UNIVERSITY OF PADOVA

Department of Land, Environment, Agriculture and Forestry

Second Cycle Degree (MSc) in Forest Science

Effects of six years snowpack manipulation on growth and phenology of common juniper (*Juniperus communis* L.) at high elevation

Supervisor

Prof. Marco Carrer

Submitted by

Francesco Forner

Student n.

2045722

ACADEMIC YEAR 2022-2023

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Abstract

Climate change is nowadays a well-known and global phenomenon with multiple effects: from the warming trend in lands and oceans, to the biodiversity and ecosystems loss, from the ice sheets shrinking, to the increase in the intensity and severity of extreme events. Among all, an issue resulting from those changing climatic conditions is the decrease of the amount and number of snow precipitation events during the snow season that, together with increased temperature, is inducing a reduction of snow cover permanence in mountain areas. This affects the distribution, growth and phenology of many plant species that live in those areas and are directly or indirectly dependent on snow cover dynamics thanks to complex evolutionary processes. It is, therefore, useful to collect as much information as possible about the new snow cover dynamics and shrinking permanence to better understand how plants will respond and how the composition of mountainous vegetation will change in the future if the current tendency will continue. This study will focus on common juniper (*Juniperus communis* L.), which is the conifer with the widest distributional range in the northern hemisphere, and its responses to different levels of snow cover. The aim is to assess the effects of snowpack duration on the phenology and growth of this species. A six-years snow manipulation experiment was carried out in an experimental plot above the treeline on previously selected plants which were subjected to altered snowpack duration (C: prolonged, S: reduced, N: natural) to simulate different snow cover lengths. During the growing seasons we collected data on phenological traits (buds' development, shoot growth). The results show that a prolonged snowpack duration had an effect in the initial growth period, in which the growth rate was slower than the other treatments, probably because of a detrimental effect that persisting snow could have on growth. A reduced snowpack duration, on the other hand, caused a higher growth in the first years because of a longer exposure to solar radiation for the photosynthesis, but, in the following years, this effect faded out. The convergence in the growth in all the treatments that we observed in the recent years could represent an acclimatation mechanism.

List of acronyms

CC: Climate change;
HW: Heatwave/s;
C: Individuals exposed to late snowmelt;
S: Individuals exposed to early snowmelt;
N: Control individuals;
SWC: Soil Water Content;
EEU: Eastern Europe;
NEU: Northern Europe;
SEU: Southern Europe;
WEU: Western Europe;
WCE: Western Central Europe;
T_{cold}: Air temperature of the coldest month;
T_{hot}: Air temperature of the warmest month;
WMO: World Meteorological Organization;
DoY: Day of the year;
GWL: Global Warming Level;
NPP: Net Primary Production.

Introduction

Climate change

Climate change (CC), the most uttered environmental term of present time is adopted to refer to the change in modern climate brought predominantly by humans. It is perhaps one of the most serious environmental issues that today's world population is facing, even though the issue is not new (Rahman, 2013).

The warming over the past century is unprecedented in the past 1000 years and only about 25% of the 20th century temperature increase can be attributed to natural variability (Crowley, 2000).

Between 1975 and 2010, land temperatures have been increasing at a rate which is more than double the rate of ocean warming (Rangwala & Miller, 2012) and, according to the 2022 European state of the climate, since 1850-1900, there's been an increase in surface air temperature of around +1.2°C globally (Figure 1), +2.2°C in Europe and +3°C in the Arctic (for the last five-years).

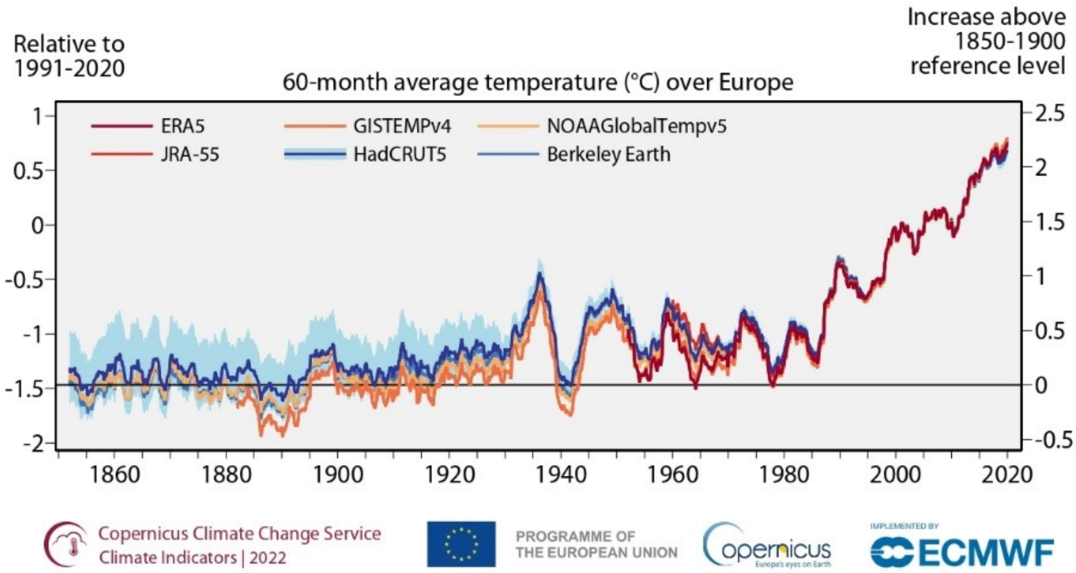


Figure 1. Global sixty-month average surface air temperature (°C) (Copernicus Climate Change Service, 2023).

Globally, the last eight years have been the warmest on record, and 2022 was the fifth warmest year on record. In Europe, summer was the warmest on record, at 1.4°C above average, and 0.3-0.4°C above the previous warmest summer, in 2021 (Copernicus Climate Change Service, 2023).

Beside the changes in global temperature, CC, according to the Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022) had impacts also on:

- Ecosystems (structure, species range shifts, phenology): CC has altered marine, terrestrial and freshwater ecosystems all around the world, many species in all ecosystems are shifting their geographic ranges and altered the timing of seasonal events. Biological responses, including changes in physiology, growth, abundance, geographic placement and shifting seasonal timing, are often not sufficient to cope with recent climate change;
- Human systems (water and food availability, health, cities and infrastructures): CC is affecting ecosystem services connected to human health, livelihoods and well-being. Droughts, floods, wildfires and marine heatwaves contribute to reduced food availability (by affecting the productivity of agricultural, forestry and fishery sectors) and increased food prices, threatening food security, nutrition and livelihoods of millions of people across regions.

Heatwaves

One of the effects of CC is Heatwaves.

Heatwaves (HW) are among the most dangerous natural hazards, rising temperatures have substantially increased the likelihood of occurrence of such major heat waves (Lhotka & Kyselý, 2022).

In Europe, they are expected to become more frequent, intense and long lasting and can have an impact on plant productivity with anomalies and remarkably low values of NPP (Net Primary Production) (Bastos et al., 2014).

The 2021 major HW was found to be the longest since 1950 and comparable to 2003 and 2010 events in terms of magnitude and spatial extent but its intensity was lower. By contrast, another recent major HW that occurred in 2019 was characterized by large intensity equivalent to the most intense 2010 event (Lhotka & Kyselý, 2022).

The 2022 Compound Drought and Heatwave event in Europe was one of the most severe in recent history, affecting large parts of the continent. Record-breaking temperatures were observed, and persistent drought continued throughout the summer. The hardest-hit areas include the Iberian Peninsula, France, and Italy, where temperatures exceeded 2.5°C above normal, and severe drought conditions persisted from May to August, which, in turn, reduced soil moisture (Tripathy & Mishra, 2023).

Summer of 2022, was also extraordinary in terms of glacier melt rates, three severe HW were identified, this is about as many events as had occurred over the 3 previous years, emphasizing the exceptionality of the year (Cremona et al., 2023).

In 2023, El Niño conditions have developed in the tropical Pacific for the first time in seven years, setting the stage for a likely surge in global temperatures and disruptive weather and climate patterns.

A new Update from the World Meteorological Organization (WMO) forecasts that there is a 90% probability that the El Niño event will continue during the second half of 2023. With a warm start to 2023 and the emergence of the El Niño phenomenon, there is an increased likelihood that 2023 will be among the warmest years on record (Figure 2). July was the hottest month on record, with scorching temperatures across Europe (World Meteorological Organization, 2023).

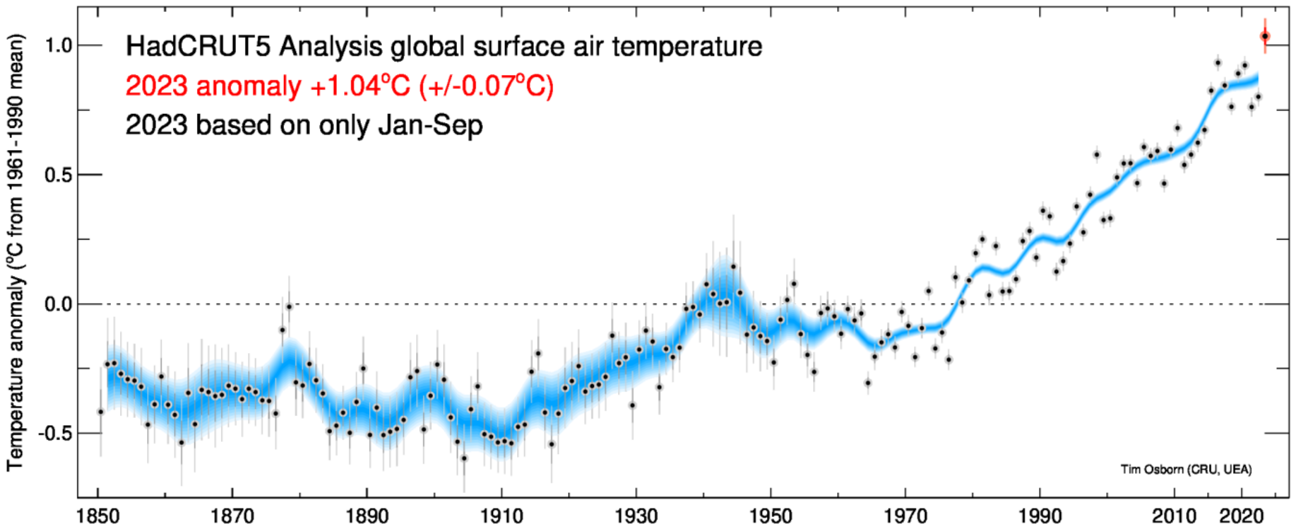


Figure 2. Annual average temperature anomalies (https://crudata.uea.ac.uk/~timo/diag/tempdecadeblocks.htm).

Mountain regions

High mountain systems such as the Alps are likely to be particularly vulnerable to CC (Theurillat & Guisan, 2001) as plant growth is primarily controlled by climate factors aggregated in periods relative to melt-out and snow-up dates.

However, as studied by Liancourt et al. (2013), CC will not produce consistent consequences across the landscape even for the same species therefore, predicting plant responses to all concurrent CC effects, appears more challenging than expected. In fact, every species behaves differently to new conditions, and it's difficult to predict the responses based only on theoretical knowledge.

Mountains are amongst the most fragile environments in the world. They are a repository of biodiversity, water and other ecosystem services (Nogués-Bravo et al., 2007). Mountain regions can be vast and diverse, and CC and its impacts on ecosystems vary greatly site wise (IPCC, 2022).

Summarizing some key points of what is known about the effects that CC has in mountain areas, we must highlight:

- *Temperature*: There's not a clear idea on how warming is going on in mountain regions respect to the rest of the world. Some studies showed that temperature increase in mountains is faster than global averages (Alexander et al., 2018); others have concluded that it's difficult to assess whether the warming rate in mountains is higher or lower than the rest of the global land surface since there's no significant difference on a global scale (Pepin et al., 2022; Rangwala & Miller, 2012). Elevation-dependent warming (EDW) does not always imply that warming is more rapid in mountains compared to lowlands, but rather that there is some systematic difference in warming rates with elevation (Pepin et al., 2022). However, the projected amount of warming for mountain areas in the 21st century is greater than that recorded in the 20th century (Nogués-Bravo et al., 2007). Warming, reduced ice, thawing permafrost and a changing hydrological cycle have resulted in the contraction of polar and mountain ecosystems (IPCC, 2022);
- *Runoff*: A slight increase in temperature can significantly affect timing in runoff events in mountainous areas (Javadinejad et al., 2020) and increased warming will cause decreases in winter and spring snowpack leading to changes in the pattern of seasonal streamflow (Rangwala & Miller, 2012);
- *Vegetation*: Plant species of mid and low elevations start to colonise higher elevations in mountains. Increasing precipitation can allow some species to occur at lower elevations in dry climates (IPCC, 2022);
- *Biodiversity*: Changes in mountain biodiversity and ecosystems have a wide range of impacts on ecosystem services and effects on people. Some mountain ecosystems, particularly those with peatlands or forests, are important carbon sinks, and CC presents a risk to these in some regions (IPCC, 2022). CC will reduce many populations, increase their isolation and, therefore, increase the extinction risk (Vittoz et al., 2013). As temperatures rise, ecosystems with 'nowhere to go', such as mountains, are considered to be more and more threatened (Loarie et al., 2009);
- *Snow cover*: The winter snow cover is one of the fastest changing climate features under current CC. In mountains this is especially evident as an upward shift of the snow line, and hence, a thinner snow cover of shorter duration at low and medium elevations (Wipf et al., 2009). A reduction in snow and ice cover reveals a less reflective surface that absorbs more solar radiation, which further enhances the initial warming alteration (Thackeray & Fletcher, 2016). Recent studies confirmed with high confidence that snow cover extent continues to decrease across the Northern Hemisphere in all months of the year (IPCC, 2022);

- *Glaciers*: Both globally and across Europe, glaciers, distinct from the two ice sheets in Greenland and Antarctica, have experienced a substantial and prolonged shrink since the mid-19th Century. This loss has intensified since around the 1990s. In specific, there was a record loss of ice from glaciers in the Alps, equivalent to 5 km^3 of ice, or an average depth across the glaciers of more than 3.5 m (Copernicus Climate Change Service, 2023).

