RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

SER SOCIETY FOR ECOLOGICAL RESTORATION

RESEARCH ARTICLE

Nitrogen fertilizer enhances vegetation establishment of a high-altitude machine-graded ski slope

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Machine grading is frequently required to prepare the terrain when building high-altitude ski slopes in the Alps. However, this kind of disturbance alters the natural environment, destroying the vegetation and hampering its reestablishment. Thus, specific restoration plans are necessary to encourage the recovery of vegetation, which is already affected by different natural constraints in this harsh environment. One of the main critical factors affecting plant growth in high-altitude areas is the lack of available nitrogen (N) in the soil. In this context, the addition of a slow-release N fertilizer was carried out in an experimental revegetated ski slope between 2,800 and 2,900 m above sea level in the western Italian Alps. Both vegetation and soil were monitored during a 5-year period in order to test the effectiveness of N addition on the restoration process. Even if effects on soil carbon and N contents were negligible, vegetation was remarkably affected by the fertilization, since the total vegetation cover and the species richness significantly increased. Against the expectations, there was a remarkable increase in spontaneous forbs, rather than in most of the sown graminoids, which slightly varied during the experimental period. Actually, graminoids responded in different ways, mostly increasing (likewise forbs), but the slight decrease of the dominant *Festuca nigrescens* (Chewing's Fescue) masked their spread. This study confirms the noteworthy role of N in high-altitude alpine soils and consequently its importance to improve the restoration process of degraded ecosystems.

Key words: alpine tundra, biodiversity, fertilization, nitrogen, restoration, sowing

Implications for Practice

- N fertilization can be effectively used to improve vegetation cover at high-altitude alpine areas.
- Colonization of ski slopes by spontaneous forbs can be facilitated by N supply.
- Positive effects of N fertilization can be already observed in the medium term.

Introduction

The intensification of human activity in the alpine areas for recreational purposes has increased the anthropogenic disturbance in high-altitude alpine ecosystems, which are particularly vulnerable because of their extremely harsh environmental conditions (Kangas et al. 2009; Meijer Zu Schlochtern et al. 2014). Among others, the presence of ski slopes is one of the most impacting human activities. The Alps are widely affected by the presence of ski domains that generally develop over large areas, ranging from the mountain up to the alpine belt, thus interacting with a huge gradient of ecological conditions.

At the highest altitudes, where soils are generally shallow and not well developed and vegetation establishment is difficult and time-demanding, the impacts on the ecosystem are more relevant and the restoration requires a long time. In particular, the use of grading machines employed to set a new ski slope produces a complete degradation of soil horizons and destroys the vegetation cover (Wipf et al. 2005; Roux-Fouillet et al. 2011). The increased erodibility caused by machine-grading is combined with an increase in erosivity due to artificial snowing, that nearly doubles the melt-water supply in spring producing an intense erosion effect (Roux-Fouillet et al. 2011; Meijer Zu Schlochtern et al. 2014).

The most common practice adopted to counteract erosion processes in high-altitude ski slopes is revegetation with an adapted seed mixture through artificial sowing. Indeed, apart from other provided ecosystem services (e.g. biodiversity, aesthetic value, feed for fauna, and water quality), the vegetation has a well acknowledged function of erosion control (Martin et al. 2010) and the different ways to improve the revegetation

Author contributions: ML, GL, MF conceived and designed the research; DB, SR, MP, DV performed the experiments; DB, SR, MP analyzed the data; DB, SR, DV, MP, GL, ML, MF wrote and edited the manuscript. MF, ML equally contributed to this work.

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doi: 10.1111/rec.13777
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.13777/suppinfo

success have been intensively studied (Urbanska 1995; Barni et al. 2007; Kangas et al. 2009). Indeed, the vegetation cover hampers soil erosion, by protecting the exposed soil from natural erosion agents and by improving the soil structure through increased organic matter content (Garcia-Pausas et al. 2017). Concerning vegetation composition, Martin et al. (2010) identified the diversity in functional groups and species richness as important factors affecting inter-rill erosion. Grasses, such as *Festuca halleri* All. (Haller's Fescue), have a crucial role for surface erosion containment because of their large quantity of fine roots (Martin et al. 2010; Pohl et al. 2011). Instead, forbs and legumes (such as *Minuartia recurva* [All.] Schinz & Thell. [Recurved Sandwort] and *Trifolium pallescens* Schreb. [Fading Clover]) are particularly well adapted to contain erosion processes in the deeper horizons of the soil, because of their long and robust root systems (Hudek et al. 2017). A species-rich vegetation community with complementary root types is optimal to reduce erosion processes (Pohl et al. 2009; Pohl et al. 2011).

Nonetheless, the vegetation establishment and its reproduction are particularly difficult at high elevations (i.e. above 2,500 m above sea level [a.s.l.]), due to several environmental constraints, such as short vegetative season, reduced soil nutrients, lack of pollinators, and high ultraviolet radiation (Körner 2003). The anthropogenic constraints worsen these critical conditions, since machine-grading alters the soil suitability for plants, while grooming produces mechanical damages to the vegetation and artificial snowing reduces the vegetative season.

According to the literature, at high altitudes plant growth and the consequent reproductive success are more affected by soil nutrients than by temperature (Theodose & Bowman 1997; Bret-Harte et al. 2004; Negro et al. 2013). Nitrogen (N) represents the most limiting nutrient, because the N cycle is largely dependent on biological activity, which is concentrated in the short warm season (Körner 2003; Freppaz et al. 2010). However, the relationship between temperature and nutrients is well-known: arctic and alpine regions have low soil nutrient contents, especially the plant-available ones, since temperature constraints hamper decomposition and mineralization processes (Körner 2003). The colonization of these areas is therefore slow and few plant species are adapted to cope with these pedo-climatic conditions (Barni et al. 2007; Freppaz et al. 2010; Negro et al. 2013).

Fertilization and organic amendment represent an effective solution to counteract these constraints by enhancing the success of the seedlings of sown species. Fertilization is an agronomic practice widely applied to foster growing and reproductive rates of several species in agricultural lands. Its effects have been demonstrated on high-altitude species as well, including grasses and other graminoids (Theodose & Bowman 1997; Bret-Harte et al. 2004) and forbs (Gough et al. 2002; Kelley & Epstein 2009). Organo-mineral fertilizers with a high percentage of fulvic and humic acids can also improve the soil structure and reduce its erodibility. Growth stimulation after long-time N addition was proven in a wide array of ecosystems: from arctic and alpine ground-layer communities (Van Wijk et al. 2004; Bassin et al. 2012) to glacier forefields (Heer & Körner 2002). However, despite its relevant interest for the management of ski slopes, recently the research on fertilization as a tool to improve high-altitude revegetation success has been mainly concentrated in the Rocky Mountains and in the arctic region (Bret-Harte et al. 2004; Kelley & Epstein 2009; Gasarch & Seastedt 2015). While several scientific studies dealing with European Alps was published until the 1990s, a few papers can be found in recent issues (e.g. Hudek et al. 2020; Scotton 2021).

