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Research Article

Evaluation of different revegetation measures on mudflow deposits in the Nature Park Sölktäler (Styria, Austria)

Bewertung unterschiedlicher Wiederbegrünungsmaßnahmen auf Murablagerungen im Naturpark Sölktäler (Steiermark, Österreich)

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Summary

In mountain regions, the likelihood of mudflows might increase due to climate change. Although mudflows are common worldwide and devastate agricultural land, virtually nothing is known about the revegetation of mudflow deposits for agricultural purposes. To provide recommendations for rapid revegetation of mountain pastures, 52 permanent plots (4 m × 4 m) on 20 revegetated mudflow deposits in the Nature Park Sölktäler were established. We evaluated different revegetation measures (seed addition alone or combined with application of straw, lime or cattle manure) two years after sowing using commercial clover-grass seed mixtures. Furthermore, 27 permanent plots on 15 unsown mudflow deposits were surveyed. Sowing seeds can considerably accelerate revegetation on siliceous mudflow deposits. *Festuca rubra*, *Agrostis capillaris*, *Lolium perenne*, *Trifolium repens* and *Lotus corniculatus* are particularly suitable for rapid grassland reestablishment, whereas *Poa pratensis* is not recommendable. A pure straw application should be avoided because it delays the revegetation success. Lime addition is not recommended because it can lead to an undesirable legume dominance if clover-grass seed mixtures are used for revegetation. The most effective measure for large-scale revegetation seems to be seed addition without additives. To facilitate revegetation on coarse-grained deposits, large rocks should be crushed using a stone mill.

Keywords: Mountain pastures, seed addition, straw application, lime addition, cattle manure application

Zusammenfassung

Die Wahrscheinlichkeit von Murenabgängen dürfte in Bergregionen durch den Klimawandel zunehmen. Obwohl Geröllmuren weltweit häufig auftreten und landwirtschaftliche Flächen zerstören, gibt es bisher keine wissenschaftliche Studien über die Wiederbegrünung von Murablagerungen für landwirtschaftliche Zwecke. Daher wurden im Naturpark Sölktäler (Steiermark, Österreich) 52 Dauerbeobachtungsflächen (4 m × 4 m) auf 20 wiederbegrünten Murablagerungen eingerichtet. Ziel der Wiederbegrünung war die rasche Wiederherstellung von Almweideflächen. Verschiedene Wiederbegrünungsmaßnahmen (Ansaat mit Strohaufbringung, Kalkung oder Rindermistzufuhr, Ansaat ohne Zusatzstoffe) wurden zwei Jahre nach der Ansaat mit kommerziellen Klee-Gras-Saatgutmischungen evaluiert. Außerdem wurden 27 Dauerbeobachtungsflächen (4 m × 4 m) auf 15 nicht angesäten Murablagerungen zwei Jahre nach der Naturkatastrophe hinsichtlich Vegetationsdeckungsgrad, Pflanzenartenzusammensetzung und Artendichte untersucht. Durch Ansaat kann die Wiederbegrünung von silikatischen Murablagerungen beschleunigt werden. *Festuca rubra*, *Agrostis capillaris*, *Lolium perenne*, *Trifolium repens* und *Lotus corniculatus* sind, im Gegensatz zu *Poa pratensis*, für eine rasche Wiederbegrünung besonders geeignet. Eine reine Strohzufuhr sollte vermieden werden, denn sie verzögert den Wiederbegrünungserfolg. Eine Kalkung ist nicht empfehlenswert, denn sie kann zu einer unerwünschten Leguminosendominanz führen, wenn kommerzielle Klee-Gras-Saatgutmischungen für die Ansaat verwendet werden. Die effizienteste Maßnahme für eine großflächige und rasche Wiederbegrünung ist eine Ansaat ohne Zusatzstoffe. Durch Zerkleinerung von Grobmaterial kann die Wiederbegrünung gefördert werden.

Schlagworte: Almweiden, Ansaat, Strohaufbringung, Kalkung, Rindermistzufuhr

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1. Introduction

Mudflows are common natural phenomena in mountain regions worldwide. They are induced by heavy rainfalls or continual rainfall. Mudflows are easily triggered on steep hillslopes if the soils are water-saturated (Skinner and Porter, 1992). Climate change may lead to more frequent heavy rainfall events (Berg et al., 2013). Consequently, in mountain regions, the likelihood of mudflows might increase worldwide. This, in turn, may necessitate more frequent and large-scale revegetation operations.

From an ecological perspective, mudflows are a natural geomorphic process, creating pioneer habitats. Mudflows modify existing landforms through the formation of erosional and depositional zones, thereby increasing habitat diversity. Today, natural initial ecosystem development can rarely be observed in Central Europe (Schaaf et al., 2011). Mudflows, however, provide a great opportunity to study ecosystem development and primary succession from the initial stage. Hence, from a scientific point of view, revegetation measures on erosional and depositional zones should be avoided to a large extent. On the other hand, mudflows are natural disasters, devastating agricultural land through burial of the vegetation cover with debris of different grain size. From an agricultural viewpoint, revegetation measures are urgently needed in order to quickly establish a closed vegetation with satisfactory forage yield and quality.

In July 2010, due to a heavy rainfall event (120 mm rainfall in three hours) numerous mudflows led to the devastation of mountain pastures in the valley Schwarzenseebach, located in the Nature Park Sölktäler (Styria, Austria). Large areas (40 hectares) of grasslands were covered with mudflow deposits. Due to the loss of pasture area, livestock population had to be reduced by half. Therefore, immediately after the natural disaster, 15 hectares of debris-covered pasture area were revegetated using two different commercial clover-grass seed mixtures and various revegetation measures aiming at the rapid reestablishment of pasture areas.

There are several studies on restoration measures in heavily disturbed locations (Rydgren et al., 2011; Baasch et al., 2012; Strobl et al., 2015). Numerous investigations have been made on primary succession on different substrate types (Rydin and Borgegard, 1988; Walker, 1989; Rebele, 1992; Chapin et al., 1994; Wiegleb and Felinks, 2001). Flaccus (1959) surveyed the natural revegetation of landslides. To our knowledge, no scientific studies have been published on the revegetation of mudflow deposits for agricultural purposes. If the reestablishment of pasture areas on mudflow deposits is to be successful and thus cost effective, it is important to have information on the most effective revegetation method to employ. Consequently, from an agricultural point of view, there is a high need for research regarding optimizing of revegetation measures on mudflow deposits. Our study differs from that of numerous restoration experiments in which a single site was chosen to evaluate the restoration success. However, the results of such single-site experiments can usually be applied to a larger landscape scale to a limited extent (Prach et al., 2014). The advantage of this study is that (1) many revegetated areas at separate locations under similar environmental conditions (climate, substrate) were investigated, (2) different revegetation measures did not influence one another through species exchange (Kirmer et al., 2012), (3) the sources of error associated with pseudoreplication (Hurlbert, 1984) were minimized and (4) the areas were revegetated according to agricultural practice.

The objectives of this study were

1. to investigate the plant species composition, species density (number of vascular plant species per plot) and total vegetation cover on sown mudflow deposits in an early stage of revegetation (two years after sowing),
2. to assess the short-term establishment success of non-sown species and
3. to evaluate the effectiveness of different revegetation measures after two years.

