In a global assessment, Uchida and Ushimaru (2014) demonstrated that highest plant and herbivore species richness can be reached by mowing twice per year, defined as intermediate mowing frequency by them. Other studies, however, could not reveal distinctive effect of timing and frequency of mowing on species richness (Oomes & Mooi 1981; Ilmarinen & Mikola 2009). Moreover, in a large variety of grasslands located in three regions of Germany, Socher et al. (2012) found a higher species richness in case of mowing once per year, than in case of mowing twice. Although it is known that European mesic hay meadows are seriously threatened by invasion of *Solidago gigantea* (Weber & Jacobs 2005) and regular mowing may be able to largely reduce its stands, only a little experimental evidence is available on this process.

Due to the contradictory results of previous empirical studies, in spite of the long history of studies on meadow management for conservation, it is still not entirely clear how intensive mowing is necessary for maintaining the high species richness and diversity of Central European mesic hay meadows. To reveal consequences of different mowing regimes on the vegetation of mesic hay meadows, we set up a field experiment in the region of Őrség National Park (Western Hungary). We have chosen alternative management regimes that are either widely used and feasible, or are recommended by conservationists.

The first alternative to be tested was traditional management. As we know from previous studies (Vörös 1986) and recent personal interviews with old farmers (Babai et al. 2015), in the area of Őrség National Park mesic hay meadows had been mown two times per year for centuries, first in May-June and then in August-September.

In the last few decades, mowing once a year became general in our study region (Hahn et al. 2012). Farmers typically manage a large number of widely scattered areas, therefore mowing twice a year is not always technically feasible or simply not profitable. Mowing twice a year is not encouraged by agri-environmental schemes either, since subsidies are already available for cutting once a year (Babai et al. 2015). As animal husbandry has dramatically declined since the 1980's, there is a surplus of hay meadows and there is no need for more intensive mowing. Since farmers optimise for the highest ratio of yield and effort, they most often choose mowing in early summer. Therefore, the second management scheme tested in our study was mowing once a year in May-June.

The third management alternative to be tested was mowing once a year in August-September. This way of grassland management is justified by the habitat requirements of numerous endangered animal species. Several previous studies have shown that some rare species would benefit from delayed first cut or only one late cut (Wakeham-Dawson & Smith 2000; Green 2002; Buri et al. 2013; Kőrösi et al. 2014). Hence, local nature conservation regulations often allow only one mowing per year late in the season.

The fourth management type was abandonment, which is a frequently observed phenomenon in Hungarian and other European farmlands. Although lack of management obviously leads to spontaneous afforestation of secondary grasslands in the long turn, it may have positive consequences in the short term, especially for certain invertebrates (e.g. Fenner & Palmer 1998; Cattin et al. 2003).

From former experimental studies, rich knowledge is available about the effect of timing and frequency of mowing on restored grasslands that were fertilized or grazed before the experiment (Oomes & Mooi 1981; Bobbink & Willems 1993; Poptcheva et al. 2009). However, there is a lack of practical knowledge regarding optimal mowing strategies to maintain plant diversity of species rich meadows within real environmental and socio-economic conditions. Accordingly, the research goals of this study were (1) to evaluate effects of different mowing regimes on plant species richness and diversity of mesic hay meadows in a medium term (7 years), (2) to determine correlations between invasive *S. gigantea*, management and species richness and (3) to provide practical recommendations for nature conservation.

Materials and methods

Study site

The study site was a mesic hay meadow located next to the Slovenian-Hungarian border, in Őrség National Park, in the valley of Szentgyörgyvölgyi stream (N46.46°, E16.19°) (Figure 1). The vegetation of the area can be identified as an *Alopecuro-Arrhenatheretum* (Máthé & Kovács 1960) Soó 1971 grassland, which community (syntaxon) corresponds to Natura 2000 habitat type 6510 "Lowland hay meadows" (European Commission 2013). Soil conditions can be characterised with rich alluvial sediments and slightly acidic pH (between pH H_2O 5.3 and 5.8), and the groundwater table is usually close to the soil surface. The average annual temperature is 9.5 °C, and the average annual precipitation is about 800 mm (Dövényi 2010). The mean elevation is 210 m, but the surface gently slopes towards the stream with a nearly flat section in the middle. Parallel to the stream, there is no perceptible difference in elevation. The stream bordered by a 5 m wide and 15 m high alder grove flows approx. 10 m far from the experimental site. On the opposite, northern side, a dirt road can be found in a similar distance. The northern part of the study site is waterlogged for several months during the spring and autumn period, contrary to the southern, 20 m wide belt, where the 1.5 m deep running stream has an intense water suction effect. The specific heterogeneity in environmental conditions allows us to study the effect of various types of timing and intensity of mowing in more stressed (drier and shady) and more balanced conditions as well.

