C. Monitoring of the Impact of the Project actions. Action C 1.2 Monitoring of water flows and sedimentation

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☐	Internal	x	Monitoring	☐	Financial		

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CONTENT

ABSTRACT

Control of the water cycle is essential for the success of any mining restoration. On the one hand, for the proper development of the introduced plant communities, it is necessary to optimize infiltration and water availability in the soil for the plants (on site effects). On the other hand, runoff and sediment emissions to the natural drainage network must be controlled to minimize the hydrological impact of mining operations (off site effects).

The expert management of the water cycle is one of the advantages of geomorphological restoration, for which a topography of hillslopes and watercourses, sized to adequately evacuate runoff, is built; in addition, a selection and management of substrates that optimize rainwater infiltration and stability against erosion is carried out.

The evaluation of soil moisture is a very useful approach to know the degree of control of the water cycle in restored mining ecosystems. This is because it is easy to measure in comparison with other phases of the water cycle, such as surface runoff, and because it provides direct information on the ecosystem recovery process.

The most relevant finding of the moisture study is the confirmation that Geomorphological Restoration by the GeoFluv method presents higher moisture levels than conventional restoration. In other words, the supply of water to the plants is higher and the control of the water cycle by the ecosystem is greater. This is very relevant for mining restoration in Mediterranean climates, where water deficit is the first limiting factor for the success of revegetation.

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. Indeed, on overburden substratum, the GeoFluv topography (divide, hillside, valley) does not offer more water than the conventional straight slopes. This leads us to conclude that the selection of the substrate and its management must be a priority objective in mining restoration. Relating this result to that obtained in the erosion study (Action C 1.1) it could be said that the topography controls more rill erosion and the substrate more runoff generation (rainfall infiltration and water availability for plants).

In this sense, we found that the colluvium substrate has had similar Soil Moisture Content levels as the natural soil of the reference ecosystem (entisol with ochric epipedion), which indicates its good hydric properties. We strongly recommend its use as a first measure to optimize water supply to plants.

The spatial pattern of soil moisture has to be taken into account for revegetation design in GeoFluv landscapes. We have verified a pattern of increased moisture in the lower part of the reliefs and other pattern of lateral variation of soil moisture, which is higher in the concavities and divides and lower in the hillsides. The variety of GeoFluv landforms favours environmental heterogeneity and thus biodiversity far from the uniformity present in conventional slopes.

INTRODUCTION

Control of the water cycle is essential for the success of any mining restoration. On the one hand, for the proper development of the introduced plant communities, it is necessary to optimize infiltration and water availability in the soil for the plants (on site effects). On the other hand, runoff and sediment emissions to the natural drainage network must be controlled to minimize the hydrological impact of mining operations (off site effects).

The expert management of the water cycle is one of the advantages of geomorphological restoration, for which a topography of hillslopes and watercourses sized to adequately evacuate runoff is built; and a selection and management of substrates that optimize rainwater infiltration and stability against erosion is carried out.

The evaluation of soil moisture is a very useful approach to know the degree of control of the water cycle in restored mining ecosystems. On the one hand, because it is easy to measure in comparison with other phases of the water cycle, such as surface runoff, and on the other hand, because it provides direct information on the ecosystem recovery process.

Therefore, sub-action C1.2 Monitoring of water flows and sedimentation has been approached from the monitoring of soil moisture, the Soil Moisture Content. This sub-action is complemented with C1.1 Monitoring of topographic evolution and erosion rate, since both processes -erosion and water availability- constitute the main abiotic constraints for the success of Mediterranean mining restorations. Moreover, they interact closely, since rill erosion, by effectively evacuating rainwater from the slope, has a significant influence on infiltration and soil moisture.

SCOPE OF THE DOCUMENT

In essence, this document intends to analyse if the offer of water to the plants is higher in the GeoFluv restorations than in the others. In other words, to what extent the ecosystems recovered by Tecmine project control the hydrological cycle. In particular, this deliverable shows the Soil Moisture Content of different restoration scenarios for a 2 years period, analysing some control factors. This has led to a number of practical consequences.

STRUCTURE OF THE DOCUMENT

The deliverable presents a classic structure of introduction, methodology, results and discussion.

The introduction points out the importance of water cycle control for the success of mining reclamation and how soil moisture content measures are a good approach for this purpose.

It does not make sense to take the pre-restoration quarry situation as baseline. However, two reference scenarios have been taken as baseline: a conventional restoration and a natural ecosystem.

The methodology section explains the instrumentation and procedure for moisture measurements, as well as the experimental design. Images of the experimental areas are presented as well as a synthetic table.

The results are shown as follows: first a synthetic figure with the mean moisture values of each monthly measurement (26 data) for all treatments. Then the results of the statistical analysis - repeated measures mixed model- with the graph of the moisture values and the data from the analysis.

Finally, the discussion analysing the main findings in the context of mining restoration science.

This deliverable is largely based on Stefany García Moreno's master's thesis (2021).

GENERAL AND SPECIFIC OBJECTIVES OF THE ACTION

This action has focused on the study of the soil moisture content (SMC) in the restored areas, comparing the effectiveness of the geomorphological restoration approach –by means of the GeoFluv method- with that of the conventional restoration approach. A natural ecosystem ("reference ecosystem") has also been included.

