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# Warmer and Poorer: The Fate of Alpine Calcareous Grasslands in Central Apennines (Italy)

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**Abstract:** Global change threatens alpine biodiversity and its effects vary across habitat types and biogeographic regions. We explored vegetation changes over the last 20 years on two Mediterranean alpine calcareous grasslands in central Apennines (Italy): stripped grasslands (EUNIS code E4.436) with *Sesleria juncifolia* growing on steep slopes, and wind edge swards (EUNIS code E4.42) with *Carex myosuroides*. Based on a re-visitation of 25 vegetation plots of 4 × 4 m, we assessed changes in overall and endemic plant species cover and richness by nonparametric Kruskal–Wallis test. We explored changes in structure and ecology using growth forms and Landolt indicators for temperatures. We identified species' contribution to temporal changes using the similarity percentage procedure (SIMPER). The results evidenced a significant decline in all species cover and richness on both plant communities with a significant decline in alpine and endemic species and in hemicryptophytes with rosette and scapose ones on stripped grasslands, as well as a decline in subalpine and suffruticose chamaephytes species on wind edge swards. Such biodiversity loss, so far observed only in the warmest and Southern Mediterranean summits of Europe, is likely attributable to the combined effect of higher temperatures; the increase in the vegetative period; and the decrease in water availability, which is particularly severe in calcareous regions. Our study suggested the vulnerability of the analyzed alpine ecosystems to global change and the importance of monitoring activities to better understand vegetation trends and adaptation strategies in subalpine, alpine, and nival ecosystems.

**Keywords:** climate change; endemic species; Landolt ecological indicator; life forms; plant diversity loss; re-visitation study; stripped grasslands; wind edge swards

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## 1. Introduction

Alpine ecosystems, distributed over the limit of forests and beyond to the snow line, are among the ecosystems most sensitive to and threatened by climate change (e.g., raising temperatures and change in precipitation patterns) [1–3]. Alpine plant communities are mainly shaped by temperatures and hydrologic features, which in turn derive from the interaction of winter precipitation, wind exposure, landscape position [4], snowpack accumulation [5], snowmelt patterns [6], and summer soil moisture [7], overall influencing the duration of the vegetative period [8].

The alpine life zone encompasses low stature vegetation above the climatic tree line worldwide and accounts for approximately 3% of the vegetated land area on Earth [9,10] and, due to their environmental and biogeographic peculiarities, they contain 4% of the Earth's flora (8000–10,000 species of plants) [4]. Alpine ecosystems in Europe host 20% of the native plants, conforming a hotspot of biodiversity [11–13]. Moreover, the complex mosaic of mountain habitats and the presence of dispersal barriers have promoted the presence of highly specialized communities [14], particularly rich in endemic and rare vascular plants [15,16]. Mediterranean summits in Europe deserve particular attention because of the presence of a high amount of endemism [17,18]. Mediterranean alpine ecosystems, having been only partially glaciated during the ice age of Pleistocene [19] and remaining isolated for very long periods, constitute a major refuge of plant species, several of which are cryophilic endemic [20].

Climate change shapes alpine vegetation and plant diversity in different ways. For instance, the increase in temperatures recorded in the last decades [21,22] has consistently altered alpine and nival species' distribution. In several European alpine plant communities, a general increase in species richness [23–25] was registered and it was explained as a "thermophilization process", which consists of the upward shifting of thermophilic plants towards higher altitudes [23,26–35], or as a "range-filling process", performed by species dispersing from existing neighbor communities within the same elevation belt [36,37].

Climate warming may likewise lead to a decline in cryophilic endemic taxa, which become particularly vulnerable because of their specialized habitat requirements, narrow distribution ranges, and low capacity to modify their geographic distribution [38]. Alpine endemics on south Europe, being distributed in small populations with low genetic diversity, are even more vulnerable to global warming [39–41].

In addition to the ongoing increase in temperatures, a reduction in winter rainfalls over the central and southern Mediterranean basin, including Italian Apennines, has been registered during the second half of the 20th century [42,43]. The combination of rising temperatures and decreasing precipitation is most likely related to a steep biodiversity decline documented by recent studies on some Mediterranean summits [23,44–46] and on some calcareous grasslands of the Alps [47].

Considering the consistent and heterogeneous changes ongoing on alpine ecosystems, likely related with both the increase in temperatures [21,22] and the reduction in annual rainfalls [1,42,48–51], the present work sets out to explore vegetation dynamics on alpine Mediterranean calcareous grasslands and swards in central Apennines (Italy). Through a re-visitation vegetation study (after 18 years), we explored the temporal changes in two alpine communities in the Maiella National Park (MNP) that are representative of the central Apennine's alpine belt: Apennine stripped grasslands, growing on steep slopes, and wind edge swards, both included in the 6170 EU Habitat "alpine and subalpine calcareous grasslands" [52,53].

We addressed the following questions: (i) what happened during the last 18 years on Apennine stripped grasslands and wind edge swards in terms of species composition, structure (growth forms), and ecology (Landolt indicator values)? (ii) Do the endemic species cover and richness changed over time?

## 2. Materials and Methods

### 2.1. Study Area

The study area, located in central Italy, includes the higher sectors (from ~2400 up to 2793 m a.s.l.) of the Maiella National Park (Figure 1), characterized by a large limestone summit plateau covered by a thick (1–3 m) mantle of debris, modelled by periglacial processes in which tectonic-karst depressions are surrounded by steep slopes [54,55]. The most prominent soils on the plateau are those with a patterned ground surface of either micro-sorted circles or micro-sorted stripes [56]. The presence of the second highest peak in the Apennines (Mount Amaro, 2793 m a.s.l.) and the great extension of the alpine ecosystems above 2000 m of elevation (59 $km^2$) [55] ensure that alpine vegetation is well expressed in terms of its typical flora [57,58].

