Using seed germination as a proxy of restoration success.

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Abstract

Ecological restoration of post-mining landscapes is critical to mitigating the environmental impacts of extraction activities. This study compares the effectiveness of geomorphic restoration (GR) versus conventional restoration (CR) techniques in improving soil water availability and seed germination dynamics in the Fortuna quarry, a Mediterranean post-mining site in Spain. Soil water content (SWC) and soil water potential (ψ) were monitored over 22 months across different restored and reference treatments, alongside seed germination by means of hydrothermal time models.

GR areas exhibited significantly higher SWC and lower ψ compared to CR areas, aligning closer to reference ecosystem conditions. A novel metric, critical soil water content (θ_{cr}), was introduced to more accurately represent field germination thresholds, integrating soil-specific properties with seed germination properties. Germination probabilities were higher in GR treatments due to improved soil hydraulic properties and topography that reduced runoff and erosion.

This research underscores the role of substrate quality and hydrological design in enhancing germination windows and ecological succession in restored areas, providing a foundation for refining restoration practices in arid and semi-arid regions.

Keywords

Geomorphic Restoration, Soil Water Content, Soil water potential, Seed Germination, Ecological Restoration

Introduction

Mining has been an essential activity for the development of human societies since early humans began using stone to craft tools. Currently, 70% of European industry relies on raw materials extracted from the subsurface, excluding energy sources (European Economic and Social Committee, 2009). In fact, according to European Commission data, mining generated approximately €45 billion and created around 295,000 jobs in Europe in 2006 (European Commission, (n.d.)) .

However, mining is an intensively transformative activity that causes significant land disturbance and impacts extending beyond the boundaries of mining operations (Hancock *et al.*, 2020). These effects are observed at local, regional, and national levels (International Bank for Reconstruction and Development / The World Bank, 2014). A fundamental tool for minimizing the impact of mining is the practice of ecological restoration.

However, the conventional approach to land restoration (Conventional restoration, CR) commonly fails, because the new topographies tend to be linear, with slopes of constant gradient or with terraces and unnaturally rigid drainage structures (Figure 1, A). Such landforms do not restore natural functions, and they are not stable over the long term (Martín Duque *et al.*, 2021). Currently, new approaches like Geomorphic restoration (GR), try to improve landscape design to reduce soil erosion and stability problems by constructing geomorphically functional landscapes (Hancock *et al.*, 2020)(Figure 1, B). Expert management of runoff, by managing topography and substratum, is the key aspect (Espigares *et al.*, 2013). Indeed, geomorphic reclamation manages to reestablish a landscape in which hydrological and erosive processes operate at rates comparable to the surrounding natural landscapes (Zapico *et al.*, 2018). And recent results indicate that geomorphic restoration could improve plant community diversity and wildlife habitat (Fleisher & Hufford, 2020).

Figure 01. Examples of (A) conventional restoration and (B) geomorphic restoration.

A

B

The next step after topography and soil reconstruction, is to start the assembling the ecosystem, usually by introducing plants which, because seed dispersal is limited, are introduced by sowing (Dixon *et al.*, 2022; Turner *et al.*, 2022). But it needs to be considered that, in Mediterranean ecosystems, soil water availability is key for plant regeneration from seeds, more so in the current scenario of climate change (Mattana *et al.*, 2022). In fact, seed germination is a bottleneck in the colonization of restored habitats (Bochet *et al.*, 2007; Byrne *et al.*, 2017).

In post mining landscapes, overland flow modifies soil moisture distribution and hence, influences vegetation dynamics and ecological succession. E.g. by means of overland flow reducing germination probabilities (Merino-Martín *et al.*, 2015).

This is especially pronounced when runoff systems are formed, which can evacuate up to 20% of the annual precipitation (Moreno-de las Heras *et al.*, 2011). Hence, it is of interest to know if geomorphic restoration, which produces landscapes with less overland flow and erosion rates (Zapico *et al.*, 2018), provides increased soil water availability for plants compared to conventionally restored areas.

The first goal of this article is to test if soil water content (SWC) is different between areas with GM restoration and areas with conventional restoration. Hence, we compare the evolution of SWC during 22 months in soils of geomorphic restoration areas and soils of conventionally restored areas from the same mined area.

But, soil water availability for plants depends on the SWC -- which dynamics in the soil depends on the environmental conditions (e.g. evaporation vs precipitation)-- and the soil hydraulic properties: the hydraulic conductivity function and the water retention curve, the latter defined as the relationship between the water content in the soil and the soil water potential (ψ) with which this soil holds the water (Hillel, 2003). That means that the water availability for plants of two different soils with the same soil water content will be different if the respective water retention curves are different. Hence, in a context of water scarcity, the selection of soil type in the GR and CR is a key issue.

Hence the second goal of this study is to understand, if soil water availability, proxied as ψ is different between areas with GR and areas with CR.

But we can add one more layer of complexity, and compare a biological proxy of soil water availability for plants between GMR and CR. In this case we chose seed germination. Hence the third goal of this article is to compare soil water availability for plants between conventional and geomorphic restoration areas using seed germination as a proxy. We choose germination because it acts as a key step for the entry of new plant species in ecosystems (Donohue *et al.*, 2010; Huang *et al.*, 2016).

Usually, to predict field seed germination, thermal germination models are used (Bradford, 1990; Frischie *et al.*, 2019) which are based on the fact that germination speed depends on temperature. Soil temperature is very relevant in geomorphic restoration, particularly in mountain mining in middle latitudes as in our case. Reconstructed topography generates opposing orientations, polar and equatorial facing slopes which in turn produce different intensity of solar radiation which will determine soil temperature (Fan *et al.*, 2020).

To build these models, seeds are germinated at different temperatures and their germination speed (seeds/day^{-1}) is studied as a function of temperature. Germination is maximum at optimum temperature (T_{opt}), and decreases as temperature increases or decreases, reaching two thresholds, T_{max} and T_{min} above and below which germination is not possible. If we know the germination speed of seeds of a species as a function of temperature and if we also know the soil temperature over time (e.g., using daily temperature averages), we can estimate the probability of seed germination on a given day or after a series of days. These models, which are called thermal time models (TT), have been used, for example, in studies of seed ecology (Frischie *et al.*, 2019) or conservation biology (Porceddu *et al.*, 2013).

Another key factor for seed germination is soil water availability, which in germination studies is estimated by ψ. Lower SWC implies lower (More negative) soil ψ and hence, less soil water availability for seed imbibition, which slows or stops the germination process (Flores *et al.*, 2017). The TT models are useful if germination occurs at times of the year or in climates where the soil does not dry out too much. But in dry environments (e.g. in Mediterranean areas) where during the germination period the soil can dry out, it is necessary to consider soil ψ when modelling seed germination.

To consider effects of ψ on germination, Hydrothermal Time Models (HTT) are used. To build these models, germination experiments are performed at different temperatures and at different ψ values. This makes it possible to obtain the germination rate as a function of temperature and a ψ threshold (ψ_b) above which seeds are able to germinate (Roundy et al., 2007). Thus, when soil ψ is above ψ_b, it is assumed that there will be an advance in the germination process as a function of temperature. Suitable soil ψ and temperature periods are referred as germination windows (GW), periods of time in which germination probability is higher than 0. This kind of models have been used previously in mining environments (Merino-Martín *et al.*, 2015).

In previous works, a soil ψ threshold is determined arbitrarily (e.g. Hardegree *et al.*, 2018) and it is assumed the same for all kinds of soils.

However, although ψ_b is commonly used to calculate germination rate (GW) (Hardegree *et al.*, 2018), we argue that ψ_b is not a consistent index for modeling seed germination when the soil-seed system is considered. The soil water retention curve illustrates the relationship between soil ψ and SWC, which varies according to soil properties, such as texture. As a result, for the same soil ψ, SWC can differ across different soils.

Given that some seeds have very low ψ_b values as -1.82 MPa or even -2MPa (Dürr *et al.*, 2015; Frischie *et al.*, 2019), using ψ_b as an indicator of the threshold beyond which seeds will not germinate in the field may lead to an overestimation of germination probability. This occurs because, in some soils, ψ_b corresponds to soil water contents below the residual water content, meaning that there is no water available in the soil for seed imbibition, regardless of the seed ψ_b.

This hypothesis is supported by Moret-Fernández et al. (2024), who observed that seed germination in sand, at a constant ψ, was completely inhibited at -0.006 MPa. These results are explained by the fact that, even if seed ψ_b << -0.006 MPa, germination does not occur because, at that soil ψ, there is no water available for germination. Therefore, in this article, we propose adding another variable to better understand the soil ψ thresholds above which seed germination occurs in the field.

For this reason, the 4th goal of this paper is to present the concept of critical SWC (θ_{cr}), which is a threshold below which seed germination in field is not possible even if the soil ψ is over ψ_b

Kildisheva et al. (2016) set a conceptual framework to understand the factors determining success in seed based resotarion (1) altered landscape and soil conditions, (2) factors relevant to seed and seedling establishment and (3) techniques used to improve restoration effectiveness and efficiency through predictive and engineering solutions. In this framework, our article links two of these factors, we test how and if modification of landscape and soil conditions drives us to an improvement of seed germination.

