DENDROMETER MEASUREMENTS OF MEDITERRANEAN-ALPINE DWARF SHRUBS AND MICRO-ENVIRONMENTAL DRIVERS OF PLANT GROWTH – DATASET FROM LONG-TERM ALPINE ECOSYSTEM RESEARCH IN THE SIERRA NEVADA, SPAIN (LTAER-ES)

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With 3 figures, 3 appendices and 1 data supplement
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Summary: Here, we present measurement data of stem diameter variability of three common woody plants, monitored in the Mediterranean-alpine biome for six consecutive years (2015–2020). These focal species (*Astragalus granatensis, Cytisus galianoi,* and *Genista versicolor*) are abundant across the Sierra Nevada mountain chain (Southern Spain) and will potentially be affected by severe future climatic changes predicted for the region, including increased aridification in a warming environment. Understanding their fine-scale radial growth-patterns in relation to local environmental parameters might gain further insights into future vegetational shifts. We therefore used 139 high-resolution dendrometers to continuously monitor specimens along a steep elevational gradient and at varying topographical positions within the heterogeneous topography of the region. Additionally, we measured on-site environmental conditions at each studied site, including soil moisture and soil temperature within the root zone. All data were recorded at hourly resolution and are presented as daily mean values. The dataset was collected as a part of our long-term alpine ecosystem research program (LTAER), which functions as the basis for our recent projects on the use of dendrometer data to better understand the physiological mechanisms and the environmental drivers of the ongoing alpine greening.

Zusammenfassung: Hier präsentieren wir Messdaten zur Variabilität des Stammdurchmessers von drei typischen verholzenden Straucharten, die sechs Jahre in Folge (2015–2020) im mediterran-alpinen Biom beobachtet wurden. Diese Schwerpunktarten (*Astragalus granatensis, Cytisus galianoi* und *Genista versicolor*) sind in der Sierra Nevada (Südspanien) weit verbreitet und werden möglicherweise von zukünftigen klimatischen Veränderungen, einschließlich zunehmender Trockenheit betroffen sein. Das Verständnis der feinskaligen radialen Wachstumsmuster ihrer Stämmchen in Abhängigkeit von den lokalen Umweltparametern kann dazu beitragen, weitere Einblicke in zukünftige Vegetationsverschiebungen zu gewinnen. Wir nutzten daher 139 hochauflösende Dendrometer, um den Stammumfang von individuellen Sträuchern entlang eines steilen Höhengradienten und an den verschiedenen topographischen Positionen der Region kontinuierlich zu messen. Zusätzlich erfassten wir an jedem Standort Bodentemperatur und Bodenfeuchte in der Wurzelzone. Sämtliche Daten wurden stündlich aufgezeichnet und sind hier als Tagesmittelwerte dargestellt. Der Datensatz wurde als Teil unseres Langzeit-Forschungsprogramms alpiner Ökosysteme (LTAER) generiert, das als Grundlage für unsere aktuellen Projekte zur Verwendung von Dendrometerdaten dient, um die physiologischen Mechanismen und die umweltbedingten Treiber des fortschreitenden alpinen Greenings besser zu verstehen.

Keywords: Arctic-alpine greening, soil moisture, soil temperature, stem diameter variation, ecophysiology, microclimatology, mountain ecology, biogeography

1 Concept and study design

Our dataset is structured according to our geographical study design. The study sites are located along an elevational climate gradient in the Mediterranean-alpine region of the Sierra Nevada, Spain (Appendix 1). Here, we chose several sites along the topographical gradient (ridge – mid-slope – snowbed) above the local alpine treeline, each transect placed at approximately 100-m intervals along the alpine elevational gradient. Thus, our design encompasses all alpine elevation zones in the region; however, the zonal elevation classification we observed partially differs from the elevation gradation described in the literature (e.g., Rivas-Martínez 1980, Lorite 2001) and exhibits complex interlocks between the elevational zones (Fig. 1). Along the low-alpine environment at 1800–2200 m a.s.l. predominant dense shrub-dominated vegetation is permeated by single trees and groups of trees consisting

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of *Quercus* and planted *Pinus* species. With elevation, the dense vegetation cover loosens up and between 2200–2700 m a.s.l. a fine-scale mosaic of scattered shrub patches, gasses, and open rock and debris gradually transitioning into a middle-alpine environment. Above 2700 m a.s.l. individual low-growing shrubs co-occur with grasses in a matrix of open rock and debris, more and more transitioning into a high-alpine environment.