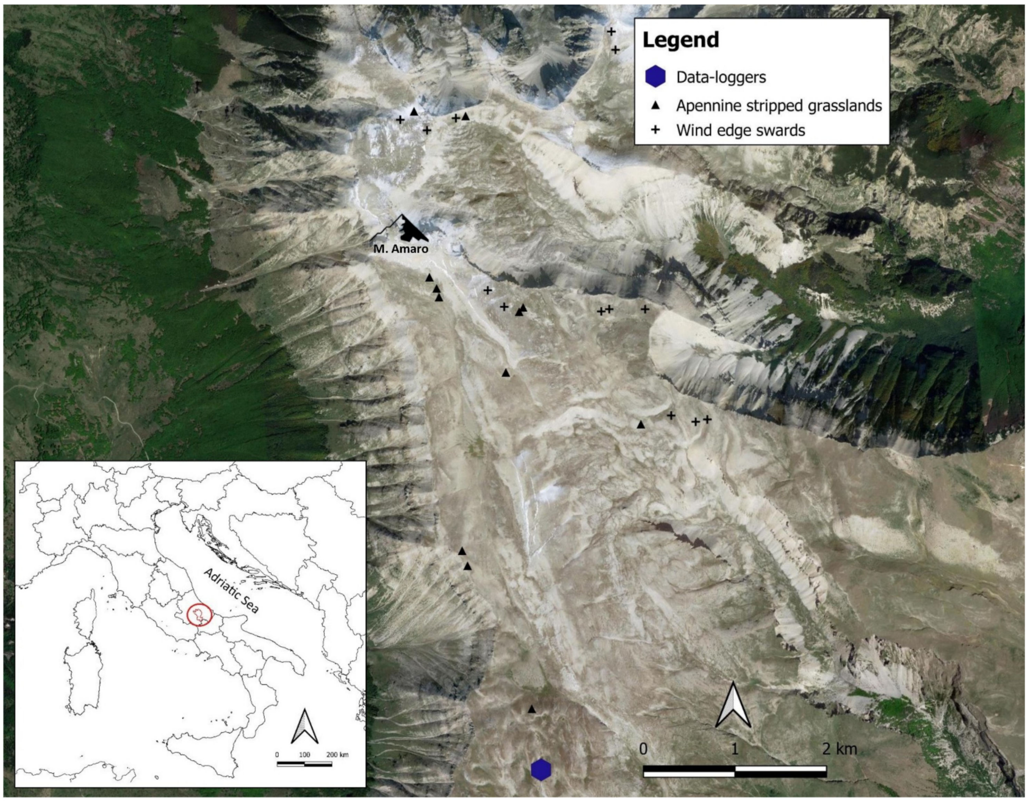


**Figure 1.** Study area (Maiella National Park) along with the distribution of vegetation plots on Apennine stripped grasslands (EUNIS code E4.436) and wind edge swards (EUNIS code E4.42) and of the GLORIA data-loggers measuring soil temperatures on Mt. Femmina Morta.

For these reasons, it is considered an adequate site for investigating climate change effects on Mediterranean alpine vegetation [31,59,60].

### 2.2. Climate Features

From a bioclimatic point of view, the analyzed summits are included in the alpine biogeographical region [61] and the climate corresponds to the subalpine–alpine humid type. As in other alpine ecosystems, the climate in central Apennines has consistently changed during the last 60 years, with a significant increase in mean annual temperatures (+1.7 °C, amounting to 0.26 °C per decade) [35,62], spring and winter minimum temperatures, and summer mean temperatures [37]. At the same time, a decrease in annual precipitations (−30 mm) and an increase in the number of very dry years per decade were also recorded [62]. Steinbauer et al. [63] in a recent paper evidenced an increase in the in situ mean soil temperatures, for central Apennines summits, of 0.5 °C per decade (since 2001), values that are above the global average warming [64].

The analysis of local time series of soil temperatures registered by data-loggers in the Majella summits in the context of GLORIA monitoring network (Global Observation Research Initiative in Alpine Environments; "IT CAM FEM": 2405 m a.s.l.) [65] evidenced a similar increase in temperatures. Specifically, we have registered a significant increase during the last two decades in the mean annual and mean autumn soil temperatures (from 2.85 °C to 3.73 °C and from 3.48 °C to 4.77 °C, respectively; Figure 2) and an increase in the vegetative period (e.g., the number of days with temperatures above 2 °C), which, during in the last twenty years, have raised from 176 to 200 days per year (Figure 2).