Before 1990s, the study site was usually mown twice per year by local farmers and no chemicals or overseeding were applied. Until the 1960s the second aftergrass was even grazed. From the late

1990s a single mowing was carried out in June or July. Since 2002 the management of the area has been carried out by the Őrség National Park Directorate, using tractor driven RK-165 type drum mowers. Due to the unified management history and topographical conditions, the original vegetation of the area was quite similar before the onset of the experimental treatment in 2007. The initial similarity of vegetation was also shown by former studies (Kőrösi et al. 2014; Szépligeti et al. 2015) carried out on this study site.

Experimental design and data collection

The study site was divided into four adjacent 20 m × 80 m stripes, each assigned to one of the following management types (going from east to west): mowing once a year in May (henceforward May-mown), mowing once a year in September (September-mown), mowing twice a year in both May and September (twice-mown), and abandonment. Every treatment stripe was further split into four 20 m × 20 m plots (Figure 1). This experimental design was motivated by two main considerations: (1) the current mowing practice is normally implemented by large tractors, which need place to turn around and are not able to manage smaller patches (e.g. in a Latin square design); (2) treatment stripes placed perpendicular to the stream bordering our study site made it possible to control for the potential confounding effect of environmental stress factors suspected near the stream.

For botanical survey, we placed 10 pieces of 2 m × 2 m sampling quadrats in all plots (n = 160 quadrats) randomly. In each quadrat, we recorded (visually estimated) cover of every vascular plant species, with an accuracy of 1 percent. Below 1 percent, we used decimal precision. In all samples, we also measured mean height of *S. gigantea* with an accuracy of 1 cm. All data were collected by the same person in the second half of May 2014, before the first cut.

Statistical analyses

We aimed to test the effects of different types of management on plant species richness, plant diversity and *S. gigantea* coverage. In models of plant species richness, management and *S. gigantea* cover were both included as explanatory variables. We also calculated Pearsons's correlation coefficients between mean height and coverage of *S.gigantea*, species richness and Shannon diversity index.

Since environmental stress factors can seriously modify features of equally treated vegetation (Moeslund et al. 2013), we intended to control for them. Assuming the water suction effect of the Szentgyörgyvölgyi stream and the modifying effect of shading of alder grove, we used the distances of sampling quadrats from the stream as a proxy of environmental stress. This approach was justified by the fact that the proportion of drought-tolerant plant species (Borhidi 1995) was noticeably higher near the stream (Appendix 1). We used generalized linear models (GLM) with appropriate error distributions (Poisson distribution for species richness and normal distribution for species diversity) or general additive models (GAM). First, a full model was constructed including all predictors that we aimed to test and then an AICc-based model selection was performed (Burnham & Anderson 2002). Parameter estimates of the best models are presented (Table I). Note that we did not perform post-hoc tests for multiple comparisons, but repeatedly ran the model with the nominal variable 'management' re-levelled (see Appendix 2).

Due to the spatial arrangement of the sampling plots, we had to take a possible spatial autocorrelation into account (Dormann et al. 2007). When significant spatial autocorrelation was revealed in model residuals by a Moran's I-test (Moran 1948), then we applied Moran eigenvector filtering to remove it (Dray et al. 2006; Griffith & Peres-Neto 2006). Neighbouring matrix was constructed using row-standardised spatial weights in 0-10 m distance (Bivand et al. 2009).

All analyses were performed with R statistical software (version 3.1.2, R Core Team 2015) using packages 'mgcv' (Wood 2006), 'MuMIn' (Barton 2014) and 'spdep' (Bivand 2014).

Results

Species richness was significantly influenced by management type, and there was no spatial autocorrelation in model residuals. Species richness was significantly higher in twice-mown plots than in other treatments. Furthermore, it was significantly higher in September-mown plots than in abandoned ones or May-mown ones (Table I, Figure 2). Although *S. gigantea* cover related to species richness negatively (see below), it did not show up in the best model (Table I). In the second best model, both management and *S. gigantea* cover were included, but the effect of the latter was not significant (results not shown). This means that *S. gigantea* cover was not significantly related to plant species richness within each management type separately (Figure3).