The global objective of this work is to study the effect of the restauration process on GW. To this end, GW will be modelled using a new index defined as critical soil water content, θ_{cr}, for seed germination.

We tested three hypotheses: (1) SWC is higher in geomorphic restoration areas than in conventional restoration areas, (2) soil water availability, estimated as soil ψ, is higher in GR than in CR, (3) germination probability is higher in geomorphic restoration areas than in conventional restoration areas because of differences on soil water availability.

Materials & Methods

Abbreviations:

CR: Conventional restoration

GR: Geomorphic restoration

GW: Germination Windows

SWC: Soil water content

ψ: Soil water potential

ψ_b: Seed base water potential.

θ_{cr}: critical soil water content,

ψ_{cr}: critical soil water potential,

Study area

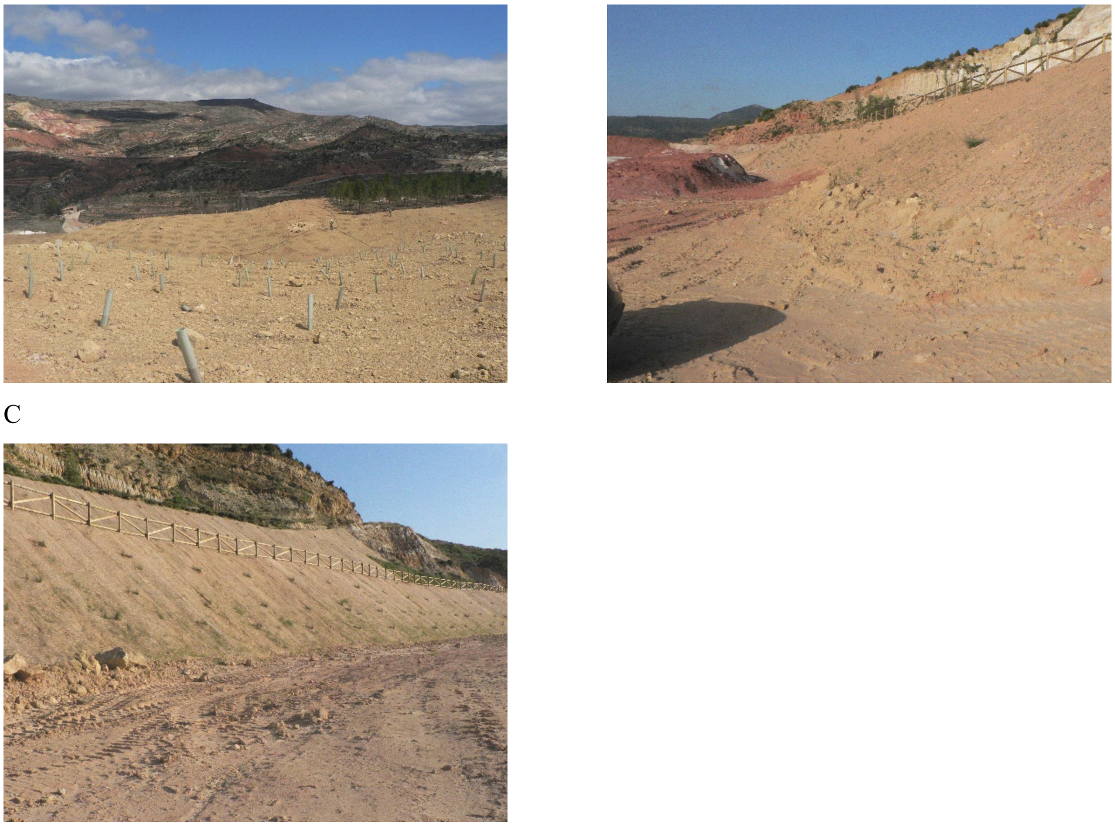
The study area is an abandoned open pit mine, the Fortuna quarry. It is located in the municipality of Ademuz (Valencia, Spain) and it is property of the Sibelco mining company where they mined siliceous sand and kaolin. It is in the Iberian Mountain Range in Eastern Spain at an altitude of around 1000 m a.s.l. The climate in the area is Continental Mediterranean, the closest meteorological station (Teruel, Valencia), which is 24 km apart and at 902 m a.s.l., registers a mean annual temperature of 12.2 ºC and mean annual precipitation of 378 mm. Winters are cold with frequent frosts (95 days per year) and summers are warm with maximum temperatures above 40 °C with monthly mean temperature in July and August above 30ºC, rainfall is scarce but evenly distributed throughout the year, and in winter it can be in the form of snow (AEMET, (n.d.), Annex Meteo).

Within the framework of the LIFE TECMINE project (Conselleria de Agricultura Desarrollo Rural Emergencia Climática y Transición Ecológica, 2015) the mine was restored using several different techniques (Turrión *et al.*, 2021). This experiment will focus on the areas restored using geomorphic restoration: RU2, and the areas restored using conventional restoration, RU4 (Turrión *et al.*, 2021). Conventional restoration was based on the talus-berm system, characterized by flat areas alternating with areas of slopes exceeding 30%. The substrate comes from overburden geological layers of a sandy-loamy nature. The topography of the geomorphological restoration is composed of gentle slopes (<20%) and meandering river channels in hydrological basins.

Figure 2. Pictures of the slopes where soil water content and temperature where measured. (A) Geomorphic restoration, GFGU in the foreground and GFGS in the background, (B) TC and (C) TM.

A B

C



4 treatments have been surveyed (Figure 2):

GFGU: A north facing 18% slope restored using Geomorphic restoration.

GFGS: A south facing 11% slope restored using Geomorphic restoration.

TC: A north facing 63% slope restored using Conventional restoration.

TM: A north facing 63% slope restored using Conventional restoration on which an organic mesh composed of natural fibers was spread.

ER: A control area, unaltered by mining, which consisted on abandoned agricultural fields covered with spontaneous vegetation in which we selected a slope of 38%.

On the Geomorphic restoration areas, in addition to the relief building, two treatments to improve soil quality and reduce erosion by managing surface runoff were carried out: (1) a layer of carbonatic colluvium was spread. This is a natural surficial deposit with appropriate physical and chemical edaphic properties collected in the surroundings of the mine (See Martín Duque *et al.*, 2021 for a definition of colluvium). This layer guaranteed a balanced proportion of sand, silt and clay compared to the clayey and sandy layers (overburden materials) resulting from mine waste which formed the slopes (Table 1). (2) A layer of composted sewage sludge mixed with pruning refuse (10%) was spread in the substrate surface at a rate of 20 tons/ha. TC and TM treatments had the overburden materials as substrate (Table 1). In each treatment soil samples were taken and soil texture calculated (Table 1).

Species selection

Selected species were, *Aegilops geniculata* Roth., *Brachypodium retusum* (Pers.) P. Beauv., *Dactylis glomerata* L., *Genista scorpius* (L.) DC., *Lolium perenne* L., *Santolina chamaecyparissus* L. and *Thymus vulgaris* L. These species were chosen because they are spontaneous colonizers of abandoned mine sites, because these species are usually sown in revegetation programs in Mediterranean continental areas or because they have a facilitative effect (Table 02).

Soil water content, temperature and local weather measurements

Soil water content θ [L^3 L^{-3}] and soil temperature T[T] where measured throughout the study period (01/06/2019 to 01/01/2022).

Soil water content was measured using a Campbell TDR 100 which was connected to a smartphone through a WiFi interface (Villoro *et al.*, 2021). Sampling points consisted of a pair of stainless-steel rods (23 cm long) nailed into the soil up to 20 cm depth with a separation between them of 5 cm. The mine was visited 22 times along the study period to measure SWC. A total of 80 sampling points where distributed along the treatments, 20 in GFGU and 15 in the other 4 treatments. The sampling points were distributed in 3 transects (perpendicular to the slope) of 5 sampling points. But in GFGU, which was a longer slope, one more transect was set, hence there were 4 transects of 5 sampling points. In ER, which was a long slope but narrower than the others, there were 5 transects of 3 points. The sampling points in the transect where distributed to capture the variability of the slope including both convex and concave areas (Nicolau *et al.*, 2022) (Annex I)

Soil temperature was measured with Campbell 107 temperature probes connected to a Campbell CR300 datalogger. Temperature probes were buried approximately 2 cm. Temperature was recorded every hour for the whole study period. Sampling points were distributed throughout treatments (5 in GFGU, 5 in GFGS and 5 in ER) in the medium part of the slopes. TC and TM where very close to each other and we have only one datalogger available so we decided to measure both with a single datalogger (3 points in TC and 2 points in TM).

Throughout the study some temperature probes where damaged, which resulted in loss of data in some periods and sampling points, the lacking periods were reconstructed using data from the other sampling points (see annex II for an explanation).

Weather data (Maximum, mean and minimum daily temperature, daily rainfall) was provided by Fundación CEAM, partner of the TECMINE project, who installed a weather station in the area during the study period.

Seed germination modelling as a function of soil climate

To build a seed germination model we need data on the effects of germination media ψ and temperature on germination.

The effect of ψ in germination is measured by knowing a threshold of ψ below which seed germination is not possible (base ψ or ψ_b), in our case the ψ_b for the study species were obtained from Merino-Martín (2015), Table 02.