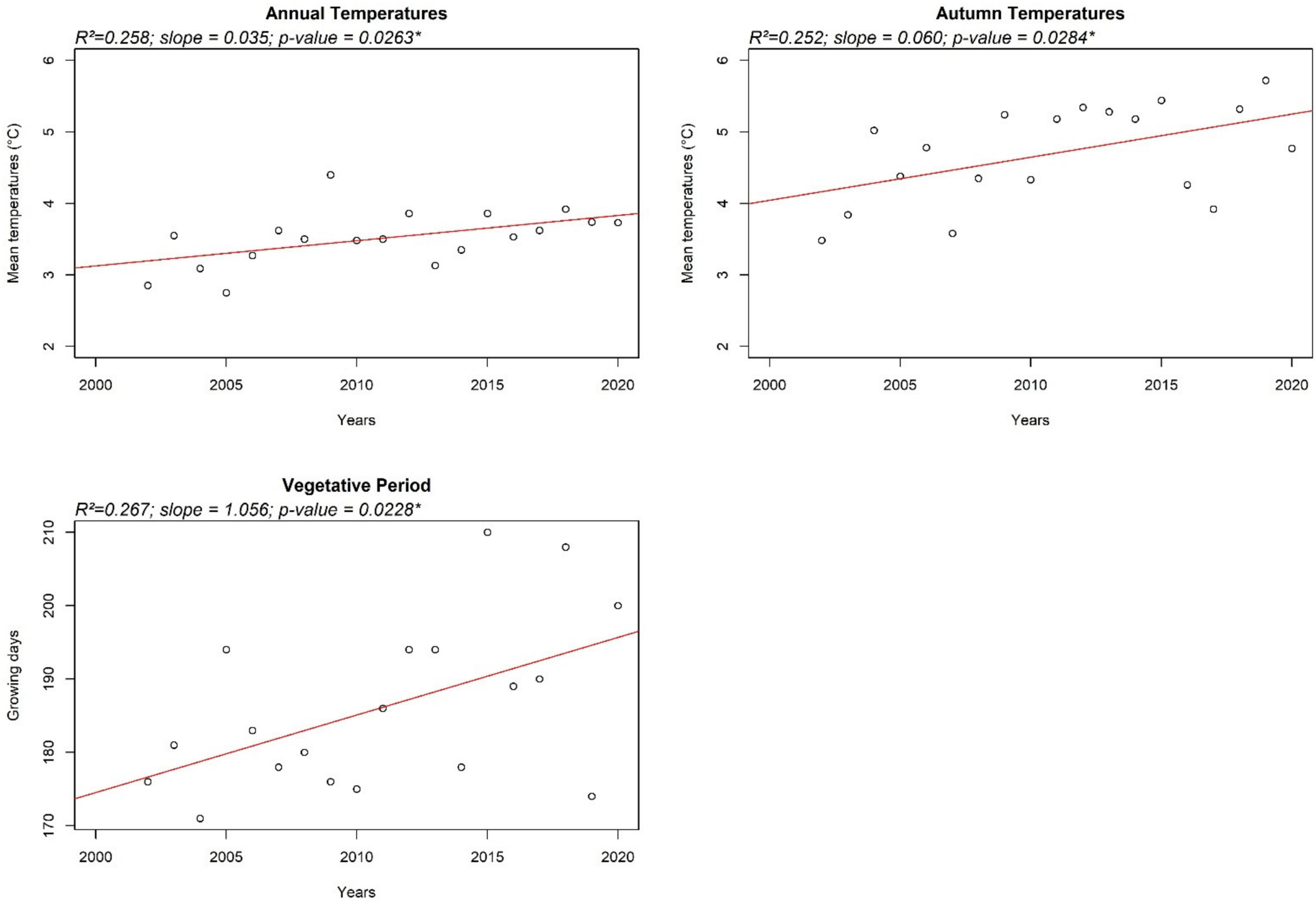


**Figure 2.** Annual and autumn (September–November) mean soil temperatures (°C) and vegetative period (e.g., the number of days with temperatures above 2 °C) for the period 2002 to 2020. Asterisks indicate significant trends. Data were retrieved from data-loggers of GLORIA monitoring network (Global Observation Research Initiative in Alpine Environments) IT CAM FEM (2405 m a.s.l.).

### *2.3. Plant Communities*

We analyzed two alpine plant communities: (a) the Apennine stripped grasslands (EUNIS code E4.436) [66], represented by *Sesleria juncifolia* scraped and garland grasslands, and (b) the wind edge swards (EUNIS code E4.42) [66], characterized by meso-xerophile and relatively continuous *Carex myosuroides* grasslands. Both communities are quite widespread in central Apennine summit areas and are of conservation concern in Europe (Habitat 6170 EU: "alpine and subalpine calcareous grasslands") [52,53]. Apennine stripped grasslands with *Sesleria juncifolia* grow on steep slopes with rendzina soils poor in organic matter and on prevalent E-SE aspects [67]. The wind edge swards with *Carex myosuroides* grow on more evolved calcareous cryoturbated soils rich in organic matter (brown rendzina) [67]. Both communities are characterized by the abundance of endemic, sub-endemic taxa, Mediterranean-montane species, and southern European orophytes [67].

Apennine stripped grasslands and wind edge swards grasslands in the study area have a very low anthropo-zoogenic pressure as they are in the core area of the Majella national park, where the livestock has been strictly regulated since more than 50 years ago [18]. The alpine zone of the park hosts the chamois (*Rupicapra pyrenaica ornata*), which, however, occurs preferentially on other environmental units as cliffs, screes, and snowbeds.

*2.4. Vegetation Data*

We re-visited, in the year 2021 (hereafter T2), 25 georeferenced phytosociological relevés previously sampled with a random-stratified sampling protocol in the year 2003 (hereafter T1). Re-visited vegetation plots are stored in VIOLA Database [60,68] and are distributed as follows: 12 on Apennine stripped grasslands and 13 on wind edge swards. Detailed local information of each revisited plot is reported in Appendix A.

Re-visitation of relevés were conducted in the same season (July–August) in order to remove the effects of phenological variability [69] and following the same sampling protocol (e.g., plot size; previous species lists; and plot headers' information: geographic coordinates, slope, altitude, and aspect) [70]. For each georeferenced vegetation plot of 16 m$^2$ (4 × 4 m), all plant species and their cover/abundance in compliance with the Braun–Blanquet scale [71,72] were registered. Vegetation plots were permanent and marked by metal pegs. The nomenclature follows the updated checklists of the vascular flora native to Italy [73]. Growth forms and chorotypes (e.g., endemic species) conform the "Flora d'Italia" [74]. We assigned to each taxa the species' ecological indicator value for temperature (T) according to Landolt [75], which ranges from 1 to 5 according to the elevation distribution of the species, which is related to the average air temperature during the growing season. We adopted Landolt T values because of their demonstrated usefulness in depicting the response of vegetation to local topographic micro-thermal heterogeneity [74]. We classified species into three groups according to the average altitudinal distribution of the species *sensu* Landolt [73]: alpine (T: 1–1.5), subalpine (T: 2–2.5), and montane (T: 3–3.5). For the endemic Mediterranean flora, without Landolt indicators, values were assigned by the authors after checking the requirements of the species in the literature [58,76]. For further quantitative analysis, we rescaled the original Braun–Blanquet cover values for each species on the percentage cover scale [77].