Specific objectives of the action "C1.2 Monitoring of water flows and sedimentation" are as follows:

- To compare SMC values between the reference ecosystem and the reclaimed ecosystems (both, conventional and geomorphological approaches).
- To determine the effect of substratum (colluvium vs overburden) on Soil Moisture Content.
- To determine the effect of topography (conventional slopes vs GF landforms) on Soil Moisture Content.
- To evaluate the influence of the slope aspect on Soil Moisture Content in the geomorphologic restored ecosystems.
- To explore the spatial pattern of soil moisture in the set of treatments and, specifically, in geomorphological restorations by comparing the three main landforms: divides, concavities (valleys) and hillsides.

DESCRIPTION OF THE BASELINE

As a baseline of the Tecmine restoration, the previous state of the quarry has not been taken, since it was a landscape of mining holes, tailings, waste substrate, inadequate to support a functional ecosystem. A conventional restoration of a space adjacent to the one that has been restored in the Tecmine project has been taken as baseline for the Action 1.1 Monitoring of topographic evolution and erosion rate. However, this adjacent dump has not been taken as a baseline in this case due to its inaccessibility. We have worked with two references. On the one hand, some slopes with conventional restoration that have been built in the Tecmine project (Figure 1) and, on the other, a natural ecosystem close to the restored quarry. It is a hillside, formerly cultivated and currently covered with scrub (Figure 2).

Figure 1. Conventional restoration monitorised as reference (baseline)

Figure 2. Natural ecosystem monitorised as reference (baseline)

METHODOLOGY

The hydrological response of the restored area has been measured in terms of soil moisture content. **The indicator has been**: weight of water in the soil in %.

Experimental layout and data collection

Soil moisture measurements were made using the Time Domain Reflectometry technique. A Campbell TDR 100 was used (Figure 3). Sampling points consisted of a pair of metal rods (23 cm long) nailed into the soil up to 20 cm depth with a separation between them of 5 cm (Figure 4).

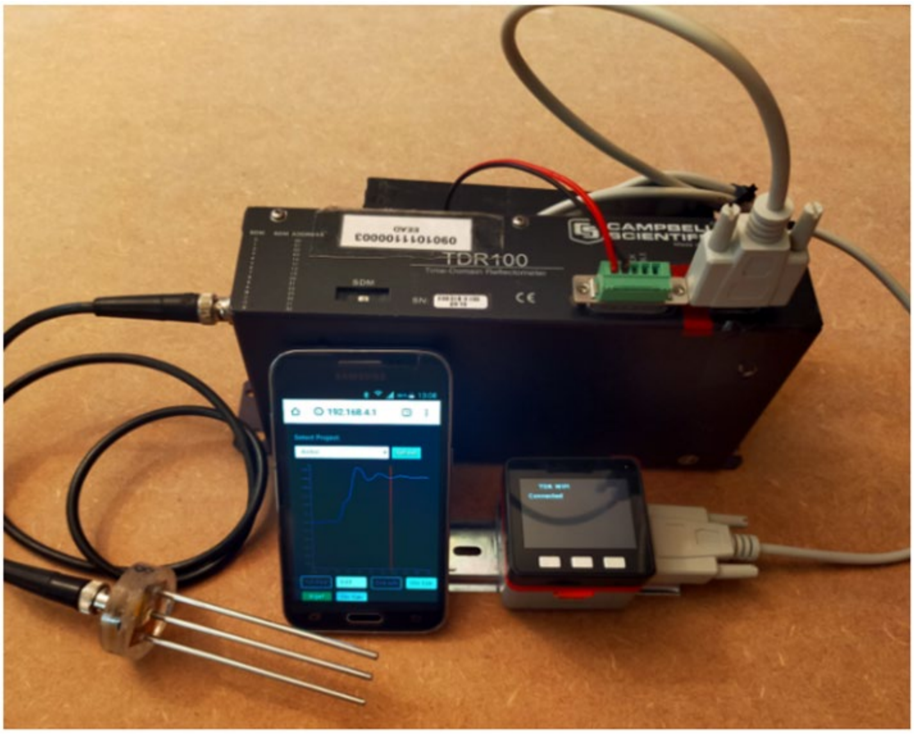


Figure 3. Campbell TDR 100 used to measure soil moisture content

Figure 4. View of the pair of metal rods 20 cm deep into the soil to which the TDR is connected to measure moisture.

The following is a description of the experimental design, which is summarised in table 1. Sampling points were established in geomorphic and conventional treatments of the quarry. Three of them within geomorphic restoration: Western GeoFluv area (GFG), Eastern GeoFluv area (GFP) and GeoFluv restoration with overburden substratum (GFEst). Two within conventional restoration (Conventional slope restoration (TC) and Conventional slope restoration with organic blanket (TM). Sampling points were also established in a vegetated area undisturbed by mining which was considered to be the reference ecosystem (ER). Table 2 summarizes the design of sampling points within the Fortuna quarry.

<u>Western GeoFluv area (GFG)</u>: The area was built with two micro basins, each facing north and south aspect, each of them included three landforms (divide, slope and valley). A colluvium substrate was spread in both of them and within the slopes were built micro catchments that drive surface runoff toward planting holes.

The Shady area was divided into 4 transects from the upper part to the bottom (longitudinal pattern), each transect had 5 sampling points nailed in different landforms (transverse pattern), see Figure 5.