The effect of temperature on germination was calculated by means of a thermal model. Seeds of the study species were germinated at 7 temperatures (4, 10, 15, 20, 25, 30 and 35ºC). The fist temperature was not 5ºC because it was done in a fridge, the rest were done in proper climatized rooms or chambers, in all cases temperatures were checked periodically and no more than 1ºC deviation was found. For each treatment 4 replicates of 50 seeds where set.

Germination experiments were carried out in 90 mm plastic petri dishes, with filter paper (BRANCHIA qualitative filter paper, 20 mm, 85 g/m^2, equivalent to Whatman 1), and distilled water.

After sowing, germination was monitored for 67 days, once a day for the first two weeks and later 2 or three days a week. Each dish was monitored until all seeds in it had germinated or died or until the end of the period. A seed was considered germinated when the radicle was clearly visible protruding from the seed cover.

Using this data, we calculated cardinal temperatures for each species for the 50% germination fraction (Zhang *et al.*, 2012). See figures and values in Annex IV.

For calculations of germination percentage, the maximum germination was considered the total number of seeds sown. This is not usual in germination experiments, in which the number of viable seeds is typically used as the measure of maximum germination potential. However, in this case, we were not focused on the effect of the treatments on germination but rather on what would happen if we were to sow these particular seed lots in the field.

Field measures

A total of 18 samples for texture and hydraulic properties (4 in GFGU, 3 in TM, 3 in GFGS, 3 in TM and 5 in ER) were collected. A single sample was taken close to each SWC sampling point. The samples for soil texture were taken from 1 to 10 cm depth soil layer and stored in a single bag. The samples were homogenized and sieved to 2 mm-size particles in the subsequent laboratory analysis. The soil texture was measured using the laser diffraction technique (COULTER LS230).

The soil hydraulic properties were measured from undisturbed soil cores (50 mm in diameter and high), which were sampled using the soil bulk density procedure (Grossman and Reinsch, 2002). The water retention curve used in the analysis was the the unimodal van Genuchten (1980) equation

$$\frac{\theta-\theta_r}{\theta_{sat}-\theta_r} = \left[\frac{1}{1+(\alpha\psi)^n}\right]^m \quad (1)$$

where n is the pore-size distribution parameter, $m = 1-(1/n)$, α [kPa] is the scale factor, and θ_{sat} and θ_r are the saturated and residual volumetric water contents, respectively. θ_r is defined as water content for which the gradient $d\theta/d\psi$ becomes zero (excluding the region near the saturated water content) (van Genuchten, 1980). The saturated hydraulic conductivity, K_s, and parameters of the water retention curve (Eq. 1) were estimated using the upward infiltration method for undisturbed soil samples (Moret-Fernández *et al.*, 2021).

As reported in the introduction section, the current models that calculate GW using ψ_b do not consider the interaction of the soil-seed system. In fact, in our study seeds, said potentials (Table 2) are well below soil residual humidity of our soils (See soil modelling section) which means that, although the seeds could potentially absorb water from the soil, there is actually no water available in the soil to be absorbed.

To attenuate this inconsistency, we propose calculating GW using a combination of ψ_b and a new index: critical soil water content, θ_{cr}, which is associated to a corresponding critical soil tension, ψ_{cr}. It denotes the minimum amount of water in soil for seed germination. Below θ_{cr} germination is not possible, even in cases where $\psi > \psi_b$. However, for $\theta > \theta_{cr}$ seeds germinate if and only if $\psi_b > \psi_{cr}$. Note two soils with equal θ_{cr} but different hydraulic properties a can present different values of $\psi_{cr.}$

We don't know what that moisture/potential value is. It would be reasonable to use the ψ corresponding to the soil residual humidity, but the Hydrus model doesn't allow for that calculation. Thus, we've arbitrarily determined it to be the ψ corresponding to 1.1 times the soil residual humidity. While this isn't very precise and likely leads to an overestimation of germination, the overestimation is still less than in previous experiments where only ψ_b was considered. Moreover, because our experiment aims to compare treatments rather than precisely predict seed germination, we believe this doesn't affect the conclusions of our work. Table 03 displays the potentials corresponding to this value of 1.1 times the residual moisture for each treatment.

Soil modelling

We had continuous measurements of temperature for the entire study period, but we only had point-in-time measurements of SWC. But our gemination experiments linked seed germination to daily data of soil ψ and temperature. Hence, we needed to obtain daily soil ψ values for each treatment.

The daily data of SWC and soil ψ of the 0-2 cm soil layer along the experiment and the different treatments was calculated using the HYDRUS-1D (Šimůnek *et al.*, 2013) model. To run HYDRUS, the weather conditions (evaporation and precipitation) and the corresponding initial values of SWC and the hydraulic properties measured from undisturbed soil samples were introduced in the model (Table 04). Water retention curves measured from undisturbed soil samples were characterized using the van Genuchten (1980) model with boundary condition. The soil profile was discretized with a 1-D mesh of 500 cells homogeneity distributed. Maximum and minimum time steps were fixed at 100 h and 86 s, respectively. Previous numerical analysis demonstrated that, under this discretization, the solution is grid independent. While atmospheric conditions with surface run off was defined in the upper boundary condition, a free drainage was selected for the lower limit. The precipitation input was obtained from Fundación CEAM meteorological station in the area (Fundación CEAM, (n.d.)). The soil water evaporation was calculated by HYDRUS-1D from daily data of maximum and minimum air temperature, relative humidity, wind speed and sunshine hours. A constant value of geographical parameters and albedo were used in all treatments.

Prior to the simulation of the daily SWC and soil ψ data of the 0-2 cm deep soil layer, a calibration and validation process of the HYDRUS model was performed. This consisted of comparing the SWC measured by TDR in the different treatments with the corresponding SWC simulated with HYDRUS once the measured soil hydraulic properties and weather conditions were introduced into the model. A good fit between measured and simulated SWC indicates that the measured hydraulic properties are realistic and therefore also the SWC and soil ψ that will be simulated for the 0-2 cm deep soil layer. For the calibration and validation process, a 0-20 cm soil profile was defined in HYDRUS. Boundary conditions, grid mesh and time steps were same as described in the previous paragraph. While data of 2019 was used to calibrate the model, validation was performed on SWC data recorded in 2020. A calibration and validation process were applied to the data collected in each of the different restoration treatments.

Once calibrated the HYDRUS model and estimated the SWC and soil ψ data of the 0-2 cm deep soil layer, the GW where calculated.

Calculation of seed germination windows

By combining the field data and the seed germination models for each species and treatment, we calculated seed germination probability.

We considered probability of germination 0 if:

1. Soil ψ was below ψ_b or θ_{crit}.
2. Soil temperature was below T_{min} or above T_{max}

If these conditions were not met then we used the thermal model to calculate seed germination probability. After that, we had a germination probability for each day of the study period.

Germination windows (GW) were defined as a day or a series of days in which the probability of germination is higher than 0. Based on this definition we calculated 3 variables to estimate the effect of geomorphic restoration on seed germination.

- W-1 number of GW with cumulative probability of germination higher than 1 along the study period. That is number of periods of one or more consecutive days in which the sum of germination probability of every day of the period is higher than 1.

- W-Ave. Average germination probability per GW

- PTG. Total accumulated probability of germination. Which is the sum of the probability of all the germination windows through the study period.

Calculation of factors limiting germination at each treatment

Seed germination could be limited by temperature (too high or too low) or by low SWC. Too much water in soil could also hinder seed germination because of lack of oxygen but we have not taken this factor into account.

To study that, we evaluated, for each day when germination probability was 0, what factor was out of the boundaries suitable for seed germination. And classified the days in 5 categories: T_{max}: germination stopped by high temperatures, T_{min}: germination stopped by low temperatures, ψ: germination stopped by potential below θ_{crit} or ψ_b and the combination of both factors: $\psi+T_{min}$, $\psi+T_{max}$, that is, when temperature and potential where out of boundaries simultaneously.

Data analyses

Differences in SWC and soil ψ among treatments were analyzed using a linear mixed effects model. The explanatory variable was restoration treatment and he response variable was SWC. To account for the fact that measures where repeated along time in the same sampling points sampling date was considered as a random factor. Calculations where done using the lme() command from the nlme R package (Pinheiro *et al.*, 2018; R Core Team, 2024). After that, pairwise comparisons among the treatments where done using Tukey method using the glht() command from the multcomp R package (Hothorn *et al.*, 2008).

Differences among factors limiting germination were analyzed using a linear mixed effects mode. The explanatory variable was the category of limiting factor and the response variable was number of days in each category. Data of all species was pooled, and to account for variability among species, they were taken into account as random factor. Calculations where done using the lme() command from the nlme R package (Pinheiro *et al.*, 2018; R Core Team, 2024). After that, pairwise comparisons among the categories where done using Tukey method using the glht() command from the multcomp R package (Hothorn *et al.*, 2008).

Results

Soil water content and soil ψ among the different treatments

There are significant differences among the treatments ($F_{4,75} = 27.4$, $p < 0.0001$). SWC of the different treatments can be separated into 3 groups (Tukey test, Fig. 01, Table 05), the higher water contents appeared in the ER and GFGU, followed by the GFGS and finally by the group formed by the conventional restoration treatments, TC and TM.