2. Methods

2.1. Study area

The study was conducted in the Schwarzenseebachtal, a north-south oriented, U-shaped mountain valley in Styria, Austria. Mean annual air temperature (1971–2000) is 5.8°C and annual precipitation averages 1,162 mm, of which 71% falls during the growing season (April to October). Mean monthly air temperature varies from -2.6°C in January to 14.6°C in July. Growing season is relatively short (about 188 days) due to the long snow cover, lasting 131 days a year on average (ZAMG, 2002). Bedrock mainly consists of different types of gneiss (Flügel and Neubauer, 1984). The most widespread soil types on freely drained sites are acid, nutrient-poor Rankers and carbonate-free Cambisols with a loamy sand texture. Carbonate-free

Fluvisols are prevalent on the alluvial sediments along the stream Schwarzenseebach. Grassland is primarily utilized as pasture during the summer season. The mountain pastures are grazed by cattle from the end of May to mid-September. Stocking rate is 0.9 livestock units (LU) per hectare during approximately four months. Few areas on the valley floor are managed as hay meadows. They are cut once a year in mid-July and have not received manure for several years. The mountain pastures are mainly covered with a *Homogyno alpinae-Nardetum* community (*Nardo-Agrostion tenuis*), representing a low productive plant community on nutrient-poor, acid soils. The traditionally managed mountain hay meadows correspond to the *Festuca rubra-Agrostis capillaris* grassland (*Nardo-Agrostion tenuis*). The riparian forest vegetation on the valley floor belongs to the *Alnetum incanae* community (*Alnion incanae*). In the montane belt, *Picea abies-Abies alba* forests (*Piceion abietis*) are the main forest types of the region (Winter, 2005; Bohner et al., 2014; Mucina et al., 2016).

2.2. Revegetation sites

All the revegetation areas investigated (N 47°17'–47°19'; E 13°52'–13°53') were located at the valley bottom and at the bottom of hillslopes in the montane belt. Altitude ranged from 1,057 to 1,136 m a.s.l. and slope angle varied from 2 to 28°. Aspect was mainly north-west. Biotic and abiotic site conditions on mudflow deposits considerably differed from the pre-perturbation state. The studied mudflow deposits represented a heterogenous mixture of unconsolidated siliceous debris of different grain size. Plant available mineral nutrient content, available water-holding capacity and microbial biomass were presumably very low due to the lack of humus and fine earth material (particles < 2 mm). Except for nitrogen (N), rocks can release essential macronutrients through mineral weathering (Gunnarsen et al., 2019). Thus, plant growth and productivity on mudflow deposits appear to be limited primarily by N. A further characteristic feature of mudflow deposits was the absence of a soil diaspore bank at the start of vegetation development, attributable to the burial of diaspores by mudflow sediments. It is assumed that unfavorable abiotic (lack of humus, N and fine earth material, water shortage) and biotic (seed limitation) site conditions may limit the revegetation success on mudflow deposits. The studied mudflow deposits were surrounded by a well-developed montane grassland vegetation (mainly *Homogyno alpinae-Nardetum* community).

2.3. Revegetation measures

Revegetation took place in August 2010. Four types of revegetation measures were undertaken: seed addition combined with application of straw, lime or cattle manure and seed addition alone (without additives). Straw, lime and cattle manure were applied to the surface of mudflow deposits at a rate of about 5, 1 and 5–10 t ha^{-1}, respectively. Straw had a very high carbon to nitrogen ratio (C:N ratio) of 90. Lime was added in the form of $CaCO_3$. No mineral fertilizers were applied to the revegetated areas and the herbage was not mown. The revegetated areas were lightly grazed by cattle (0.9 LU ha^{-1}) during the summer season. Two different commercial clover-grass seed mixtures were used for rapid revegetation. They contained 6–8 common grass species and 2–3 legumes (Table 1). Seeds were sown on the mudflow deposits by hand. The recommended seed rate for both mixtures was 26 kg ha^{-1}. All the revegetation measures were one-time measures. On some debris-covered areas, prior to the revegetation, large rocks were crushed using a stone mill.

2.4. Data collection

In 2012, the second year after sowing, 52 permanent plots were randomly established on 20 revegetated mudflow deposits. The number of permanent plots per revegetation

Table 1. Species composition of the seed mixtures used for revegetation of mudflow deposits and proportion (weight per cent) of each species (Die Saat, 2014). H = permanent pasture for harsh environmental conditions, G = permanent pasture.
Tabelle 1. Artenzusammensetzung der verwendeten Saatgutmischungen und Anteil (Gewichtsprozent) jeder Art (Die Saat, 2014). H = Dauerweide für raue Lagen, G = Dauerweide.

Plant species	Seed mixtures %	
	H	G
Trifolium repens	10	15
Trifolium hybridum	5	0
Lotus corniculatus	5	5
Poa pratensis	20	25
Festuca pratensis	15	15
Phleum pratense	15	10
Festuca rubra	10	10
Dactylis glomerata	5	10
Lolium perenne	5	10
Agrostis capillaris	5	0
Cynosurus cristatus	5	0

measure was area-dependent, leading to different number of sample plots. Since cattle manure application was restricted to a very small area, only one permanent plot could be established on the sown and manured mudflow deposit due to the strict criteria of site selection. In order to have independent replications and to minimize species exchange between different revegetation measures, the minimal distance between single permanent plots was 25 m. To avoid edge effects, plots were established in the center of each revegetation area. Distance to the undisturbed neighboring vegetation was at least 5 m. All permanent plots had the same plot size of 16 m² (4 m × 4 m). The plots were selected to be representative for each revegetation area and each plot was largely homogenous in terms of abiotic site conditions (microtopography, microclimate, grain size of the mudflow sediment). Since the plots were not fenced, all plots were lightly grazed by cattle. Each plot was permanently marked by means of large metal nails, which were fully driven into the ground at two opposite corners of the plots, enabling long-term monitoring of revegetation success. In addition, we recorded the geographical position in the center of each plot with a GPS device. In June 2012, vegetation surveys were carried out at each plot using the method of Braun-Blanquet (1951) with a modified cover-abundance scale (Bohner et al., 2014). Only vascular plant species were recorded. Furthermore, total vegetation cover, bryophyte cover, cover of plant functional groups (grasses summarized *Poaceae*, *Juncaceae* and *Cyperacae*, herbs, legumes) and straw cover were estimated visually. Taxonomy and nomenclature of plant species follow that of Fischer et al. (2008). Altitude, aspect and slope angle of each plot were also recorded. Grain size of the deposited substrate was estimated visually. Due to a lack of fine earth material, no soil samples could be taken. The unsown mudflow deposits can serve as reference sites to assess revegetation success. Therefore, we also established 27 permanent plots (4 m × 4 m) on 15 unsown mudflow deposits and surveyed total vegetation cover, bryophyte cover, plant species composition and species density in an initial stage of primary succession (two years after the natural disturbance). The ecological and sociological behavior of plant species was derived from field observations and from the literature (Grime et al., 1988; Dietl et al., 1998; Ellenberg et al., 2001). The seed size of sown species was abstracted from the BIOLFLOR database (Klotz et al., 2002). Dispersal mode of plant species was derived from Oberdorfer (2001). Total vegetation cover, cover of plant functional groups and individual cover of sown species were used to assess the effectiveness of different revegetation measures two years after sowing.