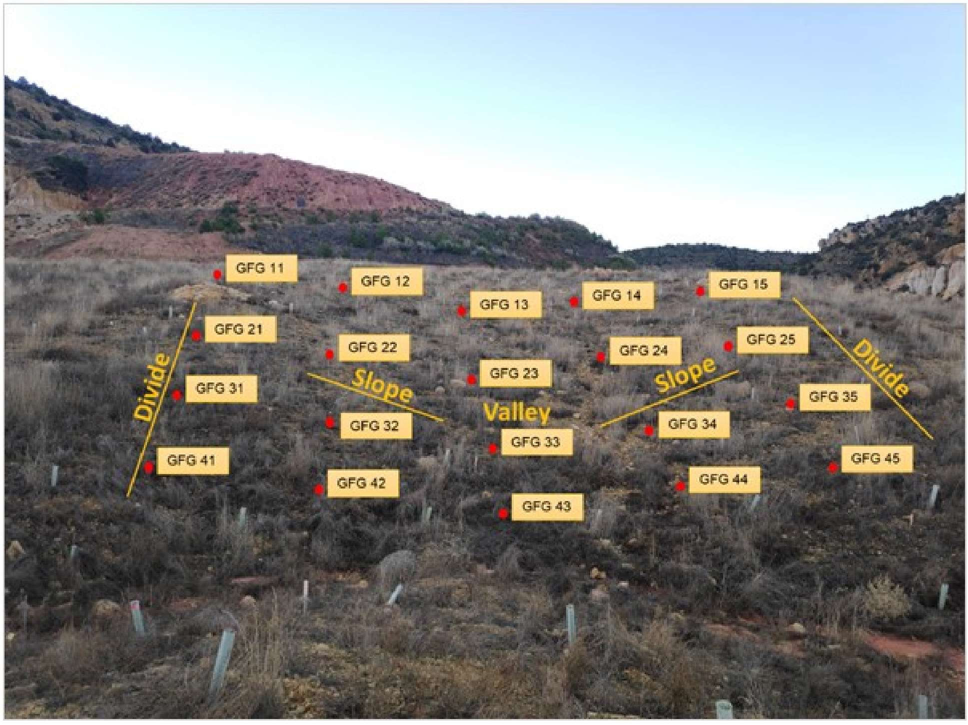


Figure 5. Distribution of sampling points in Western GeoFluv area (GFG), Shady Slope unit. Red dots correspond to the sampling points and lines show the different landforms.

In the area facing south, the sampling points were distributed with a longitudinal pattern and in the transversal landforms, forming 3 perpendicular transects through the micro basin with 5 sampling points each (Figure 6).

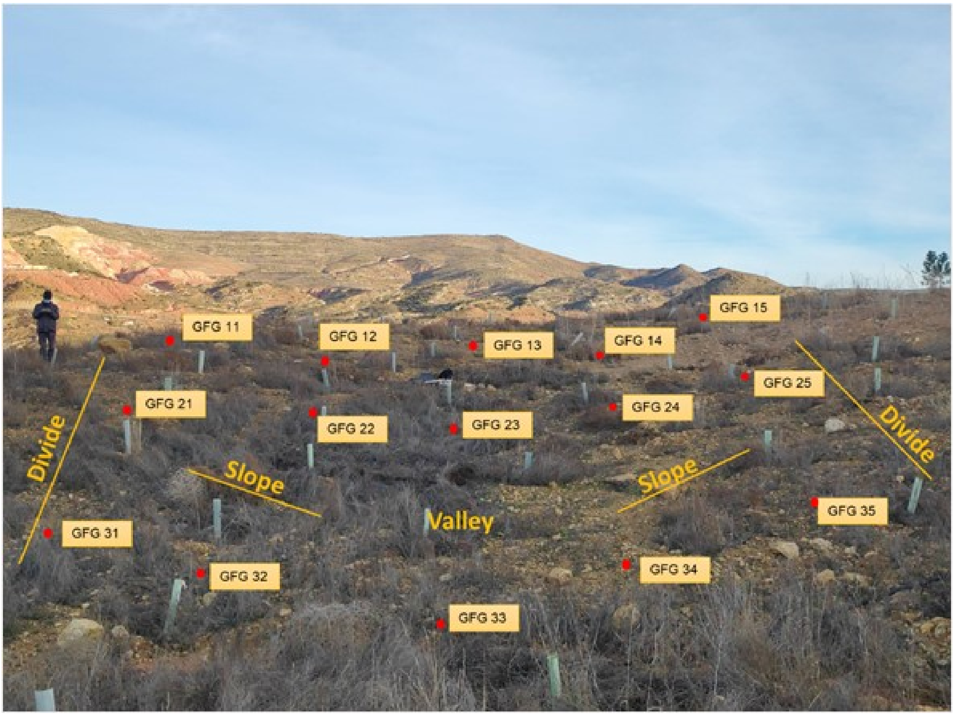


Figure 6. Distribution of sampling points in GFG, Sunny Slope unit. Red dots correspond to the sampling points and lines show the different landforms.

<u>GeoFluv restoration with overburden substratum (GFEst)</u>: This unit faces south and was covered by overburden material. Sampling points were placed in three transects perpendicular to the slope from the upper part to the bottom, each transect with 5 sampling points located in different landforms (Figure 7).

Figure 7. Distribution of sampling points in GeoFluv restoration with overburden substratum (GFEst) unit. The red dot corresponds to the sampling points and lines show the different landforms.

Eastern GeoFluv area (GFP): The unit was built with two areas, one facing west and the other facing east, the sampling points were distributed in each area with 3 transects, each of them with 5 sampling points through the different landforms (Figure 8).