There is also an effect of the treatment in ψ of the restored areas: there are significant differences among treatments ($F_{4,75} = 77.6$, $p < 0.0001$). ψ of the different treatments can be separated into 3 groups (Tukey test, fig. 02, Table 05). The treatments with higher ψ are the GFGU and GFGS. The treatment with lower ψ is TC. While RE and TM occupy an intermediate position. RE, TM and especially TC show a very high variability, which is not appreciated in the graphs because of the logarithmic scale.

Results of the germination experiments

For the three variables studied, predicted seed germination is different among treatments. In all 3 variables, a clear pattern is found which is similar in the 7 studied species.

Progress Towards Germination (PTG)

Regarding PTG, for all seven species but *G. scorpius* the pattern is clear (Figure 3), the bigger progress towards germination occurs in the reference ecosystem and in the GFGU. Being the lower values in the TM and TC the two areas with no proper geomorphic restoration treatment. With an intermediate value in GFGS. Even *G. scorpius*, when data is studied in detail (Table 06) the highest PTG occur in GFGU and RE.

Number of GW with probability of germination higher than 1 (W-1)

Regarding W-1, as happens in PTG, the pattern is clear, the most GW with germination probability higher than 1 occur in GFGU and RE (Figure 4, and table 7). In fact, in species *B. retusum* and *D. glomerata*, these treatments are the only ones which have any germination window with probability of germination higher than 1. As in PTG, GESC gives the lowest performance, with no GW with p>1.

Average germination probability per germination window (W-Ave).

As found in previous variables, the higher W-Ave is found in RE and in GFGU and the lower W-Ave is found in the conventional restoration treatments (TM and TC) (Figure 5 and Table 08). In the species with lower germination probability, *G. scorpius* and *B. retusum*, the pattern appears less clear.

What is limiting germination in each treatment?

Most of the days without germination were attributable to soil ψ falling below either ψ_b or θ_{crit} (Table 09, Figure 06). These findings underscore soil water availability as the primary constraint on germination within the study area, irrespective of restoration treatment. T_{max} was never identified as a limiting factor. In contrast, the influence of T_{min} or the combined effect of T_{min} and soil ψ was more pronounced but always well below the effect of soil ψ alone.

Discussion

We tested three hypotheses: (1) SWC is higher in geomorphic restoration areas than in conventional restoration areas, (2) soil water availability, estimated as soil tension, is higher in GR than in CR, (3) germination probability is higher in geomorphic restoration areas than in conventional restoration areas because of differences on soil water availability.

Our results confirm our first hypothesis, soils in GR areas hold more water than soils in CR areas. Regarding the second hypothesis, soil tension does not follow the expected pattern, and there are differences in soil water availability between the CR areas, interestingly, the reference ecosystem is not the one with higher soil water availability. Regarding germination, our third hypothesis, the variables studied (PTG, W1 and W-ave) fit to our hypothesis being the CR treatments the ones with the lower germination probabilities.

Geomorphological restoration deals with two key elements for the functioning of restored ecosystems: topography and substrate. What is the weight of each in the availability of water for plants? Our results indicate that the substrate plays a major role and that it is the first filter that find the seeds during colonization.

Soil quality effect is very relevant when determining SWC and soil ψ. It becomes more relevant than slope aspect, e.g. both TC and TM, despite of being north facing slopes, have less SWC and lower soil ψ than GFGS. That is remarkable, because in Mediterranean areas, slope aspect greatly determines sowing success (Bochet & García-Fayos, 2004; González-Alday *et al.*, 2008) by determining soil moisture and temperature (Seyfried *et al.*, 2021; Yu *et al.*, 2018).

Another fact indicating the relevance of soil properties is that the results using SWC and potential are not the same, which indicates that when reconstructing the soils in geomorphic restoration we not only need to take into account soil water holding capacity but the soil hydraulic properties that determine how these soils provide water to the germinating seeds or growing plants. The north facing GR treatment holds the same amount of water than the RE. But soil tension is lower in RE, indicating that soil water availability for plants is lower in RE than in GR areas.

Our results coincide with the results of Bochet et al. (2007; 2004) in road slopes. In their case, the stronger factor regulating seed germination was soil quality (cutslopes vs fillslopes) and later slope orientation (North vs South).

A key element regulating soil water content in mining in the formation of rill networks, which favor the evacuation of rainwater, decreasing infiltration into the soil (Moreno et al XXX). Geomorphological restoration areas develop less rill networks (Cita), which favours infiltration in relation to conventional restorations. In our study area, the development of rills has been very limited in the RG, given the gentle slopes. It has also been limited in RC due to the low length of the constructed slopes. Therefore, we have not been able to detect the effect of the drainage network of the RG on water availability. Therefore, the differences in SWC between RG and RC are explained by the different substrate management and slope aspect.

To solve soil quality problems usually a layer of topsoil is spread over the mine substrate (Figueiredo *et al.*, 2024; Howard & Samuel, 1979) and if topsoil is not available, the surface is covered with a mixing available matherials with certain amendments, what is sometimes called technosoil (Rodriguez-Vila *et al.*, 2017).

The methodology we propose in this work would allow for evaluating the suitability of these techno and topsoils for the germination of species expected to be sown or to colonize the area.

Based on that, geomorphic restoration should involve both, creating a landscape with adequate features to manage runoff and creating a proper soil. Relief design will determine water availability at slope level but, at plant or seed level, soil properties will determine water availability.

Regarding the seed germination variables some caveats need to be done. PTG indicates the sum of all the days with germination probability over 0, but this does not indicate that progress towards germination reached 1, which would mean that at least a seed would have germinated.

Every day with $p>0$ will contribute to the PTG, in fact there could be no days with $p>1$ at all and we could still have a high PTG. A high value of PTG could indicate several things:

- A That there have been lots of days with $p>0$.
- B That there have been only some days with $p>>0$.
- C Both

Case A would produce a series of suboptimal germination windows which could have disparate effects depending on the species:

- Could be irrelevant if the seeds do not start germination because very low SWC is not able to trigger germination because of a very slow imbibition.
- Could be harmful if SWC is enough to trigger germination but the germination window is not long enough for seed to complete germination. E.g. if phase 2 of germination (da Silva *et al.*, 2018) is reached, these germination windows would be fatal for seeds and could produce a depletion of the seed bank.
- Could be beneficial; for some seeds this dry-wet cycles could act as priming (Del Rocío Contreras-Quiroz *et al.*, 2016) improving seed germination in the following germination windows.

In Case B, high PTG will indicate short but intense germination windows, but surrounded by dry spells that could compromise seedling survival. Only species with fast germination and seedling growth could make the most of this type of germination windows (Kadereit *et al.*, 2017; Pérez-Fernández *et al.*, 2000).

Case C represents, to some extent, the ideal case. Several days of high germination probability surrounded by episodes of wet soil to improve chances of survival.

Although this is not the goal of our study, it is worth to mention that our results stress the key role of seed quality on restoration success (De Vitis *et al.*, 2020; Pedrini *et al.*, 2020). Regardless of the species adaptation to the edaphoclimatic conditions of the restored area, seed quality is key. In our case it is patent in GESC, despite of having a ψ_b similar to the remaining species and being a fast spontaneous colonizer in the study area and other quarries in the region (Personal observation and Merino-Martín *et al.*, 2012), our results indicate that sowing this particular seed lot would have been a failure, not because of misadaptation of the species, but because of seed quality (Maximum germination percentage was 50%). There is a need to improve seed quality of wild species in order to improve seeding success in restoration (Kildisheva *et al.*, 2016)

Several papers dealing with germination simulation in field had been published (Rawlins *et al.*, 2012; Roundy *et al.*, 2007: 207) since the idea was presented by Bradford (2002). But, to our knowledge, only one article does that in mining areas: Fehmi *et al.* (2014). All these articles use different arbitrary values to determine the potential threshold below which germination does not occur. However, this arbitrary determination of the threshold has the limitation that, in different soils, the same potential will have different water contents, even below the residual moisture (See the introduction). To solve this, we propose that, to determine the ψ threshold below which germination is not possible, the ψ_b of the seeds need to be used. And we propose an innovative variable which depends on the soil properties which we have called θ_{crit}. In this way we incorporate seed and soil specific nuances to the modelling of seed germination in field.

In conclusion, based in our data, besides the improvement that GR produces in runoff management (Bugosch et al 2022), GR also increases SWC and availability which translates into better conditions for seed germination.

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Tables

Table 1

Table 1. Soil properties. Mean±SD. N indicates the number of samples taken in each area. N is different among treatments because they correspond to the sampling points of a different experiment. [a] Data taken from Turrión et al. (2021), they did not provide any measure of variability or number of replicates.