Effect of Climate Change on vegetation

Global CC may already be impacting the distribution of vegetation (Kelly & Goulden, 2008). Under environmental change, species may adapt to the new conditions (phenological plasticity and/or genetic evolution) or shift their distributional ranges (several examples in distributional range shifts have been reported worldwide and for different species groups) so as to follow favourable conditions. Local or regional extinctions are expected for species that are unable to adapt or move (Vittoz et al., 2013) and rapid changes in temperature are expected to result in extinctions of cold-adapted plant species in mountains, coupled with a dramatic turnover in alpine plant communities. In some regions, projections using species distribution models (SDMs) predict up to 100% species turnover in alpine plant communities by 2100 (Alexander et al., 2018).

Range shifts are leading to northward and upwards expansions of warm-adapted taxa. These shifts have already altered species living in the boreal and alpine tundra currently, in many areas we are observing a greening in the high Arctic tundra with shrubs and trees. Plants display more stable distributions at low than at higher mountain altitudes, although microclimatic variability in some locations can buffer warming impacts. The timing of many processes, including spring leaf unfolding, autumn senescence and flight rhythms, have changed in response to changes in seasonal temperatures, water and light availability. The largest increase in length of growing season in plants has been detected in WCE (Western Central Europe), NEU (Northern Europe) and EEU (Eastern Europe), but shortening in parts of SEU (Southern Europe) driven by later senescence, increasing population growth for butterflies and moths and birds, and residence time for migrant birds. Population range shifts are projected to continue and changes in distribution are projected for major tree species in all European regions at 1.7°C GWL (Global Warming Level), with economic implications for managed forests. The longer growth season in NEU and WCE will support the establishment of invasive species. Temperatures 3.4°C GWL would make large parts of SEU and WCE suitable for pests, for example, wood beetles, and increase economic losses due to lower harvest quality of timber (IPCC, 2022).

One widespread hypothesis is that global warming will shift, in a more or less regular pattern, the climatic ranges of species or even whole vegetation belts upward along altitudinal, thermally defined gradients. When shifting upwards in elevation, species and community will not find equivalent areas with similar physiographic conditions. In this respect, the alpine belt will undergo the greatest change among all vegetation belts (Theurillat & Guisan, 2001).

The role of snow cover

Palacios and García (1997), studied the distribution of high mountain vegetation in Spain in relation to snow cover and found that if the terrain is composed of loose sedimentary material oriented in the slope direction, the snow action will become an important factor in the distribution of vegetation. Jonas et al. (2008) further, analysed the specific and combined effects of temperature, precipitation, and snow season timing on the growth of plants and found that plant growth was primarily driven by climatic factors controlled by the timing of the snowy season. In their study, Wipf et al. (2009), investigated how a substantial decrease in snow depth and an earlier snowmelt affect plant phenology, growth, and reproduction of the four most abundant dwarf-shrub species in an alpine tundra community; they concluded that changes in the snow cover can have a wide range of species-specific effects on those taxa.

Going more into specific, and focusing on the effect of CC in Juniper's growth and phenology, Tumajer et al. (2021), observed that CC affects the biogeographical patterns and adaptive capacity of this species. They found also regional differences in intra-annual patterns of *Juniperus communis* L. growth dynamics and in the response to ongoing climate change.

A study by Carrer et al. (2019), about the effects of precipitation and snowpack dynamics on prostrate forms of alpine vegetation found a negative role of winter precipitation for shrub growth, role that is maintained negative even in recent years, despite the warming trend. Finally, Unterholzner et al. (2022), studied the effects of snow cover duration on primary growth and leaf traits in common juniper at same site. Their results will be compared to the results of the present study.

The species: *Juniperus communis*

This study will focus on common juniper (*Juniperus communis* L.) (Cupressaceae), a species with wide distribution range (Figure 3) and ecological importance.

Common juniper represents one of the most typical tundra woody species at high latitude and elevation. Hence, it represents a model species to investigate physiological responses of woody species to environmental variability above the treeline ecotone (Unterholzner et al., 2022). It is among the most widely distributed gymnosperms in the Holarctic, ranging from circum-Mediterranean mountains up to subarctic tundra. This species shows a continuous distribution in northern and central Europe, but populations become progressively more fragmented towards the Mediterranean Basin

(García et al., 2000). It spans three climatically contrasting environments, where the dominant growth limitations vary between cold (Arctic and Polar and Northern Urals), drought (Mediterranean and Southern Ural), and high soil moisture (Eastern Alps) during the main part of the growing season (Tumajer et al., 2021).

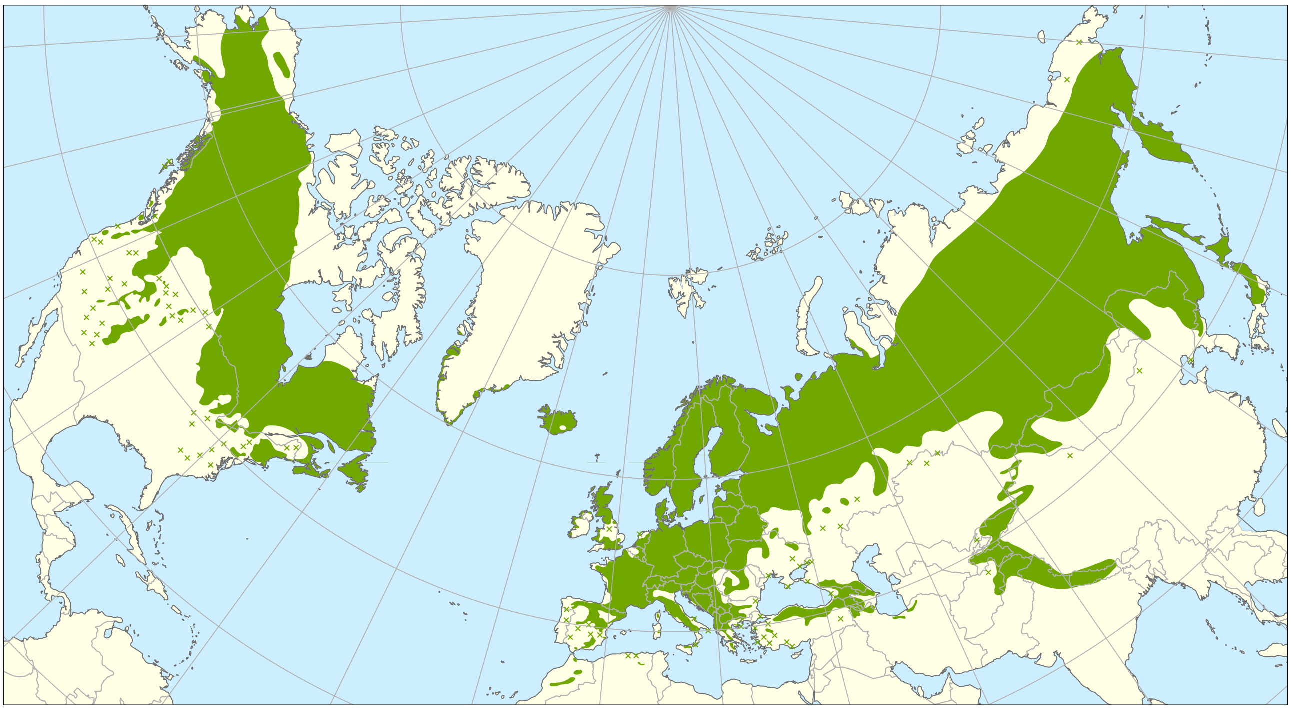


Figure 3. Geographical distribution of common juniper (Caudullo et al., 2017).

Characteristics: common juniper is an evergreen gymnosperm shrub or small tree of about 11(17) m with bark reddish-brown, usually thin, often peeling in long strips, young shoots triangular with projecting ridges. Buds c. 3 mm long with acuminate scales, juvenile foliage needle-like narrowly oblong, 5-12(15) mm long, acute apex, jointed at base, very prickly, erect to patent; leaves borne in whorls of three, persisting for three years, sessile, keeled and with a single broad white stomatal band on the upper side, sometimes divided by a green line towards the base, often with an abaxial resin gland (Thomas et al., 2007). This species is a dioecious and wind pollinated. Every spring, female individuals bear axillary cones which take more than 2 years to develop into fleshy spherical structures, called galbulae. Cones ripen fully in the autumn of the third year of development, becoming blue-grey coloured, c. 6.5 mm in diameter and containing 1±3, rarely 4, seeds per cone (García et al., 2000). Seeds, elongated, ovoid, with grooves and resin pockets over the whole seed, one seed per cone-scale, each 4-5 mm long, embedded in the resinous, mealy pulp and retained within the cone at dispersal. Male cones (strobili) c. 8 mm, solitary, maturing and shed annually, cylindrical, with (2)3-6(9) whorls of stamens (Thomas et al., 2007).

Objectives and hypotheses

The aim of this study is to assess the effects of snowpack duration on the phenology and growth of common juniper.

Specific objectives are:

- Analysing the phenological phases (buds' development, shoot growth);
- Analysing the primary growth dynamics;
- Comparing the results with those from previous years and, ultimately, attempting to identify any acclimatation or carry-over process.

The hypothesis is that early snow melt could expose juniper plants to frost damages due to low air temperatures while a long-lying cover could delay the exposure to sunlight and the onset of the vegetative period. The effects of snow cover duration on shrub primary growth will induce a positive effect in the case of early snowmelt and a negative one for late snowmelt which simulate a longer and shorter growing season.

Study area

Giau pass is located in the Eastern Italian Alps in the San Vito di Cadore municipality, in the Veneto region. Its elevation is about 2236 m a.s.l. and it's located at the base of Nuvolau and close to the Averau mountain.

From the climatic point of view, according to the Koppen climate classification, the area belongs to the group Dfc (subartic or boreal climates) which means that we are in a cold climate (T_{hot}>10°C and T_{cold}< 0°C), without dry season (precipitations are high, around 1400 mm, and uniformly distributed along the year) and with cold summer (Beck et al., 2020). The area, based on morphological and geo-lithological means, belongs to the Mesalpic domain of Alps. Considering the elevation and the temperature and precipitation values, the area is located beyond the current treeline.

From the geological and geomorphological point of view, the formations and structures (Figure 4) present in that area are:

- Wengen formation: made by turbiditic dark-grey to blackish sandstones, volcanic turbidites, volcaniclastic conglomerates and tuff sandstones, alternated with siltstones and black-marleous mudstones (Borga et al., 2002; Servizio Geologico D'Italia, 2006);
- Alpine post-glacial system: eluvio-colluvial and detritic-colluvial layer, actual, sub-actual and ancient landslides deposits (Servizio Geologico D'Italia, 2006);

- San Cassiano formation: alternation of mudstones, marls, micrites, oolitic calcarenites, bioclastic calcarenites and calcirudites, with the presence of volcanic sandstones. We have also fossils of bivalves, gastropods and echinoderms (Servizio Geologico D'Italia, 2006). Yellow calcareous layers, easy to erode and often the cause of mass movements and debris flows affecting the surface. Soils originating from these materials are rich in clay and relatively deep, with low drainage and water stagnation (ARPAV, 2005);
- Cassian Dolomite: highly dolomitised rock, usually microbialitic boundstones with grainsize of arenites, with fossils of gastropods, bivalves, corals and also stromatolites (Servizio Geologico D'Italia, 2006);
- Debris flows deposits on ice: blocks of some meters, angular clasts and fine gravel;
- Rock glacier: with dimension of about 1 km^2, big blocks with angular clasts and sandy-silty matrix (Servizio Geologico D'Italia, 2006).