Shannon diversity index was analysed by fitting a linear model, and then removing significant spatial autocorrelation from model residuals. Plant diversity was significantly influenced by the interaction between management and distance from the stream (Table I, Figure 4). Model output indicates that diversity at distance = 0 was significantly higher in twice-mown sampling quadrats than in quadrats in abandoned stripe, whereas it did not significantly differ from diversity in May- or September-mown plots. Interaction terms suggest that diversity in twice-mown plots significantly increased with distance from the stream. By re-levelling the model, we found that diversity also increased with distance in September-mown plots, although in a significantly smaller degree than in twice-mown plots. Such a relationship could not be observed in abandoned and May-mown plots. Diversity was significantly higher in May-mown quadrats than in September-mown ones close to the stream, but this difference disappeared by increasing distance from the stream (Figure 4, Appendix 2).

S. gigantea cover was close to zero in all of twice-mown plots, hence these plots were omitted from the analysis (to meet the assumption of homogeneity). According to the best GAM model, *S. gigantea* cover was significantly lower in September-mown plots than in May-mown and abandoned plots, but there was no significant difference between the two latter treatments. *S.*

gigantea cover increased in a significantly different and non-linear way with distance from stream in these three treatments (Figure 5).We found highly significant negative correlations between mean *S. gigantea* height and either species richness (r=–0.68, p<<0.001) or Shannon diversity (r=–0.58, p<<0.001). In these tests we included only those quadrats where *S. gigantea* was present. When all quadrats were included, correlations between *S. gigantea* cover and species richness (r=–0.40, p<<0.001) and Shannon diversity (r=–0.36, p<<0.001) were weaker, but still highly significant.

Discussion

Species richness and diversity

Our results revealed that both frequency and timing of mowing had significant effects on species richness and diversity of vegetation. Mowing a meadow twice, in May and September, resulted in the highest species richness and diversity of plants, whereas both variables were lowest in abandoned plots, and intermediate in plots mown once either in May or in September. This outcome is consistent with other studies (Moog et al. 2002; Poptcheva et al. 2009; Házi et al. 2011) and suggests that meadows' vegetation adapted to the management that have been applied through centuries in our study region, i.e. mowing first in May-June and the second in August-September (Babai et al. 2015). This result is also in accordance with a number of studies demonstrating that traditional management practices are the most suitable tools to maintain biological diversity of species rich grasslands (WallisDeVries et al. 2002; Schmitt & Rákosy 2007; Middleton 2012; Babai & Molnár 2014). However, they should be supported in agri-environmental schemes to avoid the risk of diversity loss and the increasing rate of land abandonment (Babai et al. 2015). Several studies showed an inverse relationship between biomass production and species richness on highly productive temperate secondary grasslands (Zobel & Liira 1997; Crawley et al. 2005; Hejcman et al. 2010; Kelemen et al. 2013), and pointed out that regular removal of biomass is necessary to maintain plant diversity (Köhler et al 2005; Ruprecht et al. 2009). The primary impact of mowing twice a year on mesic hay meadows vegetation is the effective suppression of all dominant species, thereby providing space and light for less competitive species. Twice-mown, shorter sward allows more light to reach the ground surface than denser and taller sward of once-mown meadows (Jutila & Grace 2002). Furthermore, the amount of litter and nutrient replenishment of the soil is also reduced by more intensive mowing (Oelmann et al. 2009). These conditions together facilitate seedlings germination and development of less competitive plant species in twice-mown meadows (Bissels et al. 2006).

Solidago gigantea

Our results highlight that mowing two times per year is necessary to prevent effectively the invasion of *S. gigantea*. In plots infested by *S. gigantea*, many species were displaced owing to its shoot height and clonal, rhizomatous growth strategy (Prach & Pyšek 1999). This outcome explains the landscape-level expansion of *S. gigantea* and the retreat of characteristic meadow species due to land use changes, i.e. with the exchange from the traditional mowing frequency to mowing once a year and abandonment of mowing. Therefore more intensive mowing is necessary to stop invasion and to restore meadow vegetation, as proposed by Hartmann and Konold (1995).

In cases when mowing twice a year is not feasible, our results suggest that late mowing is more efficient to prevent invasion of *S. gigantea*. In May-mown plots, *S. gigantea* started a vigorous vegetative spread after mowing and was able to continue it during the entire growing season. In September-mown plots, stands of *S. gigantea* grew thinner, although remained permanent. This result suggests that it is more sensitive to mowing during the flowering period when most nutrients are invested in sprout and florescence. Late mowing therefore weakens polycormons more efficiently. In addition, late mowing favours the spread of native competitor species. This is in agreement with findings of Meyer and Schmid (1999), which showed that shoot density of *Solidago altissima* is reduced by competition.