2.5. Data analysis

The normality of data and the homogeneity of variances were tested using Shapiro–Wilk test and Levene's test. To evaluate the significance of treatment differences, one-way analysis of variance (ANOVA) with Games-Howell post-hoc tests was used. Kruskal–Wallis tests followed by Mann–Whitney tests were also used for testing differences between management treatments. The results were quite similar. Therefore, only values based on ANOVA are presented here. Correlation analyses were performed using Pearson correlation coefficient. All the results were stated as statistically significant if $p < 0.05$. Statistical data analyses were performed with R 3.3.4 (R Core Team, 2017).

3. Results

The results of our vegetation surveys are summarized in Tables 2–3 and Figures 1–6. In the second year after sowing, mean total vegetation cover ranged from 36 to 75%, being lowest on plots with seed addition and straw application and highest on the plot with seed addition and cattle manure application. The proportion of grasses on vegetation cover was highest on plots with seed addition alone (without additives) and lowest on plots with seed

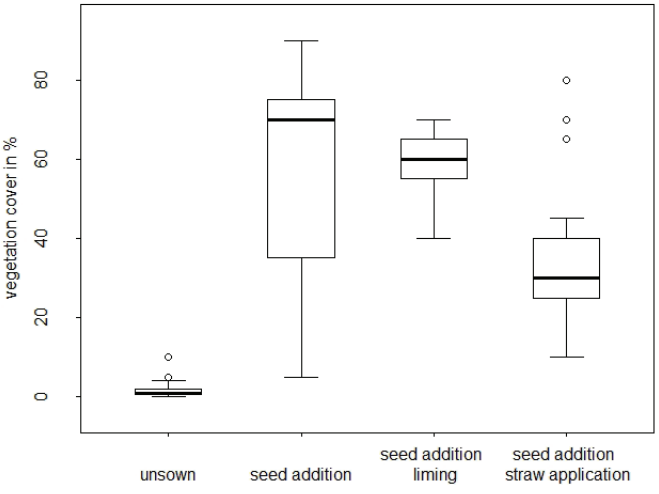


Figure 1. Total vegetation cover (%) on unsown (no addition of seeds, n = 27) and sown (seed addition alone, n = 27; seed addition and liming, n = 5; seed addition and straw application, n = 19) plots
Abbildung 1. Vegetationsdeckung (%) auf nicht angesäten (keine Zufuhr von Samen, n = 27) und angesäten (nur Ansaat, n = 27; Ansaat mit Kalkung, n = 5; Ansaat mit Strohaufbringung, n = 19) Aufnahmeflächen.

Table 2. Species density (number of vascular plant species per plot, 4 m × 4 m), total vegetation cover, proportion of grasses, herbs and legumes on vegetation cover, bryophyte cover and percentage of non-sown species (proportion of non-sown species of the total number of plant species per plot) according to the revegetation measure. V% = variation coefficient (%).
Tabelle 2. Artendichte (Anzahl Gefäßpflanzen pro Aufnahmefläche, 4 m × 4 m), Vegetationsdeckungsgrad, Anteil der Gräser, Kräuter und Leguminosen an der Vegetationsdecke, Moosdeckung und Anteil nicht angesäter Arten an der Gesamtartenzahl pro Aufnahmefläche in Abhängigkeit von der Wiederbegrünungsmaßnahme. V% = Variabilitätskoeffizient (%).

	unsown	seed addition	seed addition and liming	seed addition and straw application	seed addition and manure application
number of plots	27	27	5	19	1
species density (mean)	13	31	22	27	19
V%	48	34	33	31	
species density (median)	11	29	17	24	
mean vegetation cover (%)	2	56	58	36	75
V%	133	43	20	54	
proportion of grasses (%)		33	27	17	26
V%		43	27	65	
proportion of herbs (%)		1	1	1	1
V%		78	20	53	
proportion of legumes (%)		22	30	18	48
V%		68	19	65	
mean bryophyte cover (%)	0.4	5	10	2	1
V%	87	108	0	166	
mean non-sown species (%)		67	48	61	42
V%		14	26	18	

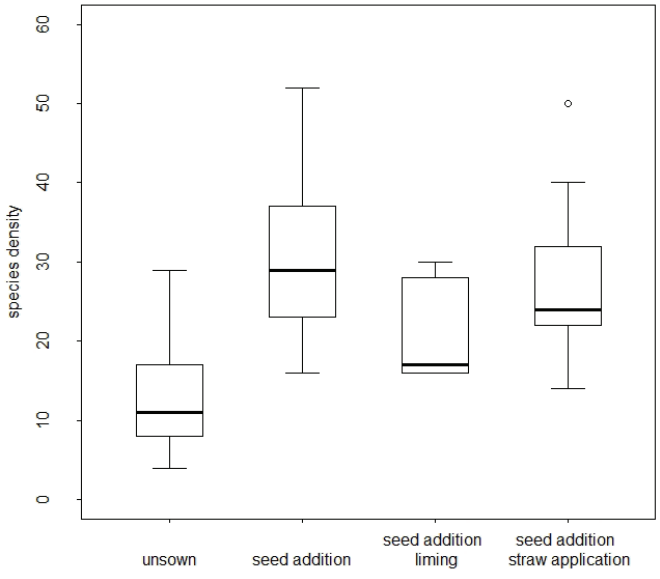


Figure 2. Species density (number of vascular plant species per plot, 4 m × 4 m) on unsown (no addition of seeds, n = 27) and sown (seed addition alone, n = 27; seed addition and liming, n = 5; seed addition and straw application, n = 19) plots.
Abbildung 2. Artendichte (Anzahl Gefäßpflanzen pro Aufnahmefläche, 4 m × 4 m) auf nicht angesäten (keine Zufuhr von Samen, n = 27) und angesäten (nur Ansaat, n = 27; Ansaat mit Kalkung, n = 5; Ansaat mit Strohaufbringung, n = 19) Aufnahmeflächen.

addition and straw application. The proportion of legumes on vegetation cover was highest on the plots with seed addition and cattle manure application and lowest on plots with seed addition and straw application. The proportion of herbs on vegetation cover was 1% regardless of the revegetation measure. Across all the revegetation measures, we observed a significant positive correlation between grass and herb cover ($r = 0.57$, $\rho = 0.000$). Legume cover also correlated significantly and positively with herb cover ($r = 0.66$, $\rho = 0.000$), suggesting that sown grasses and legumes as a group did not prevent successful establishment of particular non-sown herbs on mudflow deposits. Mean cover of bryophytes varied from 1 to 10%, being highest on plots with seed addition and liming and lowest on the plot with seed addition and cattle manure application. Mean cover of woody species was less than 1%. On plots with straw application, straw cover ranged from 10 to 80%, indicating marked patchiness in the distribution of straw. The relationships between straw cover and total vegetation cover, grass cover, herb cover and legume cover are shown in Figures 7–10. Straw cover correlated significantly and negatively with total vegetation cover ($r = -0.91$, $\rho = 0.000$), grass cover ($r = -0.77$, $\rho = 0.000$), herb cover