The main aim of our research was to assess if fertilizer addition could accelerate restoration processes of a high-altitude ski slope, machine-graded, and subsequently reseeded, through vegetation enhancement. In detail, we hypothesized that N fertilization could improve the soil and make it more suitable for plant growth. Thus, the specific objectives of the experiment were to assess if the fertilization was effective in: (1) improving the C and N availability of the soil; (2) increasing the vegetation cover and (3) its diversity; and (4) achieving a vegetation composition similar to those of the surrounding natural communities. According to the literature, the first two objectives were expected to be achieved, while we hypothesized a little effect of fertilization on plant diversity and no significant effect on the abundance of spontaneous species from the surrounding natural areas.

Methods

Study Area

The experiment was carried out at the "Olen" ski slope of the "MonterosaSki" resort, northwestern Italian Alps (45°52′28″N, 7°52′22″E). The area, located in the alpine belt, is characterized by an endalpic sub-oceanic climate. From 2007 to 2018, the area

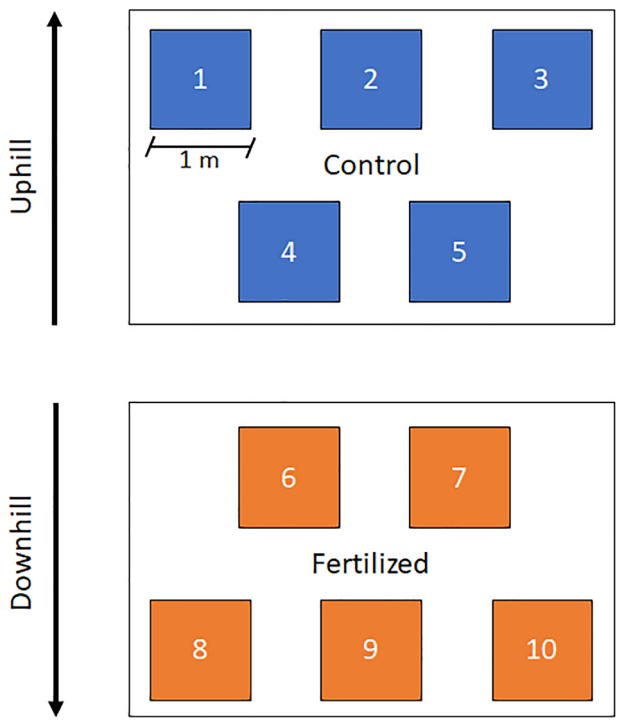

Figure 1. Experimental design of the surveyed sites. Each quadrat represents an experimental plot: blue for fertilized ones and orange for control ones.

had a mean annual air temperature of −2.2°C, a mean cumulative annual snowfall of 818 cm, and a mean annual liquid precipitation of approximately 400 mm (Pintaldi et al. 2020). The snowpack usually persists from late October–early November, to late May–early June, when snowmelt starts (Quaglia et al. 2020). Soils originated from michaschists, which determines a sub-acid reaction and were classified by Freppaz et al. (2019) as Skeletic Dystric Regosol and Skeletic Umbrisol (Arenic) according to IUSS Working Group WRB (2015).

The spontaneous vegetation was mainly represented by alpine tundra species, dominated by plants (mainly hemicryptophytes) belonging to alpine communities typical of siliceous substrates (i.e. *Androsacetalia alpinae* phytosociological order). Snowbed communities (i.e. *Salicetalia herbaceae*) and wind-edge communities (i.e. *Caricetalia curvulae*) were sparsely represented. These vegetation communities were identified as habitat 8,110 "Siliceous screes of the montane to snow levels" (Annex 1 of Council Directive 92/43/ECC).

Experimental Design

The ski slope monitored in the present study was built in 2009. Three sites of the slope were sown in September 2009, after the machine-grading, with a seed mixture adapted for the revegetation of areas with acidic substrate over 1,700 m a.s.l. (ReNatura Saatbau; the complete list of plant seeds in the mixture is provided in Table S1), with a sowing density of 50 g/m^2. After germination, the overall vegetation cover remained unvaried and slightly above 40% until 2015, thus a fertilization experiment was established to improve the vegetation cover. The three selected study sites were located along the ski slope. Site 1 was located at 2,899 m a.s.l., with an aspect of 129°N and a slope of 18.7°. Site 2 was 96 m far away, at an altitude of 2,875 m a.s.l., with an aspect of 96°N and a slope of 18.8°. Finally, site 3 was 440 m far from site 2 at an altitude of 2,801 m a.s.l. and was characterized by an aspect of 90°N and a slope of 1.4°. The fertilization experiment was set in the three sites, five vegetative seasons after the sowing, that is, in September 2015. Each site was split into two parallel strips along the slope and two contrasting treatments were applied: the bottom strip was fertilized while the top strip was never fertilized and used as control. The fertilization was applied to the bottom strip to avoid a possible leaching from fertilized to control str. Ten permanent 1 × 1–m plots were positioned at each site, five in the fertilized and five in the control strip, respectively, at a mean distance of 0.75 m each other within each strip. A diagram of the experimental design is provided in Figure 1. Fertilization was applied once per year at the beginning of September with 100 kg/ha of slow-release N-based organo-mineral fertilizer (AZOTOP 30, Scam), whose