Recommendations for conservation

Our results indicate that the highest botanical richness and diversity of mesic hay meadows can be reached by the traditional mowing frequency. Mowing regularly twice a year is necessary to prevent spreading of *S. gigantea*, and control native competitive species, which hinder the growth of many rare and less competitive species, often being of conservation importance. That means, reduced mowing intensity could not maintain diversity, not even in those regions, which are not threatened by invasion of *S. gigantea*. Mowing both in May and in September does not just correspond to traditional meadow management, but it provides both the highest quantity and quality of hay (Kun 2014). Therefore, it could be applied widespread in the region, though there are some counterarguments. First, mowing twice a year is not always feasible. For instance, there is often no need or no resource for the second cut or weather conditions make hay making difficult in September. Second, there are threatened species, such as *Phengaris alcon* butterfly and its host plant *Gentiana pneumonanthe,* or the ground-nesting bird *Crex crex*, which do not tolerate mowing in May or mowing twice a year. Moreover, some studies underlined that decreasing plant species richness of untreated spots is often combined with an increased diversity of the arthropod fauna (Southwood et al. 1979; Fenner & Palmer 1998; Cattin et al. 2003), which means that efforts to promote plant diversity can lead to reduced diversity of certain invertebrates. In addition, various types of timing and frequency of mowing have different effects on numerous individual plant species as well (Bissels et al. 2006; Leng et al. 2011).

To overcome these problems, conservation goals must be clearly defined on each single site, and conservation efforts should be concentrated on most valuable grasslands. Mowing once a year in May-June could be applied on those meadows, where competitive species are already limited by some additional environmental stress (e.g. in xeromesophilous grasslands). Late mowing in August-

September is recommended in those meadows, which harbour invertebrates or birds of conservation concern (Wakeham-Dawson & Smith 2000; Kőrösi et al. 2014); and which are invaded by *S. gigantea* but only one mowing per year is feasible. Alternatively, mosaic type mowing could be applied, by splitting the same meadow into twice and once mown parts, or leaving uncut refuge areas at every mowing. This mowing regime might be appropriate to maximize zoological and botanical values of mesic hay meadows (Fenner & Palmer 1998; Cizek et al. 2012; Kőrösi et al. 2014).

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Appendix 1

Mean moisture indicator values (Borhidi 1995) of plant species weighted with cover. Higher values indicate higher water demands.

	Row Nr.	MS	M	S	A
road	1	5.48	7.1	7.06	6.18
	2	6.18	6.56	6.79	7.18
	3	5.59	5.46	5.87	6.09
stream	4	4.65	4.78	4.98	4.76

Appendix 2

Parameter estimates of best models for each response variable with management as a nominal variable re-levelled. Re-levelled models are identical; re-levelling shows pairwise differences between management types without multiple comparisons. Significant terms are in bold. "d" means distance from the stream.

Response variable	Predictors	Estimate (±SE)	*p*-value
Species richness	**mowing in May & Sept (intercept)**	3.59 (±0.026)	<< 0.001
	abandoned	-0.399 (±0.042)	<< 0.001
	mowing in May	-0.317 (±0.041)	<< 0.001
	mowing in Sept	-0.186 (±0.039)	<< 0.001
	abandoned (intercept)	3.19 (±0.032)	<< 0.001
	mowing in May	0.082 (±0.045)	0.065
	mowing in May & Sept	0.399 (±0.042)	<< 0.001
	mowing in Sept	0.213 (±0.043)	<< 0.001
	mowing in May (intercept)	3.27 (±0.031)	<< 0.001
	abandoned	-0.082 (±0.045)	0.065
	mowing in May & Sept	0.317 (±0.041)	<< 0.001
	mowing in Sept	0.131 (±0.042)	0.002
	mowing in Sept (intercept)	3.40 (±0.029)	<< 0.001
	abandoned	-0.213 (±0.043)	<< 0.001
	mowing in May	-0.131 (±0.042)	0.002
	mowing in May & Sept	0.186 (±0.039)	<< 0.001
Shannon index	**mowing in May & Sept (intercept)**	1.86 (±0.081)	<< 0.001
	abandoned	-0.263 (± 0.114)	0.022
	mowing in May	0.135 (±0.111)	0.226
	mowing in Sept	-0.219 (±0.121)	0.071