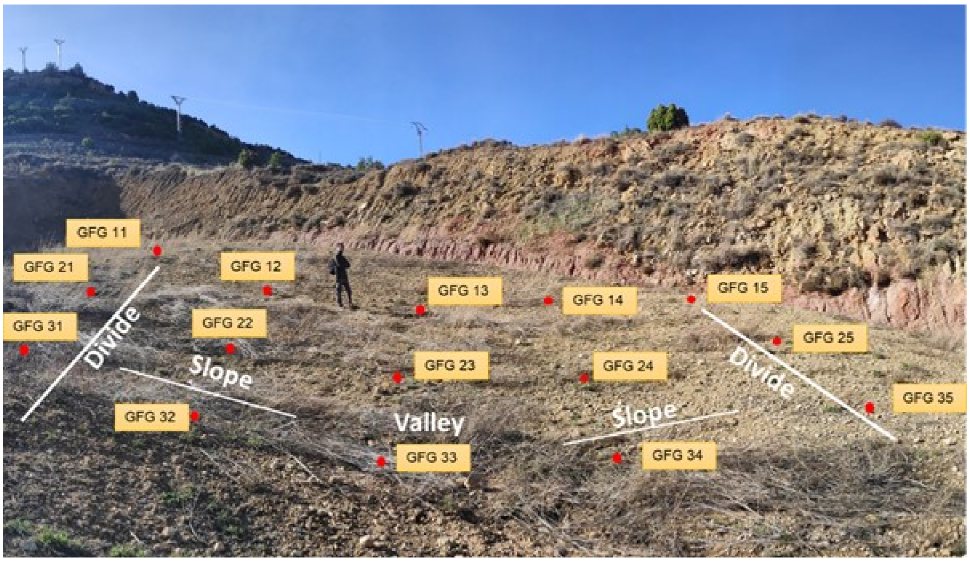


Figure 8. Distribution of sampling points in the Eastern GeoFluv area (GFP) unit. Red dots correspond to sampling points and lines show the different landforms

Conventional slope restoration (TC) and Conventional slope restoration with organic blanket (TM). There were 2 areas restored with the conventional approach, one of them with an organic blanket over the substrate (TM) and the other without it (TC). In both of them, sampling points were established in 3 transects from the upper part to the bottom of the slope, each transect with 5 sampling points (Figure 9).

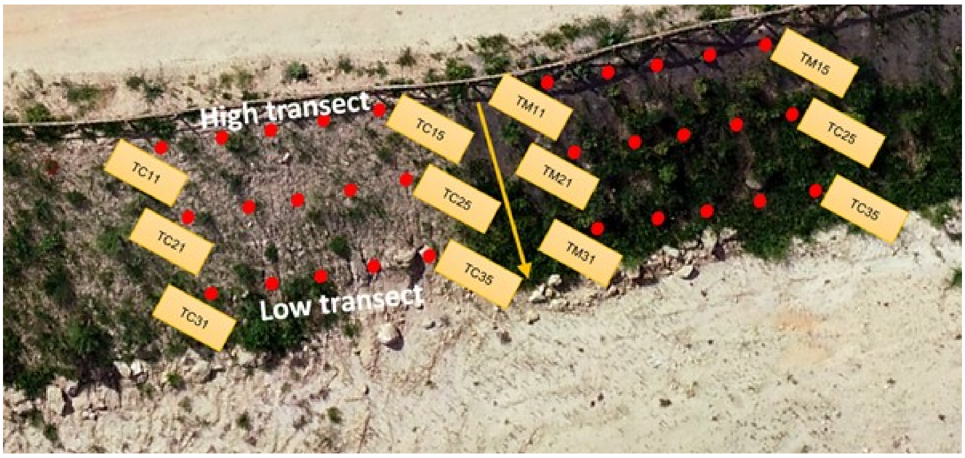


Figure 9. Distribution of sampling points in Conventional slope restoration (TC) and Conventional slope restoration with organic blanket (TM). Red dots correspond to the sampling point, arrow showing the direction of the slope.

Reference ecosystem (ER): This is a natural hillside, formerly cultivated and currently covered with scrub where 5 transects were established, each of them with 3 sampling points. The soil is poorly developed and consists of an A horizon (ochric) and a C horizon (entisol).

Figure 10. Distribution of sampling points in the reference ecosystem area (ER). Red dots correspond to the sampling point, the arrow is showing the direction of the slope.

SMC data were taken monthly from 11 july 2019 to 27 august 2021 (26 data) except for GFEst, which started 06 july 2020.

Table 1. Experimental design for Soil Misture Content monitoring in Fortuna quarry (Life Tecmine)

Treatment	Unit	Landform	Aspect	Substrate type	Transects	Sampling points (per transect)
Geomorphic restoration	GFG	Drainage divide	North	Colluvium	4	2
		Slope	North	Colluvium	4	2
		Valley	North	Colluvium	4	1
		Drainage divide	South	Colluvium	3	2
		Slope	South	Colluvium	3	2
		Valley	South	Colluvium	3	1
	GFP	Drainage divide	Este	Colluvium	3	2
		Slope	Este	Colluvium	3	2
		Valley	Este	Colluvium	3	1
		Drainage divide	West	Colluvium	1	3
		Slope	West	Colluvium	3	3
		Valley	West		1	3
	GF Est	Drainage divide	South	Overburden	3	2
		Slope	South	Overburden	3	2
		Valley	South	Overburden	3	1
Conventional restoration	TC	Slope	North	Overburden	3	5
	TM	Slope	North	Overburden + organic layer	3	5
Reference ecosystem	ER	Slope	North	Vegetation cover	5	3

Data analysis

The hypothesis was that soil moisture values (dependent variable) change depending on Treatment, Landform, Aspect, Substrate type and Transects. When the model assumptions were met or data could be transformed (log, square root) a mixed linear model of repeated measures was used employing the “nlme” R package (Pinheiro, Bates, DebRoy, D, & R Core Team, 2014). If model assumptions were not met, a non-parametric test (Friedman) was used including the “visit” as a repeated-measures (Mendiburu & Yaseen, 2020).