Table 3. Mean cover (%) of sown species according to the revegetation measure. n = number of plots, f = frequency (%), mc = mean cover (%) of the sown species, V = variation coefficient (%).
Tabelle 3. Mittlere Deckung der angesäten Arten in Abhängigkeit von der Wiederbegrünungsmaßnahme. n = Anzahl der Aufnahmeflächen, f = Stetigkeit (%), mc = mittlere Deckung (%) der angesäten Art, V = Variabilitätskoeffizient (%).

	seed addition (n = 27)			seed addition and liming (n = 5)			seed addition and straw application (n = 19)			seed addition and manure application (n = 1)		
	f	mc	V	f	mc	V	f	mc	V	f	c	V
Trifolium repens	100	16.37	67	100	29.00	0	100	18.97	51		38.5	
Trifolium hybridum	96	3.52	111	100	2.40	34	100	7.74	86		22.0	
Lotus corniculatus	100	6.12	85	100	4.60	133	100	5.79	82		15.5	
Poa pratensis	15	0.07	267	40	0.14	186	37	0.22	135		0.6	
Festuca pratensis	85	1.60	113	100	1.44	68	100	1.99	54		4.5	
Phleum pratense	100	1.42	57	100	1.44	68	100	1.83	55		3.0	
Festuca rubra	100	12.38	54	100	18.10	20	100	15.61	35		15.5	
Dactylis glomerata	100	1.35	69	100	1.62	53	100	1.86	51		4.5	
Lolium perenne	92	6.18	97	100	2.10	39	100	2.98	73		15.5	
Agrostis capillaris	100	13.48	73	100	3.00	0	100	3.33	146		1.5	
Cynosurus cristatus	50	1.04	137	100	4.24	150	63	1.77	116		3.0	

(r = -0.92, ρ = 0.000), legume cover (r = -0.75, ρ = 0.000) and bryophyte cover (r = -0.57, ρ = 0.011). Surprisingly, straw cover did not correlate with species density, number of non-sown species and percentage of non-sown species (proportion of non-sown species of the total number of plant species per plot). There was no correlation between slope angle and the surveyed vegetation parameters. On the sown plots, mean species density varied from 19 to 31 and the mean percentage of non-sown species ranged from 42 to 67%, being greatest on plots with seed addition alone and lowest on the plot with seed addition and manure application, respectively (Table 2). On the plots with seed addition alone or combined with straw application, the non-sown species were usually the main contributors to the total species density. Species density, number of non-sown species and percentage of non-sown species did not correlate with the total vegetation cover, grass cover or legume cover. An analysis of variance (ANOVA) revealed that the revegetation measures had a significant influence on the total vegetation cover (ρ = 0.000), grass cover (ρ = 0.001), herb cover (ρ = 0.003) and species density (ρ = 0.000). Seed addition had a significant effect on the total vegetation cover (ρ = 0.000) and species density (ρ = 0.000). Straw application had a significant effect on the total vegetation cover (ρ = 0.020), grass cover (ρ = 0.000) and herb cover (ρ = 0.006).

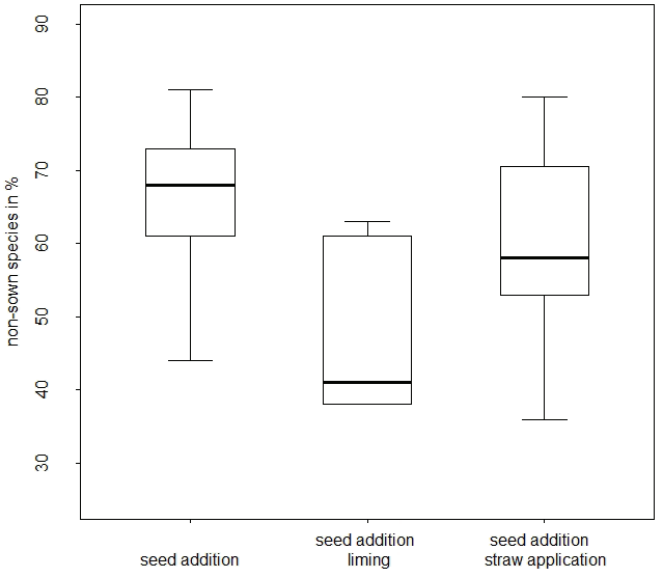


Figure 3. Percentage of non-sown species (proportion of non-sown species of the total number of plant species per plot) on sown (seed addition alone, n = 27; seed addition and liming, n = 5; seed addition and straw application, n = 19) plots.
Abbildung 3. Anteil nicht angesäter Arten an der Gesamtartenzahl pro Aufnahmefläche auf angesäten (nur Ansaat, n = 27; Ansaat mit Kalkung, n = 5; Ansaat mit Strohaufbringung, n = 19) Aufnahmeflächen.

After two years of vegetation development, dominant species were the sown grasses *Festuca rubra, Agrostis capillaris* and *Lolium perenne* as well as the sown legumes *Trifolium repens, T. hybridum* and *Lotus corniculatus*, depending

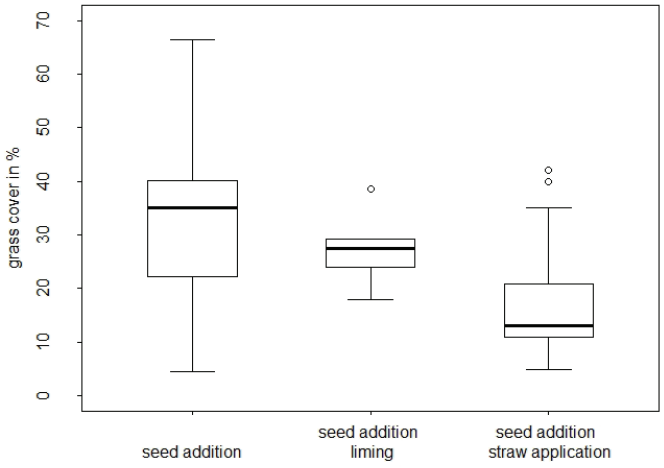


Figure 4. Proportion of grasses on total vegetation cover as a function of the revegetation measure (seed addition alone, n = 27; seed addition and liming, n = 5; seed addition and straw application, n = 19).
Abbildung 4. Anteil der Gräser an der Vegetationsdecke in Abhängigkeit von der Wiederbegrünungsmaßnahme (nur Ansaat, n = 27; Ansaat mit Kalkung, n = 5; Ansaat mit Strohaufbringung, n = 19).