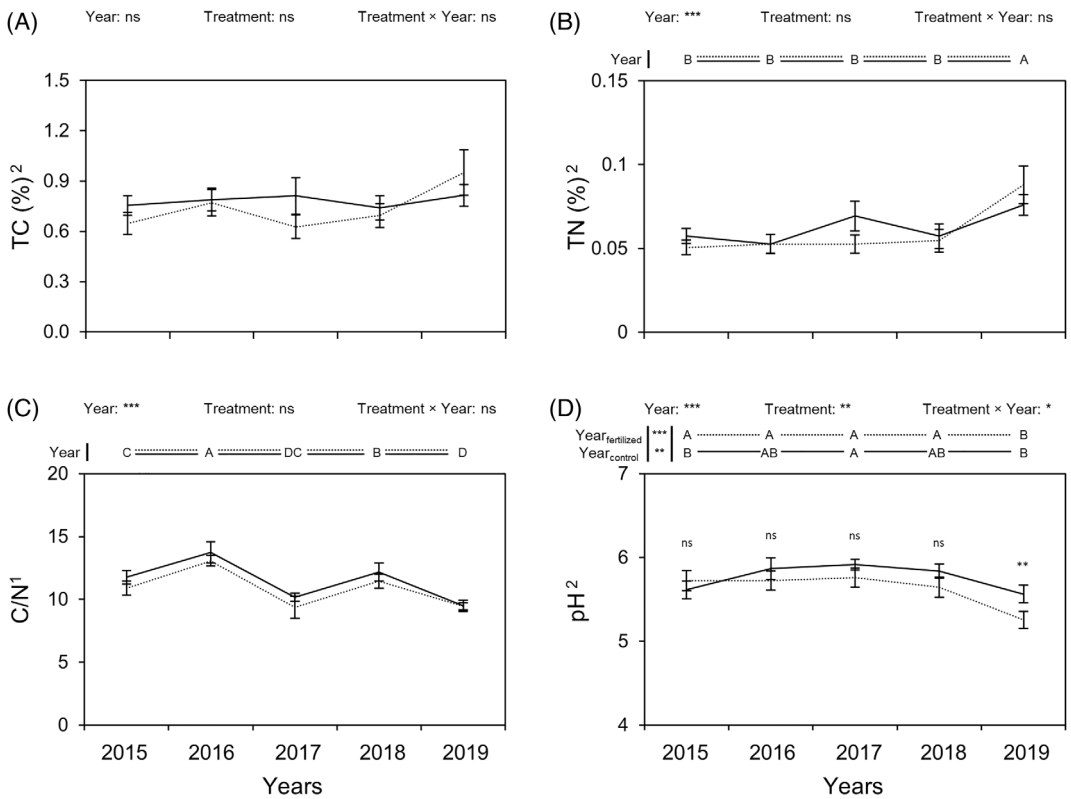

Figure 2. Comparison between fertilized (dashed line) and control (solid line) along the 5 years (2015–2019) for (A) total carbon (TC), (B) total nitrogen (TN), (C) C/N, and (D) pH. Error bars represent ± SE. Apex numbers after variable names indicate the data distribution specified in the respective model: 1, Gaussian; 2, gamma. In the upper part of each figure the significance of year, treatment, and year × treatment is provided (ns, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$). Differences between treatments and among years are provided according to Tukey's post-hoc tests.

composition is reported in Table S2. The application of 30 kg/ha of N was an intermediate amount between the values reported by most of the studies carried out in tundra ecosystems (e.g. Deshaies et al. 2009; Sundqvist et al. 2014) and those produced by atmospheric deposition in the Alps according to Rogora et al. (2006), in order to avoid an imbalance in the root/shoot ratio. The fertilizer had a high percentage of humic and fulvic acids (36%) to enhance the soil structure and the nutrients retention. The fertilizer was distributed at the end of the growing season to maximize the slow-release effect on the plant–soil system in the following year.

Vegetation surveys and soil sampling were carried out in September, once per year for 5 years, in 2015, 2016, 2017, 2018, and 2019.

Soil Data

At each site, one soil sample (at 5 cm depth) was collected close to every permanent plot at the beginning of September, before fertilization. Soil samples were dried at 45°C and sieved at 2 mm mesh size. An aliquot was milled and sieved subsequently at 0.5 mm mesh size. The pH of the 2-mm sieved soil samples was measured in water at a soil-to-solution volume ratio of 1:2.5. Total carbon (TC) and total nitrogen (TN) were determined in the 0.5-mm sieved soil samples using a C/H/N analyzer (Elementar Vario EL). Since the soil material was free of carbonate, the total C was considered as organic C. The C/N ratio was then calculated dividing TC by TN.

Vegetation Data

Vegetation composition was surveyed within each quadrat plot along the two diagonals with the vertical point-quadrat method (Daget & Poissonet 1971). Each plant touching a steel needle at every 2-cm interval was identified and recorded. For each diagonal, 50 points were surveyed, starting at 20 cm from the upstream corner of the plot, for a total of 100 recordings in each plot. To avoid occasional species missing, the complete list of all the other species in the 1 × 1–m plot was recorded. Species nomenclature followed Landolt et al. (2010). The surveys were carried out at the same date of soil sampling and fertilization, corresponding to the optimal phenological stage of vegetation.

For each vegetation survey, the proportion of the total number of recording points where whatever species was recorded on the 100 points of the vegetation survey was considered as the total vegetation cover. Similarly, the frequency of occurrence of each recorded plant species was calculated as the number of occurrences of every species on the 100 points of vegetation survey and considered as an estimate of each species cover. According to Tasser and Tappeiner (2005) a cover of 0.3% was attributed to each occasional species not occurring on the diagonals but recorded in the plot area. Species diversity was evaluated as both species richness (total number of species per plot) and Shannon index (Magurran 1988). For every plot, species number and cover of sown and spontaneous species and of graminoid, forb, and legume functional groups, were calculated.

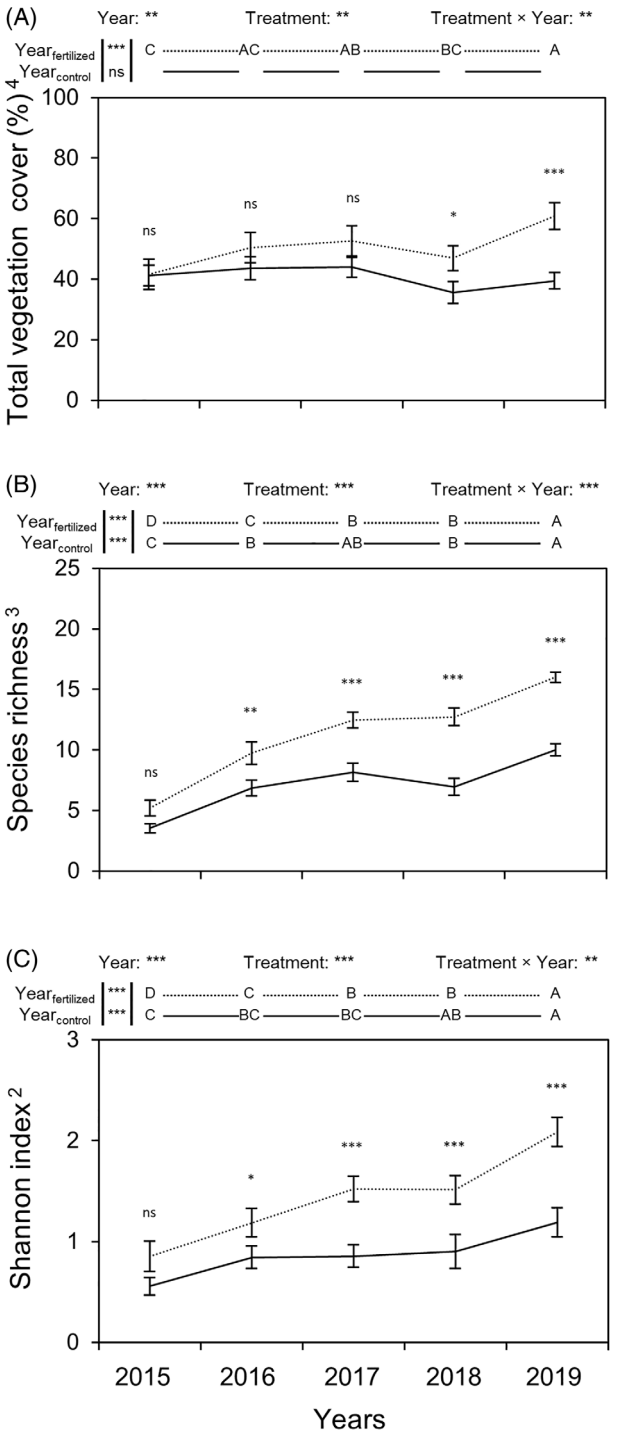

Figure 3. Comparison between fertilized (dashed line) and control (solid line) along the 5 years (2015–2019) for (A) total vegetation cover, (B) species richness, and (C) Shannon index. Error bars represent ± SE. Apex numbers after variable names indicate the data distribution specified in the respective model: 2, gamma; 3, Poisson; 4, beta. In the upper part of each figure the significance of year, treatment, and year × treatment is provided (ns, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$). Differences between treatments and among years are provided according to Tukey's post-hoc tests.