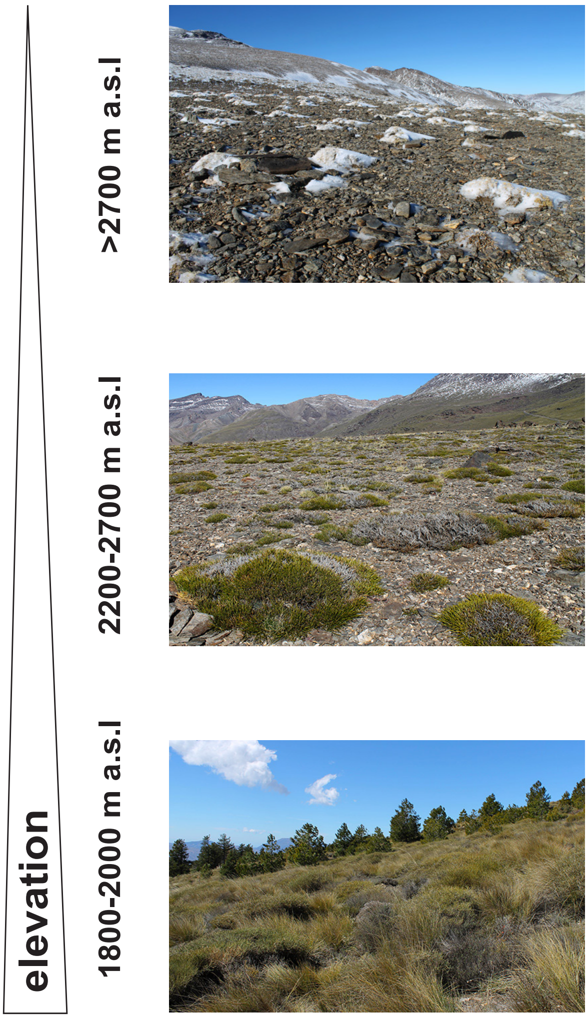

Fig. 1: Photos illustrate the entire range of alpine elevation zones covered by our research design

2 Structure, metadata, and legend of our dataset

Our dataset contains 139 individual dendrometer curves (Fig. 2) and is organised according to the following attributes:

dendro
Stem diameter of shoots measured with dendrometers (type DRO; Ecomatik, Dachau/Germany) near the shoot base as close to the assumed root collar as possible (approximately 1–5 cm above ground). We avoided positions near stones and small depressions, inside the radius of other larger shrub species, and near patches of wind erosion. The dendrometer sensor was placed as close to the living cambium cells as possible, after dead outer bark was removed. Unit: Micrometer [µm]

dendroStartZero
Annual stem diameter variability curves starting at zero (dendro - initial stem diameter at the beginning of the study period). Unit: µm

temperature
Soil temperature measured within the root zone (15 cm below ground surface), recorded using ONSET's HOBO loggers (type H21-002) and type S-TMB-002 temperature sensors (±0.2 °C accuracy). Unit: °C

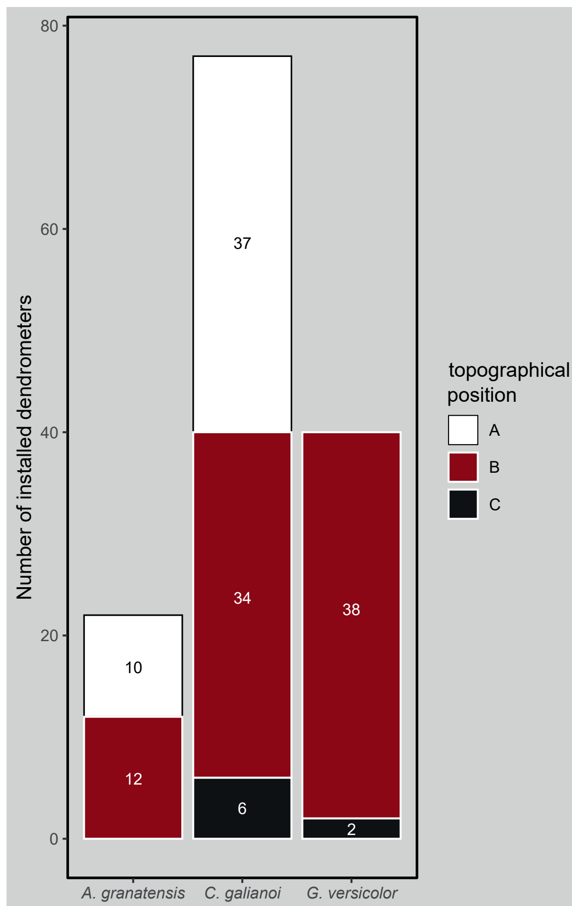

Fig. 2: Number of specimens and sites used in this study

moisture
Soil moisture measured within the root zone using type S-SMD-M005 soil moisture sensors (±3 % accuracy). Unit: m³ water/m³ soil

id
Unique id given to each monitored specimen. Form: Abbreviation for region, elevation (m a.s.l.), abbreviation for position, abbreviation for species, id for the dendrometer installed (if multiple dendrometers were mounted on one specimen).