*2.5. Statistical Analysis*

After a brief inspection of the species list on T1 and T2, we compared for both of the analyzed communities the number and cover of overall and endemic species over time by the nonparametric Kruskal–Wallis test for equal medians on ranked data (cover and richness).

Furthermore, we explored the changes in vegetation structure and ecology using the growth forms [78] and Landolt indicators values for temperatures.

We also identified the species that contribute most consistently to differences between the two temporal steps (T1 and T2) using a similarity percentage procedure (SIMPER) [79].

All analyses were performed in R statistical computing program [80] using the Vegan package [81] and PAST (paleontological statistics software for education and data analysis) [82].

## 3. Results

The recorded species list included 91 vascular plant species and subspecies mainly belonging to *Asteraceae*, *Fabaceae* and *Poaceae* families—72 on the Apennine stripped grasslands and 76 on the wind edge swards. A total of 23 of the total species were endemic (about 25%), with 21 occurring on stripped grasslands (29%) and 17 on wind edge swards (22%) (Table 1). Most of the endemic species were scapose hemicryptophytes (48%) and suffruticose chamaephytes (22%; Table 1).

**Table 1.** Endemic species present in the analyzed alpine plant communities along with their relative growth form (*sensu* Pignatti et al. [74]), average altitudinal distribution of the species, and species' ecological indicator value for temperature (EIVs T) *sensu* Landolt [75]. CH pulv: pulvinate chamaephytes; CH suffr: suffruticose chamaephytes; H caesp: caespitose hemicryptophytes; H ros: hemicryptophytes with rosette; H scap: scapose hemicryptophytes; and T scap: scapose therophytes.

| Species | Growth Form | Average Altitudinal Distribution | EIVs T |
|---|---|---|---|
| *Achillea barrelieri* subsp. *barrelieri* | H scap | Alpine | 1.5 |
| *Alyssum diffusum* subsp. *diffusum* | CH suffr | Montane | 3 |
| *Androsace vitaliana* subsp. *praetutiana* | CH suffr | Alpine | 1.5 |
| *Armeria gracilis* subsp. *majellensis* | H ros | Subalpine | 2 |
| *Carduus chrysacanthus* | H scap | Subalpine | 2.5 |
| *Cerastium thomasii* | CH suffr | Alpine | 1.5 |
| *Erysimum majellense* | H scap | Subalpine | 2.5 |
| *Festuca violacea* subsp. *italica* | H caesp | Alpine | 1.5 |
| *Galium magellense* | H scap | Alpine | 1.5 |
| *Helictochloa praetutiana* subsp. *praetutiana* | H caesp | Subalpine | 2.5 |
| *Leontopodium nivale* | H scap | Alpine | 1.5 |
| *Myosotis graui* | H scap | Subalpine | 2.5 |
| *Noccaea stylosa* | CH suffr | Subalpine | 2 |
| *Pedicularis elegans* | H ros | Subalpine | 2.5 |
| *Phyllolepidum rupestre* | CH suffr | Alpine | 1.5 |
| *Ranunculus pollinensis* | H scap | Subalpine | 2.5 |
| *Rhinanthus wettsteinii* | T scap | Subalpine | 2 |
| *Saxifraga italica* | CH pulv | Alpine | 1 |
| *Scorzoneroides montana* subsp. *breviscapa* | H ros | Alpine | 1.5 |
| *Trifolium pratense* subsp. *semipurpureum* | H scap | Montane | 3.5 |
| *Valeriana saliunca* | H scap | Alpine | 1 |
| *Viola eugeniae* subsp. *eugeniae* | H scap | Subalpine | 2.5 |
| *Viola magellensis* | H scap | Alpine | 1 |

The temporal comparison (T1 vs. T2) of species richness and cover per plot for the entire pool by Kruskal–Wallis test evidenced similar temporal trends on both of the studied plant communities. We registered a significant decrease in overall species cover and richness per plot on stripped grassland ($P_{same} < 0.01$ and $P_{same} = 0.03$, respectively) and on wind edge swards ($P_{same} = 0.04$ and $P_{same} < 0.01$, respectively) (Figure 3).

Similarly, we registered a significant decline in endemic species on stripped grassland (cover $P_{same} < 0.001$; richness $P_{same} = 0.04$) (Figure 3).

Concerning the average altitudinal distribution of the species, we detected on stripped grassland a significant decrease in alpine species per plot (cover $P_{same} < 0.01$ and richness $P_{same} = 0.03$) and, on wind edge swards, a decline in subalpine species (cover $P_{same} = 0.02$ and richness $P_{same} < 0.01$) (Figure 4).

We also observed some changes in vegetation structure, with stripped grasslands registering a significant decrease in cover for the hemicryptophytes, in particular for the hemicryptophytes with rosette (H ros) and scapose hemicryptophytes (H scap) ($P_{same} < 0.01$ and $P_{same} = 0.04$, respectively), and the wind edge swards showing a significant reduction in cover for the suffruticose chamaephytes (CH suffr) species over time ($P_{same} < 0.01$) (Figure 5).

According to the similarity percentage analysis (SIMPER) (Table 2), 8 of the 72 species for Apennine stripped grasslands and 7 of the 76 species for wind edge swards contributed to 50% of the observed temporal differences (T1 vs. T2) in vegetation composition. Two of these declining species are endemics (*Armeria gracilis* subsp. *majellensis* and *Festuca violacea* subsp. *italica*).