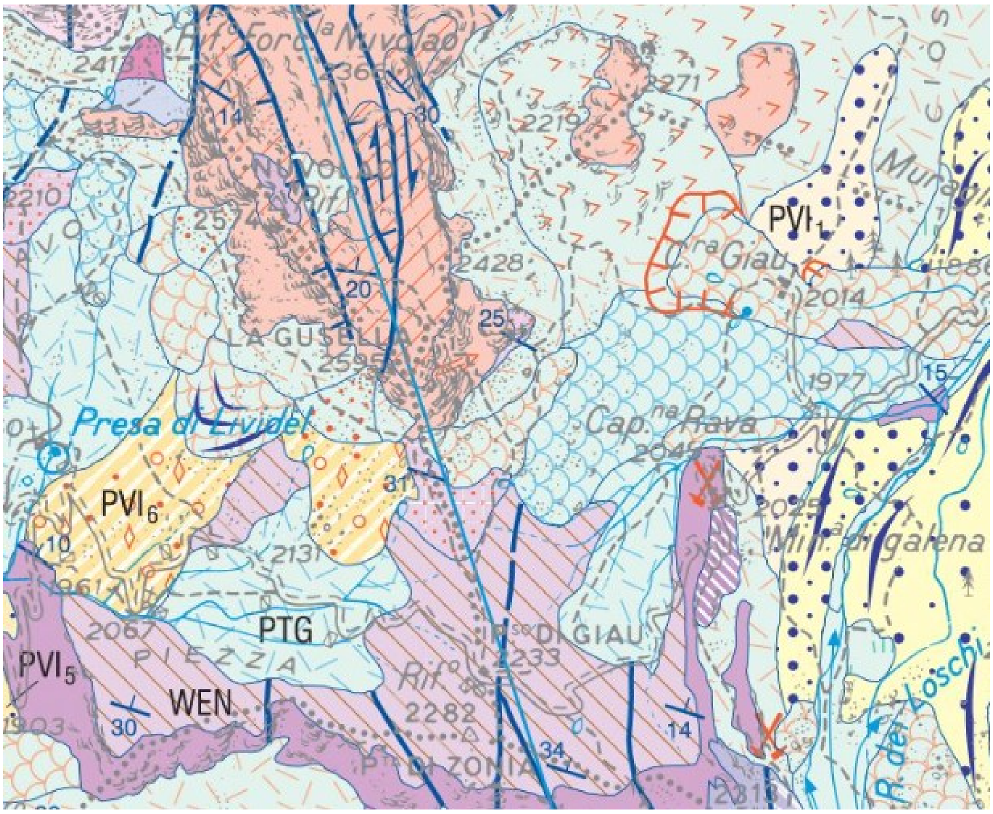


Figure 4. Geological map of the area surrounding the Giau pass. WEN: Wengen formation; PTG: Alpine post-glacial syntheme; PVI: Piave syntheme (Servizio Geologico D'Italia, 2006, edited).

From the botanical point of view, in the area are present many different species and they are listed as follows, divided according to the family and in alphabetical order:

Asteraceae

- *Bellis perennis* L.;
- *Cirsium spinosissimum* L.;
- *Crepis aurea* (L.) Cass.;
- *Lentodon hispidus* L.

Brassicaceae

- *Biscutella laevigata* L.;
- *Cardamine amara* L.

Caryophyllaceae

- *Silene vulgaris* (Moench) Garcke

Cyperaceae

- *Carex nigra* (L.) Reichard.

Ericaceae

- *Erica carnea* L.;
- *Rhododendron ferrugineum* L.;
- *Vaccinum sp.*

Fabaceae

- *Anthyllis vulneraria* L.;
- *Lotus corniculatus* L.;
- *Trifolium thalii* Vill.

Gentianaceae

- *Gentiana nivalis* L.

Geraniaceae

- *Geranium sylvaticum* L.

Lamiaceae

- *Hormium pyrenaicum* L.

Lentibulariaceae

- *Pignicula leptoceras* Rchb.

Orchidaceae

- *Coeloglossum viride* (L.) Hartm;
- *Dactylorhiza majalis* (Rchb.) P.F.Hunt & Summerh;
- *Gymnadenia conopsea* L.

Orobanchaceae

- *Bartsia alpina* L.;
- *Pedicularis elongata* A.Kern.

Polygalaceae

- *Polygala alpestris* Rchb.

Primulaceae

- *Primula farinosa* L.;
- *Soldanella alpina* L.

Ranunculaceae

- *Caltha palustris* L.;
- *Clematis alpina* L. (Miller);
- *Pulsatilla alpina* (L.) Delarbre;
- *Ranunculus acris* L.

Rosaceae

- *Geum montanum* L.;
- *Geum rivale* L.;
- *Trollius europaeus* L.

Salicaceae

- *Salix hastata* L.

Poaceae

- *Anthoxanthum odoratum* L.;
- *Avenella flexuosa* L.;
- *Calamagostris villosa* (Chaix) J.F. Gmel;
- *Nardus stricta* L.

1) *Dactylorhiza majalis* (Rchb.) P.F.Hunt & Summerh

2) *Crepis aurea* (L.) Cass.

3) *Geum rivale* L.

4) *Geum montanum* L.

5) *Clematis alpina* L. (Miller)

6) *Erica carnea* L.

Figure 5. Some of the plant species found in the area.

In addition to those just listed, since we are above the treeline, we do not have many arboreous species. In detail, we have a sporadic and irregular presence of: *Larix decidua* Mill., *Pinus mugo* Turra, *Picea abies* (L) H. Karst and *Pinus cembra* L.

Experimental site

The study will take place above the tree-line, nearby Giau pass (46°29’10’’N - 12°03’23’’E, Figure 6). The site measures about 30 m x 4 m, East/South-east facing, with around 20° slope and it is located on top of a small descending ridge, parallel to the slope, in which snow melts earlier.

The site was also selected for its accessibility, being just a few meters from the public road, which is easily reached by car, it is ease in: bringing work material and tools there and performing all the measurements and sampling.

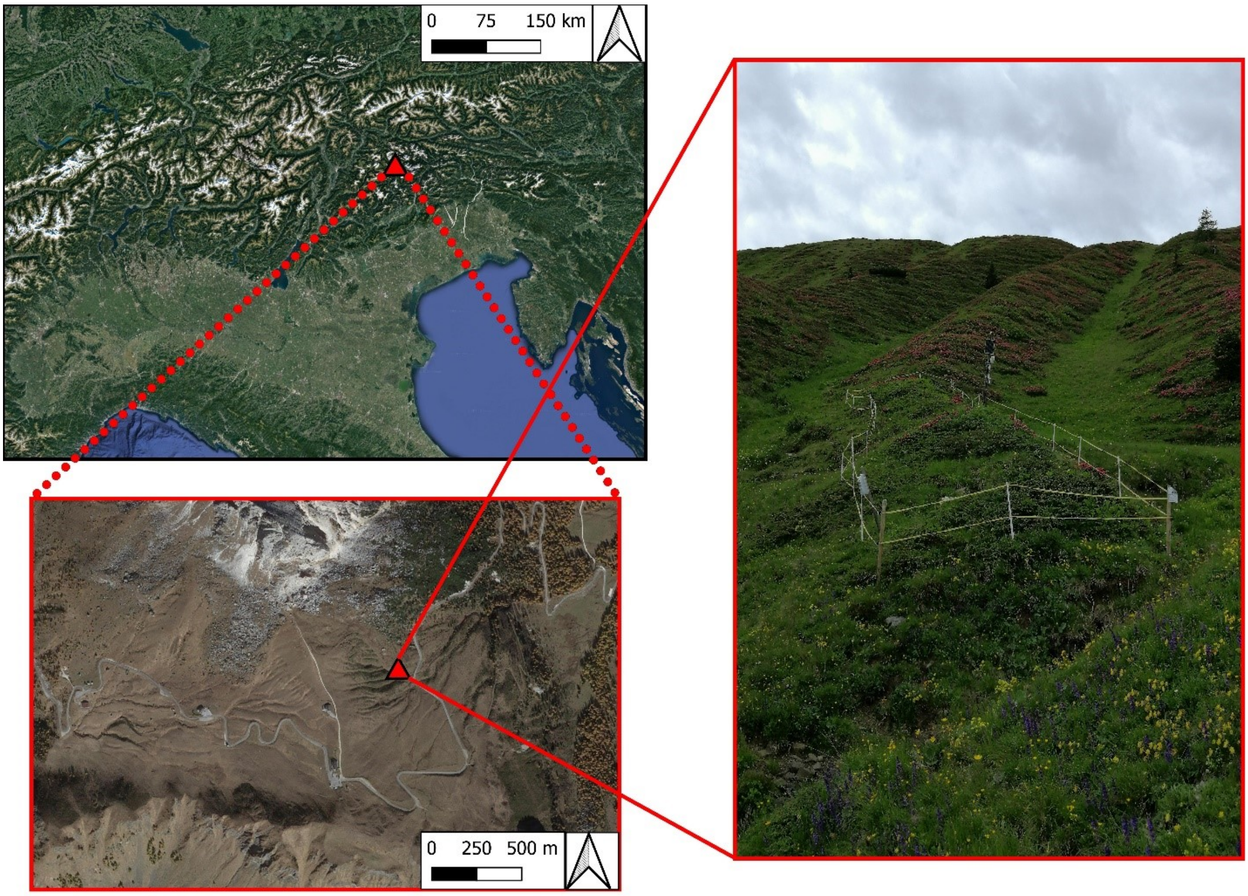


Figure 6. Geographical location of the study area (source: Google Satellite).

Figure 7. Meteorological station.

In the middle of the experimental plot, University of Padova installed a meteorological station (Figure 7), powered by a solar panel, that every 15 minutes takes two measurements of the air temperature at 2 m above ground with Type T Thermocouple (error ± 0.5◦C) (Unterholzner et al., 2022). The station is also equipped with temperature sensors placed inside the stems and in the soil around it of one individual per treatment collecting two measures every 15 minutes

Beside temperature, the station also takes one measure per treatment of the SWC (Soil Water Content) every hour through TDR (Time Domain Reflectometry) method, with probes that were previously calibrated for the soil type (precision ± 2%; Campbell Scientific co. Mo. SC615) (Unterholzner et al., 2022).

All the recorded data can be downloaded with a pc.

In the area there is also a trap camera that takes a picture of the site every 15 minutes and it's mainly used during the snowy season to check the amount of snow cover and the melting dynamics. It is extremely useful to plan field activities and perform the operations that will be described in the section "Materials and methods".

Since 2017, a snow manipulation experiment on common juniper is taking place at that site, 15 plants have been selected and are the object of the study.

Materials and methods

Snowpack manipulation

The 3 different groups of individuals are subjected to different snow permanence conditions as follows:

- In 5 of them, toward the end of the snowy season and when mean snowpack depth reaches around 50 cm, snow is manually removed to simulate an early snow melting (S) (Figure 8): to facilitate and to avoid to damage the plants during this operation, thin metallic nets have been put over the individuals, so it is easier to remove the snow without damaging juniper branches;
- 5 shrubs are manually covered with snow to simulate late snow melting (C) (Figure 8): these ones will be also covered with reflective insulating thermal sheets (padding in aluminium and polyester) 1.5 mm thick, to postpone the melting process as much as possible. Every 1-2 weeks snow that was melt was replaced manually with fresh one taken from the surroundings. This operation has to be done paying attention to not compromise the surrounding area (i.e., leaving holes and areas without snow) and causing a local change in the albedo that can influence the snowmelt in the experimental site;
- 5 individuals will be left undisturbed as control (N).

The dates of beginning and ending of the snow manipulation depend, as well as all the other operations, on the intra-annual weather conditions, which are different each year.

As the site is in a pasture area, to prevent grazing/trampling damage to the plants by cattle or other animals, such as deer, fake electric fences are used to isolate the entire area, during the summer period.

Figure 8. Plants subjected to treatment C (left) and S (right).

Buds' development

Few weeks after individuals C have been exposed, with the removal of the thermal sheets and the complete melt of the remaining snowpack, the measurements of buds' growth stage started, also for the other plants.

A visual assessment of their development has been made using the following scale:

Code	Description	Picture
/	Absence of gems or dead shoot.	/
1	Small bud, not so turgid, closed.	
2	Bigger than the 1 and closed.	
3	Big, turgid, with leaves.	

4	Same as 3 with leaves that start to open and to show growth.	

When the bud's shoot starts to grow, shoot elongation measurements start to take place

Shoot elongation

Shoot elongation was measured with a calliper at least once a week in the first period, when the growth is faster, to obtain a curve with a proper resolution and then, approximately after one month, when the growth starts to slow down, every 2 weeks until the growth stabilizes and shoots reach their maximum length. Usually, this process lasts until late September.

The measure is taken from the base of the shoot to half the size of its bud.

The shoots that are used for the measurement have been the same till the beginning of the measurements in 2018 in order to compare their growth's rate and amount each year. In order to be recognised after every season, they were labelled with coloured tags and associated to different alphanumerical codes. In the first year of the experiment (2018), only 1 branch per plant was used for the measures. The next year (2019) in each plant, 2 more branches have been added, for a total of 3 per plant, and labelled with numbers (1, 2 and 3); for each branch, 3 shoots have been chosen and named with letters (1a, 1b, 1c, 2a, 2b, 2c and so on). Then, from 2020, other 3 branches per plant (4, 5, 6) and shoots per branch (4a, 4b, 4c and so on) have been added to the measurements to increase the precision and the number of measures.

Field and lab activities

The following table shows the dates in which snow manipulation, phenological and growth measurements have been performed.