elevation
Elevation above sea level. Unit: m a.s.l.

species
One of the three monitored shrub species: *Astragalus granatensis* (Lamarack), *Cytisus galianoi* (Talavera & Gibbs) and *Genista versicolor* (Boiss.) (Fig. 3). All three species are widely distributed across the Sierras of Southern Spain (Talavera & Gibbs 1997, Brummitt 2001, Melendo et al. 2003), with *G. versicolor* preferring slope positions, while *A. granatensis* and *C. galianoi* are common across heterogeneous topographical positions.

position
Topographical position of the sampled specimen (cf. Fig. 4 and Appendix 2). All three positions are characterised by slightly differing environmental conditions and vary in snow cover.

A: Exposed ridge positions. These positions usually experience no snow cover during cold and windy winter periods. Shallow fresh snow cover appears during short periods, which melts away early as to high solar radiation. As to strong wind exposure, shrub height is low (< 25 cm) and vegetation cover is patchy with open rock and debris at the surface .

B: Positions alongside south-facing mid-slopes. These positions experience periodic snow cover during longer winter periods as a result of wind drift and lee-side effects in complex topography. The moderate snow depth of up to 2 m persists over weeks, re-establishes after warmer winter periods, and may last into the spring period (especially at high elevations) after a long, cold and snow-rich winter. Shrub height may reach up to 80 cm, shrub diameter up to 280 cm, and vegetation cover is dense with individual stones and debris, only.

C: Late snow beds alongside south-facing slopes. Pronounced concave slope curvature results in local snow depth maxima of > 2m, which is persistent throughout the winter and may last into the summer period (especially at high elevations). As to the heavy load of snowpack, plant height is low (< 30 cm) and

Fig. 3: Photos of sampled species *Astragalus granatensis* (Lamarack), *Cytisus galianoi* (Talavera & Gibbs) and *Genista versicolor* (Boiss.)

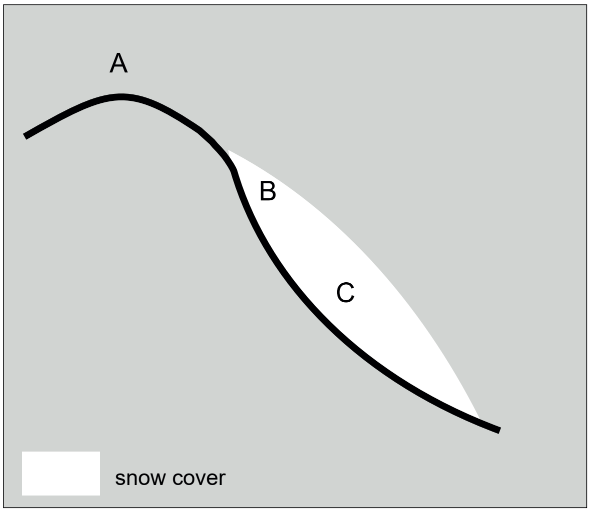

Fig. 4: Study design along the micro-topographic gradient

wet debris is unstable during and after snowmelt. Patchy vegetation persists of mainly grasses and single shrubs.

date
Date, at which the measurement was taken. Hourly measurements were aggregated to daily mean values.

specimen
Number to identify the specimen at the respective site. This is especially important, when multiple specimens were sampled at the same site.

dendrometer
Number of the dendrometer installed at the respective specimen.

longitude/latitude
Geographical position of the sampled specimen for which the measurement was taken.

3 Data content

The dataset contains time series with daily resolution, averaged from hourly measurements. The data are organised according to multiple characteristics, including species, study region, elevation and topographic position. Therefore, it allows for grouped usage and comparison in various ways.

An example for a comparative approach is presented in Appendix 3. Here we compare annual stem diameter change of three contrasting topographical positions (exposed ridges, slopes, and local depressions) (Appendix 3A), by grouping and averaging the dendrometer measurements of 47 and 84 individually installed dendrometers, respectively. Variations between these positions, as well as between the three focal species are clearly discernible from this representation. At the same time the curves show seasonal patterns, as well as interannual variability between the monitored years. For example, it becomes clear from this illustration that stem diameter change is highly variable between species. Yet, all species share a more or less distinct phase of stem diameter decline in spring or early summer and subsequent growth cessation during the summer months, most likely linked to the summer-dry conditions experienced at the monitored sites.