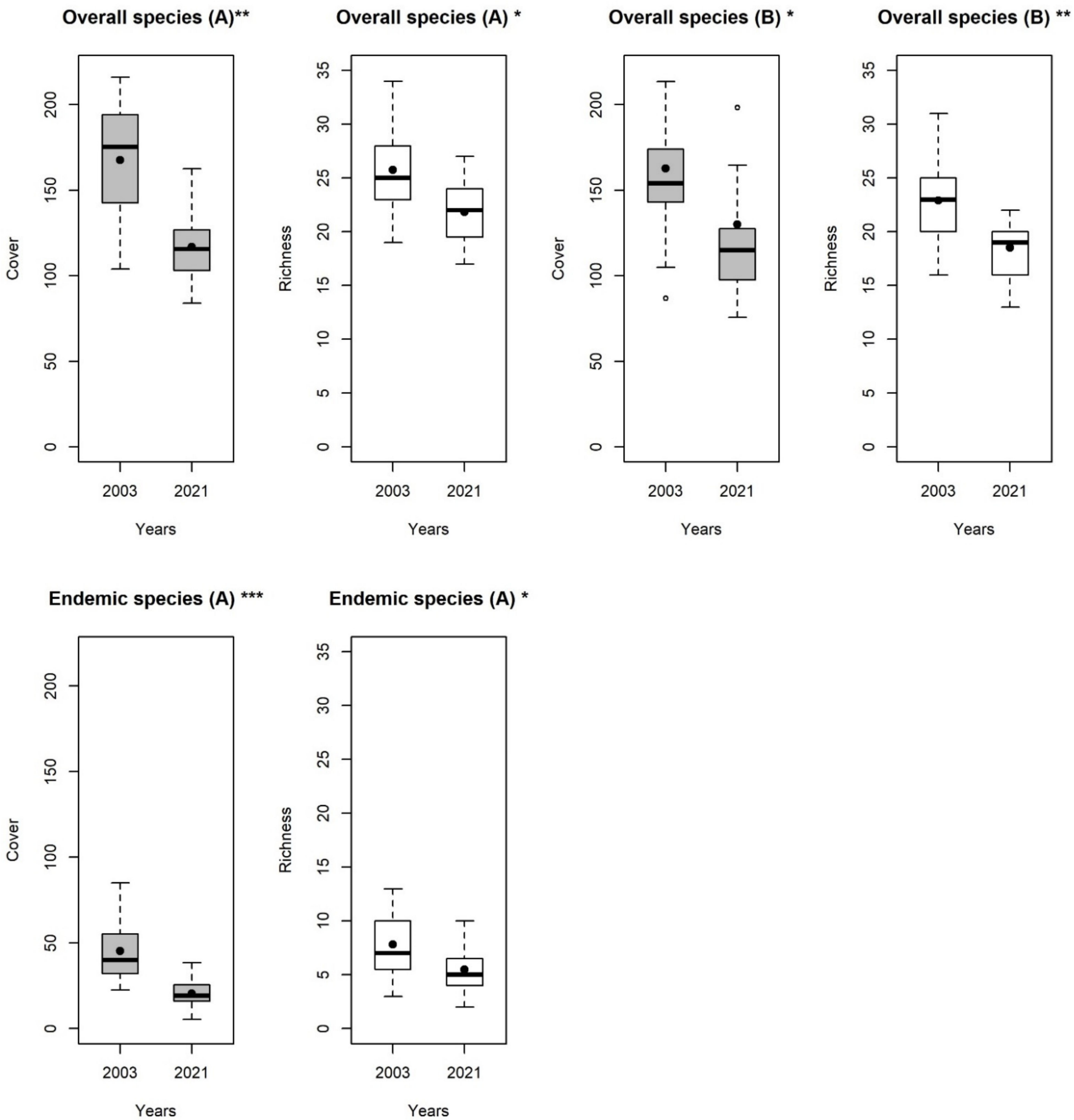


**Figure 3.** Boxplot comparing cover (grey) and species richness per 4 × 4 m plot (white) of overall and endemic species in two time steps (T1: 2003 and T2: 2021) in Apennine stripped grasslands (A) and wind edge swards (B). Only the significant results are reported. Asterisks indicate significant differences according to the Kruskal–Wallis test for equal medians (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