Data Analysis

Soil and vegetation variables were modeled with generalized linear mixed models (GLMMs) to test for differences between treatments through time. Treatment, year, and their interaction were set as fixed factors, while plot nested within site were set as a random factor to account for the repeated measure structure. The continuous variables were modeled with both Gaussian and gamma functions, while count variables were modeled with both Poisson and negative-binomial functions. Between the two models run for each variable, the one with the lowest Akaike's information criterion value was considered as the best fitting model and retained (Zuur et al. 2009). The data distribution chosen for each response variable is indicated in the graph of each variable (Figs. 1–4). Total vegetation cover, the cover of spontaneous and sown species, and of graminoids, forbs, and legumes were modeled with beta distribution, being percentage variables in a 0–1 interval. Since this distribution does not accept 0 and 1 values, and because 0 was a frequent value, cover values were previously corrected with Smithson and Verkuilen (2006) transformation. Tukey's post-hoc tests were performed to ascertain significant differences among treatments within each year and among years within each treatment. When the interaction was not significant, Tukey's post-hoc tests were performed separately for treatment and year to evaluate the single factor effects (Wei et al. 2012).

The GLMMs were performed in the version 3.6.2 of R environment (R Core Team 2019) with the "glmmTMB" package (Brooks et al. 2017), while Tukey's post-hoc tests were performed with the "emmeans" and "multcomp" packages (Hothorn et al. 2008; Lenth 2020).

A redundancy analysis (RDA) was performed to assess the relationships among soil and vegetation data. Two main matrices were arranged: (1) a vegetation matrix, with the SRA of the functional groups, the total vegetation cover, the number of species, and the Shannon index; (2) a soil matrix, including pH, TN, TC, and C/N. Only the "graminoids," "forbs," and "legumes" functional groups were included in the first matrix because the "sown" and "spontaneous" species groups were highly correlated with the previous ones. The two matrices were standardized (z-scores) because they had different units of measurement. The RDA was performed with the statistical program Past 4.04 (Hammer et al. 2001). The significance of the analysis was assessed with Monte Carlo test (999 permutations).

Additionally, to investigate the response of single plant species to fertilization during time, a principal response curve (PRC) analysis was performed in the R environment with the

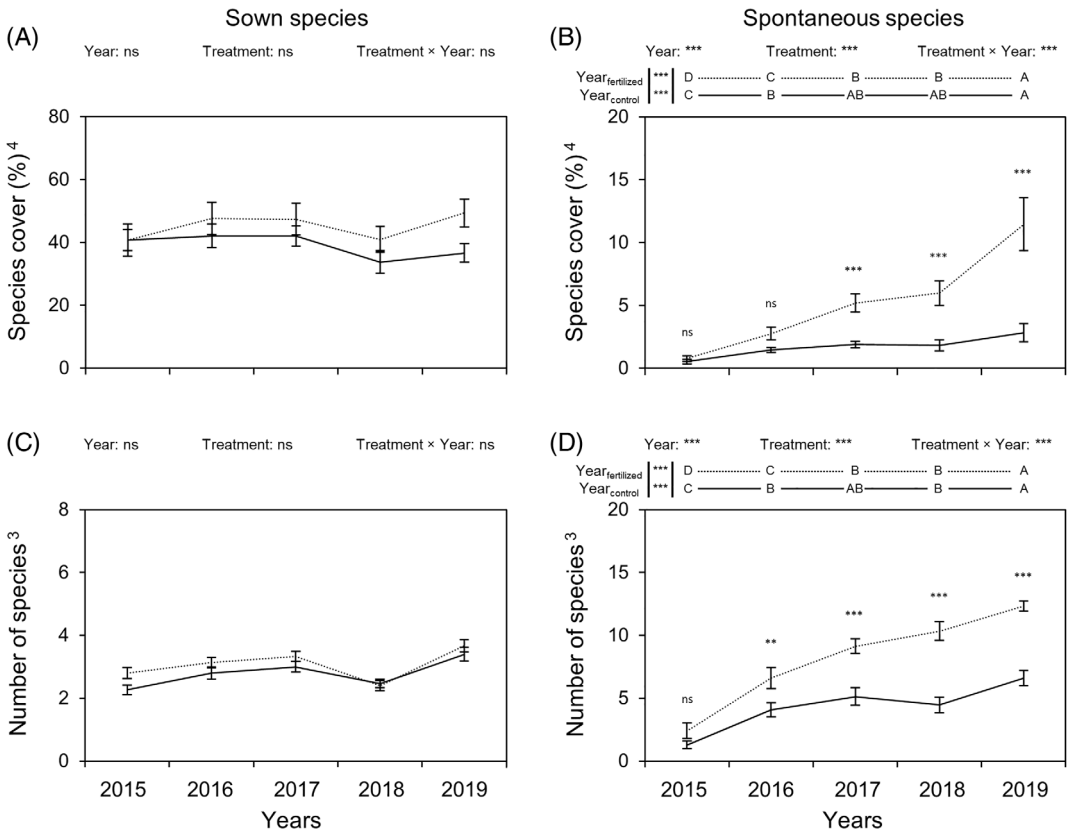

Figure 4. Comparison between fertilized (dashed line) and control (solid line) along the 5 years (2015–2019) for (A) cover of sown species, (B) cover of spontaneous species, (C) number of sown species, and (D) number of spontaneous species. Error bars represent SE. Apex numbers after variable names indicate the data distribution specified in the respective model: 3, Poisson; 4, beta. In the upper part of each figure the significance of year, treatment, and year × treatment is provided (ns, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$). Differences between treatments and among years are provided according to Tukey's post-hoc tests.

package "vegan" (Oksanen et al. 2019). For each of the four monitored years a permutational multivariate analysis of variance (PERMANOVA) using Bray–Curtis dissimilarity distance was carried out to assess the difference in plant species composition between fertilized and control treatments, using the software Past version 4.04 (Hammer et al. 2001).

Moreover, a set of two-sample paired tests was used to evaluate the variations in each species cover between the beginning (2015) and the end (2019) of the experiment within both treatments. Normal distribution of the differences in each species cover between 2015 and 2019 by paired samples was checked in order to choose the best fitting test: for normally distributed differences, a paired *t* test was carried out, otherwise a nonparametric Wilcoxon test was chosen (Hammer et al. 2001). These analyses were performed with Past version 4.04 as well.