While these curves show averaged daily measurements, we also present total annual stem diameter change summarised as boxplots in Appendix 3C. These data were obtained by comparing dendrometer measurements at the start and end of each measured year. While the focus in Appendix 3A is on seasonal patterns, Appendix 3C highlights interannual variation and trends over six of the monitored years (2015–2020). For example, it becomes clear that during this period 2016 was the year with the highest overall stem diameter change for all species and at all topographical positions.

For direct comparison, we additionally present environmental measurements (soil moisture and soil temperature, measured within the root zone of the sampled specimens) with the same resolution and structure (Appendix 3B). This allows for a direct visual interpretation of climate-growth relations. The curves reveal comparatively little variation between topographical positions, while there are clear interannual differences in timing of the dry period in summer. Similarly, the dataset allows for comparison along an elevational or regional gradient, as well as more complex statistical analysis.

4 Background information

We started our long-term alpine ecosystem research program in the Sierra Nevada, Spain (LTAER-ES) in 2012, based on a pioneer program from the central Norwegian mountains (LTAER-NO), which was already established in 1992 (see Löffler et al. 2021). From the comprehensive experiences of our Norwegian program (e. g. Köhler at al. 1994, Löffler 1998, 2002, Löffler 2003, Löffler & Wundram 2003, Löffler & Pape 2004, Pape & Löffler 2004, Löffler 2005, Löffler & Finch

2005, Löffler et al. 2006, Löffler 2007, Rössler & Löffler 2007, Rössler et al. 2008, Wundram & Löffler 2008, Pape et al. 2009, Wundram et al. 2010, Hein et al. 2014a,b), we made use of technical infrastructure in the Sierra Nevada, which had proven resistant to the harsh alpine environment for many year. As such, after numerous installations of technical equipment had run, the first time-series of micro-environmental data emerged and offered new opportunities for different novel projects. We had also started with dendroecological studies on dwarf shrubs in Norway (Bär et al. 2006, 2007, 2008, Meinardus et al. 2011), and we had equipped different shrubs species with numerous dendrometers along multiple arctic-alpine ecological gradients, from which the first dendrometer studies resulted recently (Dobbert et al. 2021a,b,c, Löffler et al. 2021).

Our micro-environmental data revealed new insights into the functioning of arctic-alpine ecosystems (Pape & Löffler 2016, 2017), and were subject to further dendroecological studies on different focus dwarf shrubs in comparative approaches (Weijers et al. 2018a,b,c, Weijers & Löffler 2020). During the recent phase of our long-term program, we used high-resolution near-ground temperature data to assess the thermal niches of alpine plant species (Löffler & Pape 2020), and in combination with soil moisture data also those of soil microbes (Frindte et al. 2019); both approaches ran on a novel machine learning approach which statistically combined the biological attributes with our onsite micro-environmental drivers. Furthermore, we looked closely into growth responses of deciduous and evergreen species to long-term micro-environmental constraints, and for the first time, we made use of high-precision dendrometers to monitor radial growth of dwarf shrubs at unprecedented temporal resolution, bridging the gap between classical dendroecology and the underlying growth physiology of a species (e.g. Dobbert et al. 2021a,b,c). Recently, these data are subject to comparative approaches of different biomes, namely the arctic-alpine (Norway) and the Mediterranean-alpine (Spain). Hereby, we transposed our concepts and tools from the long-term projects in Norway to the Sierra Nevada data to gain similar results for the Mediterranean-alpine environment.

All in all, our long-term alpine ecosystem research program contributes to the ongoing scientific debate on future ecosystem responses to global change (Löffler et al. 2011). Our novel dataset, published here, as such offers meaningful interpretations of biological phenomena driven by soil temperatures and soil moisture. The theoretical concept of the underlying geographical ecosystem research was developed in Leser & Löffler (2017).