Date	Snowpack manipulation	Buds' development	Shoot elongation measurements	Samples collection
16/02/2023				
22/03/2023				
06/04/2023				
02/05/2023				
09/05/2023				
18/05/2023				
25/05/2023				
31/05/2023				

20/06/2023				
28/06/2023				
03/07/2023				
12/07/2023				
17/07/2023				
28/07/2023				
02/08/2023				
09/08/2023				
22/08/2023				
05/09/2023				
27/09/2023				

The first day in which the S individuals were manually freed from the snow cover was 16/02/23 and this operation continued in the other dates until it was necessary. The reflective insulating thermal sheets were removed from C individuals on the date 25/05/23, creating a difference of snowpack duration between S and C of 97 days. The following table summarizes the difference in snowpack duration in the present and previous years of the experiment.

Year	Difference
2018	88
2019	132
2020	66
2021	71
2022	82
2023	97

Table 1. Difference (C-S) of days under the snowpack in 2023 and in the past years.

Results

Meteorological data

Precipitation

In Figure 9 it's shown the amount of precipitation measured from the meteorological station of ARPAV located in the Falzarego Pass (approx. 6 km from Giau Pass, 46°31'08.04''N - 12°00'33.84''E) at 2090 m of altitude. Data have a daily resolution and the available data of the current year (2023) are up to August 31st.

In 2022 we had quite homogeneous precipitation events concentrated in the period from May to September and in November-December, with only one peak corresponding to a more intense event during the first days of June. In 2023 we had, in the period 01/01-31/08, almost the same amount of precipitation than fell during all the year of 2022 (953.4 mm against 991 mm) which allows us to say that 2023 will receive a higher amount of precipitation than 2022. On the 28th of August 2023, there was a huge event, with 88 mm measured only in this day and frequent storms, especially in the mountains and middle-northern plain (ARPAV, 2023).

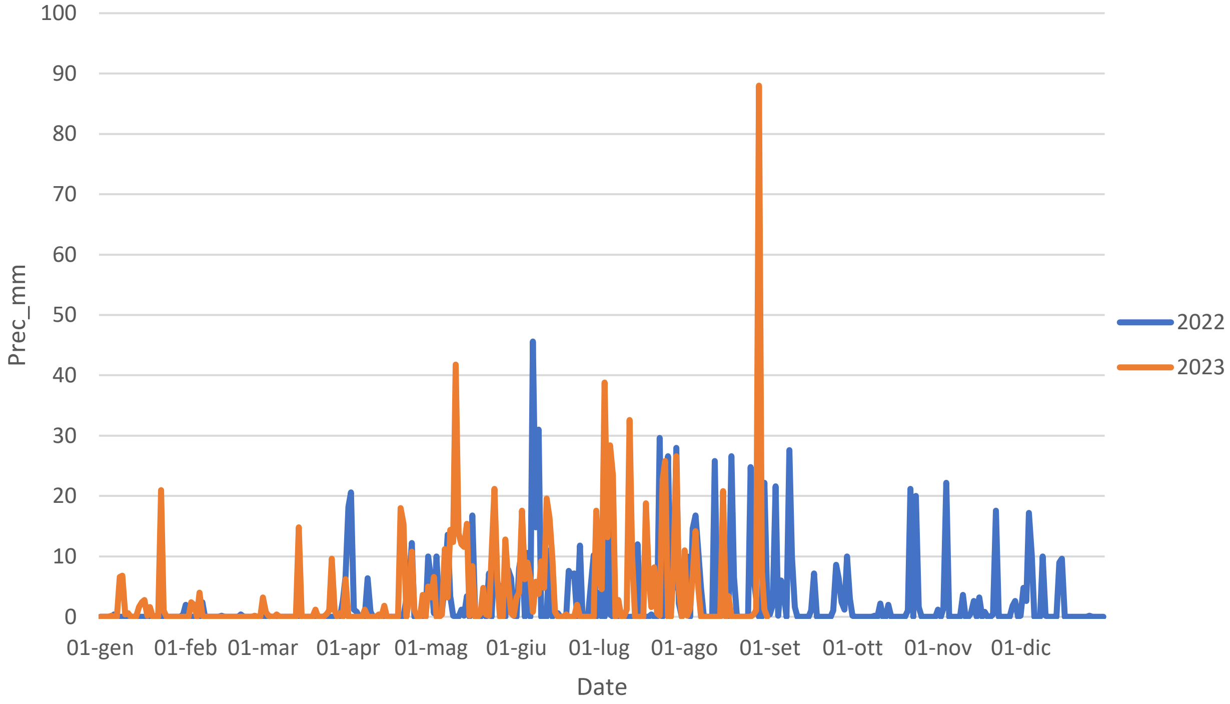


Figure 9. Amount of precipitation (mm) measured in Falzarego Pass during 2022 and 2023 (ARPAV, 2022-2023).

The following chart (Figure 10) shows the cumulative precipitation over the year for each year of treatment. We can see that 2021 and 2022 were the driest years with, respectively, 1076.4 mm and 991 mm; 2018, 2019 and 2020 were the most humid and 2023, up to the 31st of August, is showing values in line with these three.

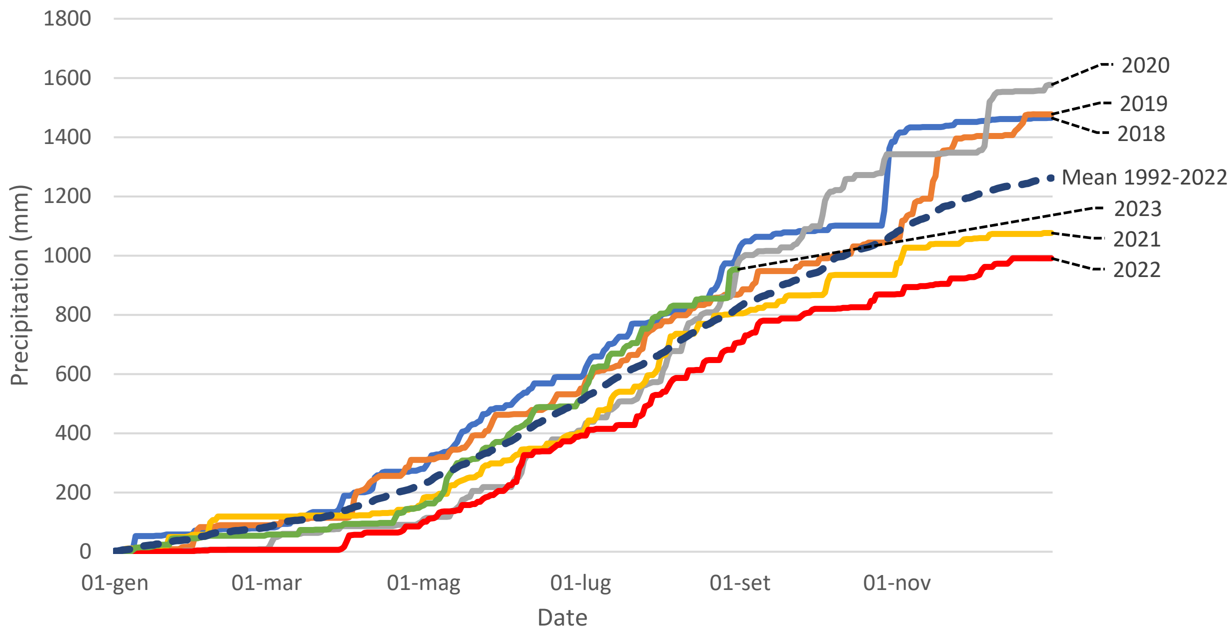


Figure 10. Cumulative precipitation over the period 2018-2023.

Focusing on solid precipitations, Figure 11 shows the values of snowpack height measured by ARPAV from 2019 to 2023 at the Giau pass. We can observe how in the last two years snowpack height was at his lowest, 2019 had even less snow cover but with only two measurements, therefore snow cover record for that year is not complete.

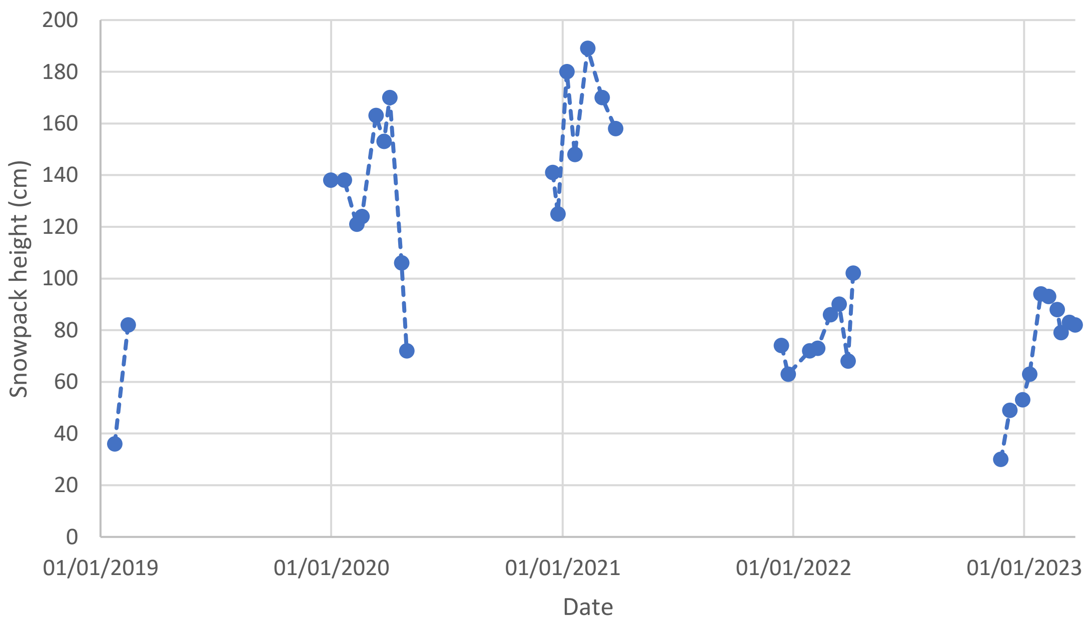


Figure 11. Snowpack height in the period 2019-2023 (ARPAV).

Temperature

In Figure 12 we can observe how the air temperature (Ta) changed during each year of the experiment; the data come from the temperature sensor of the meteorological station located in the study area. From the results, it's possible to observe that there's a highly significant tendence (*p<0.001*), shown by the dotted trendline, of a constant rising in the mean air temperature. These results can confirm the global trend of rising in temperature.

The lowest temperatures recorded were between -17.9°C and -19.7°C from 26/02/18 to 28/02/18.

The highest temperature recorded was of 20.7°C on the date 27/06/19.

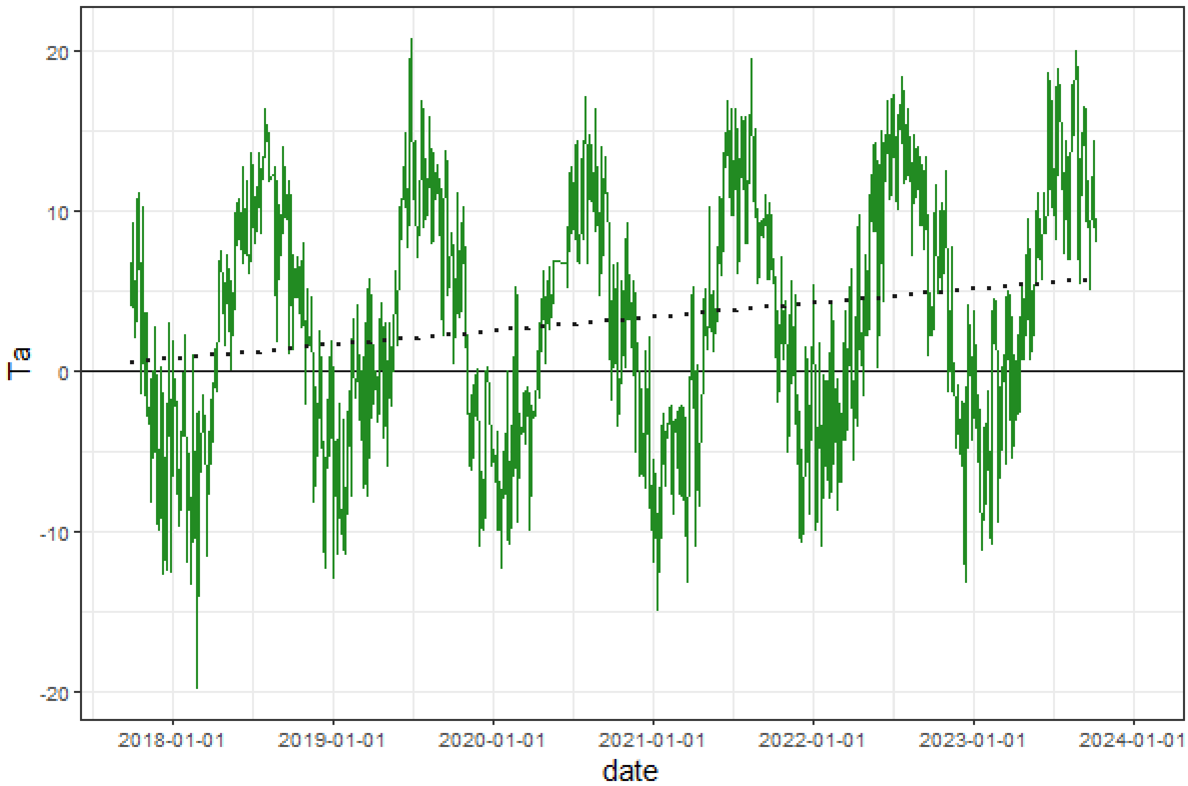


Figure 12. Air temperature (°C) data from 26/09/17 to 06/10/23.