	d: May-Sept	0.013 (±0.002)	<< 0.001
	d: abandoned	-0.013 (±0.002)	<< 0.001
	d: May	-0.011 (±0.002)	<< 0.001
	d: Sept	-0.009 (±0.002)	< 0.001
	abandoned (intercept)	1.60 (±0.078)	<< 0.001
	mowing in May	0.398 (± 0.112)	< 0.001
	mowing in May & Sept	0.263 (±0.114)	0.022
	mowing in Sept	0.044 (±0.111)	0.692
	d: abandoned	-0.001 (±0.002)	0.612
	d: May	0.002 (±0.002)	0.335
	d: May-Sept	0.013 (±0.002)	<< 0.001
	d: Sept	0.005 (±0.002)	0.061
	mowing in May (intercept)	1.99 (±0.079)	<< 0.001
	abandoned	-0.398 (± 0.112)	< 0.001
	mowing in May & Sept	-0.135 (±0.111)	0.226
	mowing in Sept	-0.355 (±0.116)	0.003
	d: May	0.002 (±0.002)	0.392
	d: abandoned	-0.002 (±0.002)	0.335
	d: May-Sept	0.011 (±0.002)	<< 0.001
	d: Sept	0.002 (±0.002)	0.353
	mowing in Sept (intercept)	1.64 (±0.082)	<< 0.001
	abandoned	-0.044 (±0.111)	0.692
	mowing in May	0.355 (±0.116)	0.003
	mowing in May & Sept	0.219 (±0.121)	0.071
	d: Sept	0.004 (±0.002)	0.032
	d: abandoned	-0.005 (±0.002)	0.061
	d: May	-0.002 (±0.002)	0.353
	d: May-Sept	0.009 (±0.002)	< 0.001
S. gigantea coverage	**abandoned (intercept)**	46.96 (± 4.13)	<< 0.001
	mowing in May	-9.50 (± 5.84)	0.107
	mowing in Sept	-22.18 (± 5.84)	<< 0.001
	mowing in May (intercept)	37.47 (± 4.13)	<< 0.001
	abandoned	9.50 (± 5.84)	0.107
	mowing in Sept	-12.68 (± 5.84)	0.032
	mowing in Sept (intercept)	24.79 (± 4.13)	<< 0.001
	abandoned	22.18 (± 5.84)	< 0.001
	mowing in May	12.68 (± 5.84)	0.032

Table I. Estimates of best models for each response variable. Mowing in May and September was the reference level of management (intercept in GLMs and GAMs). 'd' denotes distance from the stream. Significant terms are in bold.