largely upon the revegetation measure (Table 3). Among the sown species, only *Poa pratensis* failed to establish at most sites. Some short-lived arable weeds (*Anthemis arvensis, Cyanus segetum, Tripleurospermum inodorum*) and cereals (*Hordeum vulgare, Secale cereale, Triticale rimpaui*) were found only on plots with straw cover, indicating that they were introduced by straw application. With the exception of *Dracocephalum moldavica*, regionally rare and endangered species were absent in the studied plots. *D. moldavica* was recorded as a single individual with low vigor. In Austria, this annual herb is very rare and non-native (Fischer et al., 2008). It has been introduced to mudflow deposits presumably as a contaminant of sown seed. *Lolium* × *boucheanum,* another contaminant, was present with few individuals. Of the non-sown species, those with a relatively low mineral nutrient requirement were predominant (*Anthoxanthum odoratum*, *Carex pallescens*, *Luzula multiflora*, *Potentilla erecta, Veronica officinalis*), indicating nutrient-poor mudflow sediments. Typical *Nardo-Agrostion tenuis* species (e.g., *Nardus stricta*) were observed only occasionally with low abundance. In contrast, *Achillea millefolium* agg., *Cerastium holosteoides, Prunella vulgaris, Ranunculus acris ssp. acris* and *T. pratense* were successful colonizers. High-nutrient indicator species, such as *Rumex alpestris*, occurred only as isolated individuals. Several moisture indicator species (e.g., *Cirsium palustre, Galium uliginosum, Deschampsia cespitosa, Juncus effusus*) were able to grow on mudflow deposits, indicating sufficient water availability presumably due to plentiful and well distributed rainfall in the study area. Species characteristic of disturbed habitats (e.g., *Plantago major ssp. major*, *Poa supina*, *Ranunculus repens*, *Sagina procumbens*) were sporadically recorded. Ruderal species and invasive neophytes were absent in the studied plots, presumably due to nutrient and seed limitation. Gap species, particularly *Euphrasia officinalis ssp. rostkoviana*, were frequently present. *Atocion rupestre* was the most abundant typical pioneer species. Tree species that occurred more frequently were saplings of *Acer pseudoplatanus*, *Alnus alnobetula, Picea abies, Salix caprea* and *S. myrsinifolia*. Pioneer tree species like *Betula pendula* and *Larix decidua* were scarce. Apart from *Vaccinium myrtillus*, which occurred with few, small individuals, no dwarf shrubs had become established. Only two fern species, *Athyrium filix-femina* and *Thelypteris limbosperma*, were found in very small numbers.

The colonization ability of non-sown species seems to be strongly influenced by the dispersal mode. Species that can be dispersed over greater distances by wind (e.g., *A. pseudoplatanus, A. alnobetula*, *C. palustre, Epilobium montanum, Petasites albus, S. myrsinifolia, Scorzoneroides autumnalis, Senecio sylvaticus*, *Taraxacum officinale* agg.) were frequently found. Interestingly, species that are dispersed by ants (e.g., *Ajuga pyramidalis*, *Anemone nemorosa*, *C. pilulifera*, *L. luzuloides*, *L. multiflora*, *Moehringia trinervia*, *Thymus pulegioides*, *V. officinalis, Viola biflora*) were relatively abundant too.

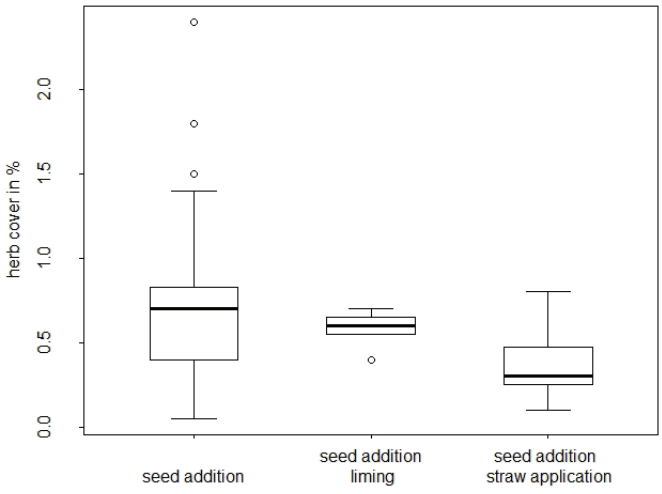


Figure 5. Proportion of herbs on total vegetation cover as a function of the revegetation measure (seed addition alone, n = 27; seed addition and liming, n = 5; seed addition and straw application, n = 19).
Abbildung 5. Anteil der Kräuter an der Vegetationsdecke in Abhängigkeit von der Wiederbegrünungsmaßnahme (nur Ansaat, n = 27; Ansaat mit Kalkung, n = 5; Ansaat mit Strohaufbringung, n = 19).

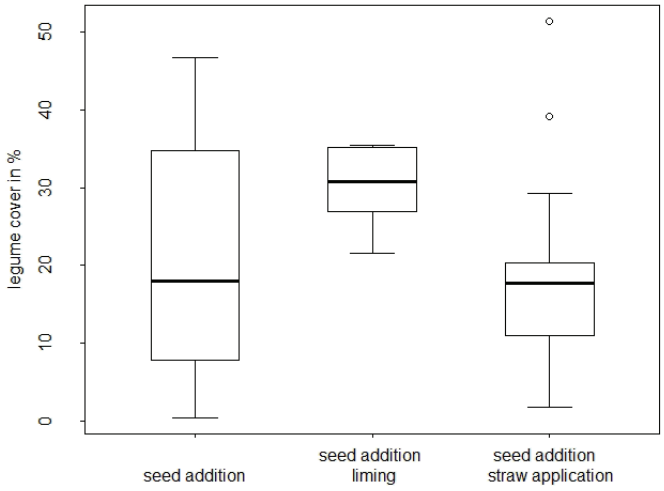


Figure 6. Proportion of legumes on total vegetation cover as a function of the revegetation measure (seed addition alone, n = 27; seed addition and liming, n = 5; seed addition and straw application, n = 19).
Abbildung 6. Anteil der Leguminosen an der Vegetationsdecke in Abhängigkeit von der Wiederbegrünungsmaßnahme (nur Ansaat, n = 27; Ansaat mit Kalkung, n = 5; Ansaat mit Strohaufbringung, n = 19).

In the second year of primary succession, the unsown mudflow deposits represented species-poor pioneer habitats with sparse plant cover and short vegetation height. Mean total vegetation cover on unsown plots was only 2% and species density was highly significantly lower than on the sown plots (Table 2, Figures 1-2). Small- and medium-growing (< 50 cm), acid-tolerant species prevailed (data not shown). Plant species with highest frequency were *A. capillaris* (70%), *L. multiflora* (52%) and *F. rubra* (44%), each of them showed low percent cover (0.5–1%). Within two years, many of the typical species of the surrounding *Homogyno alpinae-Nardetum* community did not establish. Pioneer species such as *A. rupestre*, *E. montanum*, *Geranium robertianum*, *P. albus*, *Poa nemoralis, Tussilago farfara* and *V. biflora* occurred in low abundances. *A. alnobetula* and *L. corniculatus* were the most abundant N-fixing plants. A few tree species (*A. pseudoplatanus, P. abies, A. alnobetula, Salix spp.)* were capable of colonizing mudflow deposits within two years.

4. Discussion

Our findings are representative of large-scale revegetation measures on siliceous mudflow deposits in the montane belt in areas of temperate climate. However, the vegetation data varied strongly within different revegetation measures, indicating small-scale spatial heterogeneity (e.g., patchy distribution of straw and diaspores, humus patches, microsites with higher nutrient and water supply) on the revegetated areas. Thus, multiple, randomly located, large (at least 16 m²) sample plots for each revegetation measure are needed to evaluate the revegetation success on mudflow deposits.