	Sand	Silt	Clay	Texture	Organic carbon ($g \cdot kg^{-1}$)	N	Data origin
GFGU	43.7 ± 3.0	39.5 ± 2.1	16.8 ± 1.0	Loam	5.60 ± 1.76	4	Our
GFGS	43.7 ± 3.5	39.2 ± 2.5	17.09 ± 1.0	Clay Loam	3.46 ± 1.30	3	Our
TC	64.3 ± 1.8	26.8 ± 1.6	8.9 ± 0.5	Sandy Clay Loam	1.07 ± 0.18	3	Our
TM	60.6 ± 1.4	29.3 ± 1.1	10.0 ± 0.3	Sandy Clay Loam	1.48 ± 0.34	3	Our
ER	54.7 ± 1.9	30.7 ± 0.6	14.6 ± 1.4	Sandy Clay Loam	30.42 ± 3.38	5	Our
Colluvium	43	35	22	Clay Loam	-	-	a
Sandy overburden	84	12	4	Loamy Sand	-	-	a
Clayey overburden	6	62	32	Clay	-	-	a

Table 2

Table 2. List of species included in the study showing the reasons why they were selected and base water potential (ψ_b). Spontaneous colonizer: these species are usually found growing spontaneously in abandoned mine sites (Merino-Martín, 2015), Facilitative effect: these species modify its environment in such a way that increases colonization by other species (Merino-Martín, 2015), Commonly used in restoration: These species are easily available in seed providers and produce high plant cover in a short time in restored areas in Continental Mediterranean environments (Vidal-Macua 2020, Turrión 2021). Data on ψ_b taken from Merino-Martín (2015)

	Spontaneous colonizer	Facilitative effect	Commonly used in restoration.	ψ_b (MPa)
Aegylops geniculata	X			−1.161
Brachypodium retussum	X	X		−0.724
Dactylis glomerata			X	−0.741
Genista Scorpius	X	X		−0.611
Lolium perenne			X	−0.766
Santolina chamaecyparissus	X	X		−0.620
Thymus vulgaris	X	X		−0.569

Table 3

Table 03. Residual soil water content for each treatment (θ_{res}), the soil water content critical threshold (θ_{crit}) which is 1.1* θ_{res} and the corresponding soil ψ at θ_{crit}.

	θ_{res}	θ_{crit}	ψ at θ_{crit}
TM	0.0137	0.1511	-1.669
TC	0.0190	0.0209	-1.559
GFGU	0.0174	0.0191	-0.6152
GFGS	0.0172	0.0189	-0.5971
ER	0.0302	0.0332	-1.513

Table 4

Table 04. Soil properties of each treatment used to feed the soil model.

	K	alfa_w	alfa_d	n	sat	K darcy (cm/s)	Sat total	Densidad	res
TM	0,0012	0,1490	0,0749	1,7667	0,2923	0,0025	0,3431	1,5870	0,0137
GFGU	0,0006	0,1610	0,0807	1,7983	0,2683	0,0016	0,3705	1,6466	0,0174
ER	0,0012	0,1650	0,0837	1,6604	0,3726	0,0237	0,4780	1,1828	0,0302
TC	0,0009	0,1422	0,0718	1,7130	0,3065	0,0005	0,3564	1,5985	0,0190
GFGS	0,0117	0,4232	0,2131	1,7386	0,3599	0,0012	0,3482	1,6225	0,0172

Table 5

Table 05. Soil water content (SWC) and soil water potential (ψ) in the different treatments as measured along the study period.

	ER	GFGS	GFGU	TC	TM
SWC (XX, mean±SD)	14.8±7.2	12.7±5.6	14.7±6.71	9.0±6.5	9.5±5.9
ψ (MPa, mean±SD)	-203±894	-37±69	-44±47	-2 623±23 794	-832±10 106

Table 6

Table 6 Values of PTG (total sum of germination probability along the study period) for the different species at each treatment

	A. geniculata	*B. retusum*	*D. glomerata*	*G. scorpius*	*L. perenne*	*S.chamaecyparissus*	*T. vulgaris*
GFGS	41.81	5.51	17.739	0.663	37.573	29.850	25.288
GFGU	51.09	7.39	21.487	0.792	45.406	36.533	30.167
TM	37.63	5.36	15.937	0.658	33.642	27.069	22.561
TC	38.67	5.55	16.366	0.675	34.560	27.807	23.119
RE	54.38	8.07	21.997	0.807	46.514	37.357	29.984

Table 7

Table 07. W-1, number of germination windows with probability of germination higher than 1 for the different species at each treatment

	A. geniculata	*B. retusum*	*D. glomerata*	*G. scorpius*	*L. perenne*	*S. chamaecyparissus*	*T. vulgaris*
GFGS	9	0	0	0	7	5	3
GFGU	14	2	3	0	12	9	7
TM	9	0	0	0	6	3	4
TC	10	0	0	0	7	3	4
RE	13	2	5	0	11	9	7

Table 8

Table 08 W-ave, average germination probability per germination window, species and treatment. Mean±SD.

	A. geniculata	*B. retusum*	*D. glomerata*	*G. scorpius*	*L. perenne*	*S. chamaecyparissus*	*T. vulgaris*
GFGS	0.523±0.438	0.098±0.102	0.222±0.191	0.026±0.020	0.470±0.388	0.383±0.344	0.333±0.309
GFGU	0.774±1.081	0.164±0.270	0.326±0.438	0.033±0.043	0.688±0.932	0.571±0.847	0.464±0.690
TM	0.482±0.423	0.103±0.110	0.204±0.179	0.026±0.024	0.431±0.373	0.356±0.347	0.309±0.301
TC	0.502±0.433	0.107±0.112	0.213±0.183	0.027±0.024	0.449±0.382	0.371±0.355	0.321±0.307
RE	0.877±1.486	0.175±0.304	0.367±0.585	0.035±0.045	0.763±1.243	0.612±1.026	0.461±0.722

Table 09

Table 09. Number of days along the study period, which lasted 944 days, in which each limiting factor hindered germination (Mean ± SD). Data pooled for all species. Letters indicate differences among limiting factors based on linear mixed effects model plus estimated marginal means using Tukey method for comparing the estimates. *** = p-val < 0.0001

	p-val	T_{max}	T_{min}	ψ	$\psi+T_{min}$	$\psi+T_{max}$
GFGS	***	0.00a	25.57±28.67a	523.14±26.90b	18.86±26.90a	0.00a
GFGU	***	0.00a	62.57±37.40a	434.14±37.56b	30.57±37.19a	0.00a
RE	***	0.00a	58.29±48.67a	413.57±40.98b	30.57±41.58a	0.00a
TC	***	0.00a	46.14±24.05a	497.86±52.51b	48.14±52.51a	0.00a
TM	***	0.00a	43.71±23.04a	503.43±53.50b	50.57±53.50a	0.00b