Figure 13 shows the peculiarity of 2023 in terms of temperatures at the end of the growing season. Indeed, if we look at the red trendline, mean temperatures remained warm for the period and quite constant since mid-July, showing a slightly descending trend only in the last few days recorded.

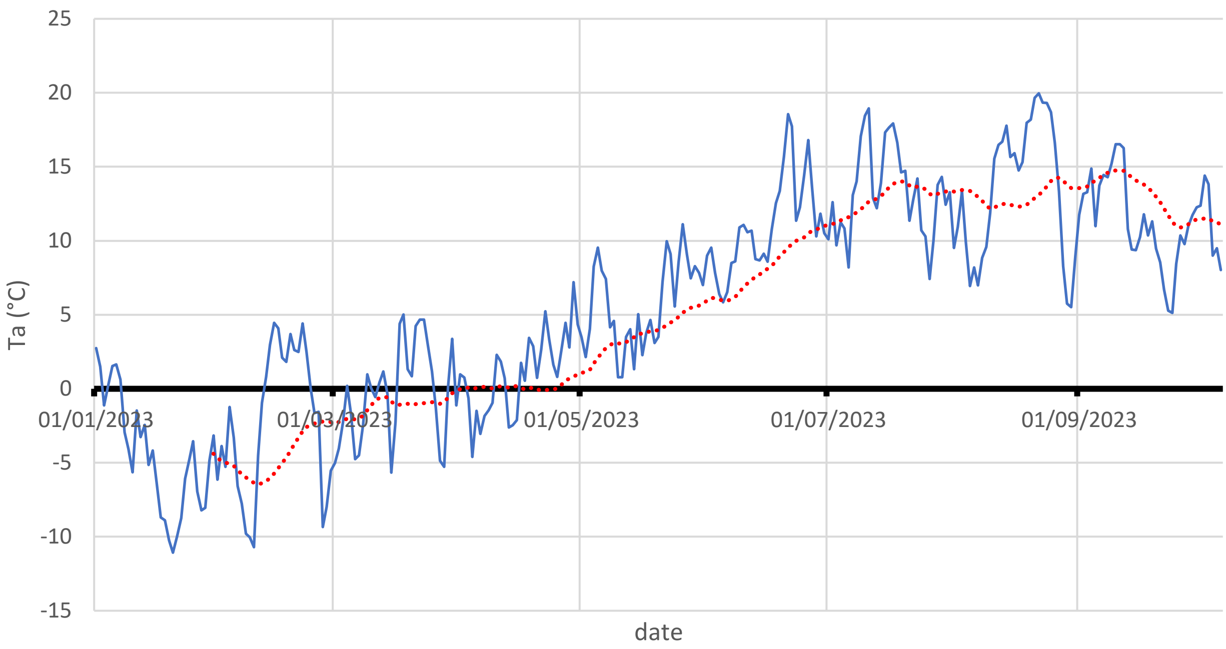


Figure 13. Temperature trend in 2023.

In Figure 14 we can see the deviation of the last period of 2023's temperature tendency line (red) from those of the other years.

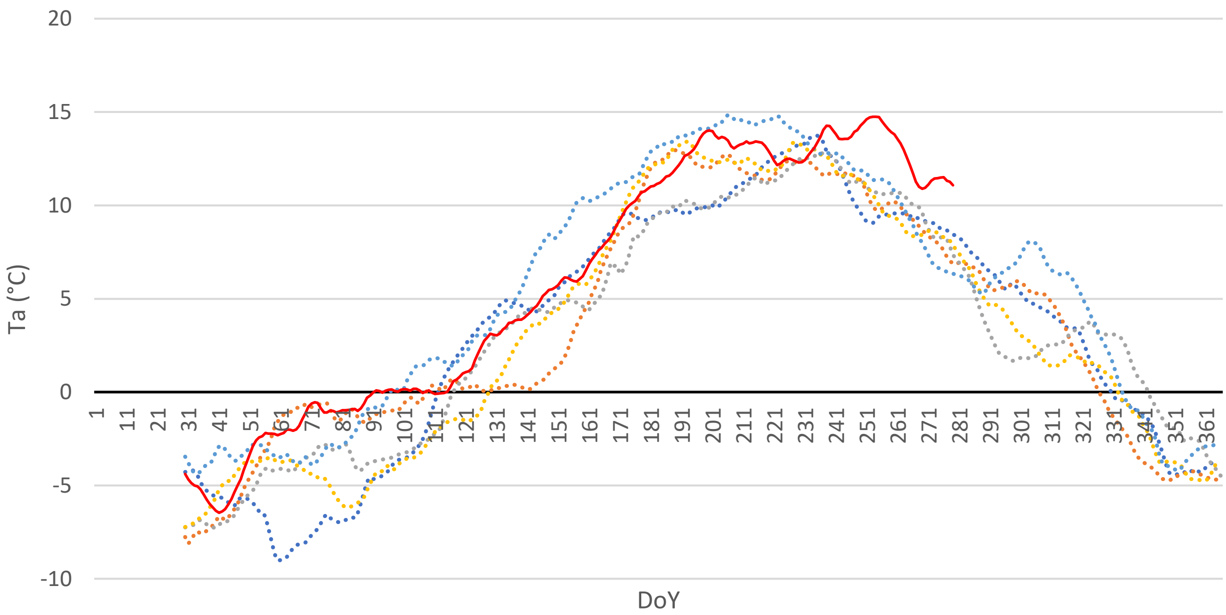


Figure 14. Temperature trends in the period 2018-2023.

Figure 15 shows the variation in the soil temperature over the years and the difference among treatments. We can appreciate that C individuals experienced the lowest variations, while N, and even more S, undergone the highest thermal excursions, mainly in the first period after they've been exposed.

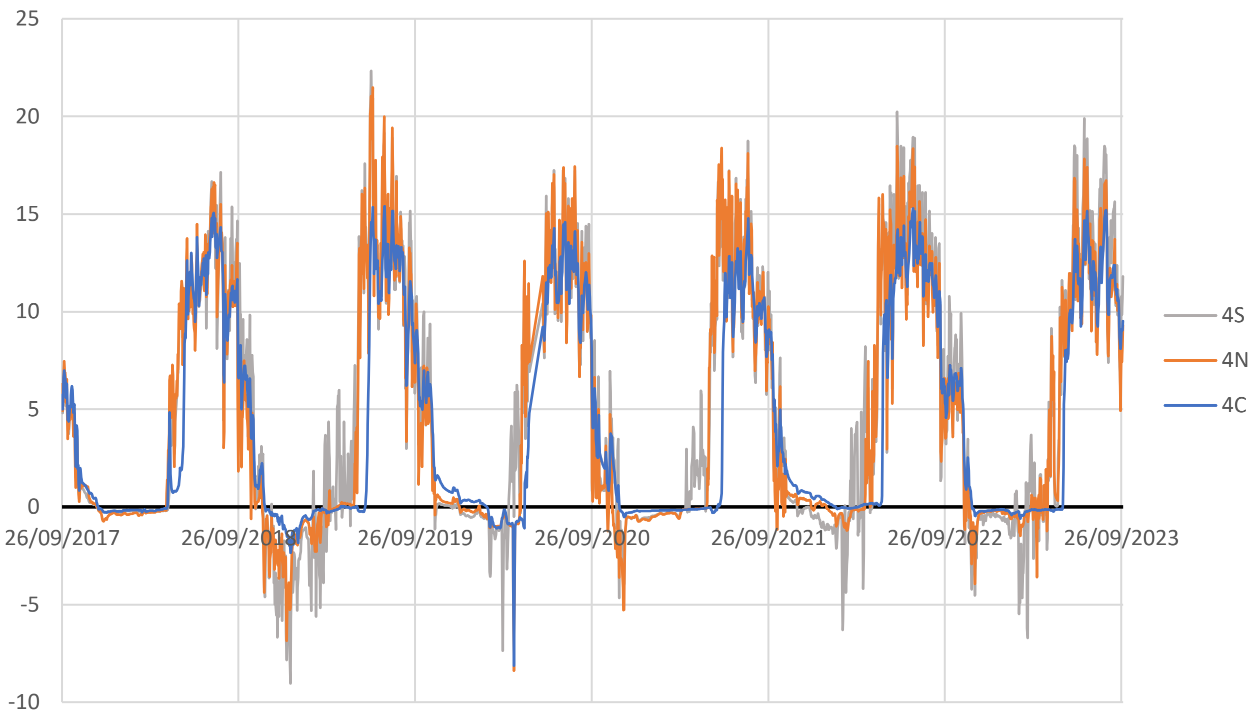


Figure 15. Soil temperature data (°C) from 26/09/17 to 06/10/23.

Soil water content (SWC)

From the results of the SWC measurements (Figure 16), we can appreciate that all the treatments follow a similar pattern, but, in S, values are higher than in the other two and are more sensitive to changes.