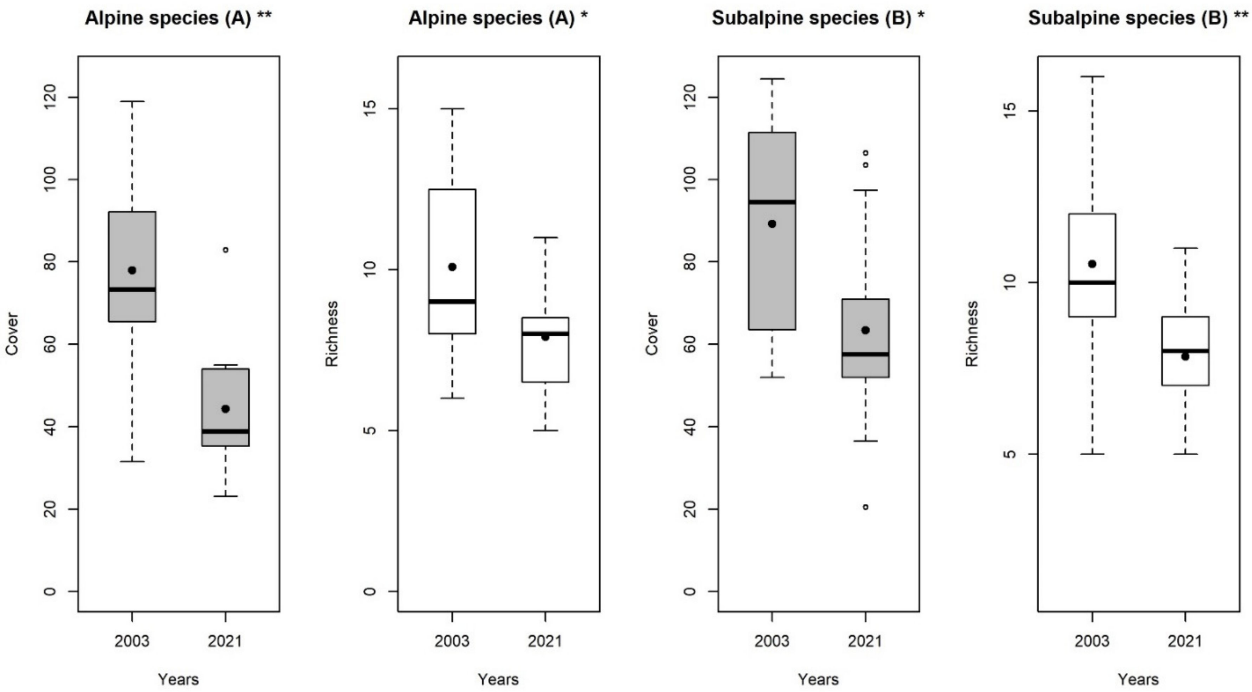


**Figure 4.** Boxplot comparing cover (grey) and richness per 4 × 4 m plot (white) of alpine species (T: 1–1.5) and subalpine species (T: 2–2.5) in two time steps (T1: 2003 and T2: 2021) in Apennine stripped grassland (A) and wind edge swards (B). Only the significant results are reported. Asterisks indicate significant differences according to the Kruskal–Wallis test for equal medians (* $p < 0.05$, ** $p < 0.01$).

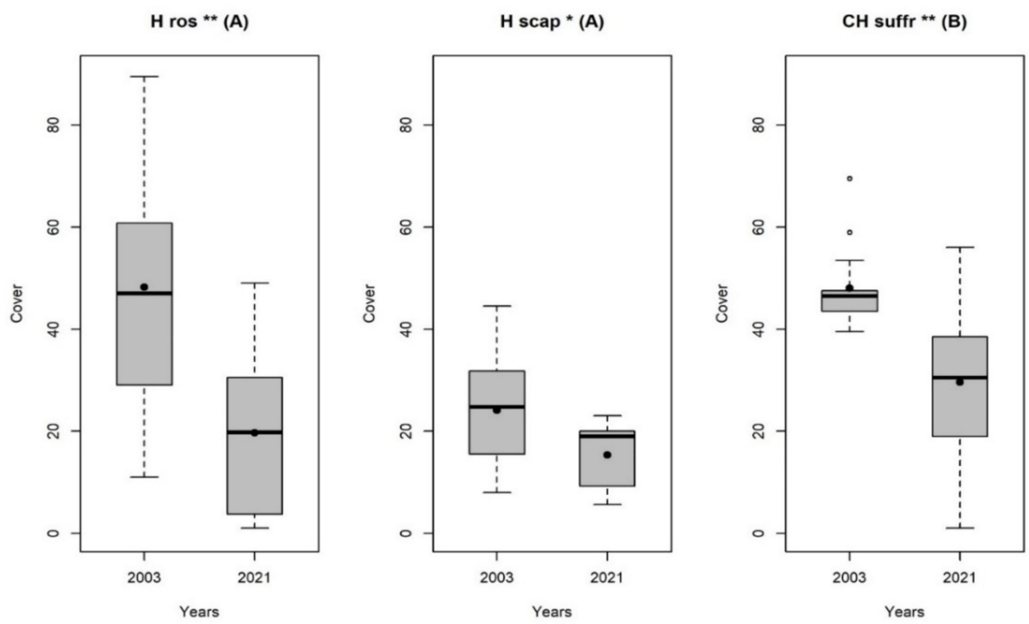


**Figure 5.** Boxplot comparing cover of growth forms (*sensu* Pignatti et al. [74]) in two time steps (T1: 2003 and T2: 2021 in Apennine stripped grasslands (A) and wind edge swards (B). H ros: hemicryptophytes with rosette; H scap: scapose hemicryptophytes; CH suffr: suffruticose chamaephytes. Asterisks indicate significant differences according to the Kruskal–Wallis test for equal medians (* $p < 0.05$, ** $p < 0.01$).

**Table 2.** Plant species that contribute up to the 50% to floristic changes over time (T1: 2003 and T2: 2021) assessed by the similarity percentage procedure (SIMPER) [79]. For each taxon, the growth form, the average altitudinal distribution of the species (Range), and species' ecological indicator value for temperature (EIVs T) *sensu* Landolt [75], as well as the specific and cumulative contribution and the mean cover on T1 and T2, are also reported.

| Plant Community | Species | Growth Form | Range | EIVs | Species Contribution (%) | Cumulative Contribution (%) | Mean Cover | |
|---|---|---|---|---|---|---|---|---|
| | | | | T | | | T1 | T2 |
| Apennine stripped grasslands | *Plantago atrata* subsp. *atrata* | H ros | Alpine | 1.5 | 10 | 10 | 20.5 | 8.8 |
| | *Anthyllis vulneraria* subsp. *pulchella* | H scap | Montane | 3 | 7.9 | 17.9 | 11.7 | 15.4 |
| | *Carex kitaibeliana* | H caesp | Subalpine | 2 | 7 | 25 | 18.5 | 20.6 |
| | ° *Armeria gracilis* subsp. *majellensis* | H ros | Subalpine | 2 | 6.7 | 31.7 | 14.8 | 3.1 |
| | ° *Festuca violacea* subsp. *italica* | H caesp | Alpine | 1.5 | 6.4 | 38 | 13.9 | 7.3 |
| | *Poa alpina* subsp. *alpina* | H caesp | Alpine | 1.5 | 5.6 | 43.6 | 12 | 2.6 |
| | *Helianthemum oelandicum* subsp. *alpestre* | CH suffr | Subalpine | 2.5 | 5 | 48.6 | 7 | 4.5 |
| | *Silene acaulis* subsp. *bryoides* | CH pulv | Alpine | 1 | 4.1 | 52.7 | 5.9 | 5.6 |
| Wind edge swards | *Carex kitaibeliana* | H caesp | Subalpine | 2 | 12.4 | 12.4 | 25.1 | 20.3 |
| | *Helianthemum oelandicum* subsp. *alpestre* | CH suffr | Subalpine | 2.5 | 11.1 | 23.5 | 39.4 | 23.3 |
| | *Salix retusa* | CH frut | Alpine | 1.5 | 7.9 | 31.4 | 5.9 | 13.3 |
| | ° *Festuca violacea* subsp. *italica* | H caesp | Alpine | 1.5 | 5.7 | 37.1 | 10.7 | 4.9 |
| | *Carex myosuroides* | H caesp | Alpine | 1.5 | 5.4 | 42.5 | 4.3 | 8.5 |
| | *Oxytropis campestris* | H scap | Alpine | 1.5 | 4.2 | 46.7 | 5.9 | 2.6 |
| | *Anthyllis vulneraria* subsp. *pulchella* | H scap | Montane | 3 | 4.2 | 50.9 | 14 | 14 |