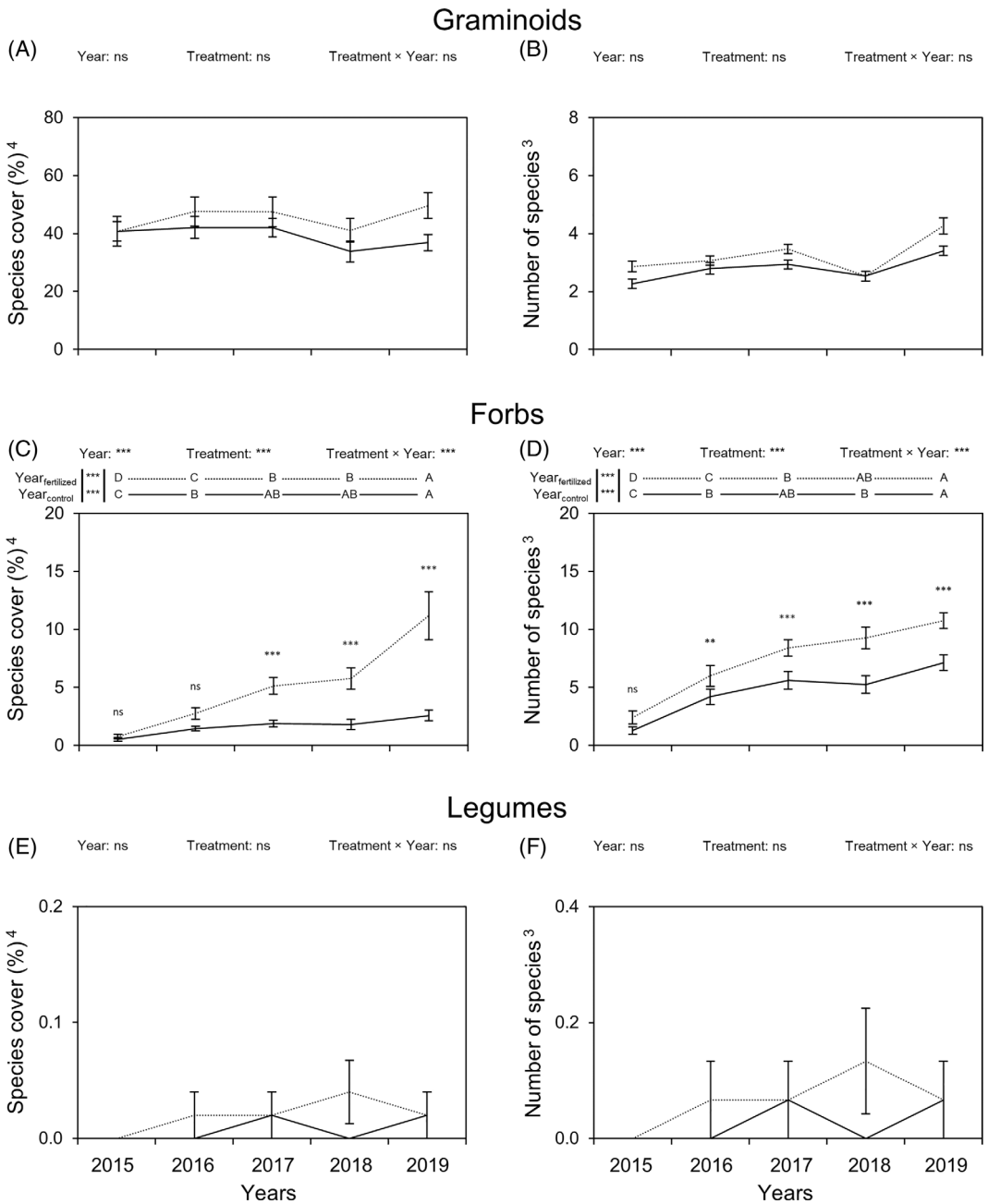

Figure 5. Comparison between fertilized (dashed line) and control (solid line) along the 5 years (2015–2019) for (A) cover of graminoids, (B) number of graminoids, (C) cover of forbs, (D) number of forbs, (E) cover of legumes, and (F) number of legumes. Error bars represent ± SE. Apex numbers after variable names indicate the data distribution specified in the respective model: 3, Poisson; 4, beta. In the upper part of each figure the significance of year, treatment, and year × treatment is provided (ns, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$). Differences between treatments and among years are provided according to Tukey's post-hoc tests.

Results

Soil properties and plant community variables were homogeneous between treatments and among sites at the beginning of the experiment (Table S3). The GLMM results highlighted no significant difference in 2015 data, while the analyzed variables were differently affected by the fertilization in the following years (Figs. 2–5 & 7).

Effects of N Fertilization on Soil Properties

Soil properties weakly varied among years and between treatments (Fig. 2). Particularly, no significant differences were found in TC, while a slight increase in TN contents was observed in both treatments only in 2019 compared to the previous years (Fig. 2A & 2B). Concerning C/N ratio, temporal variations among years were moderate showing a weak decreasing trend, while no differences between treatments were found (Fig. 2C). A significant effect of treatment × year interaction for pH was observed but its values varied only in 2019 compared to previous years in fertilized plots and in 2017 compared to the beginning (2015) and the end (2019) of the experiment in control ones, respectively (Fig. 2D). The GLMM did not show any significant difference between fertilized and control treatments within years in pH values, except for 2019 when fertilized plots had lower values. The RDA showed significant ($p < 0.001$) relationships between soil and vegetation features, though with only an overall explained variance of 14.4% (9.1% for the first axis, 5.3% for the second one; Fig. 6). Particularly, the decreasing pH and the increasing TN were confirmed by the RDA biplot, which also confirmed the weak importance of TC. Indeed, the first axis explained most of the variation due to the fertilization as shown in Figure 6B. The RDA also showed a negative relationship of C/N with the vegetation variables, even if no effects of fertilization were highlighted by the GLMM for this variable.

Effects of N Fertilization on Plant Community

A total of 38 species was found within the experimental plots during the five monitored years, six of which from the seed