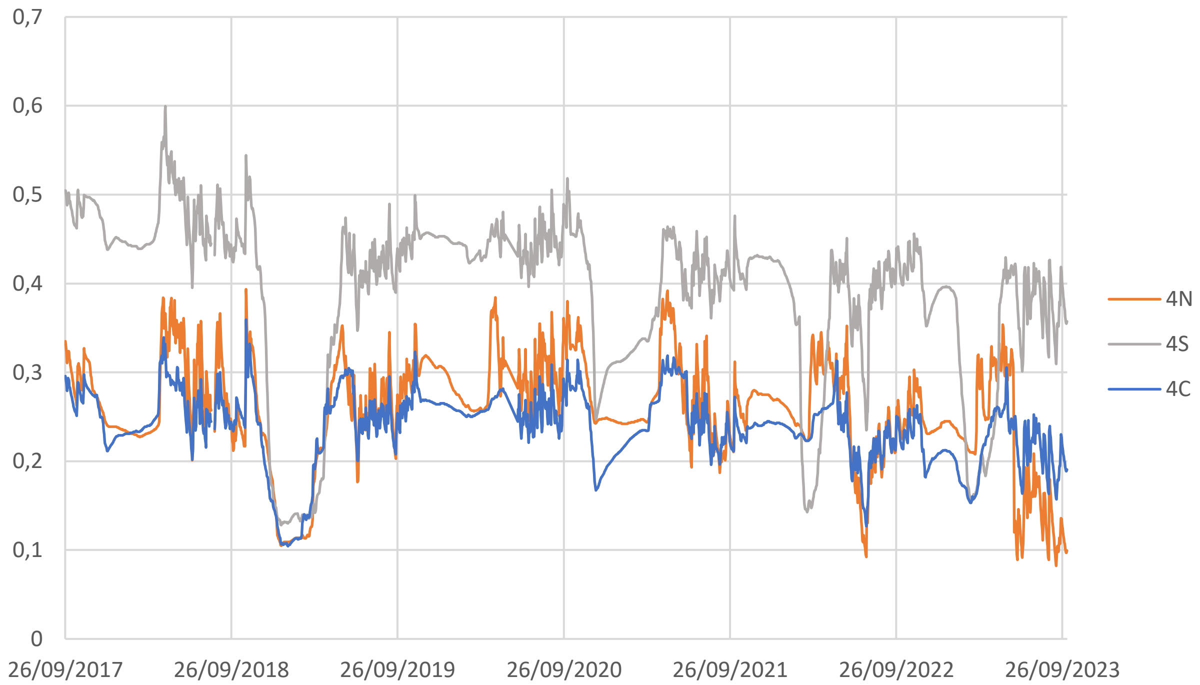


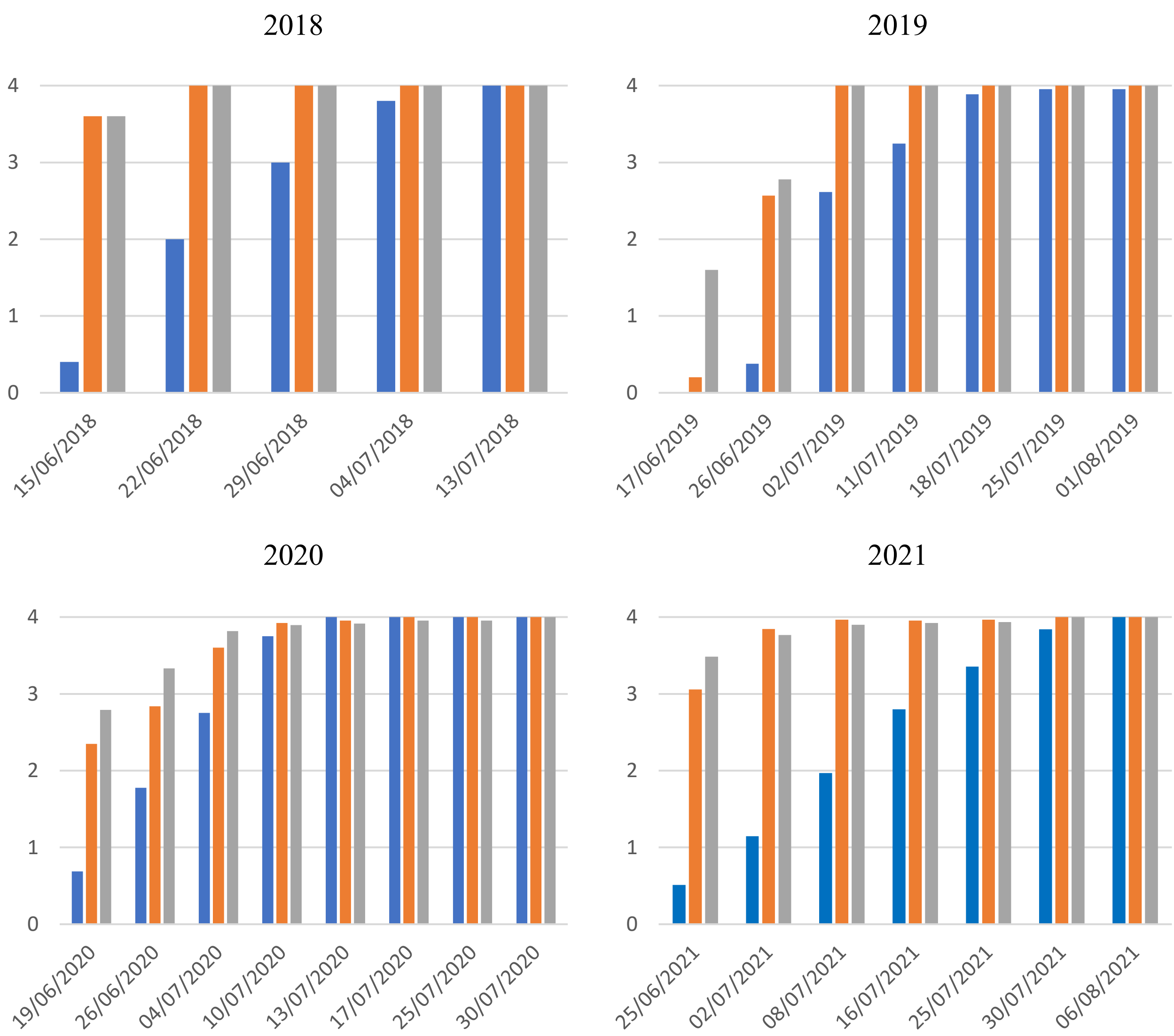
Figure 16. SWC from 26/09/2017 to 06/06/2023.

Buds

In Figure 17 we can see the results of buds' development measure, divided by year. Values are obtained by computing the mean of each branch for each treatment.

It's possible to notice that, except for 2023, C plants always had a slower buds' development and the onset of the opening and the complete development occurs later than N and S.

In 2023, I observed a similar trend to that of C during the other years (delayed opening onset and development), it's shown by N individuals, while C and S follow a comparable development, without big differences. However, it's correct to point out that, during this year, the measurements might have started too late; buds' development, in fact, on the first day of monitoring, was already on an advanced stage.



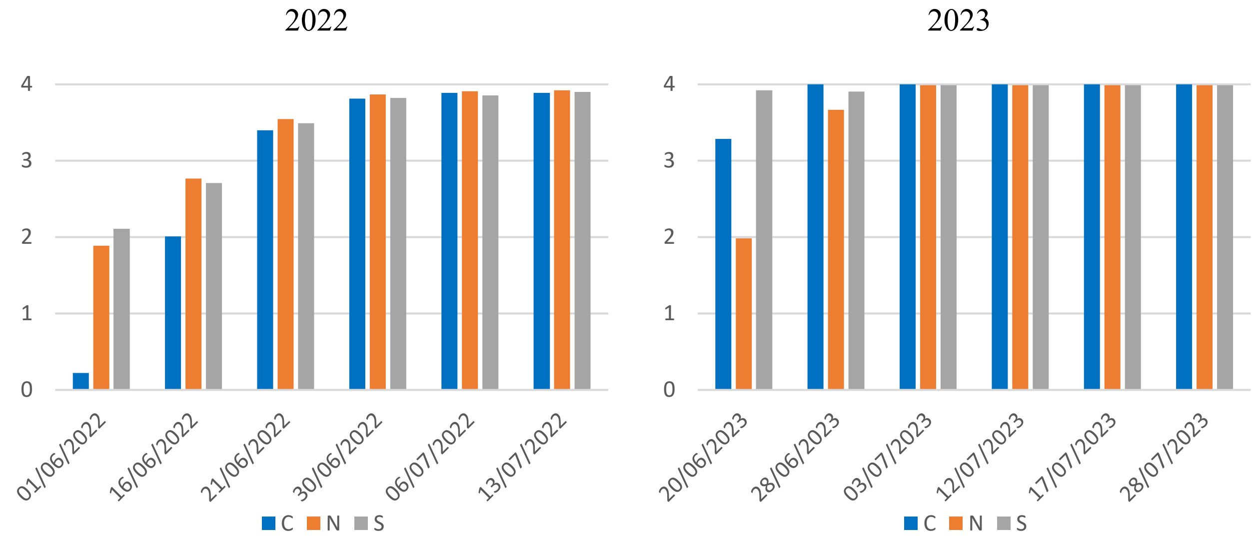


Figure 17. Results of buds' development measurements for each year over the period 2018-2023, divided by treatment, and the stage of development ranges from 1 to 4.

In Figure 18 we can see more in detail the DoY in which each treatment reached the complete development (stage 4). S and N are quite aligned in the dates, except for a little difference in the last two years; C individuals, who had less time to develop, reached stage 4 later than S or N, except for 2022, in which they needed the same number of days as S and in 2023, in which they followed N plants.

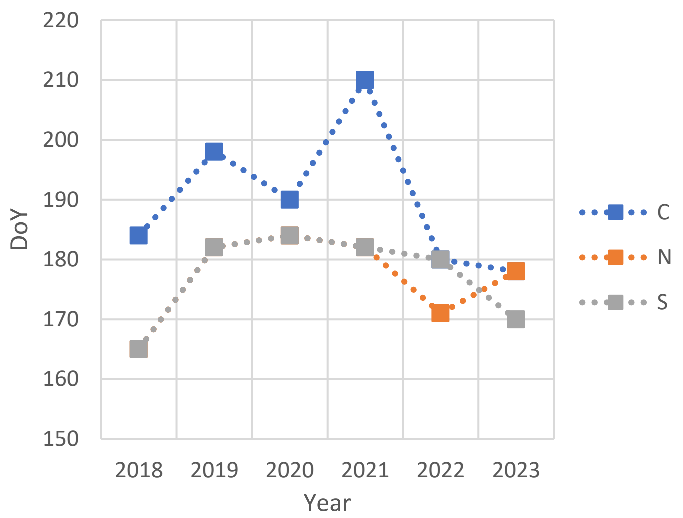


Figure 18. DoY in which buds reached stage of development 4.

Shoot elongation

In Figure 19 are shown the results of the shoot elongation measurements for each type of treatment for all the years of the experiment (2018-2023) together. Values are obtained by computing the mean of each branch per treatment. We can see that there are years when the difference among treatments is higher and others in which they are quite similar and this will be discussed later.

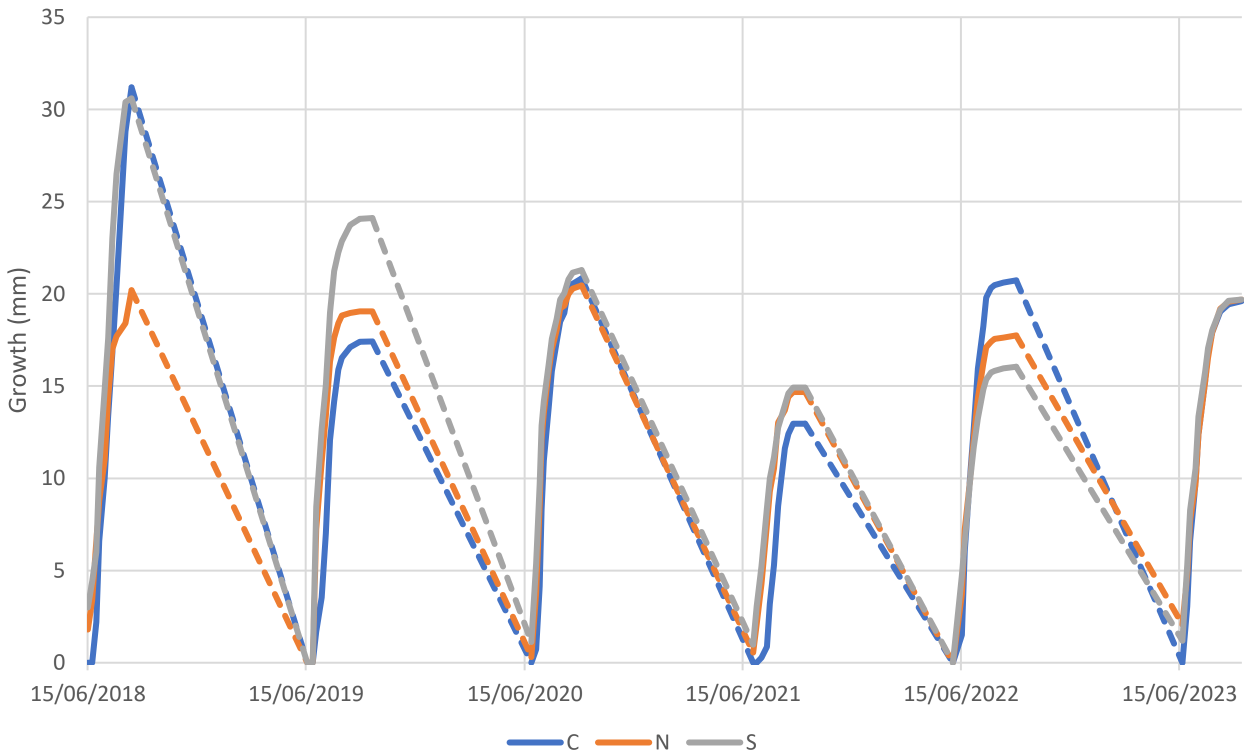


Figure 19. Shoot elongation during all the years of the experiment, divided by treatment.

If, from the previous figure, we consider only the growth values of S individuals at the end of the season (Figure 20), it's possible to appreciate a slow decreasing, highly significant (*p=0.0046*), trend of shoot elongation that reach slightly more than 10 mm after six years.

The other two treatments show no such difference.

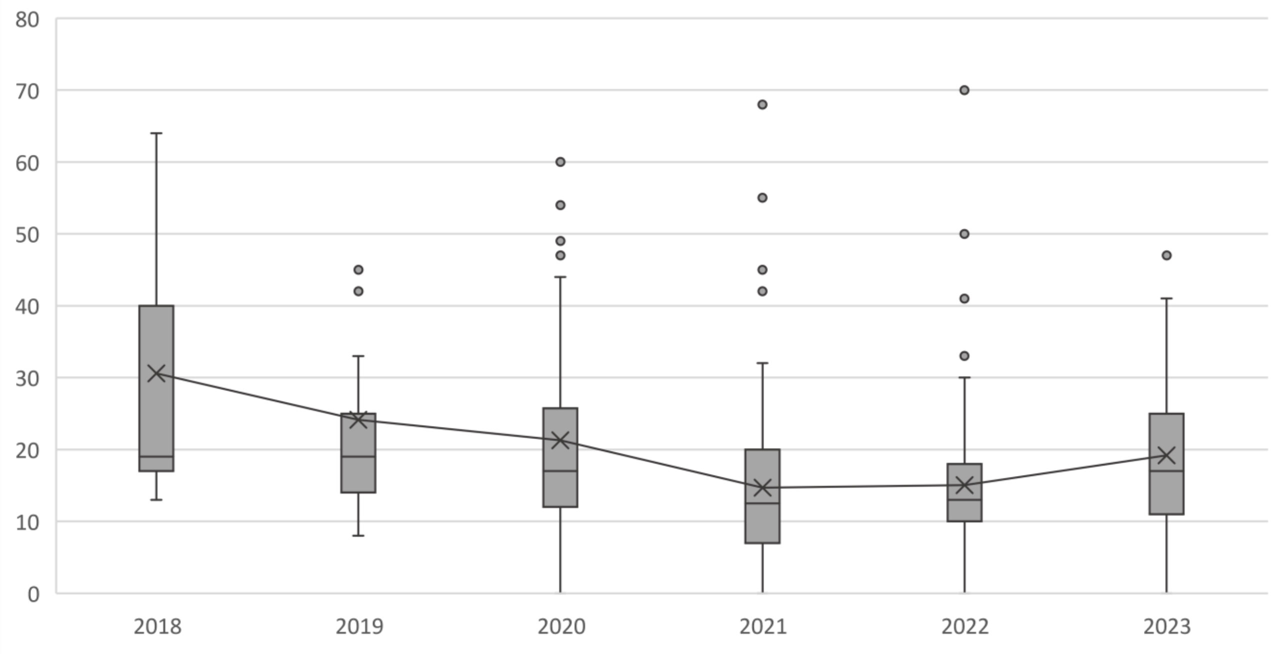


Figure 20. Growth of S individuals at the end of the season over the six years of the experiment. The representation includes the 1st and 3rd quartiles (box), maximum and minimum relevant values (whiskers), outliers (points), median lines, mean markers and lines.