Figures

Figure 1

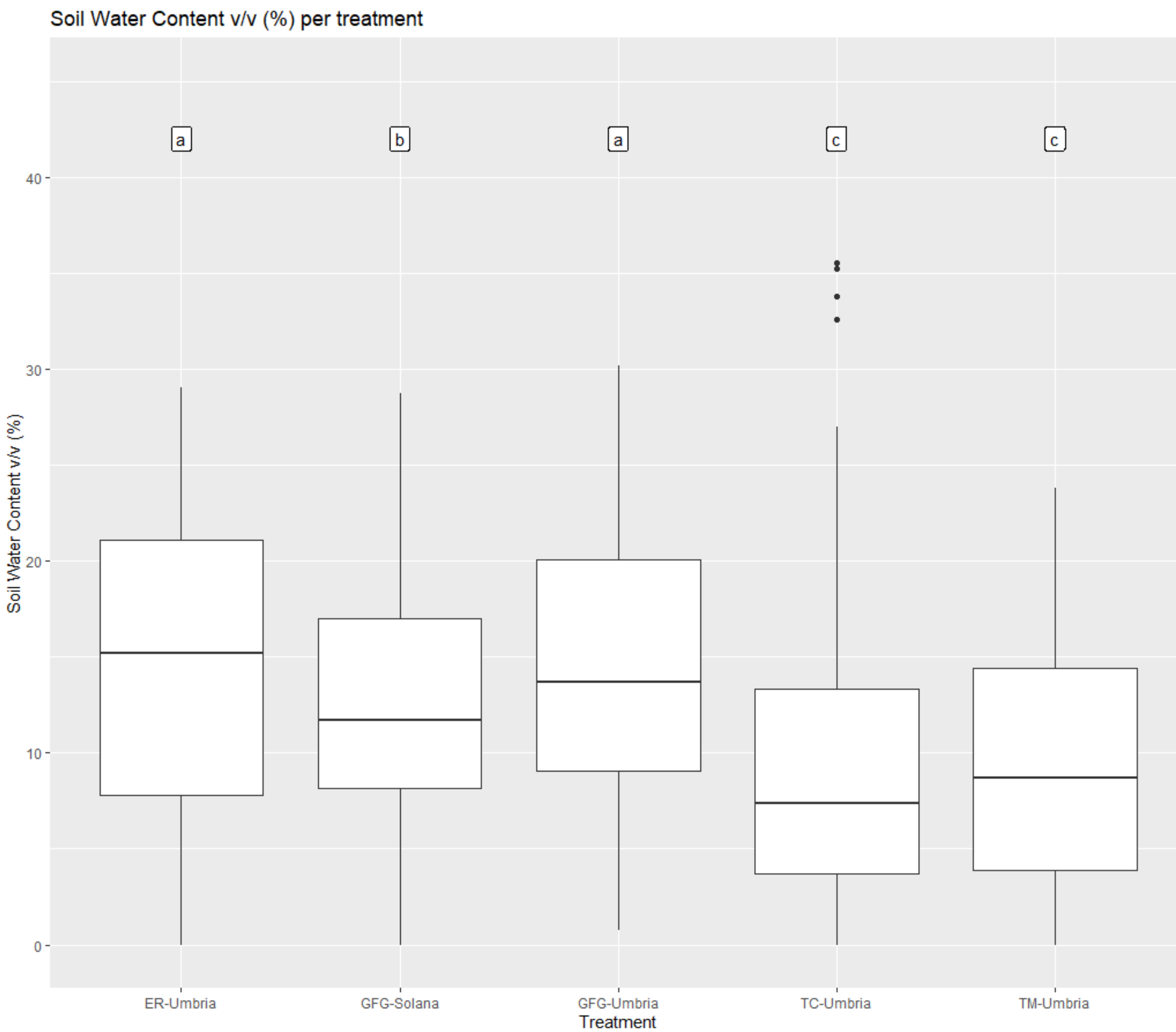
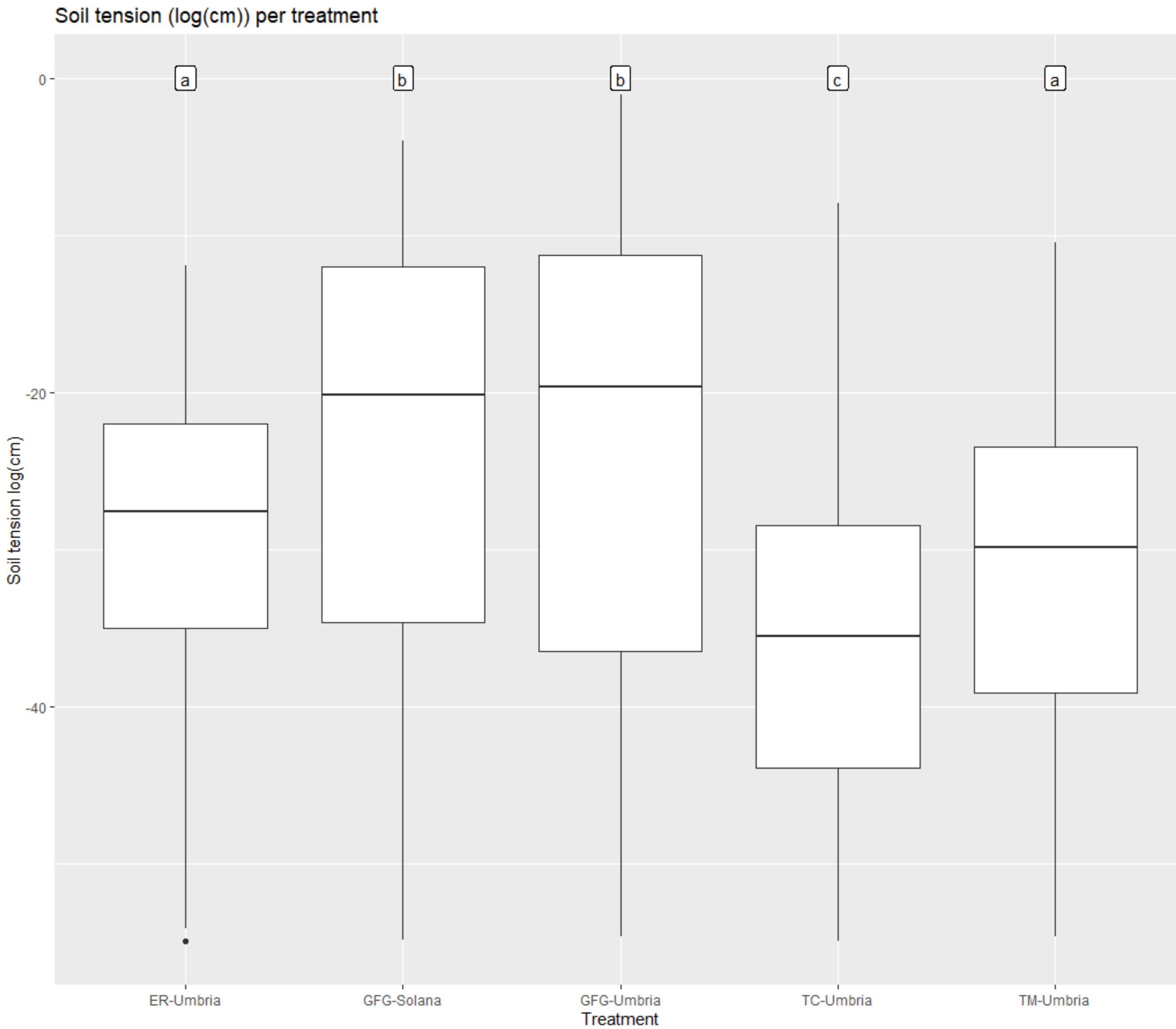
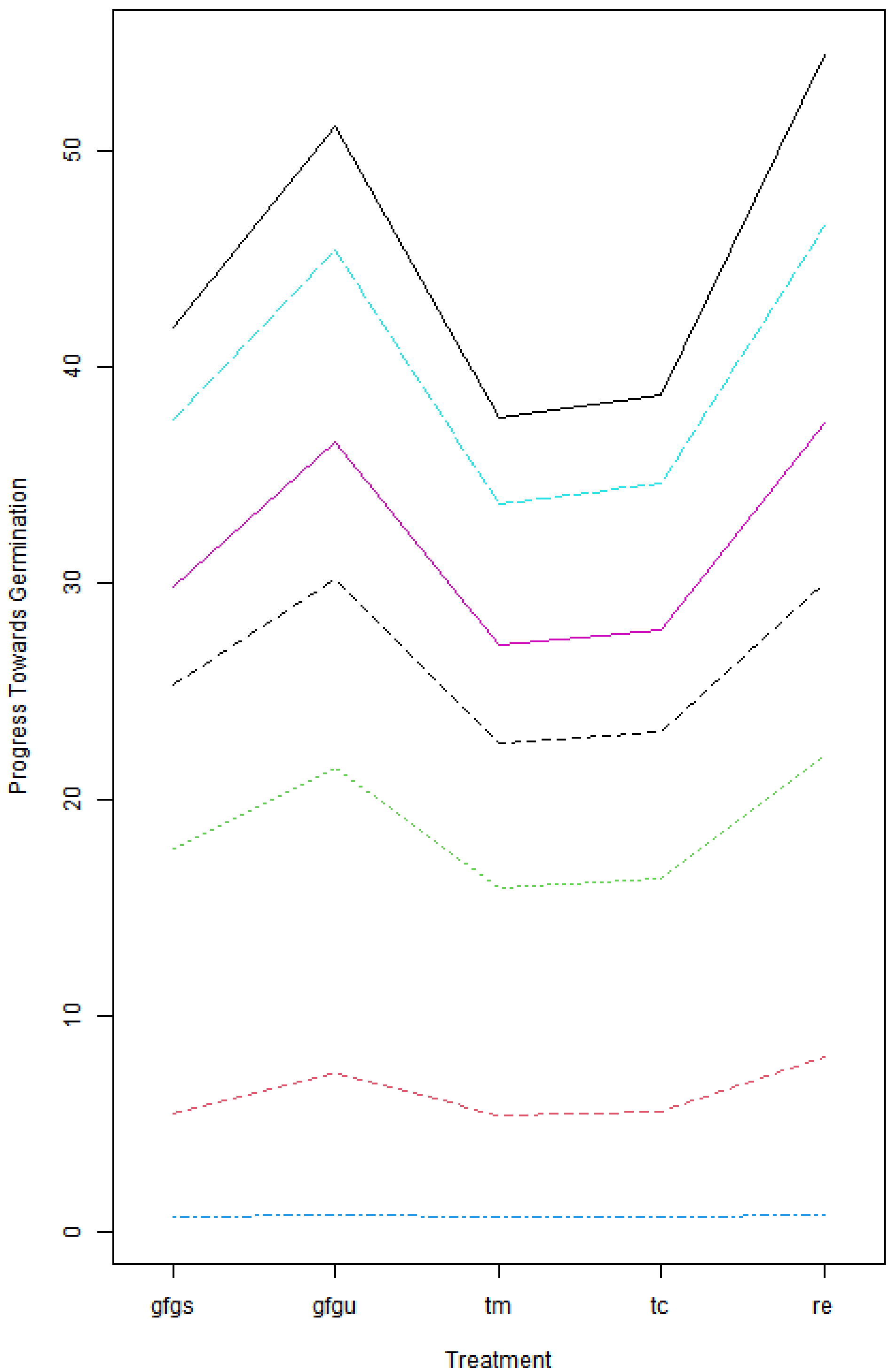