Figure captions

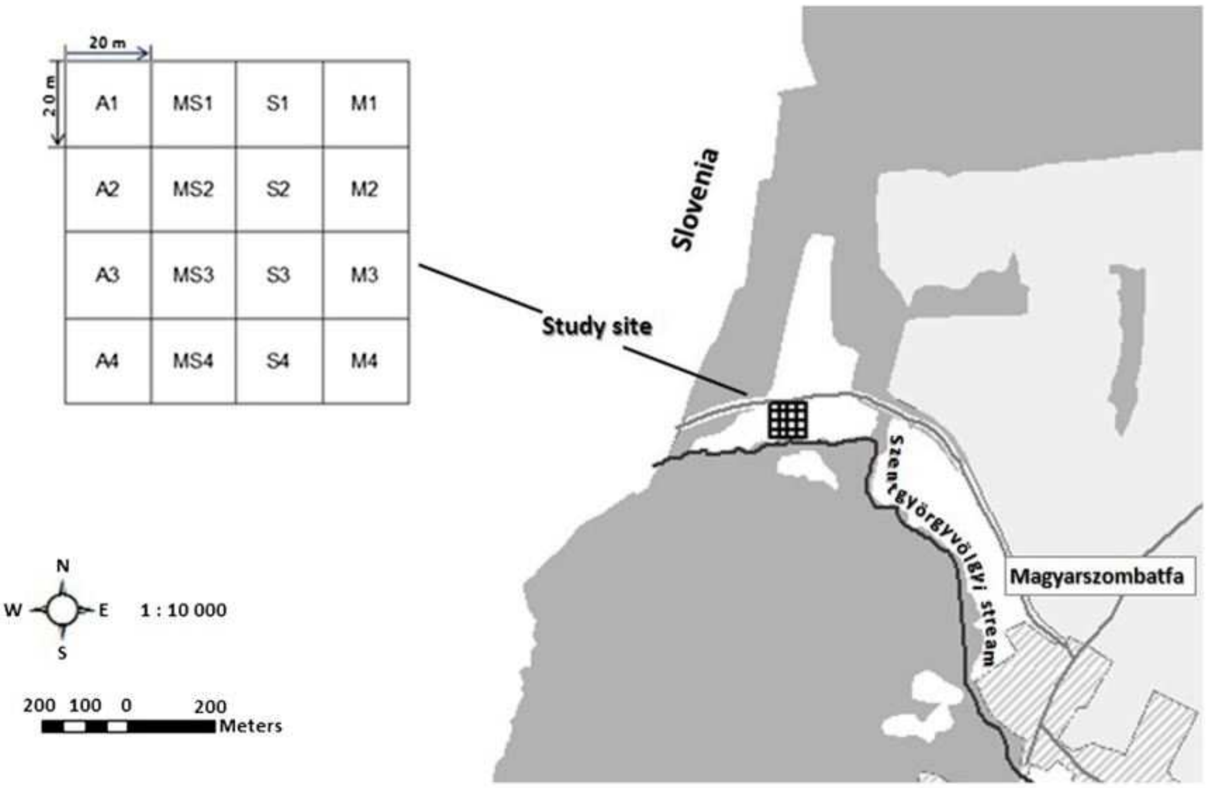

Figure 1. Location of study site, and the experimental design. Codes of treatment bands: *A* – abandoned, *MS* – mown in May and September, *S* – mown in September, *M* – mown in May. White: grassland; dark grey: woodland; light grey: plough land; streaked: built-in area; dark grey line: road; black line: stream.

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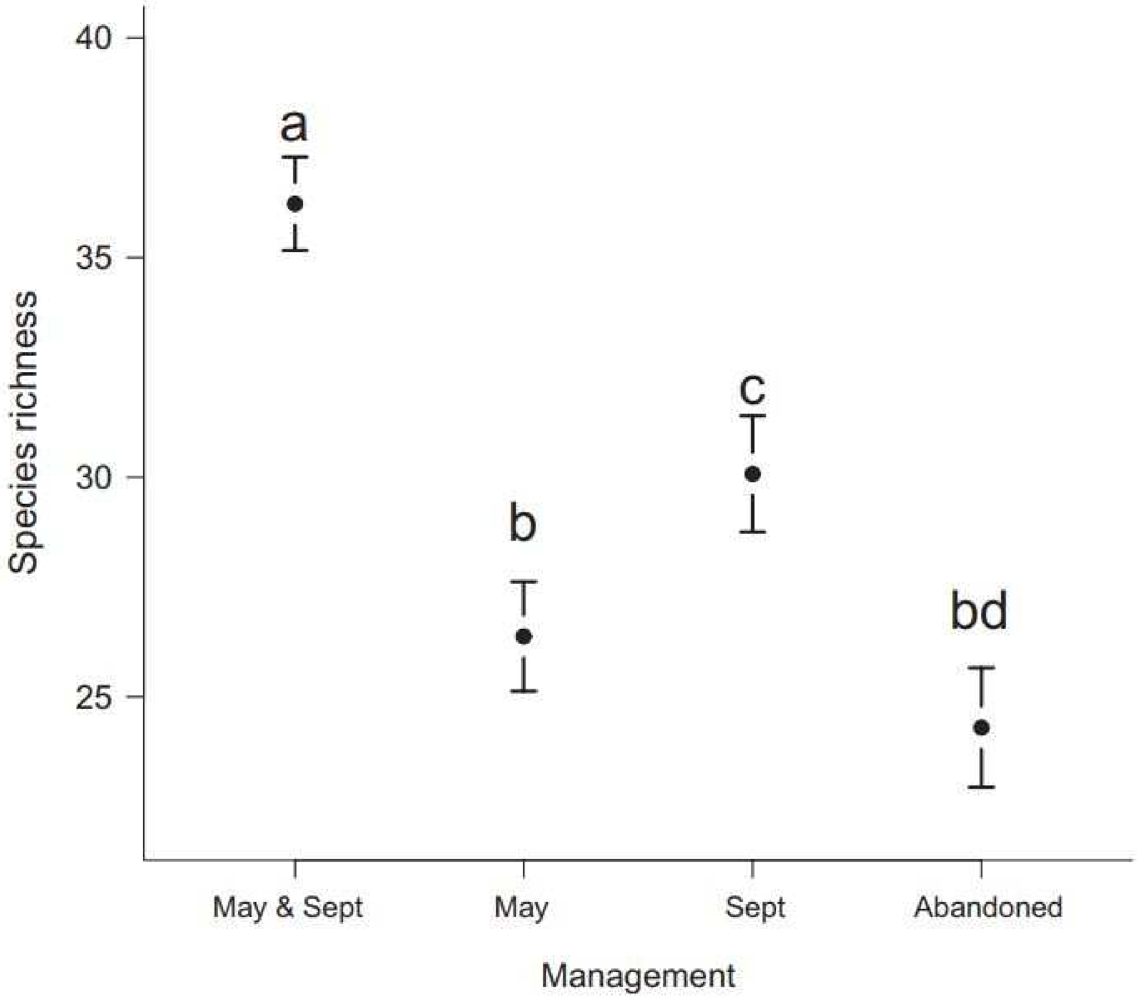