To detect differences among factors, a post hoc pairwise test was carried employing the emmeans command of the "nlme" R package or using Wilcoxon signed-rank test if the data fitted the model requirements. All statistical tests were performed with R Studio software (R Core Team, 2020). Results were considered statistically significant if p-values were lower than 0.05. See Figure 18 for a diagram showing the analysis flow.

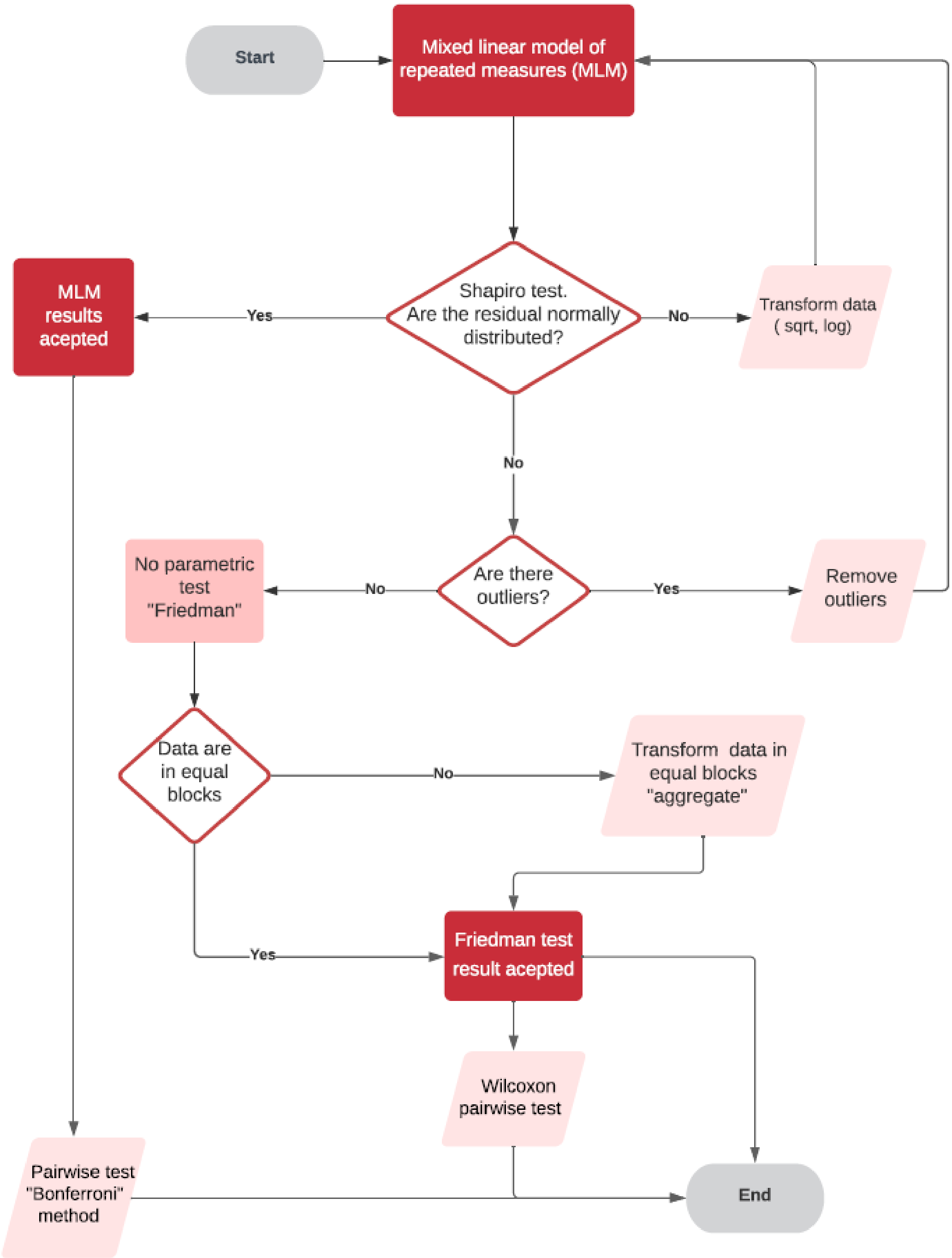


Figure 11. Flow chart of the statistical process used to analyze soil moisture data.

RESULTS

The results are presented as follows: Firstly, a descriptive graph with the moisture values recorded in all treatments between July 2019 and August 2021. Next, the results of the statistical analyses on the effect on SMC of the different treatments and environmental factors considered are shown.

Figure 12 shows the mean moisture values for each treatment over the 2 years of monitoring (26 measurements). It can be seen that the TC and TM treatments, which correspond to conventional restoration, have the lowest moisture values. Moreover, it can be seen that this tendency is accentuated over time.