Figure 2



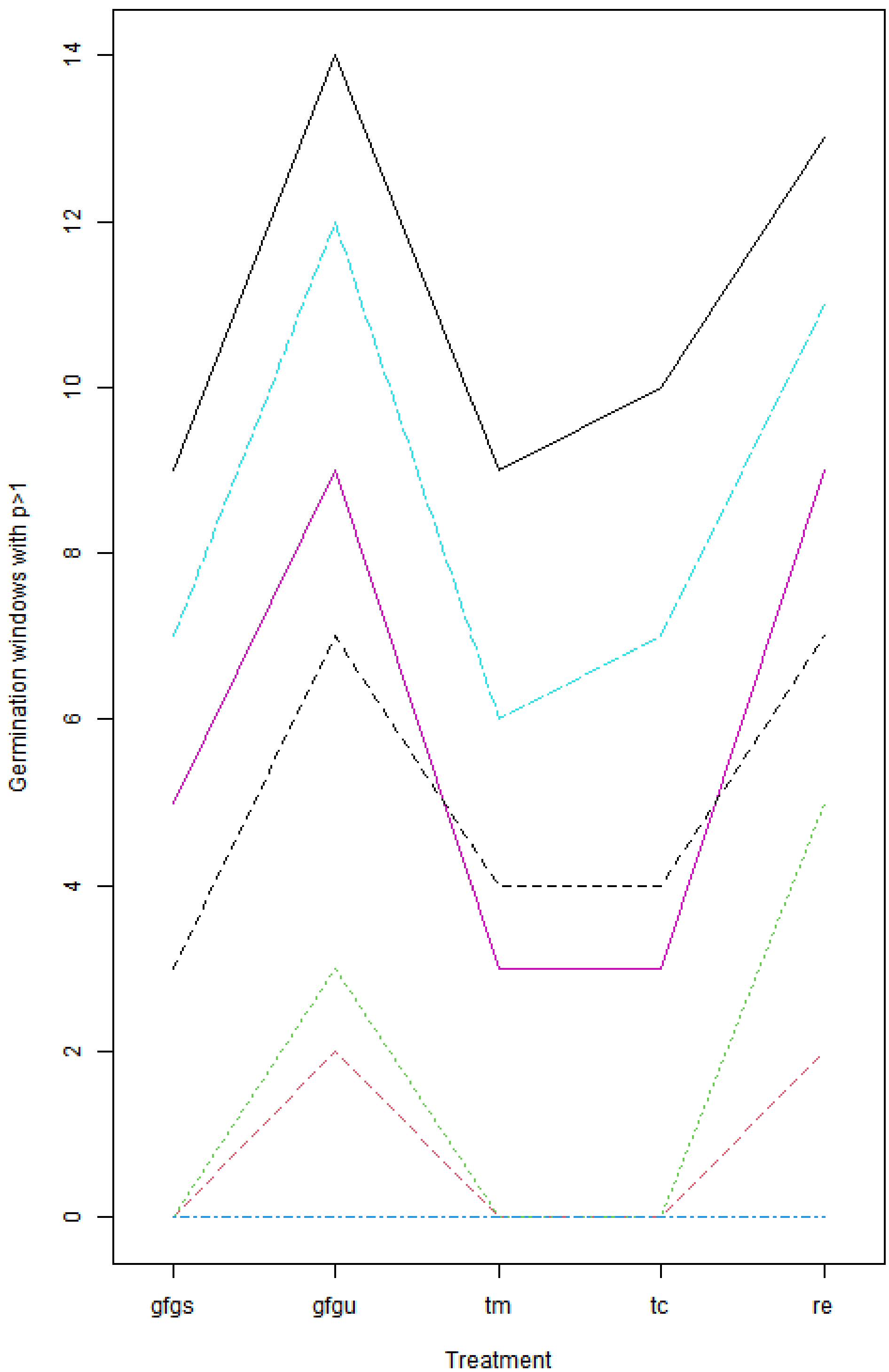
Soil tension (log(cm)) per treatment
Soil tension log(cm)
0
-20
-40
a
b
b
c
a
ER-Umbria
GFG-Solana
GFG-Umbria
TC-Umbria
TM-Umbria
Treatment

Figure 3



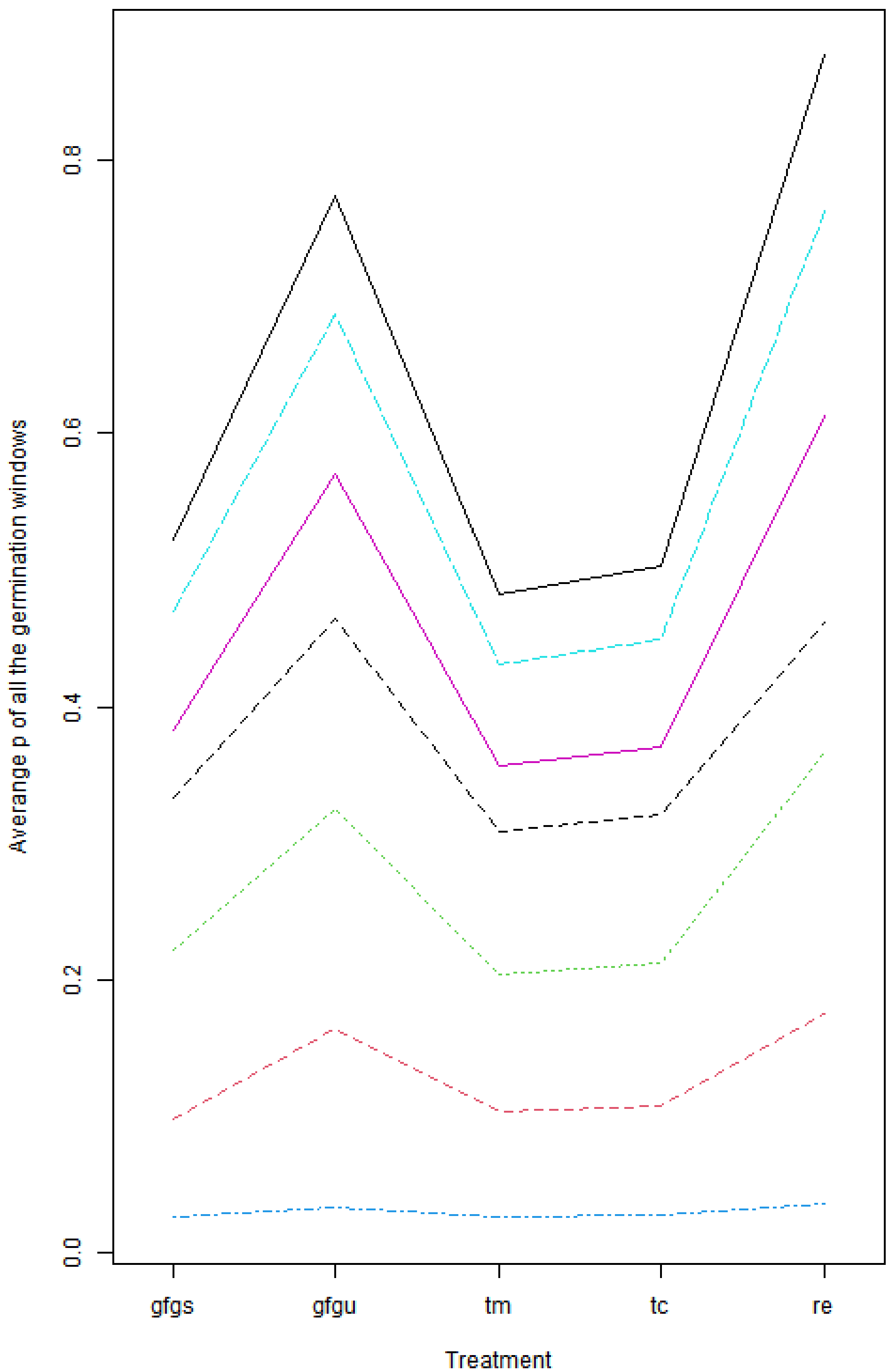
Progress Towards Germination
0
10
20
30
40
50
gfgs
gfgu
tm
tc
re
Treatment