In the second year of primary succession, total vegetation cover and species density were highly significantly lower on unsown plots compared to the sown ones, indicating slow natural revegetation of mudflow deposits by a few early successional species. Main reasons for the slow revegetation process and low floristic diversity might be both the extreme abiotic site conditions (lack of humus and fine earth material, N deficiency) and the absence of a soil diaspore bank at the start of primary succession. It is well known that primary succession takes place very slowly primarily because of N deficiency and lack of diaspores in the substrate (Drury and Nisbet, 1973; Rebele, 1992; Chapin et al., 1994). Our findings agree with those of Flaccus (1959) and Chambers et al. (1990), who observed that natural revegetation is a very slow process on landslide deposits. N-fixing plants, particularly *A. alnobetula* and *L. corniculatus*, were able to colonize the unsown plots within two years. In the course of primary succession, symbiotic N-fixers are often early colonizers due to N shortage (Chapin et al., 1994).

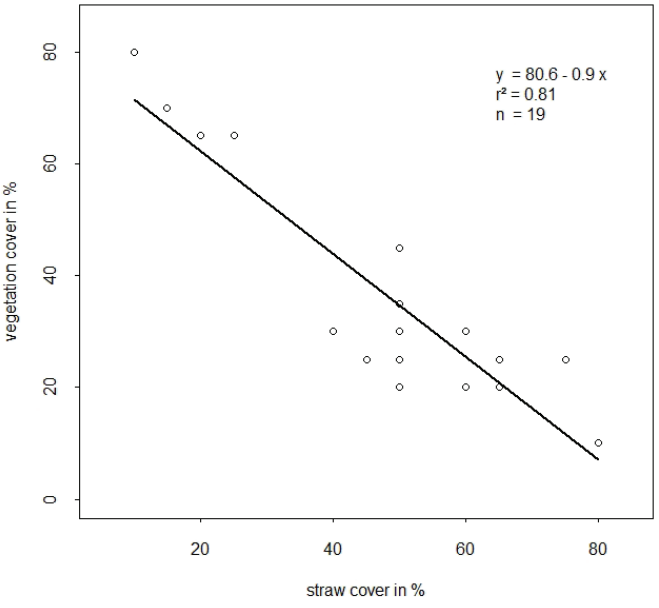


Figure 7. Relationship between straw cover (%) and total vegetation cover (%) on sown plots.
Abbildung 7. Beziehung zwischen Strohdecke (%) und Vegetationsdeckung (%) auf angesäten Aufnahmeflächen.

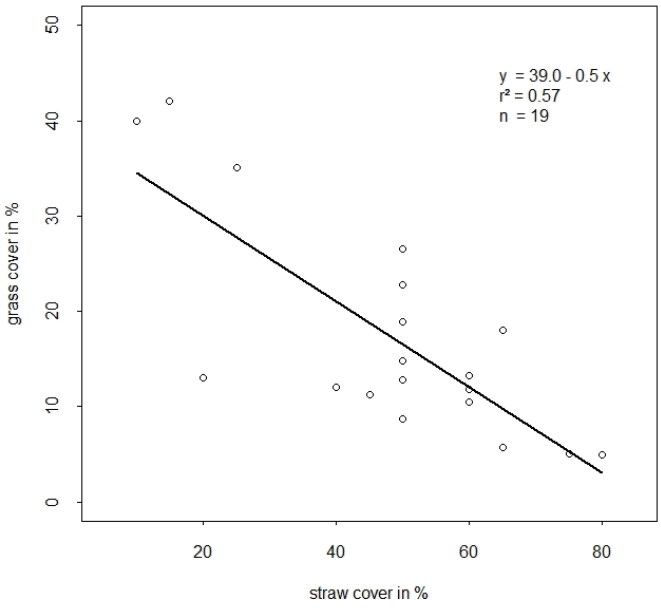


Figure 8. Relationship between straw cover (%) and proportion of grasses on total vegetation cover (%) on sown plots.
Abbildung 8. Beziehung zwischen Strohdecke (%) und Anteil der Gräser an der Vegetationsdecke (%) auf angesäten Aufnahmeflächen.

In the second year after sowing, mean total vegetation cover on plots with seed addition alone was 56% compared to 2% on unsown plots, indicating that revegetation on mudflow deposits was primarily "seed limited." Hence, sowing seeds can considerably accelerate revegetation on mudflow deposits. This finding is supported by several other studies (Ödman et al., 2011; Hagen et al., 2014; Auestad et al., 2016), suggesting that "spontaneous" revegetation generally proceeds much slower than "assisted" revegetation by seed sowing. Within two years, sown species were not able to form a closed vegetation cover, favoring non-sown species, thereby increasing species density. However, typical *Nardo-Agrostion tenuis* species like *N. stricta* were less successful in colonizing mudflow deposits, presumably because of the inefficient dispersal of diaspores from the surrounding populations and/or their inability to grow on humus-free mudflow sediments. The majority of non-sown species were locally abundant grassland, forest and forest border species. Most of them had cover values less than 2%. On unsown plots, the number of species (on average 13 per plot) was highly significantly lower than the number of non-sown species (on average 21 per plot) on plots with seed addition alone. We assume, therefore, that the colonization of mudflow deposits by species from the surrounding vegetation was not significantly limited by the presence of sown species two years after sowing.

On the contrary, our data indicate facilitation of particular non-sown species by sown species, presumably due to the unfavorable abiotic site conditions on mudflow deposits, creating sufficient "gap space" (germination niches) for seed germination and establishment of stress-tolerant non-sown species. Few species were also introduced as contaminants in the seed mixture. In harsh abiotic environments, establishment of particular species is facilitated by sheltering effects of vegetation such as shading (Ryser, 1993; Freund et al., 2014). Under more favorable environmental conditions (fertile soil), however, the use of a commercial seed mixture, particularly when combined with a fertilizer, usually inhibits the establishment of non-sown species through competitive exclusion by competitively superior sown species, leading to a low floristic diversity (Hagen et al., 2014; Auestad et al., 2016).

The slow natural revegetation on unsown plots indicates that the mudflow deposits investigated were initially characterized by a lack of viable diaspores. Diaspores were introduced by man (seed mixture, straw, cattle manure), wind and animals (game and grazing livestock, ants). Surface runoff (water dispersal) presumably played only a minor role because of the convex surface form of mudflow deposits. Seed dispersal by man, wind, game and grazing livestock can occur over long distances (> 100 m).

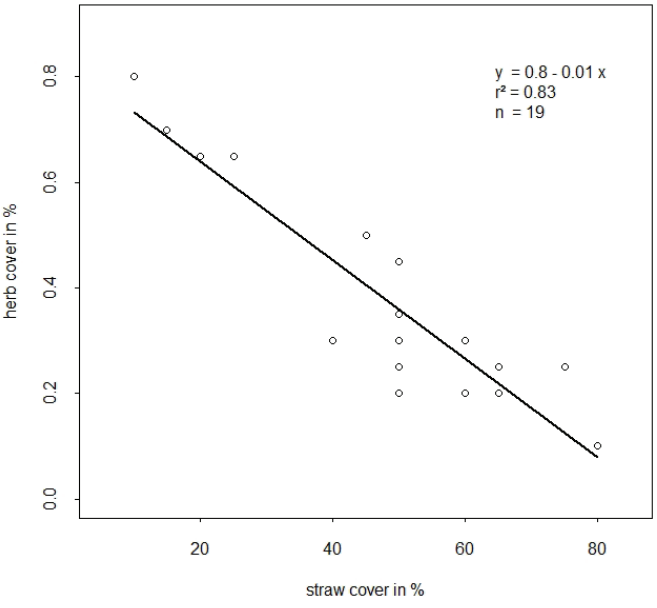


Figure 9. Relationship between straw cover (%) and proportion of herbs on total vegetation cover (%) on sown plots.
Abbildung 9. Beziehung zwischen Strohdecke (%) und Anteil der Kräuter an der Vegetationsdecke (%) auf angesäten Aufnahmeflächen.