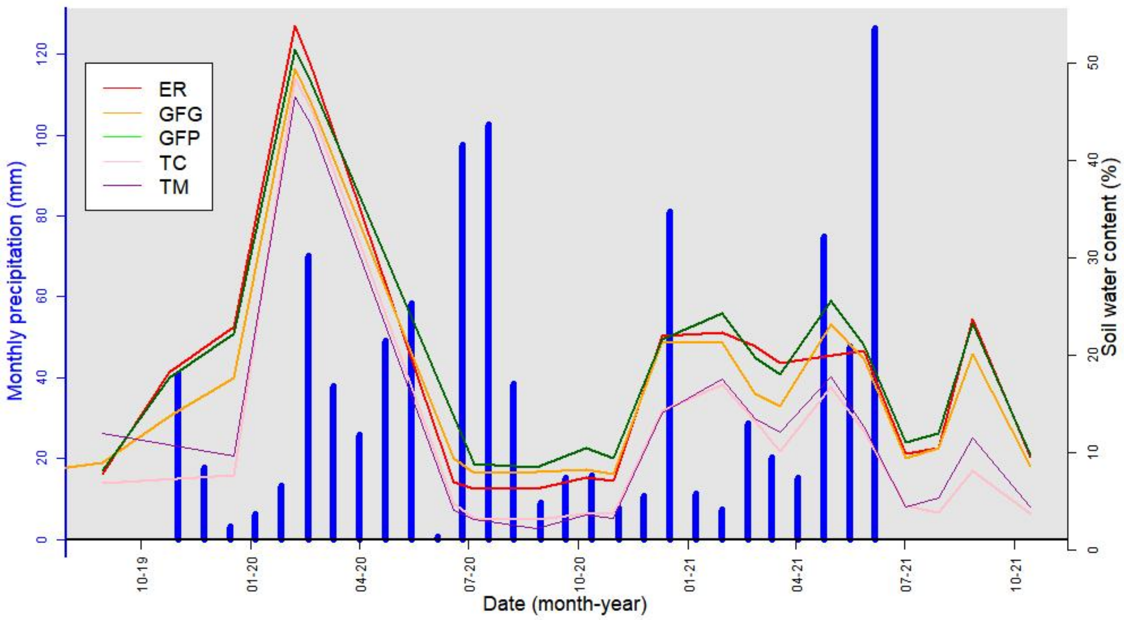
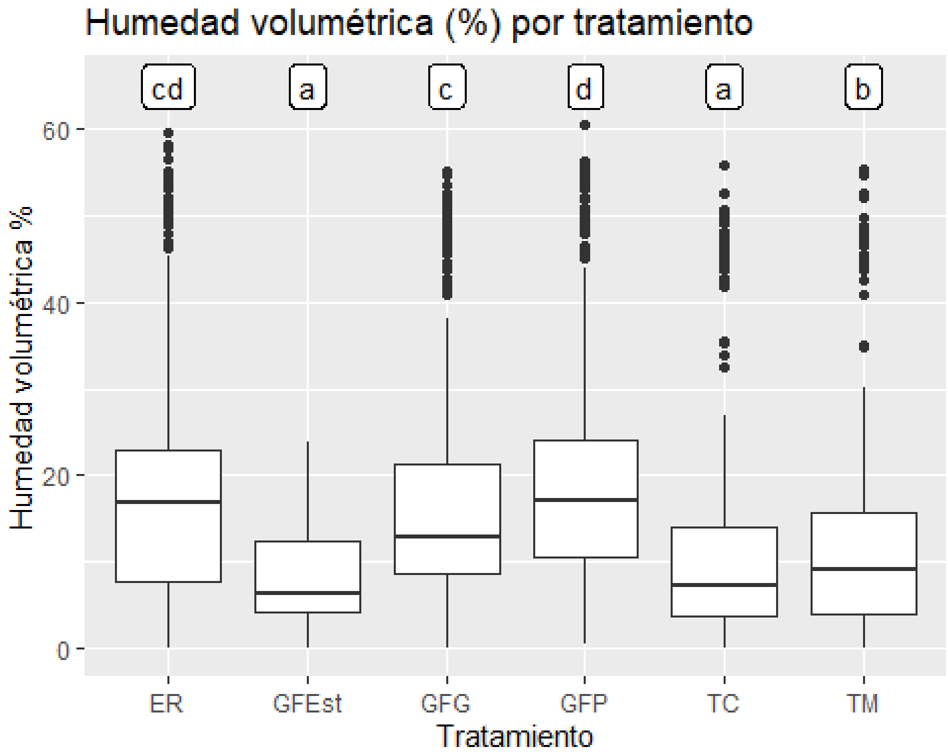


Figure 12. Mean moisture values per treatment over time. The blue bars indicate monthly rainfall. The treatments are as follows: ER: Reference ecosystem. GFG: Western GeoFluv area. GFP: Eastern GeoFluv área. TC: Conventional slope restoration. TM: Conventional slope restoration with organic blanket.

The mixed linear model of repeated measures indicates that there are statistically significant differences in the moisture contents between the different treatments (Figure 13). From the lowest to the highest moisture content, they are ordered as follows:

1. Conventional slope restoration (TC) and GeoFluv restoration with overburden substratum (GFEst).
2. Conventional slope restoration with organic blanket (TM).
3. Western GeoFluv area (GFG).
4. Reference Ecosystem (ER).
5. Eastern GeoFluv área (GFP).

The Reference Ecosystem does not differ significantly from GFG and GFP.