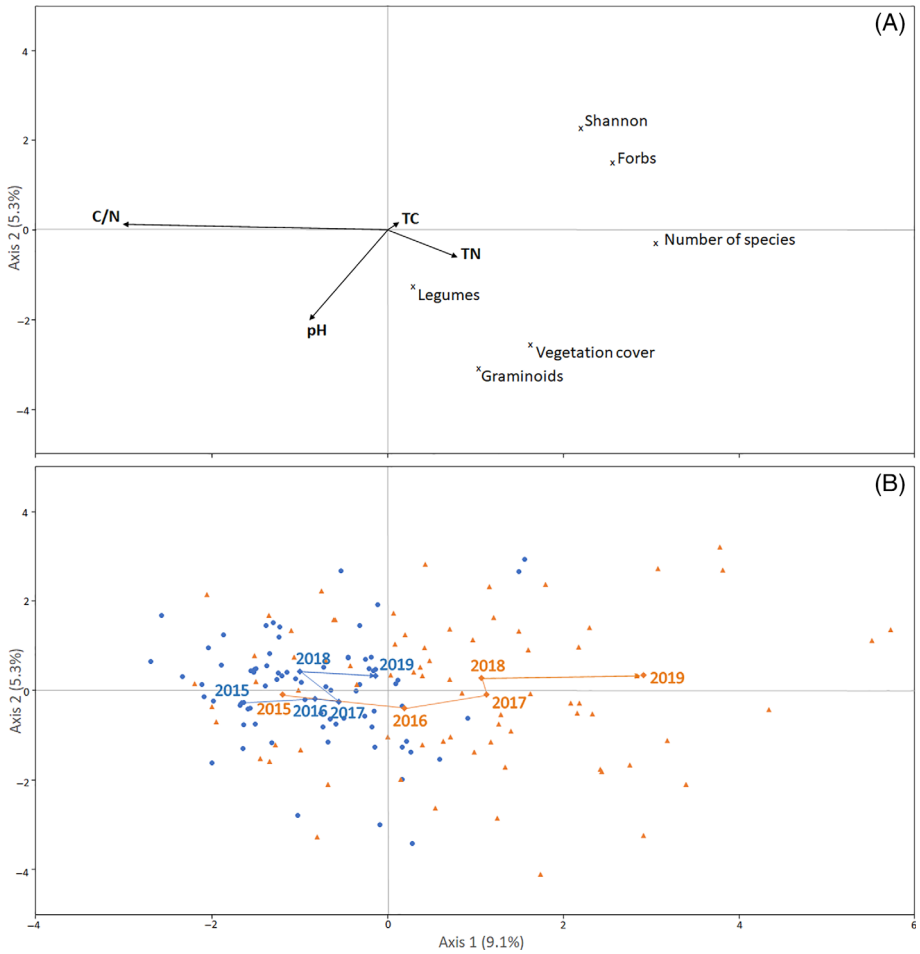

Figure 6. (A) RDA ordination biplot showing the relationships among vegetation (identified by crosses) and soil (identified by arrows) variables. The length of the arrows is proportional to their importance and the direction of the arrows shows their correlation with the axes. (B) RDA ordination plot showing the distribution of the monitoring plots across the years 2015–2019. Rhombi identify the centroids of the fertilized and control plots within each year, while blue dots and orange triangles identify the control and fertilized plots, respectively. The percentage variance explained by each axis is reported in brackets.

mixture sown in 2009. Five sown species belonging to the graminoid group (*Agrostis capillaris* L. [Common Bent], *Festuca nigrescens* Lam. [Chewing's Fescue], *Phleum rhaeticum* [Humphries] Rauschert [Rhaetian Timothy], *Poa alpina* L. [Alpine Meadow-grass], and *Poa variegata* Lam. [Violet Meadow-grass]) and one was the legume *Trifolium pratense* ssp. *nivale* Ces. (Snow Clover). Spontaneous species were instead dominated by forbs (29 species; Table 1), while graminoids and legumes were represented by two (*Agrostis rupestris* All. [Rock Bent] and *Luzula spicata* [L.] DC. [Spiked Woodrush]) and one (*Trifolium thalii* Vill. [Thal's Clover]) species, respectively.

Total vegetation cover did not differ between treatments in 2015 (Fig. 3A), but a gradual increase in the fertilized plots through time determined significantly higher values in this treatment compared to control in 2018 (+11.4%) and 2019 (+21.4%), respectively.

Species richness and Shannon index significantly increased during the experimental period in both treatments, but with higher values in the fertilized than in the control plots (Fig. 3B & 3C). This trend was observed in the differences between treatments within years as well, from 2016 onwards.

Both cover and number of sown species had no significant variation between treatments and among years (Fig. 4A & 4C). Conversely, spontaneous species cover and number significantly increased in both treatments from 2015 to 2019 (Fig. 4B & 4D). The fertilized plots showed higher values than the unfertilized ones from 2017 onwards for species cover and

Table 1. List of recorded sown and spontaneous species (belonging to the three functional groups) with the relative species cover (average value ± standard error of the mean) at the beginning (2015) and the end (2019) of the experiment for fertilized and control treatments. Levels of significance according to the *t* test between 2015 and 2019 for each species within treatment are indicated as: ns, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

		Fertilized			*Control*		
Species	*Functional Group*	*2015*	*2019*	*p*	*2015*	*2019*	*p*
Sown							
Agrostis capillaris	Grasses	0.17 ± 0.133	2.01 ± 0.627	**	0.02 ± 0.020	0.61 ± 0.246	*
Festuca nigrescens	Grasses	34.20 ± 5.793	27.67 ± 3.744	ns	36.80 ± 3.696	30.33 ± 3.461	ns
Phleum rhaeticum	Grasses	0.72 ± 0.350	2.91 ± 0.852	*	0.31 ± 0.204	1.10 ± 0.540	ns
Poa alpina	Grasses	5.68 ± 1.306	16.55 ± 2.646	***	3.62 ± 0.779	4.39 ± 1.218	ns
Poa violacea	Grasses	—	0.22 ± 0.200	ns	—	0.15 ± 0.091	ns
Trifolium pratense ssp. *nivale*	Legumes	—	—	ns	—	0.02 ± 0.020	ns
Spontaneous							
Agrostis rupestris	Grasses	—	0.15 ± 0.070	*	—	0.27 ± 0.267	ns
Luzula spicata	Grasses	0.02 ± 0.020	0.13 ± 0.070	ns	—	—	ns
Androsace alpina	Forbs	—	0.04 ± 0.027	ns	—	0.02 ± 0.020	ns
Arenaria biflora	Forbs	0.02 ± 0.020	0.02 ± 0.020	ns	0.02 ± 0.020	—	ns
Armeria alpina	Forbs	0.02 ± 0.020	—	ns	—	—	ns
Cardamine bellidifolia	Forbs	0.02 ± 0.020	0.34 ± 0.095	**	—	0.14 ± 0.040	**
Cardamine resedifolia	Forbs	0.02 ± 0.020	0.60 ± 0.129	***	—	0.10 ± 0.038	*
Cerastium cerastioides	Forbs	—	1.27 ± 0.482	***	—	0.33 ± 0.052	***
Cerastium uniflorum	Forbs	0.12 ± 0.039	0.31 ± 0.080	*	0.04 ± 0.027	0.06 ± 0.032	ns
Draba aizoides	Forbs	—	—	ns	—	—	ns
Euphrasia alpina/minima	Forbs	0.04 ± 0.027	—	ns	0.04 ± 0.027	—	ns
Gentiana bavarica	Forbs	0.02 ± 0.020	—	ns	0.02 ± 0.020	—	ns
Gnaphalium supinum	Forbs	0.04 ± 0.027	0.71 ± 0.209	***	0.04 ± 0.027	0.27 ± 0.063	**
Leontodon helveticus	Forbs	—	0.26 ± 0.142	*	—	0.02 ± 0.020	ns
Leucanthemopsis alpina	Forbs	0.04 ± 0.027	1.20 ± 0.427	***	0.06 ± 0.032	0.23 ± 0.067	*
Minuartia recurva	Forbs	—	—	ns	—	—	ns
Minuartia sedoides	Forbs	0.17 ± 0.070	1.49 ± 0.628	**	0.17 ± 0.091	0.26 ± 0.027	ns
Oxyria digyna	Forbs	—	—	ns	—	—	ns
Phyteuma hemisphaericum	Forbs	—	0.02 ± 0.020	ns	—	—	ns
Ranunculus glacialis	Forbs	—	0.02 ± 0.020	ns	—	0.02 ± 0.020	ns
Sagina saginoides	Forbs	0.08 ± 0.035	2.25 ± 1.143	***	0.04 ± 0.027	0.36 ± 0.134	**
Salix herbacea	Forbs	—	0.25 ± 0.131	*	—	0.10 ± 0.038	*
Salix serpyllifolia	Forbs	—	0.02 ± 0.020	ns	—	—	ns
Saxifraga bryoides	Forbs	—	0.14 ± 0.040	**	—	—	ns
Saxifraga oppositifolia	Forbs	0.02 ± 0.020	0.02 ± 0.020	ns	—	—	ns
Saxifraga seguieri	Forbs	—	—	ns	—	—	ns
Sedum alpestre	Forbs	0.02 ± 0.020	0.25 ± 0.065	**	—	0.08 ± 0.035	*
Senecio halleri	Forbs	—	0.04 ± 0.027	ns	—	0.02 ± 0.020	ns
Silene acaulis	Forbs	0.10 ± 0.038	1.31 ± 0.516	***	0.09 ± 0.068	0.47 ± 0.326	*
Thlaspi rotundifolium	Forbs	0.02 ± 0.020	0.07 ± 0.067	ns	—	—	ns
Veronica alpina	Forbs	—	0.49 ± 0.139	**	—	0.10 ± 0.038	*
Trifolium thalii	Legumes	—	0.02 ± 0.020	ns	—	—	ns