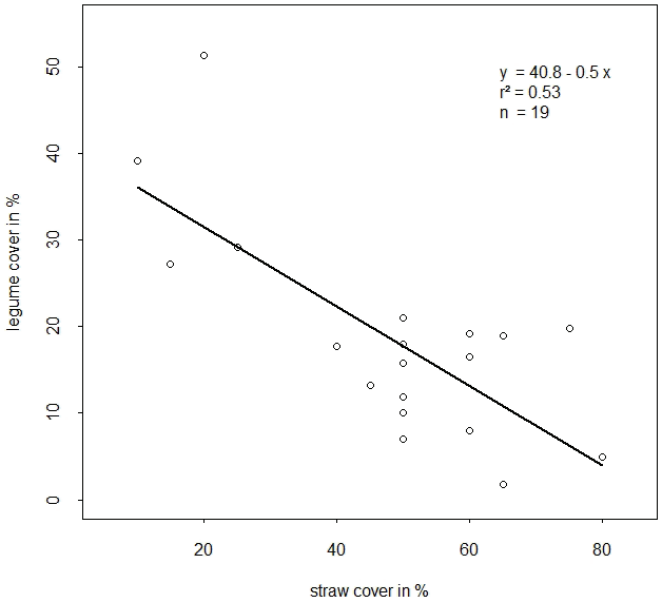


Figure 10. Relationship between straw cover (%) and proportion of legumes on total vegetation cover (%) on sown plots.
Abbildung 10. Beziehung zwischen Strohdecke (%) und Anteil der Leguminosen an der Vegetationsdecke (%) auf angesäten Aufnahmeflächen.

Ants, however, transport seeds only over a distance of a few meters (Nierhaus-Wunderwald, 1995; Bakker et al., 1996). Since cattle have grazed the mudflow deposits only occasionally, we assume that non-sown species have colonized mudflow deposits mainly through wind dispersal of diaspores from the surroundings. According to Wiegleb and Felinks (2001), wind dispersal is of utmost importance at the beginning of primary succession. However, colonization through vegetative regrowth from surviving propagules (rhizome fragments, root stocks) in the mudflow sediment cannot be ruled out. Our findings suggest that anemochorous species but also myrmycochorous species can colonize mudflow deposits very quickly if the abiotic environment (e.g., grain size of the deposited substrate) and biotic interactions (competitors) are suitable for seed germination and seedling establishment. It can thus be concluded that the presence of diaspore sources in the surroundings (especially close to mudflow deposits), and hence, the local species pool has a great influence on the revegetation success on mudflow deposits in an early stage of vegetation development. If seed sources are very close to the newly-deposited virgin substrates, succession may progress quickly (Rebele, 1992).

Commercial clover-grass seed mixtures were used for rapid revegetation of mudflow deposits. Thus, the sown plots were characterized by a scarcity of herbs and herb species in the second year after sowing. Depending on the revegetation measure, the revegetated areas were either grass-dominated (seed addition alone), legume-dominated (seed addition combined with the application of lime or cattle manure) or grass-legume-codominated (seed addition combined with straw application). Of the sown species, *F. rubra, A. capillaris, L. perenne, T. repens, T. hybridum* and *L. corniculatus* frequently showed relatively high percent cover (up to 40%). *F. rubra* or *A. capillaris* was usually the dominant grass species on the sown plots. Both forage grasses were also present in the surrounding vegetation of the mudflow deposits (Winter, 2005). We observed a competitive interaction between these two species: either *F. rubra* or *A. capillaris* achieved high cover values on the sown plots. Our data suggest that *F. rubra* has a higher interspecific competitive ability than *A. capillaris* under the conditions of lime or straw application. *A. capillaris* is an acidity indicator (Ellenberg et al., 2001) and hence sensitive to liming (Grime et al., 1988). *A. capillaris* has small seeds with low seed weight (Klotz et al., 2002). Small seeds are believed to require more light for germination than the larger ones (Baskin and Baskin, 2014). We assume, therefore, that *A. tenuis* seeds germinate poor in the dark, leading to a much lower mean *A. tenuis* cover on plots with straw application compared to the plots with seed addition alone. In contrast, *F. rubra* has relatively large and heavy seeds (Klotz et al., 2002). Thus, the seeds presumably germinate equally well in the light and in the dark, increasing germination success under the condition of straw application. *F. rubra* has an exceptionally wide ecological amplitude and is therefore a successful colonizer in many habitats of low to intermediate productivity (Grime et al., 1988). In general, the cover of sown tall grasses (*Dactylis glomerata*, *Festuca pratensis*, *Phleum pratense*) was low due to N deficiency in the substrate. Of the sown species, only *P. pratensis* did not establish successfully. Obviously, this desirable but slowly germinating species (Dietl et al., 1998) has a poor competitive ability under conditions of N shortage. Due to its modest colonization ability, *P. pratensis* is not recommended for rapid revegetation of mudflow deposits and should therefore be excluded from seed mixtures used for rapid revegetation of siliceous mudflow deposits.

The mudflow deposits investigated were virtually humus-free, being N-limited habitats with high light availability to plants prior to the revegetation. Thus, N-fixing herbaceous and woody plants (legumes, *A. alnobetula*) had an enormous competitive advantage over non-N-fixing plants

(particularly grasses) because the former can acquire N by symbiotic fixation of atmospheric N_2 (Lloyd and Pigott, 1967). On many sown plots, the proportion of legumes on the total vegetation cover was greater than 30%, which is too high from an agricultural viewpoint (Buchgraber, 2018). Of the sown legume species, *T. hybridum* can form dense stands on mudflow deposits in the first two years after sowing (particularly on plots with additional straw or cattle manure application), being remarkably effective in suppressing both sown and non-sown species mainly through light deprivation. Thus, *T. hybridum* can be regarded as an undesirable species when increased floristic diversity and high nature conservation value are revegetation targets. *T. hybridum* should therefore be omitted from seed mixtures used for ecological restoration.

The cover of sown legumes was higher, though not significantly, on plots with seed addition and liming than on plots with seed addition alone, indicating that lime addition can have a positive effect on legume growth. In particular, *T. repens* benefited from liming. The positive response of *T. repens* to lime addition on acid soils is well documented (Snaydon, 1962). Our results show that the application of lime to humus-free, N-limited mudflow deposits can result in an undesirable legume dominance if commercial clover-grass seed mixtures are used for revegetation. This, in turn, can impede the germination and establishment especially of non-sown species through shading, leading to a lower species density. Moreover, application of lime inhibits the recolonization of calcifugous species from the surroundings. Thus, lime addition to humus-free, siliceous mudflow deposits is not recommended. On strongly acid soils (pH < 5.0), however, liming is an important measure for soil improvement to increase forage quality and quantity (Bohner, 2010; Schaumberger et al. 2020).