In Figure 21 are shown the values of elongation divided by year.

In general, there is a faster growth rate at the beginning that, after a few weeks, slowly decreases and then stabilizes at the end of the growing season (usually in middle-late September). The most significant difference, that can be appreciated in Figure 19 and Figure 21, between treatments is the irregular growth in 2018 and 2019. This could be explained by the lower number of shoots selected for each plant during these first two years of the experiment.

C individuals had always the shortest elongation, however, except for 2019 and 2021, at the end of the season, they've always reached the other individuals (in terms of absolute growth). In 2018 and 2022, they even reached higher values.

During the last four years, the growth of S individuals is almost in line with that of the control individuals (N). However, in 2018 and 2019, they reached higher length values than N.

During the current year we had the least difference between treatments, compared to all the other years, in terms of growth rate and values. C individuals began their growth a week later from N and S, but then they reached the values of the other two and also started to stabilize in the same period. This pattern, though with slight yearly differences, occurred every year. Indeed, C individuals have always begun their growth a later, and with a slower rate than the others.

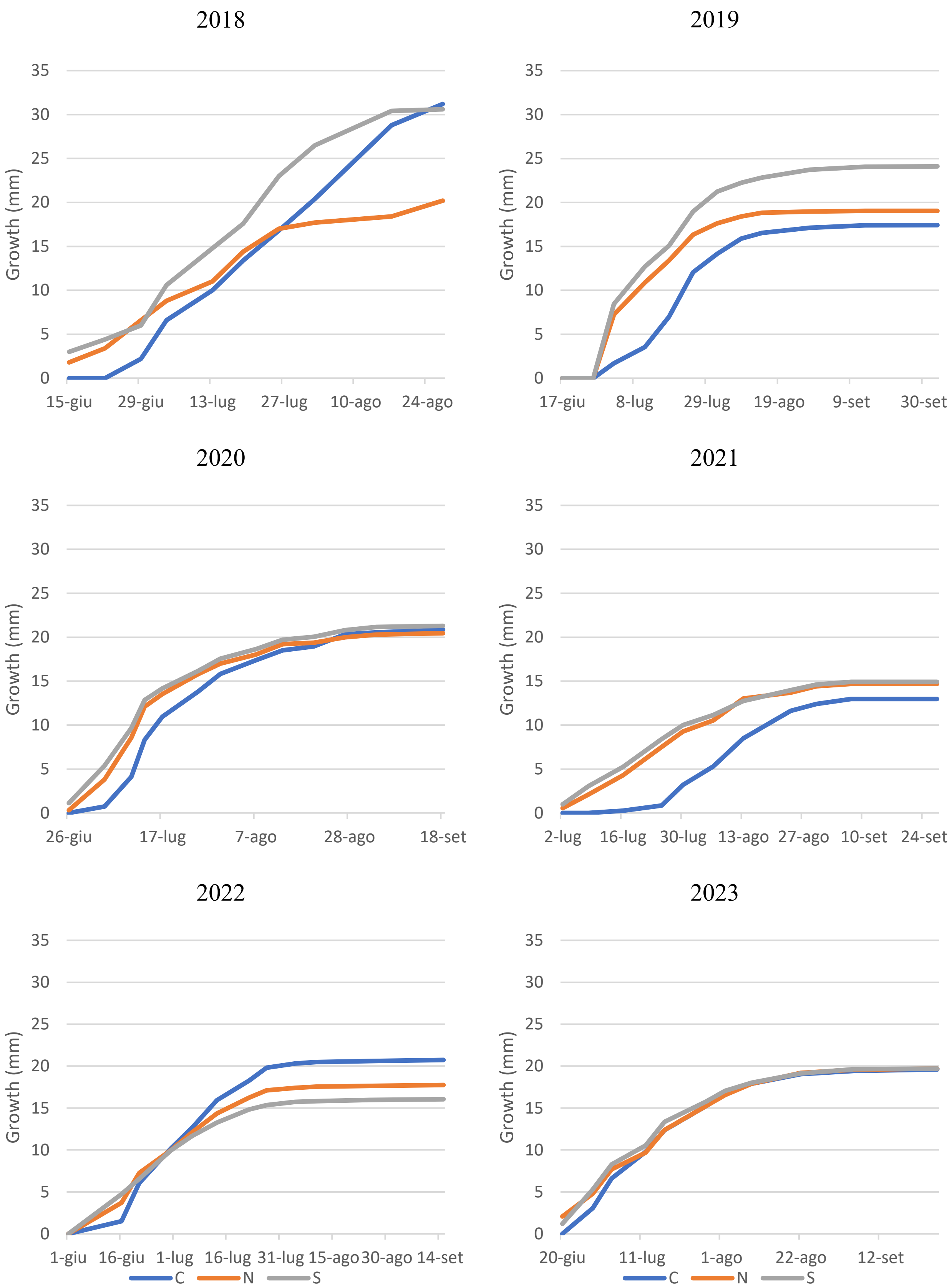


Figure 21. Shoots' growth over the period 2018-2023.

If we look at the day of the year (DoY) in which plants of different treatments started their growth, the results are shown in Figure 22. The period of growth onset ranged for all the years of the experiment from half June to end of July.

Focusing on the different treatments, it's possible to see that C plants began their growth later than S and N in half of the years, while in the remaining three they started in the same days.

S and N plants showed always an equal or similar day in the onset of the elongation.

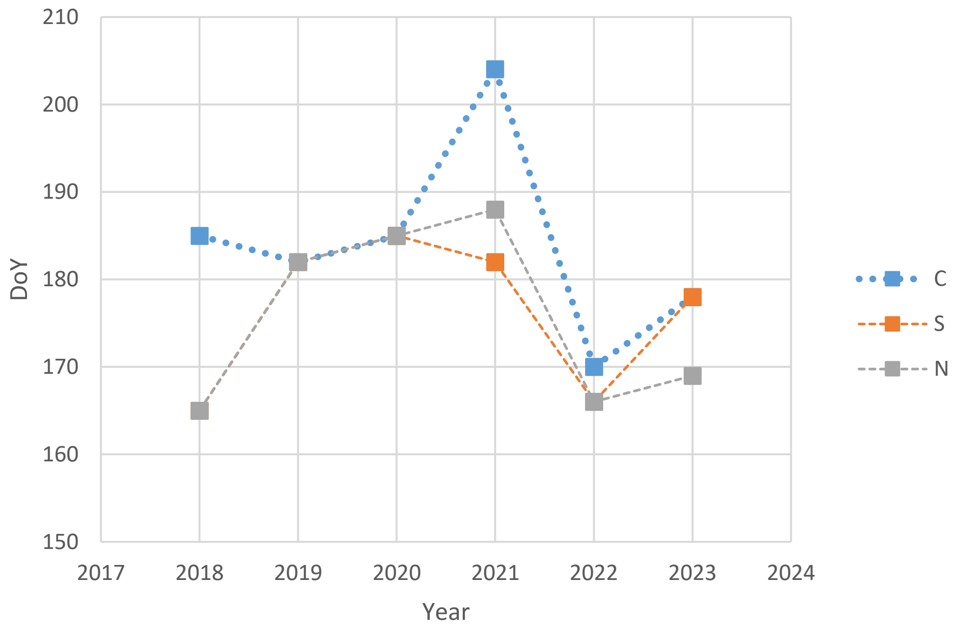


Figure 22. Day of the year (DoY) in which shoot elongation started.

In Figure 23 it's shown the maximum length of all the shoots at the end of the growing season during all the six years and divided by treatment. N individuals always displayed stable values throughout the years, while C and S had higher values at the beginning and then they stabilized.

We can see that the difference between treatments is higher in the first years and tend to decrease up to 2023 in which it's the lowest.

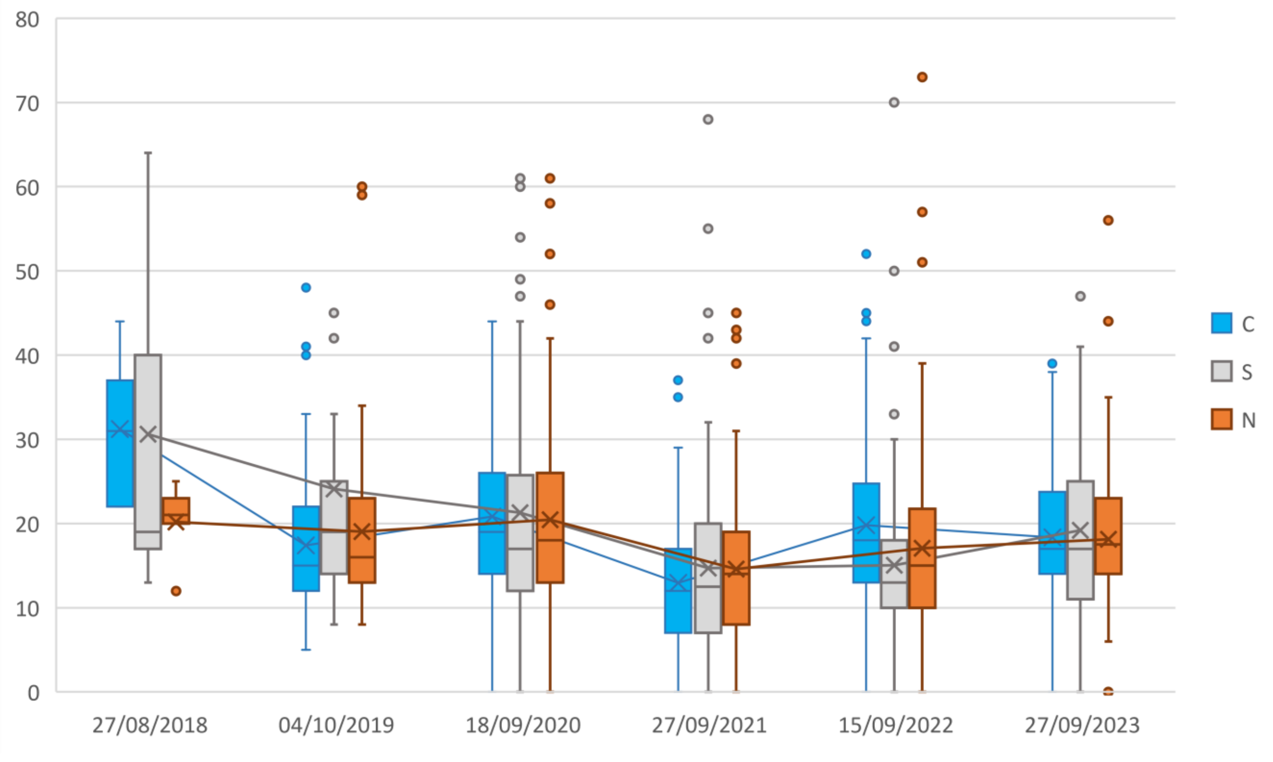


Figure 23. Maximum length of all shoots at the end of the growing season. The representation includes the 1st and 3rd quartiles (box), maximum and minimum relevant values (whiskers), outliers (points), median lines, mean markers and lines.

Figure 24 shows which treatment had the highest performance in terms of maximum growth at the end of each season. We can appreciate also here the decrease in the differences between treatments.

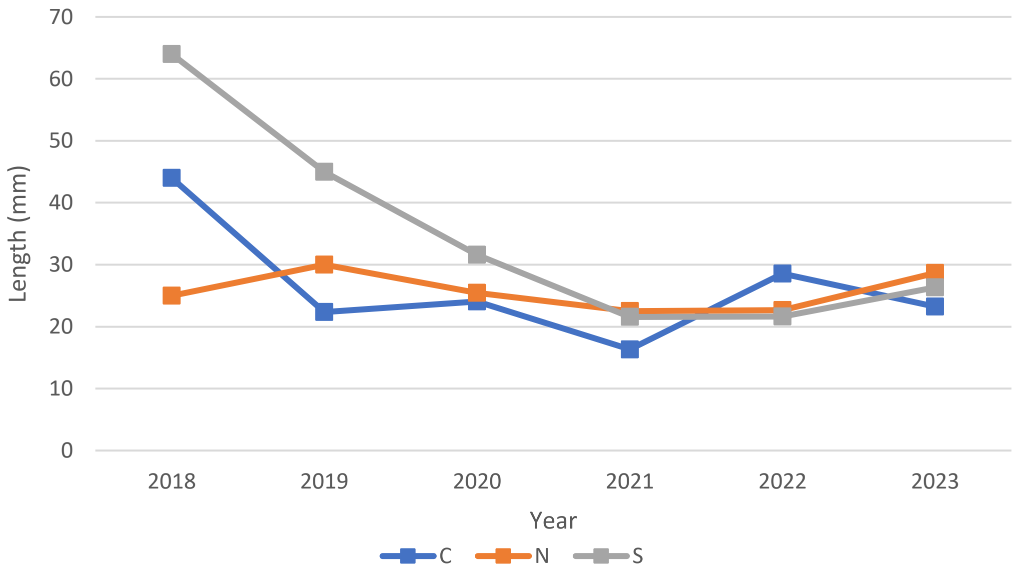


Figure 24. Highest length values at the end of the growing season.

The following table shows the results of the t-Test: Two-Sample Assuming Equal Variances computed considering the length of each shoot at the end of the growing season. We can see that the only result statistically relevant (red) is the different growth of C and S individuals in 2022; we have also other two results (C and N in 2018, C and S in 2019) that are almost significant.