The dataset supplement is available online via: https://doi.org/10.3112/erdkunde.2022.ds.01

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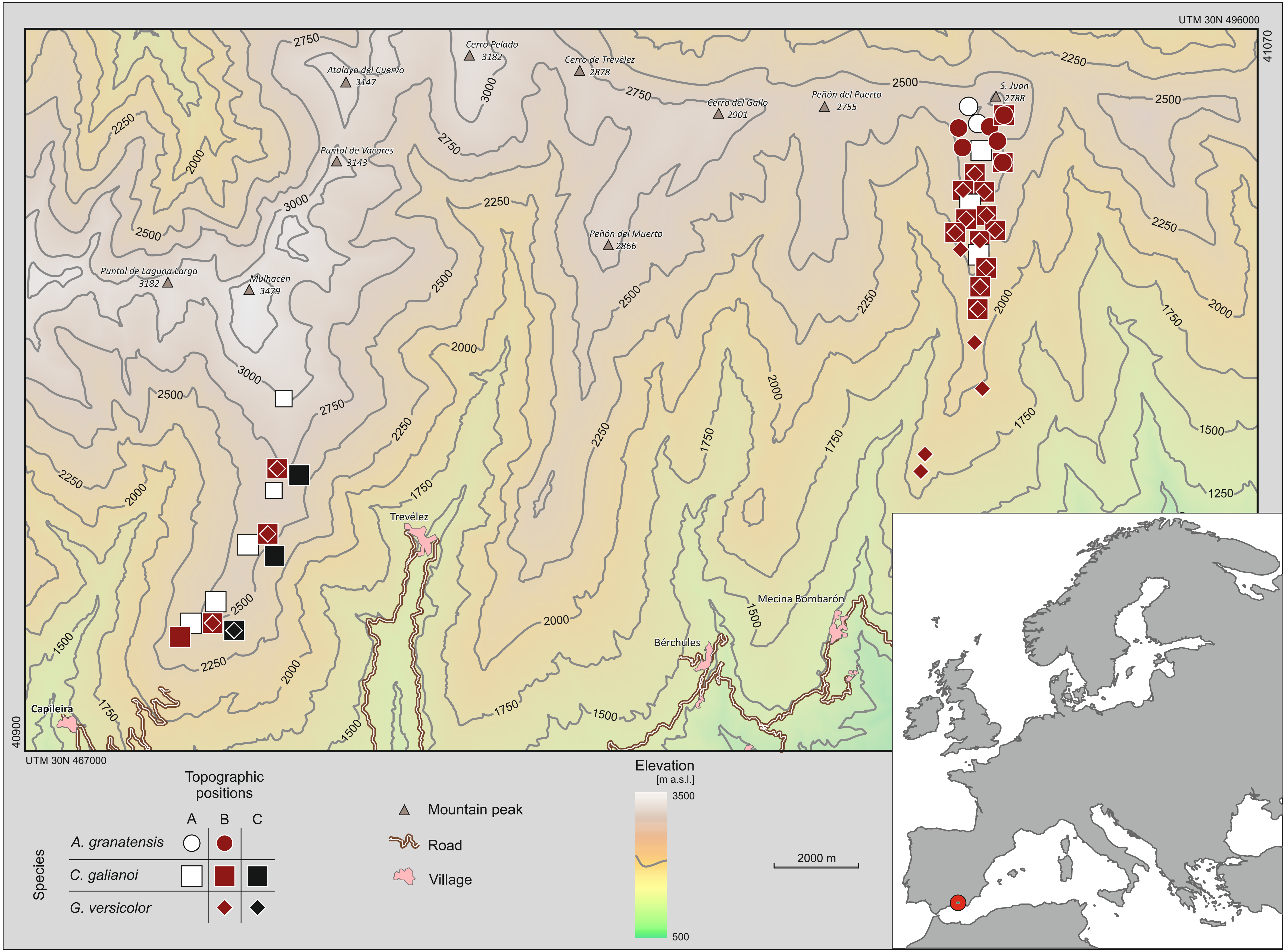
Appendix 1: Map of the studied mountain region and location of the sampling sites along the elevation gradient



Appendix 2: Topographical positions along the micro-topographic gradient

A: *ridge*

Photos illustrate three typical ridges dominated by open rock and debris with patchy vegetation

B: *mid-slope*

Photos show characteristic mid-slope sites where, from top to bottom, *A. granatensis, C. galianoi,* and *G. versicolor* are the predominant shrub species, each co-occurring with grasses (first and foremost *Festuca clementei)*

C: *snowbed*

Photos show, from top to bottom, a snow-free snowbed common in late summer and autumn, a snow-covered snowbed common throughout the winter until early summer, and a snowbed with scattered vegetation that decreases from the outside in

Appendix 3: Exemplary dendrometer series (A) and micro-environmental data (B) from three topographical positions (A = exposed ridges, B = slopes, and C = local depressions). The presented curves represent averaged series and transparency indicates standard deviation. C summarises annual stem diameter change (measured stem diameter at the end of the year – measured stem diameter at the start of the year).