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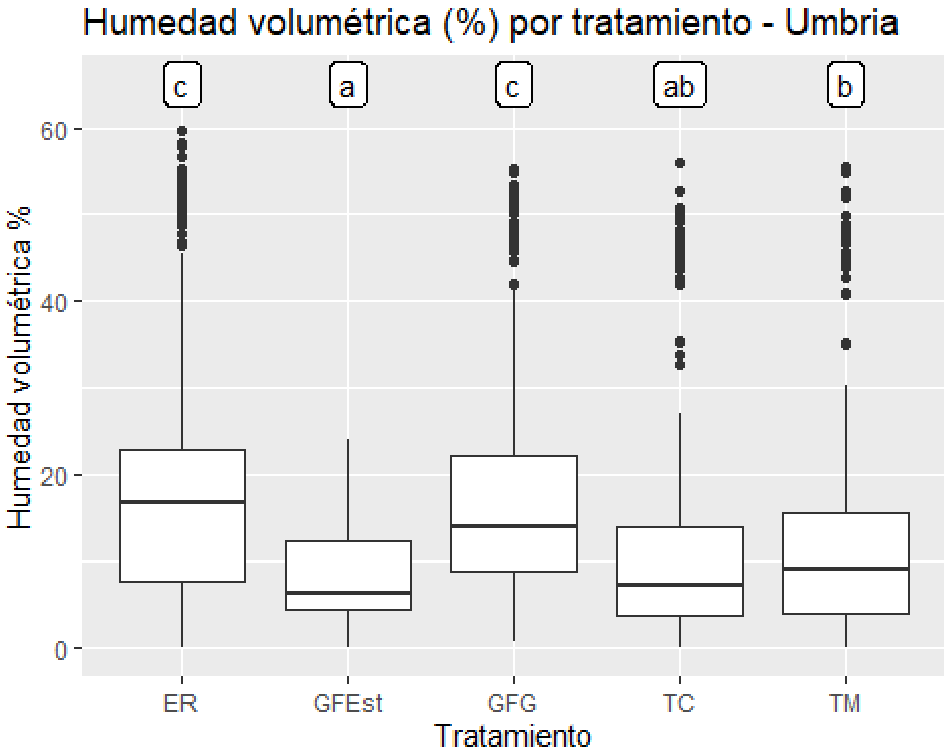
##                numDF denDF  F-value p-value
## (Intercept)        1  2293 396.9688  <.0001
## trat               5  2293 222.7132  <.0001
```

Figure 13. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture between treatments during the study period. Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: ER: Reference ecosystem. GFEst: GeoFluv restoration with overburden substratum. GFG: Western GeoFluv area. GFP: Eastern GeoFluv área. TC: Conventional slope restoration. TM: Conventional slope restoration with organic blanket.

A second statistical analysis has been made about the treatments but eliminating the effect of the aspect, so that only north-facing treatments have been included. Results also indicate that there are statistically significant differences in the moisture contents between the different treatments (Figure 14). From the lowest to the highest moisture content, they are ordered as follows:

1. GeoFluv restoration with overburden substratum (GFEst).
2. Conventional slope restoration (TC)
3. Conventional slope restoration with organic blanket (TM)
4. Western GeoFluv area (GFG) and Reference Ecosystem (ER).

The Reference Ecosystem does not differ significantly from the GFG, although it has higher values.

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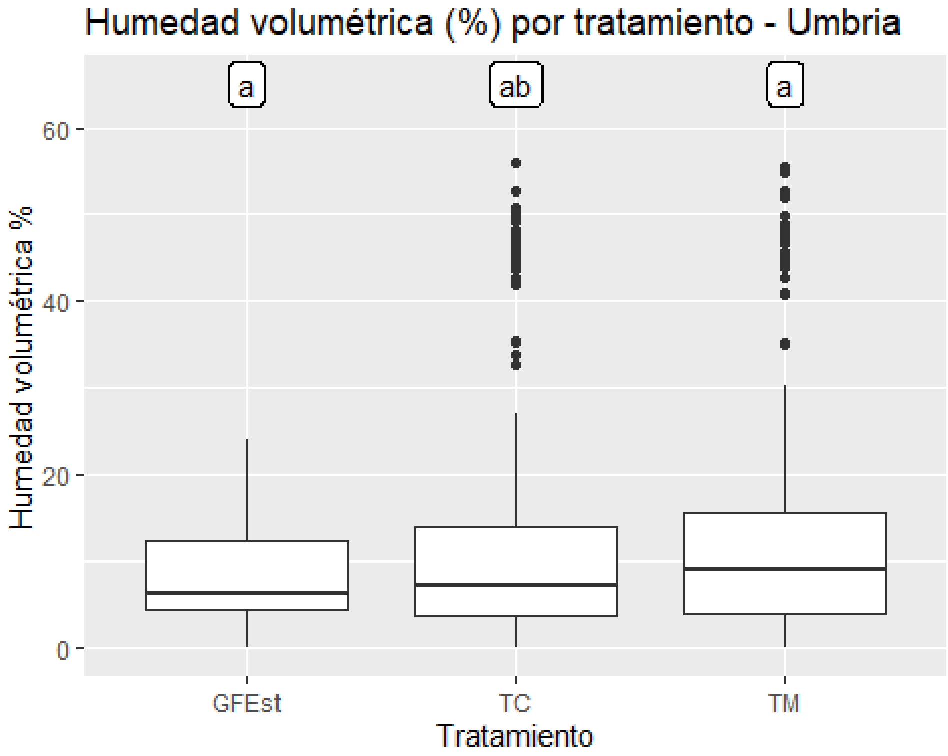
##              numDF denDF  F-value p-value
## (Intercept)     1  1428 340.2481  <.0001
## trat            4  1428 147.1439  <.0001
```

Figure 15. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture between north-facing treatments during the study period. Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: ER: Reference ecosystem. GFEst: GeoFluv restoration with overburden substratum. GFG: Western GeoFluv area. TC: Conventional slope restoration. TM: Conventional slope restoration with organic blanket.

To determine the effect of topography on SMC an analysis was conducted with the three treatments covered by overburden, so that the effect of the substratum is eliminated. Results show no significant differences among the three treatments: GeoFluv restoration with overburden substratum (GFEst), Conventional slope restoration (TC) and Conventional slope restoration with organic blanket (TM) (Figure 16).