Total vegetation cover was highest on the plot with seed addition and cattle manure application, indicating that plant growth and productivity on mudflow deposits were rather nutrient than water limited. Manuring promoted primarily *T. repens, T. hybridum, L. corniculatus* and *L. perenne* at the expense of *A. capillaris*, suggesting that the sown species differ in their response to cattle manure application on mudflow deposits. Moreover, the establishment of several non-sown species was inhibited by cattle manure application, resulting in a lower species density compared to the other revegetation measures. It is well known that manuring favors a few fast-growing, highly productive, more-nutrient-demanding sown species such as *L. perenne* and inhibits the establishment of slower-growing, less productive and less-nutrient demanding, shade-intolerant non-sown species, leading to a decrease in species density (Hagen et al., 2014). The present study demonstrates that *L. perenne*, a desirable pasture grass, is more competitive than *A. capillaris* in case of cattle manure application to mudflow deposits, indicating that the "competitive power" of sown species changes with the nutrient supply in the substrate. Similarly, Whitehead (1995) found that manuring usually encourage *L. perenne* relative to *A. capillaris*. Cattle manure application considerably increased legume growth, indicating inadequate supply of phosphorus and potassium in the substrate. Tall grasses (*D. glomerata*, *F. pratensis*, *P. pratense*, *Arrhenatherum elatius*), however, benefited only slightly from manuring. The percent cover of each species did not exceed 5%, leading to a plant community with low above-ground plant biomass compared to the plant communities on nutrient-rich soils. The beneficial effect of cattle manure application on legume growth might be attributable to the minimal competition by tall grasses as a result of N deficiency in the substrate. This may explain why sown legumes can grow vigorously on mudflow deposits at one-time cattle manure application and low-intensity grazing. At high soil mineral N levels, however, legumes are usually suppressed by tall grasses (Rebele, 2000). Legumes grow well only when the supply of N is insufficient for maximum grass growth (Whitehead, 1995). It should be noted, however, that our findings concerning cattle manure application to mudflow deposits cannot be generalized due to a lack of replications.

Our data show that straw is an effective long-range dispersal agent for seeds of arable species, contributing to species density on revegetated areas for a short time. The emergence of arable species compensates in part the species loss resulting from straw application. Two years after surface application, straw was still present (up to 80% cover) on mudflow deposits, indicating a very low decomposition rate presumably due to severe N deficiency for decomposers. Straw application had a significant negative effect on total vegetation cover, grass cover and herb cover. In particular, the small-seeded *A. capillaris* was strongly inhibited due to unfavorable conditions for seed germination and seedling establishment. A thick straw layer (> 5 cm deep) generally can prevent the seed germination of plants and seedling establishment through light deprivation and mechanical impediment for seedling emergence (Facelli and Pickett, 1991). According to Voigtländer and Jacob (1987), many grasses and herbs have a light requirement for germination. Thus, they are particularly sensitive to straw application.

Since legumes generally do not require light for germination (ISTA, 2016), they are less negatively affected by surface-applied straw. On the contrary, *T. hybridum* even benefited from straw application, indicating high tolerance to straw application presumably due to low light sensitivity of *T. hybridum* seeds. Moreover, straw decomposition usually causes net N immobilization, which in turn reduces inorganic N supply to plants (Cheshire et al., 1999). In particular, the growth of grasses is impeded due to their generally high N requirement (Woodmanse and Duncan, 1980). In N-limited habitats, microbes require additional N to decompose plant material with high C:N ratio such as straw (Barrett and Burke, 2000). Therefore, a pure straw application to N-limited mudflow deposits should be avoided. On exceptionally hot-dry locations, on sites susceptible to erosion and on sites where seeds are easily moved horizontally on the soil surface by wind action or water runoff, however, surface application of straw is a suitable restoration technique (Baasch et al., 2012; Scotton et al., 2012).

Revegetation success also depended on grain size of the deposited substrate, being less successful on areas with particularly high content of coarse surface substrate than on areas with plenty fine-grained substrate. It appears that fine-grained deposits facilitate rapid grassland reestablishment, presumably because of a better exploitation of water and nutrient resources by plants as a result of greater root zone. This result is in agreement with Hagen et al. (2014), who found in a greenhouse experiment that the growth of *F. rubra* and *F. ovina* was much lower on the coarse mineral soil than on the fine mineral soil. Under certain conditions, however, coarse surface substrate can also be advantageous for the initial plant colonization through trapping of seeds and vegetative propagules (Jumpponen et al., 1999).

Further vegetation development on mudflow deposits depends largely on humus build-up, which is a very slow process, and N accumulation in the substrate by N-fixing plants. In particular, on legume-dominated sown areas, the inorganic N supply to plants may increase substantially due to the decomposition of N-rich legume residues, which in turn facilitates the growth of grasses in later stages of vegetation development (Whitehead, 1995).

To our knowledge, this is the first report on the large-scale revegetation of mudflow deposits for agricultural purposes. Our findings are representative of siliceous mudflow deposits in the montane belt of the Nature Park Sölktäler. Further systematic studies on revegetation measures in different landscapes, altitudes and substrate types are necessary for a more comprehensive evaluation of the effectiveness of different revegetation measures on mudflow deposits. Our results obtained two years after sowing must be considered as preliminary. A much longer time period (10 years) is needed for evaluation of the long-term revegetation success (Turnbull et al., 2000; Verhagen et al., 2001; Auestad et al., 2016; Storm et al., 2016). Nevertheless, our preliminary findings can be used for optimizing revegetation measures on siliceous mudflow deposits in the montane belt in areas of temperate climate. Further research should focus on the possibility to use fresh (undried), seed-containing hay from local grasslands (*Festuca rubra-Agrostis capillaris* meadows) or locally collected seed mixtures for rapid revegetation of siliceous mudflow deposits (Kiehl et al., 2010; Baasch et al., 2012; Auestad et al., 2016).

5. Conclusions and implications for practice

Based on our vegetation data, the following conclusions and recommendations for rapid revegetation of siliceous mudflow deposits in the montane belt for agricultural purposes in areas of temperate climate can be made:

- Seed limitation appears to be the most important revegetation constraint. Hence, sowing seeds can considerably accelerate the reestablishment of mountain pastures on mudflow deposits.
- On mudflow deposits, due to the unfavorable abiotic site conditions, several species from the surrounding vegetation can establish without being suppressed by the sown species.
- *F. rubra*, *A. capillaris*, *L. perenne*, *T. repens* and *L. corniculatus* are particularly suitable for rapid grassland reestablishment, whereas *P. pratensis* is not recommendable.
- On mudflow deposits, a lack of humus (N deficiency) favors the establishment of legumes at the expense of grasses.
- A pure straw application should be avoided, because it delays the revegetation success.
- Lime addition is not recommended, because it can lead to an undesirable legume dominance if commercial clover-grass seed mixtures are used for revegetation.
- Cattle manure application seems to be particularly suitable for grassland reestablishment, increasing vegetation cover rapidly.

- Seed addition without additives appears to be the most effective revegetation measure for rapid and large-scale reestablishment of pasture areas.
- To facilitate revegetation on coarse-grained deposits, large rocks should be crushed using a stone mill.

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