° Endemic species.

In the stripped grasslands, we observed the reduction in cover on six of these eight species and four of them are alpine (T = 1–1.5). Only two species, the montane *Anthyllis vulneraria* subsp. *pulchella* and the subalpine *Carex kitaibeliana*, increased in cover over time.

In the wind edge swards, the species that contributed most to the decreasing plant cover value over time were the subalpine (T = 2–2.5) *Carex kitaibeliana* and *Helianthemum oelandicum* subsp. *alpestre*. Only two species, the alpine *Salix retusa* and *Carex myosuroides*, increased their cover and the montane *Anthyllis vulneraria* subsp. *pulchella* remained stable over time.

## 4. Discussion

The re-visitation after 18 years of stripped grasslands and wind edge swards vegetation plots in central Apennines evidenced an important decline in plant diversity with a significant decrease in species richness and cover and the loss of some endemic species. It also evidenced significant alterations in plant communities' structure and ecology with a reduction in alpine and hemicryptophytes in stripped grasslands with *Sesleria juncifolia* and in subalpine and suffruticose chamaephytes in wind edge swards with *Carex myosuroides*.

Similar decreasing trends in species richness and cover over time were observed in other Mediterranean and alpine summits in Europe. For instance, a decrease in alpine plants was observed in Mediterranean summits of Corsica [23], Sierra Nevada [44], and Crete [45], and those changes were attributed by the authors to biological effects of climate warming and the consequent decrease in water availability [44].

Similarly, Porro et al. [46] have observed a decline in plant diversity in northern Apennines and Nicklas et al. [47] described a slow and progressive loss of species richness in the calcareous grasslands of the Alps. Such biodiversity decline registered on some mountain summits is most likely a result of a combination of rising temperatures and decreasing summer precipitations occurring in southern Europe during the last decades [41,83–85]. Indeed, during the last five decades, a general increase in annual mean temperatures [86–88] with a decrease in annual precipitations and an extension of the dry summer season [43,89,90] across the Italian peninsula and Europe were recorded.

In this light, the increase in soil temperatures registered in the study area (by the GLORIA network data loggers), in particular in autumn, as well as the prolongation of the growing season (e.g., later accumulation of snow and earlier meltdown), should be related with the decline in species' diversity registered in both stripped grasslands and wind edge swards. For instance, the warmer conditions registered in autumn could stimulate the premature germination of seeds [91] and the production of early seedlings that are not able to survive to the following harsh winter conditions (e.g., steep diurnal temperature range and the alternation of warm and very cold days) [92,93].

Notice that the decline in species richness registered during the last 18 years in the stripped grasslands is a result of the drop in alpine (e.g., *Plantago atrata* subsp. *atrata* and *Poa alpina* subsp. *alpina*) and endemic plants (e.g., *Festuca violacea* subsp. *italica*). Alpine species are cryophilous taxa, which are vulnerable to the increase in temperatures and the decrease in soil water availability [29,30,33,35,85]. Concerning the observed decline in endemic plants, similar results were reported in recent studies carried out in the southern Mediterranean summits of Europe such as Sierra Nevada [44] and Crete [45], and those changes were interpreted by the authors as a reaction of vegetation to climate change. We also observed in stripped grasslands a decline in hemicryptophytes with rosette (H ros) and scapose hemicryptophytes (H scap) (e.g., *Plantago atrata* subsp. *atrata*, *Armeria gracilis* subsp. *majellensis*, *Ranunculus pollinensis*, *Scorzoneroides montana* subsp. *Breviscarpa* and *Viola eugeniae* subsp. *eugeniae*), which are common in continuous grasslands [35,94] and are weakly adapted to cope with the new climatic conditions (e.g., higher temperatures, the prolongation of the growing season, and the consequent increased water stress) [63].

The decline in diversity values observed in the wind edge swards is due to the decrease in subalpine species (e.g., *Carex kitaibeliana*, *Helianthemum oelandicum* subsp. *alpestre*), which may be attributable to the harsher environmental conditions registered during the last decades [2]. Indeed, the prolongation of the growing season (e.g., later accumulation of snow and earlier meltdown) likely promoted in wind edge swards steeper diurnal temperature ranges and higher winter frost stress, limiting both the development and survival of several subalpine species [62,95]. On the other hand, the stability of the stress-tolerant and cold-adapted alpine species, in which wind edge swards in central Apennines are rich [96], is likely due to their ability to cope, at least so far, with such effects of climate change. The observed species cover changes in the wind edge swards vegetation structure are due to the decrease in suffruticose chamaephytes (CH suffr; e.g., *Helianthemum oelandicum* subsp. *alpestre*, *Iberis saxatilis* subsp. *saxatilis*, *Noccaea stylosa*). As observed by Steinbauer et al. [63] on alpine ridges across southern European summits, in our case too, climate warming seems to induce a decrease in cushion plants cover.