from 2016 onwards for species number, and the difference between fertilized and control further increased during the following years.

The variations in terms of functional groups between treatments and among years are reported in Figure 5. No significant difference was found concerning graminoid species cover and number. On the other hand, forb species increased both in terms of species cover and number in the fertilized and unfertilized treatments during time, as shown in Figure 4C and 4D. However, the fertilized plots showed higher values than the control ones for both the forb species cover (from 2017) and the number of species (from 2016). The presence of legumes in the experimental plots was marginal, with a limited number of occasional individuals belonging to the two clovers (*T. pratense* ssp. *nivale* and *T. thalii*), which did not experience any significant variation, neither among years nor between treatments (Table 1; Fig. 5E & 5F). This positive relationship between vegetation covers and diversity and fertilization were highlighted also by the RDA (Fig. 6), which explained the positive relationship between vegetation variables and TN. The vegetation variables were generally positioned in the right part of the biplot, which was mainly associated with the effects of fertilization, as shown in Figure 6B.

Concerning the botanical composition of fertilized and control plots at single species scale, the PRC ($F = 21.133$; $p < 0.001$) showed that the treatment had a negligible effect in the variation of most of the single species cover. The species which mostly contributed to fertilized and control plots differentiation were *P. alpina* and *F. nigrescens*, which increased and decreased, respectively, in fertilized plots throughout time (Fig. 7). The PERMANOVA highlighted the absence of differences in species composition between treatments in 2015, while it confirmed the presence of significant variations between fertilized and unfertilized plots already from 2016 onwards (Fig. 7).

As far as the variation in time of the single species cover for each treatment was concerned (Table 1), 15 spontaneous species and three sown species increased in fertilized plots in 2019 compared to 2015. In control plots, instead, the species cover increased only for 10 spontaneous and one sown species, respectively. The cover of *P. alpina* increased 4-fold between 2015 and 2019 in fertilized plots, while it did not change in the unfertilized ones, being the species with the largest difference between fertilized and control treatments. Conversely, the most abundant species *F. nigrescens* decreased in both treatments, even if the variations were not significant.

Discussion

The results of the present work highlighted a significant effect of N-based organo-mineral fertilizer on high-altitude disturbed and restored soils and, particularly, on the sown and spontaneous vegetation.

Magnani et al. (2017) provided data for the undisturbed soils of the same study area, that differed from those of the machine-graded ski slope analyzed in the present study. This should be related to a higher abundance of skeletal fraction and a lower organic matter content in machine-graded soils (Negro et al. 2013), decreasing the suitability for the vegetation. The pH was slightly higher on managed soils, probably because of artificial snowing (Rixen et al. 2003; Kangas et al. 2009; Meijer Zu Schlochtern et al. 2014). The high organic matter accumulation in the upper horizons, typical of these kind of environments (Freppaz et al. 2010), was destroyed almost completely by the machine-grading, as indicated also by Negro et al. (2013).

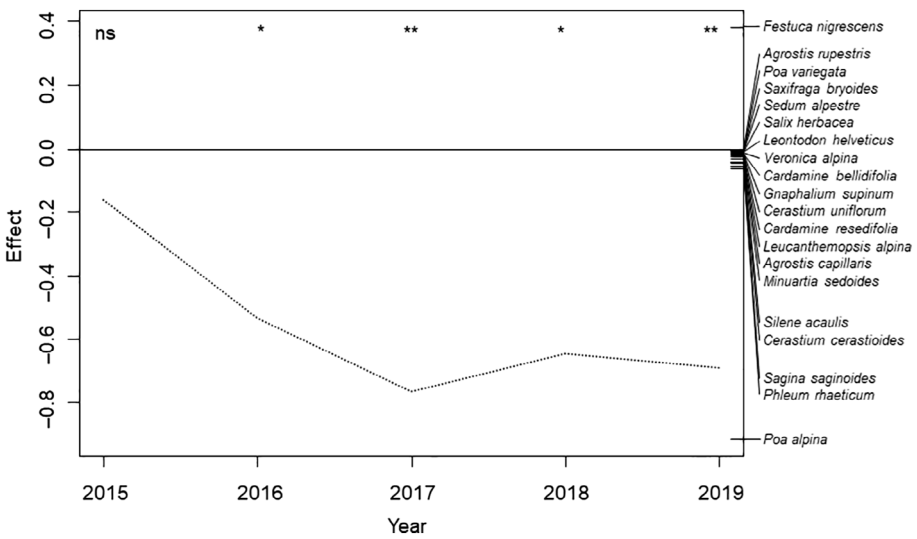

Figure 7. Principal response curve (PRC) diagram showing the difference between fertilized (dashed line) and control (solid line) treatments on vegetation composition throughout time (2015–2019). Significant species are shown on the right side. Only species present in at least five plots in 2019 are listed. For each year, significant differences between fertilized and control treatments are shown in the upper part of the graph according to PERMANOVA (ns, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).