		P(T<=t) two-tail		
	Observations	C_N	S_N	C_S
2018	5	0.052	0.321	0.956
2019	45	0.442	0.162	0.059
2020	90	0.801	0.694	0.824
2021	90	0.203	0.944	0.247
2022	90	0.089	0.210	0.002
2023	90	0.850	0.500	0.599

Table 2. t-Test on the growth of the different treatments.

If we repeat the same test on the shoots' length at halfway of the growing season (around July 30) we obtain the results shown in Table 3 in which we have more significant values (red). We can say that the treatments C and S had an influence in shoots' growth in the first period of the vegetative season.

		P(T<=t) two-tail		
	Observations	C_N	S_N	C_S
2018	5	0.513	0.389	0.557
2019	45	0.053	0.163	0.004
2020	90	0.350	0.718	0.221
2021	90	2.98E-13	0.516	1.90E-11
2022	90	0.097	0.172	0.002
2023	90	0.876	0.253	0.303

Table 3. t-Test computed on the measurements in late July.

In Figure 25 it's presented the difference between the maximum growth of C or S individuals and the control individuals (N). In both cases, after an initial positive difference of about 10 mm (which means that they grew more than the controls), the treatments started to rapidly converge to length values similar to the N.

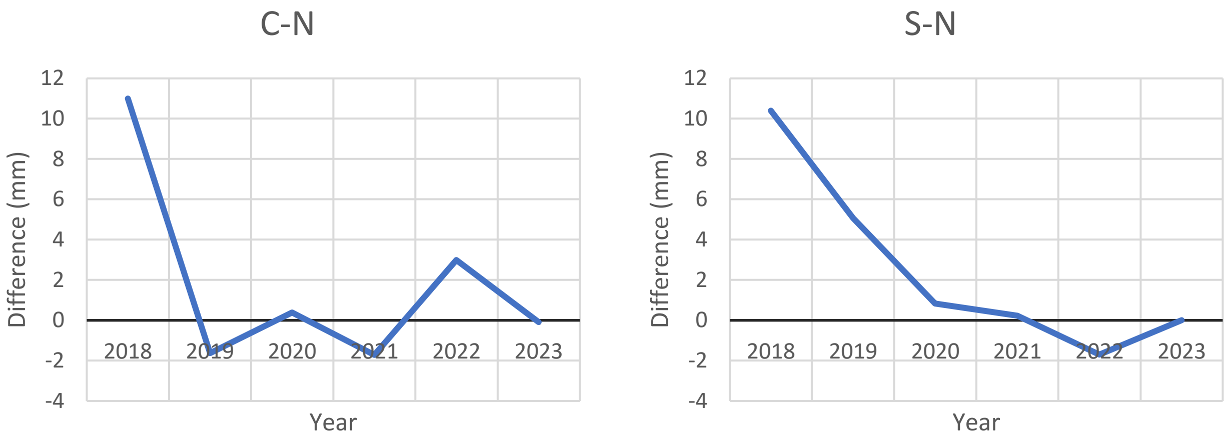


Figure 25. Difference between C and S and the control individuals.

Discussion

Meteorological data

Precipitation

The data from the Falzarego Pass (Figure 10) confirm what has been said in the introduction about the extreme weather years in 2021 and 2022, which have been the driest years over the period 2018-2023. Indeed, precipitations were low throughout the whole year. Probably because of that, these have been the years with the lowest branch elongation at the end of the season, with likely a carry-over effect in 2023 (Figure 23, Figure 24). Also in 2020, precipitations followed a similar pattern as 2021 and 2022, especially for summer months, however from mid-August there were more rain events and it turned out to be the rainiest year.

However, the observed descending trend in the maximum length started before 2021, when precipitations were at their highest, therefore the reasons for such behaviour should be related to something else respect to precipitation.

Where precipitation patterns do change, the impacts may be more significant than those of temperature, but they are not necessarily straightforward. In particular, the seasonal distribution and variability can be more important than the total amount (Morison & Morecroft, 2007). In this case study, precipitation have been quite uniform during all the years, except for 2018 in which there were two periods (September-November and November-December) without rain/snow, though when the growing period was already ended.

Focusing on the amount of snow cover (Figure 11), the low values of 2022 and 2023 may be due to a combined effect of low precipitations in the beginning of the year and higher temperature from year to year.

Temperature

Where precipitation patterns do not change, a rise in temperature alone will inevitably have an impact on the water balance of vegetation: evapotranspiration rates rise and there can be an effect on the snow cover duration (Morison & Morecroft, 2007).

In 2019, during the March- May period, we recorded a significant mean temperature variability, with rapid fluctuations around zero and with thermal excursions up to 14°C. Then, in the same year, at the beginning of the vegetative season, growth was faster for S and N individuals respect to all the other years. If we give a look at the temperatures in that period, we have the highest recorded temperature of 20.7°C on the date 27/06/19. Plant growth doesn't seem to be influenced by the unstable spring temperatures during that year.

On the 29th of May 2022, according to the temperature data, we had a late frost event, with a minimum air temperature of – 2.05 °C. This event has probably caused the formation of a frost ring, recorded for that year, in S plants. Frost rings are traumatic tissues, which can be observed in both broadleaf and coniferous species, composed by unusual axial parenchyma cells and tracheids with irregular structure and appear in the annual ring as a layer of crushed and bent xylem cells (Glerum & Farrar, 1966). Samples recently taken on all the individuals showed the formation of a frost ring in 2022 in 7 branches out of 10 in S plants (Figure 26), 5 out of 10 in N and just 1 out of 10 in C ones. This can confirm that the snow cover can protect plants from late frosts, its absence, with early onset of the vegetative season, could lead to a higher risk of damages.

Figure 26. Stem section of shoot 3S2b in which we can appreciate the frost ring.

On the opposite side, 2023 will likely be one of the warmest years on record (World Meteorological Organization, 2023), with recorded temperatures that stayed relatively warm for the period until late October (Figure 13, Figure 14). However, these conditions don't seem to promote growth rate or growth amount.

Buds

The prolonged snow cover had an effect in C plants by delaying the onset of buds' development which needed more time to reach the complete growth respect to the other two treatments (Figure 18).

Regarding late frosts, for buds the situation seems different than shoots, therefore, S individuals don't seem to be affected by the early exposure to frost damages and/or high solar radiation that

could slow down their development. Unterholzner et al. (2022) did not observe any significant sign of frost damage, like dead branches or needles, during the period 2018-2020.
Considering the longer snow-free time that S had to withstand respect to the other treatments, we should expect a faster development than C and N. However, in some years (2018-2021-2022) they followed the N, in others (2019-2020-2023) they developed faster, so there's no clear sign of difference.

An interesting result is that C buds, in the last two years, seem to be adapting to the treatment and aligning the days in which the stage 4 is reached with those of S and N. Even the differences in the development rate are lower in 2022 and 2023, therefore it will be useful to continue these measurements in the following years to clarify this phenomenon.

Shoot elongation

By modifying snowpack permanence, we induced a longer (S) or shorter (C) vegetation period for the three different groups, and therefore some changes in their phenology. One of the consequences is that shrubs have been exposed for a longer or shorter period to low temperatures and frosts, influencing their growth. Even if arctic and alpine plants have a lower optimum temperature (0°C) than temperate species (15°C) for shoot growth (https://openoregon.pressbooks.pub), earlier exposure to free air compared to natural snowpack melting might increase the risk of damages due to freezing events (Unterholzner et al., 2022). Moreover, snow cover melting beside defining the beginning and length of the summer growing season, with water and nutrients released from the snowpack, can influence soil moisture and nutrient status until later in the summer (Wipf & Rixen, 2010). Additionally, Zeng & Jia (2013) found strong correlations between phenology and the timing of snow cover. Growing season length influences stature, growth rate, and developmental schedules and these effects can be appreciated from the individual to the ecosystem scales (Galen & M. L. Stanto, 1993).

In this study, individuals subjected to a prolonged snowpack duration (C) showed a significant delay in the onset of shoot elongation (Figure 22) in only three of the six years of experiment, so we could say that, in this case, the treatment doesn't clearly affect this parameter. It seems that there is an influence in the growth velocity of C shrubs, at least during the first period, which is slower than S and N ones. Later, indeed, the rate and the length reached comparable values to those of the other two treatments.
This phenomenon is confirmed by the study of Pellizzari et al. (2014), in which they found that late-persisting snow could have a detrimental effect on secondary growth which can delay the onset or slow down the first phases of the growing season, reducing the period of cambial activity. This

could be mostly related to the physical effect of the snow cover that filters the incoming solar radiation blocking photosynthesis, rather than the collateral reduction in soil temperature (Pellizzari et al., 2014).

If we consider all the six years of experiment, the prolonged snow cover duration doesn't seem to be able to influence the final length of the new shoots in C individuals, except in the first two years (Figure 23, Figure 24, Figure 25).

This could be justified because a greater snow cover provides better insulation and thus increases temperatures and promotes microbial life under the snow, resulting in an increased nutrient supply for shrubs at the beginning of the growth period of the following year (Hallinger et al., 2010; Wahren et al., 2005; Wipf et al., 2009; Wipf & Rixen, 2010). The extent of this influence may depend on the balance between the negative (root damage) and positive effects (increased nutrient availability) (Wipf et al., 2009).

However, there can be a tipping point, when the amount of snow becomes too much that the advantage of better insulation is outweighed by the disadvantage of the shortening of the vegetation period (Hallinger et al., 2010).

Another mechanism that we can consider for the convergence in growth between shrubs is the acclimatation of the individuals in response to the new induced changes leading to an adjustment of the growth values to the pre-treatment conditions or in line with control individuals (N).

Unterholzner et al. (2022), that conducted the study in the previous years, found a remarkable converging tendency between treatments over years for primary growth dynamics, leaf area, leaf dry weight and, partially, also for starch leaf content.

This may suggest a plant's progressive acclimation to the new conditions across time that could be explained considering that *Juniperus* species are usually highly resistant to dry conditions and are adaptable to stressful environments (Hazubska-Przybył, 2019), to nutrient-poor conditions and frost tolerant (Thomas et al., 2007).

In the first three years, S plants grew more than N and C, probably because of the prolonged growing season and thanks to the higher exposure to solar radiation improving the photosynthesis. Therefore, the lengthening of the growing season will likely have a direct impact on both net C uptake and respiration (Euskirchen et al., 2006).

In the following years, it seems that some kind of adaptation mechanism took place that adjusted the growth of C individuals to values similar to N ones. An early snow melt leads to a higher risk of experiencing late frosts because snow cover provides protection against frosts which is a crucial stressor at these elevations, especially on early-exposure sites (Unterholzner et al., 2022).

Even if the same study highlighted a low frost impact on S plants, observing all the six years of the experiment, the situation seems different (Figure 20). A hypothesis that may explain this negative trend of length values, considers that plants could have been compromised by the effects of late frost events over the six years that, all together, created damages and outweighed the effects of the prolonged growing season.

Other considerations

What could have been done before initiating the treatments in 2017/2018 was to measure the shoot elongation and all the other parameters of all plants at least for two years. This preliminary assessment would provide insight into the growth of these plants before any treatment. After this preliminary work, the experiment could have started with its regular procedure.

In this way, we would establish a more robust baseline, enhancing our confidence in attributing observed differences among plants to the specific treatments rather than other site- or individual-specific factors.

Additional studies are needed to disentangle the role of the different abiotic (environmental and climatic) and biotic (e.g., competition) components to get insight into shrubs' responses (Unterholzner et al., 2022).

Also, to have a more accurate overview on the study area, could have been taken also measures of random juniper plants in the surroundings of the experimental site and compare their growth with those from the site.

Conclusions

Taking into account the aforementioned limitations of this study, we can still appreciate that:

- The different amount of precipitation recorded in the different years doesn't seem to have an influence in the primary growth. Rather, the relatively high temperatures recorded in June 2019 may have led to a faster growth just for the S and N individuals, while the C, until June, where still under the snow cover, and for this reason warm temperature might not have played any role;
- A prolonged snowpack persistence, is able to induce a delay in the first phenological phases (buds' development), however, the same doesn't happen for shoot's growth which is delayed only in three years out of six. What is affected is the growth rate in the initial growth phase, that is slower than in the other treatments;
- A reduced snowpack persistence led S plants to have a higher growth in the first years of the experiment that progressively decreased and adjusted to values like C or N. Also, it could have exposed plants to a higher risk of frost damages. Beside this, no influence has been highlighted in buds' development.

This study should continue to better understand if there is an acclimatation mechanism taking place, or if the observed trend is due to other physiological or biological mechanisms.

Finally, we can make some assumptions:

- The response is transient;
- Common juniper's high growth plasticity can be confirmed;
- Late frosts might play a role in S growth;
- The snow cover permanence doesn't seem to influence shoot's growth, while it might play a role in the initial growth period;
- Snow cover can protect plants from late frosts' damages.

Based on *Juniperus communis* L. high growth plasticity (Tumajer et al., 2021; Unterholzner et al., 2022), on the changing climatic conditions and on the results of this six years experiment it's still difficult to clearly predict how growth trends and phenological changes will occur in this shrub species at high elevation in the near future.

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