Figure 2. Mean species richness in each management type. Error bars indicate 95% confidence intervals. Letters indicate significant differences.

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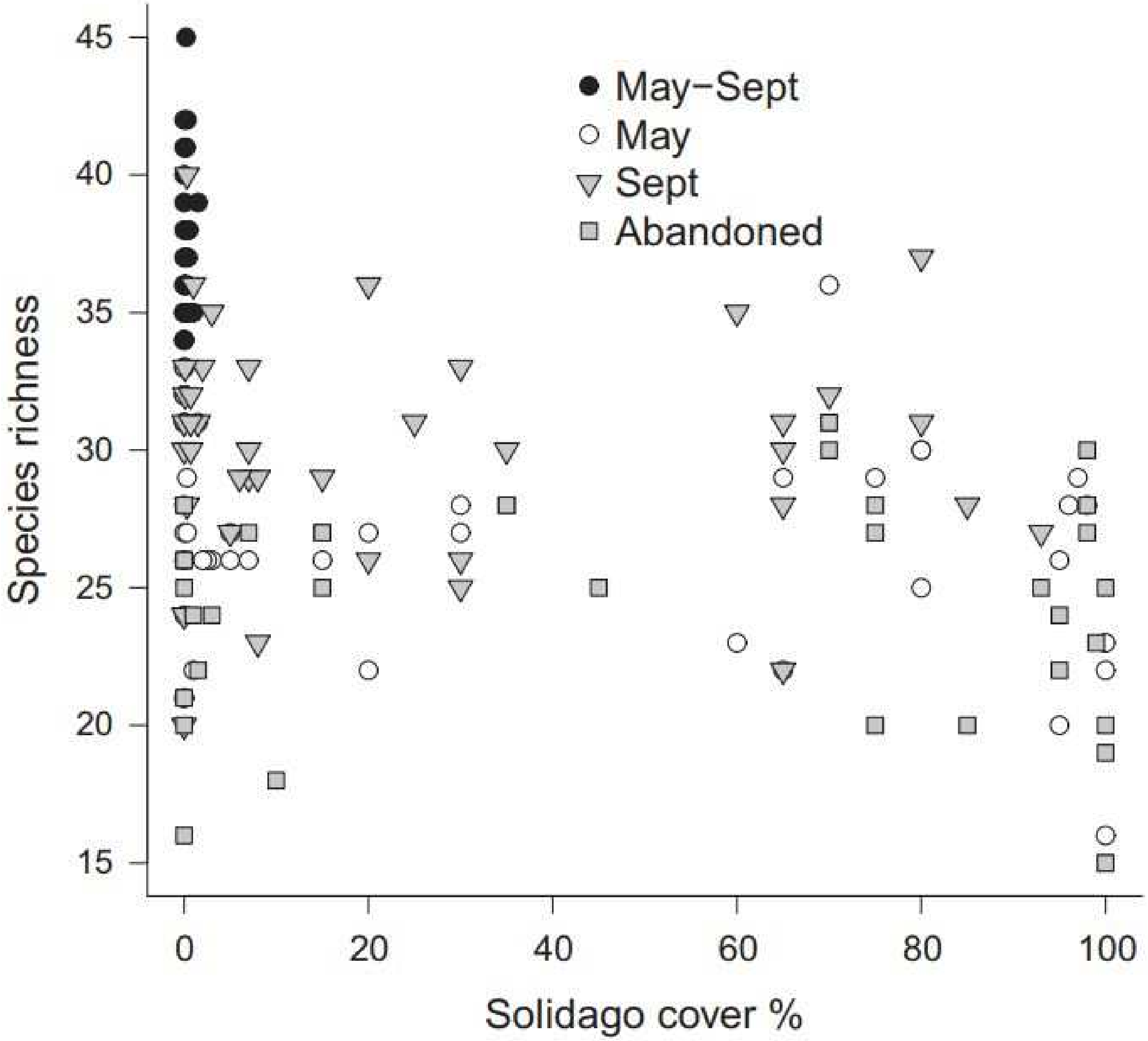

Figure 3. Relationship between species richness and coverage of *Solidago gigantea* in each management type.