Indeed, TC and TN had lower values than the surrounding undisturbed soils in the same area because of the lower organic matter content. As N is tied to the organic matter, fertilization is particularly important in these harsh environments where labile N is less than 3% of TN (Freppaz et al. 2010); vegetation needs nutrients to increase its biomass and the organic matter in the soil consequently. The slow rate of plant growth and the short vegetative season may be very limiting to the accumulation of organic matter and hence the retention capacity of nutrients. Contrarily to our hypothesis, the fertilization did not have any significant effect on soil properties according to the GLMM. However, C/N differed significantly from year to year showing a slightly decreasing trend, both in control and fertilized. Rather than to the applied treatment, this strong interannual variation may be due to climatic conditions or to the management of the ski slope, which can be artificially snow-covered causing alterations in the nutrients cycling and in the duration of the snowpack (Rixen et al. 2003, 2004; Keller et al. 2004). Even if the variance explained by the RDA was low, the importance of C/N provided by this analysis could be explained by the increase in TN, not associated with a significant increase in TC, thus decreasing the ratio. The decrease observed in pH values during time (especially in fertilized plots) could be the beginning of the soil response to fertilization, as shown also by the increase in TN in the last year of the study. Also TC slightly increased in 2019, but not significantly. The measured variations in soil properties were unexpectedly seldom significant, the effects of fertilization could therefore potentially become relevant in the longer term. Indeed, the whole fertilizer was likely absorbed by the vegetation or partially leached during the months following the fertilization, causing the absence of differences between treatments in the soil, particularly in the amount of TN. The death and decomposition of plant roots and leaves likely increasing through fertilization could lead to an enhancement of organic matter content and its retention of TN in a longer term. This could take probably years or decades to happen in these harsh environments and specific investigations appear advisable.

The fertilizer had beneficial effects on vegetation, which increased with time in terms of both species richness and cover. However, the response was different between sown and spontaneous species, and among functional groups.

The increase in species diversity occurred in both treatments, but was more pronounced in the fertilized one, and the gap between treatments increased with time as well. These changes were mostly related to the increase in spontaneous species number and cover. This unexpected result is in contrast with most of the literature dealing with fertilization in alpine areas. Indeed, a decreased or unvaried species richness after fertilization was found for instance by Gough et al. (2000) and Rajaniemi (2002), which could be explained by the high vegetation cover in their study areas, where the competition for resources was strong. In our study area instead, the total herbaceous cover was about half of the total available plot surface (57.1 ± 1.52%, average value of the 30 plots ± standard error), so the competition for light, water and soil nutrients was limited. Consequently, single plants probably took advantage from nutrient addition, in particular N, which is well-known to be the main limiting factor at high altitude (Körner 2003). As expected, the N supply led to an increase in total vegetation cover, thus confirming its relationship with vegetation productivity for temperate to boreal and alpine ecosystems (Vitousek & Howarth 1991). Fertilization is particularly relevant in areas where legumes and other N-fixing species are lacking (Körner 2003), like the present study site, where the two legume species were occasionally present only in a few plots.

A noteworthy difference in the response to treatments of sown and spontaneous species was recorded. Indeed, the sown species did not spread, even after fertilization, while the colonization of spontaneous species occurred in both treatments. However, this increase was particularly relevant in the fertilized plots, where the fertilizer probably produced a more suitable substrate for seedlings growth, yielding a cover of spontaneous plants four times higher than in control plots. The differences were remarkable also in terms of the number of spontaneous species which colonized the experimental sites during the monitoring period. Some of them (i.e. *T. thalii, L. spicata*, *Saxifraga bryoides* L. [Moss Saxifrage], *Salix serpyllifolia* Scop. [Thyme-leaved Willow], and *Phyteuma hemisphaericum* L. [Globe-headed Rampion]) developed only in fertilized plots, while others (i.e. *Cerastium uniflorum* Clairv. [One-flowered Mouse-ear], *Leontodon helveticus* Mérat [Swiss Hawkbit], *Minuartia sedoides* [L.] Hiern [Cyphel], and *A. rupestris*) in both treatments, but their cover increased significantly only in the fertilized ones. The enhancement of spontaneous species related to fertilizer addition was also observed by Rajaniemi (2002), Gough and Hobbie (2003), and Bret-Harte et al. (2004) in similar environments. According to Urbanska (1995) the establishment of spontaneous species is mainly due to colonization from the natural surroundings, because their seeds are lacking in the seed bank of machine-graded slopes.

The effects of fertilization on functional groups followed a very similar pattern to that of sown and spontaneous species. The cause was a sharp overlap between sown species and graminoids, and between spontaneous species and forbs. The only spontaneous graminoids were *A. rupestris* and *L. spicata*, while no forbs at all germinated from the seed mixture: the only germinated non-graminoid plant was the legume *T. pratense* ssp. *nivale*.

The lack of substantial variations in sown species and graminoids was not in agreement with most of the studies in tundra environments (e.g. Shaver et al. 2001; Bret-Harte et al. 2004; Kelley & Epstein 2009), where fertilization enhanced grass sprouting and consequently their cover. Indeed, in the present trial the overall cover of graminoid species was unvaried but among them some variations were observed. Particularly, the increase in *P. alpina* and *P. rhaeticum* covers after fertilization was hidden by the decrease of the dominant *F. nigrescens*. This was confirmed also by PRC analysis, which showed that the largest contribution on species cover variation after fertilization was due to *P. alpina*, rather than to any forb.

The increasing trend of forbs greatly overlapped that of spontaneous species, with a remarkably higher increase in fertilized areas. However, not all the authors found that fertilizer addition could enhance forbs growth. For instance, Diemer (1992) and

Morecroft and Woodward (1996) reported no variations in *Ranunculus glacialis L.* (Glacier Crowfoot) and *Alchemilla alpina* L. (Alpine Lady's-mantle) growth after fertilization in an alpine environment. These different outcomes highlighted that different forb species may display a different response to fertilization in high-altitude environments and suggest to address focused trials in further research.

Our initial hypotheses were partially confirmed. Indeed, while N addition was effective in enhancing the overall vegetation cover, no significant effects were observed on soil properties as we would have expected. The most surprising results were the benefits of fertilization on the vegetation composition, both diversity and naturalness, especially considering the constraints of the high-elevation environment where the experiment was carried out. Therefore, this study highlights the importance of N content in alpine soils and suggests addressing future research for the assessment of long-term effects of different kinds of fertilizers, in different study sites across the European Alps, possibly differing in substrate and management conditions.

Acknowledgments

The authors thank the technical director of Monterosa 2000 S.p.A., Ing. C. Francione, for his kind collaboration. The "Angelo Mosso" Institute was an important operational base for the experiment, we therefore express high gratitude to its director Professor P. G. Montarolo. We must also acknowledge the many people who participated in the survey campaign: A. Ala, A. Gorlier, G. Nota, R. Pagani, E. Perotti, M. Probo, E. Quaglia, and E. Treves. This work was supported by Monterosa 2000 S.p.A; and by SuperG H2020 Project (grant number 774124). Open Access Funding provided by Universita degli Studi di Torino within the CRUI-CARE Agreement.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Composition of the seed mixture used for revegetation.
Table S2. Composition of the slow-release fertilizer used in the experiment.
Table S3. Mean and standard deviation of the analyzed variables among sites and treatments (control and fertilized).

Coordinating Editor: Shi Kui Dong

Received: 4 April, 2022; First decision: 4 July, 2022; Revised: 22 August, 2022; Accepted: 22 August, 2022