Figure 4



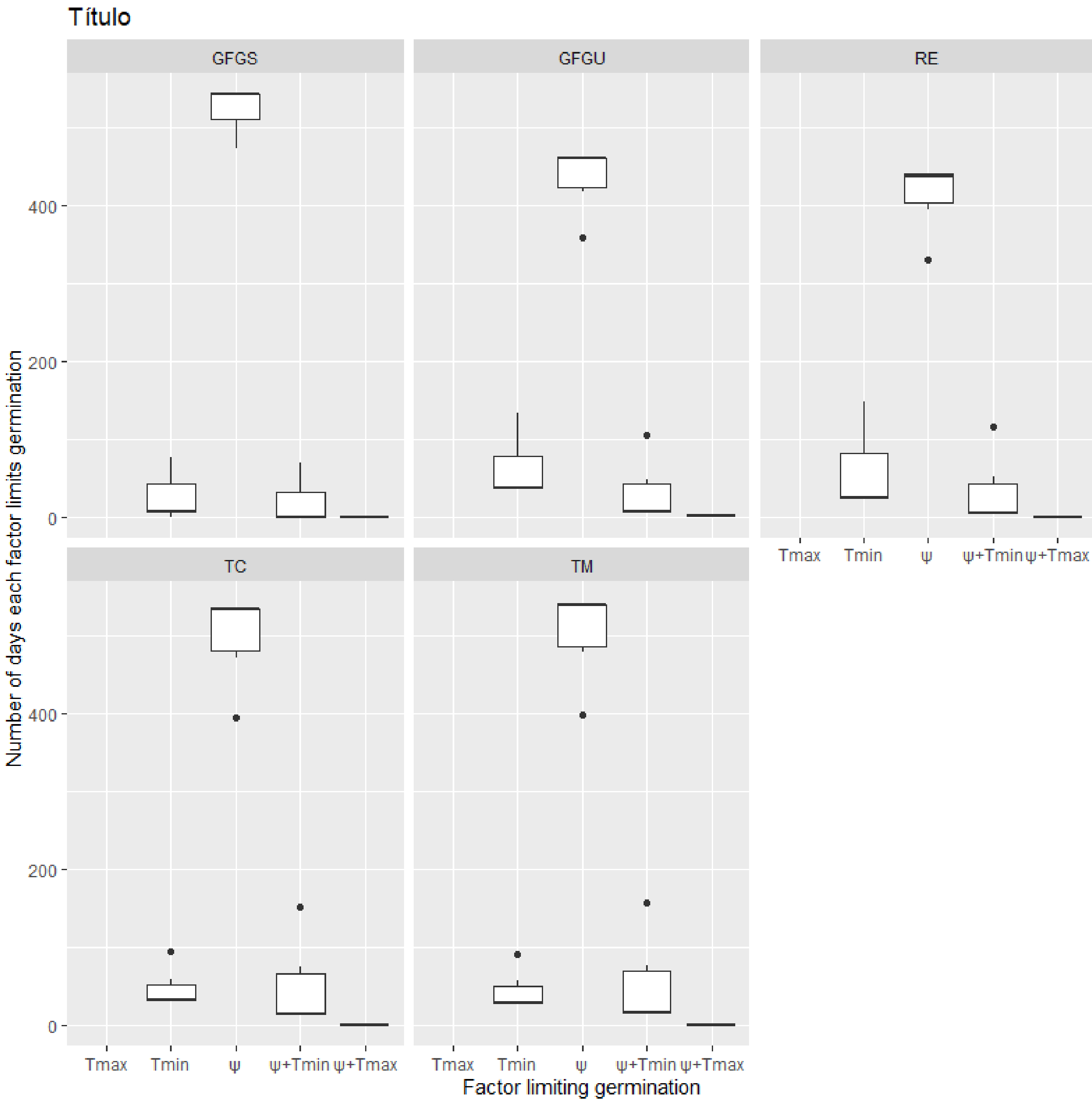
Germination windows with p>1
14
12
10
8
6
4
2
0
gfgs
gfgu
tm
tc
re
Treatment

Figure 5



0.0
0.2
0.4
0.6
0.8
Averange p of all the germination windows
gfgs
gfgu
tm
tc
re
Treatment

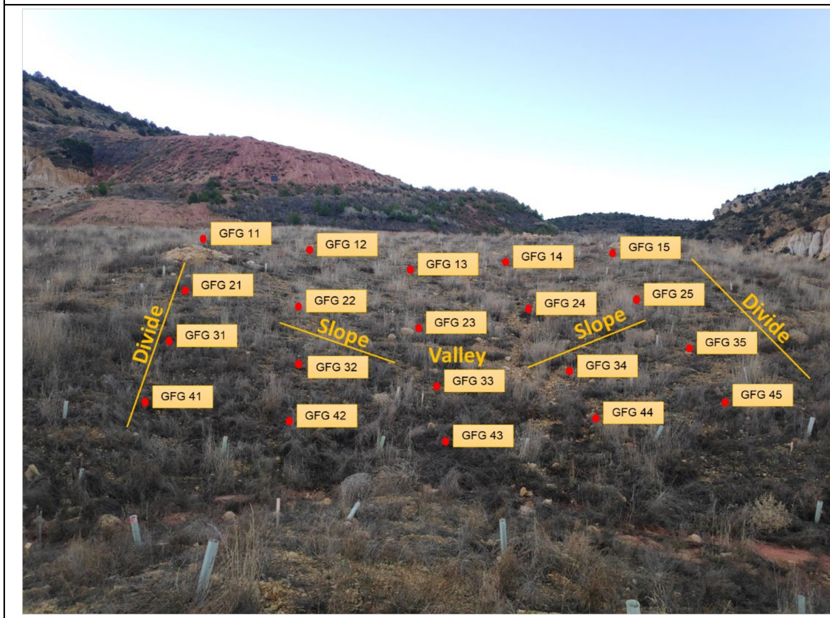
Figure 6


Título
GFGS
GFGU
RE
TC
TM
Number of days each factor limits germination
Factor limiting germination
0
200
400
Tmax
Tmin
ψ
ψ+Tmin
ψ+Tmax

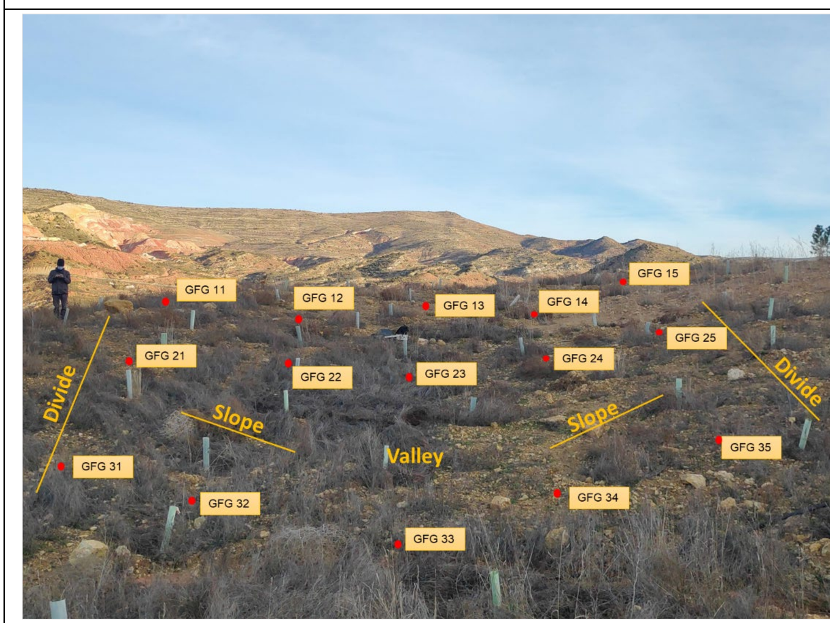
Annex I distribution of the sampling points in the slopes

Images taken from: García Moreno, R. S. 2021. Eco Hydrology of Reclaimed-Quarry Landscapes Under Mediterranean Climate in Spain. Degree Thesis. Czech University of Life Sciences of Prague. Faculty Of Environmental Sciences.

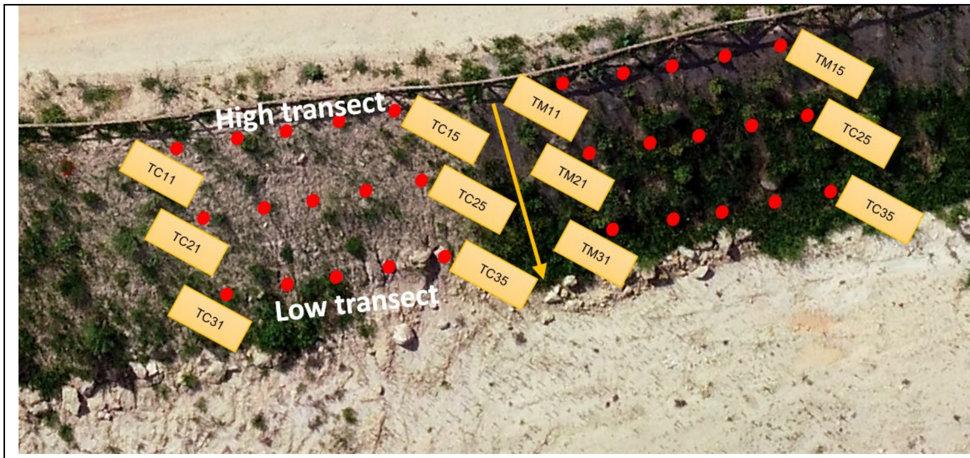
GFGU



GFGS



TC and TM



High transect
Low transect
TC11
TC21
TC31
TC15
TC25
TC35
TM11
TM21
TM31
TM15
TC25
TC35

ER

ER11
ER12
ER13
ER51
ER52
ER53

Annex II

Lost data in temperature measurements were replaced based on the following criteria:

Replace lacking data using average data from other treatments with similar geographic orientation. In this case lacking data from GFGU, ER, TC/TM were used to supply each other. This is reasonable because, in medium latitudes, we will expect that temperature is mainly determined by geographic orientation (Seyfried *et al.*, 2021). But in some cases, there were neither data from north facing treatments, then data from the south facing treatment was used, which is not as good approximation as using same orientation, but it happened only in 7% of the dates.

In the case of GFGS, the only south facing slope, there was no choice but to replace lost data with an average of any available north facing treatments in the lost dates.

The proportion of data corrected by using other sampling is as follows:

GFGU [north facing]: 37% of data lacking. 30% of the data coming from North facing treatments. 7% coming from south facing treatments.

GFGS [south facing]: 14% of data lacking, all replacing data coming from North facing treatments.

ER [north facing]: 44% of data lacking, 37% of the data coming from north facing treatments. 7% coming from south facing treatments.

TC/TM [north facing]: 33% of data lacking, 26% of the data coming from north facing treatments. 7% coming from south facing treatments.