The observed decline in plant species richness and cover registered on central Apennines stripped grasslands and wind edge formations is most likely related to the rise in temperatures, the increased vegetative period, and the reduction in soil water content, which are impinging European summits and are particularly severe in calcareous regions [47]. The temperature rise registered in the study area in combination with a series of exceptionally dry summers (2003, 2015, 2021) [97], frequent summer storms with high runoff particularly detrimental on a karstic bedrock [98], and the convention winds promoting high evapotranspiration, likely all contribute to the observed change in plant diversity values.

Our study evidenced a particular process of diversity loss ongoing on alpine stripped and wind edge grasslands, which had not been observed so far on other plant communities in central Apennines. In fact, previous studies on the Mediterranean Apennines registered a stability of species richness and an increase in plant cover on *Pinus mugo* scrubs [37,76] on scree and snowbeds vegetation [35,94]. Such a temporal increases in plant cover and richness have been attributed to range filling processes (e.g., greening) and to the upward shift of montane/subalpine species towards the alpine and nival belts (e.g., thermophilization process), both promoted by climatic warming [33,76,99]. Southern mountains of the northern hemisphere (such as those in the Mediterranean area) host several species' range-edge populations [41,47,100], which are more vulnerable to climatic changes than core populations [51,101–104].

The observed decline in plant species diversity is particularly worrying if accounting for the most updated climate change models that, for mountain areas in south Europe, have predicted increasing temperatures, decreasing precipitations, and a lengthening summer season [43,64,89,90]. Similarly, recent climatic projections for the next 50 years on Mediterranean mountains have predicted an increase in temperatures (+1.4 °C) and a reduction in precipitation (−4.8%) [42]. Altered climatic conditions that are shrinking the European mountain flora [23] are even more dangerous on Mediterranean areas, like the analyzed alpine stripped and wind edge grasslands, which, being rich in endemics [23,105–107], should have permanent damage on biodiversity.

These endemic alpine plant populations already placed at maximum local elevational gradients could face "mountaintop extinction" [104] and survive only in "warm-stage microrefugia", geomorphologic niches that constantly maintain cold-air pooling and temperature inversions [108], with implications for the conservation of regional biodiversity.

Our results evidenced the urgent need for identifying "warm-stage microrefugia" in alpine protected areas able to support "climate-smart" in situ conservation planning for the Mediterranean mountains [106,109]. Such microrefugia could form a network of conservation sites of taxonomic and genetic diversity (e.g., alpine endemics), which should be strictly protected [108,110]. Those measures should be integrated with ex situ conservation practices, such as those locally implemented in the Majella Seed Bank [111], both complementary cost-effective actions [112].

## 5. Conclusions

The present re-visitation study evidenced significant changes over the last 18 years in the stripped grassland and wind edge swards plant communities in central Apennines.

Both plant communities showed a significant decrease in plant species cover and richness. As on Apennine stripped grassland, we observed a loss in alpine and endemic species, on wind edge swards, a reduction in subalpine species was registered. These changes are likely attributable to the combined effect of higher temperatures, the increase in the growing period (e.g., later accumulation of snow and earlier meltdown), and the decrease in soil water availability triggered by global change.

This study evidenced an ongoing biodiversity loss on calcareous alpine grasslands of mountaintops in central Apennines, which had so far been observed until now only in the warmest and Southern Mediterranean summits of Europe. Furthermore, in our study area, the stripped and garland calcareous grasslands (especially those dominated by *Sesleria juncifolia*) have been revealed to be the most sensitive to this effect.

The current re-visitation study contributed to increasing our knowledge about vegetation changes in central Mediterranean mountain top plant communities and underlined the need for monitoring activities on these sentinel ecosystems, which are increasingly threatened by global change.

Analogous monitoring research should be carried in other Mediterranean high mountains, where consistent effects of climate change are forecasted in order to better understand local vegetation trends and adaptation strategies in subalpine, alpine, and nival ecosystems.

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## Appendix A

**Table A1.** Headers information of each re-sampled plot in both the studied plant communities.

| Plant Community | Relevé Number | Relevé Area ($m^2$) | Altitude (m a.s.l.) | Aspect | Slope (Degree) |
|---|---|---|---|---|---|
| Apennine stripped grasslands | 1 | 16 | 2555 | E | 15 |
| | 2 | 16 | 2563 | E | 18 |
| | 3 | 16 | 2601 | NW | 15 |
| | 4 | 16 | 2483 | S | 13 |
| | 5 | 16 | 2558 | SW | 5 |
| | 6 | 16 | 2614 | S | 20 |
| | 7 | 16 | 2539 | S | 15 |
| | 8 | 16 | 2572 | S | 22 |
| | 9 | 16 | 2501 | S | 34 |
| | 10 | 16 | 2400 | N | 6 |
| | 11 | 16 | 2554 | NE | 7 |
| | 12 | 16 | 2567 | E | 7 |
| Wind edge swards | 1 | 16 | 2658 | | 7 |
| | 2 | 16 | 2524 | NW | 10 |
| | 3 | 16 | 2529 | SW | 10 |
| | 4 | 16 | 2525 | NW | 7 |
| | 5 | 16 | 2479 | S | 5 |
| | 6 | 16 | 2481 | S | 7 |
| | 7 | 16 | 2481 | E | 4 |
| | 8 | 16 | 2610 | SW | 22 |
| | 9 | 16 | 2617 | E | 10 |
| | 10 | 16 | 2665 | SE | 16 |
| | 11 | 16 | 2597 | NE | 18 |
| | 12 | 16 | 2598 | E | 12 |
| | 13 | 16 | 2536 | SE | 20 |

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