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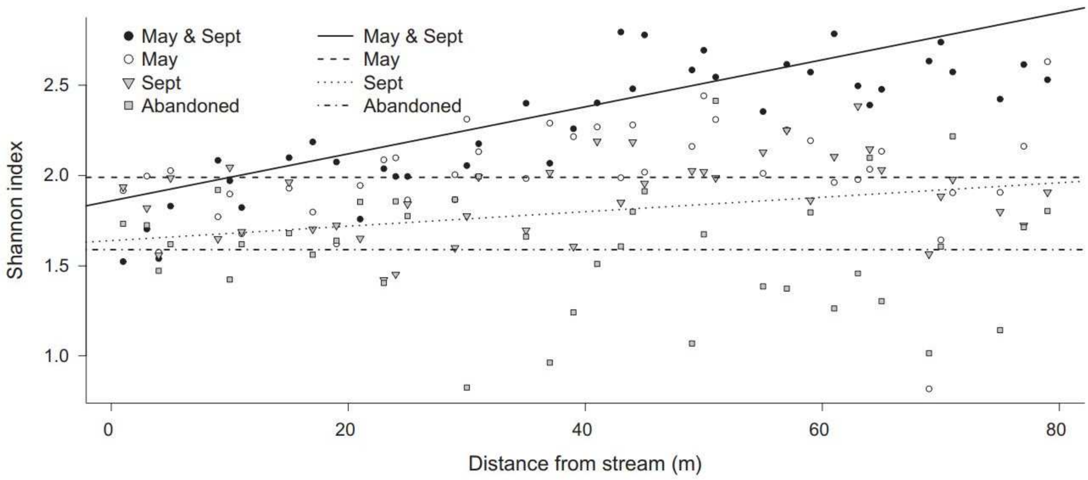

Figure 4. Relationship between Shannon’s diversity index and distance from stream in each management type. Lines represent regression slopes.

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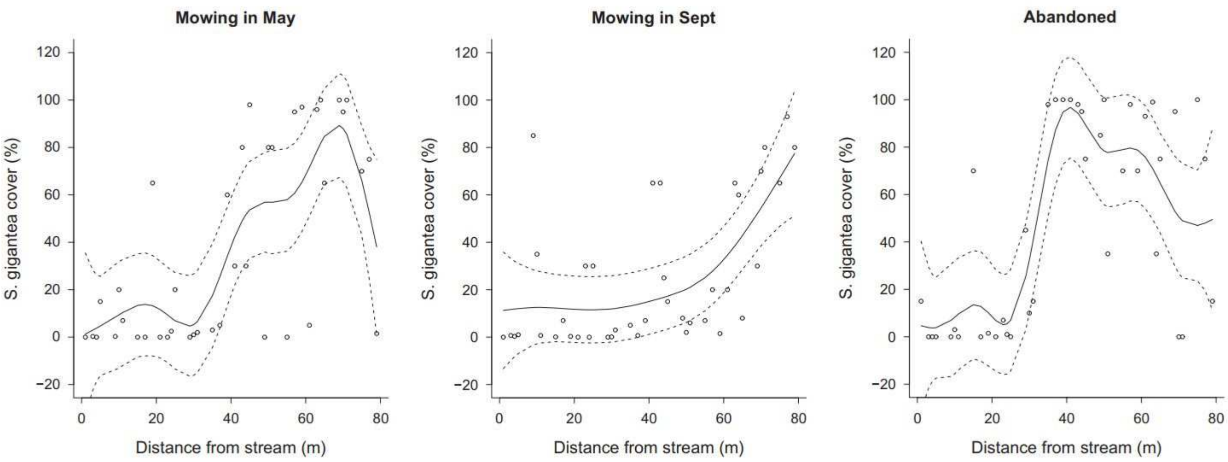

Figure 5. Relationship between *Solidago gigantea* coverage and distance from the stream. Estimated smoothing curves (thin plate regression splines) with point-wise 95% confidence bands and observed values in three treatments.

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