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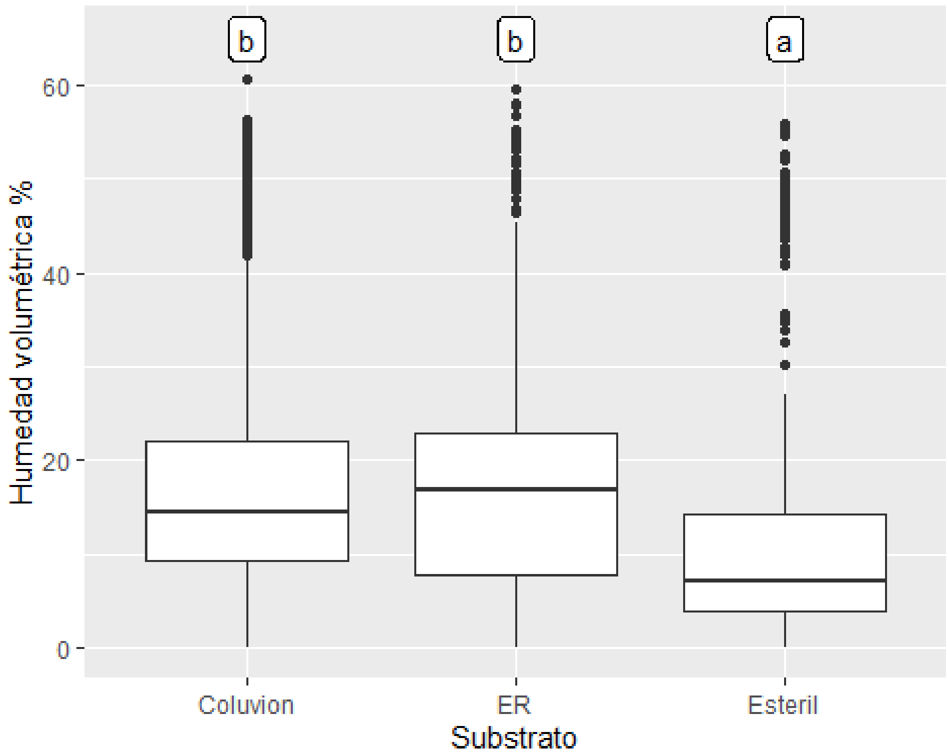
##               numDF denDF   F-value p-value
## (Intercept)      1   747 203.12956  <.0001
## trat             2   747   3.83939  0.0219
```

Figure 16. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture between overburden covered treatments during the study period. Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: GFEst: GeoFluv restoration with overburden substratum. TC: Conventional slope restoration. TM: Conventional slope restoration with organic blanket.

To determine the effect of substrate type on SMC, an analysis was performed with all treatments. Overburden has significant lower moisture values than colluvium and reference ecosystem (Figure 17).

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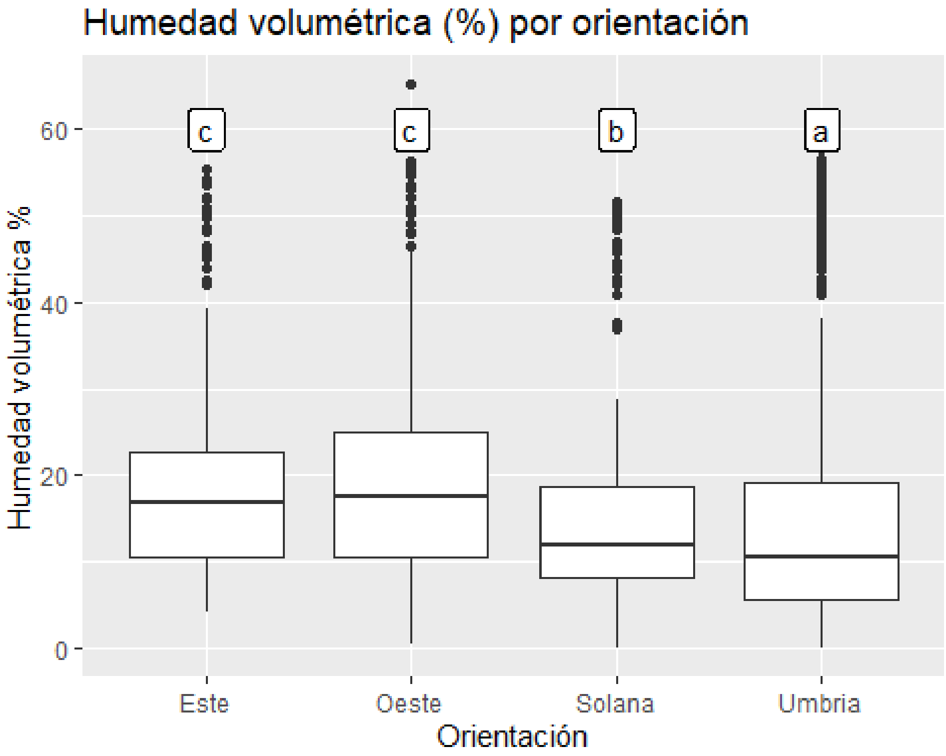
##             numDF denDF  F-value p-value
## (Intercept)     1  2296 390.9529  <.0001
## sub             2  2296 518.6242  <.0001
```

Figure 17. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture in the three types of substratum. All treatments have been included in the analysis. Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: Coluvion (colluvium); ER (Reference ecosystem); Estéril (overburden).

Figure 18 shows the results of the statiscal analysis on the effect of the aspect on SMC. There are statistically significant differences in the moisture contents between the different treatments. From the lowest to the highest moisture content, they are ordered as follows: North-facing slopes; South-facing slopes; and East and West-facing slopes.




```
##              numDF denDF  F-value p-value
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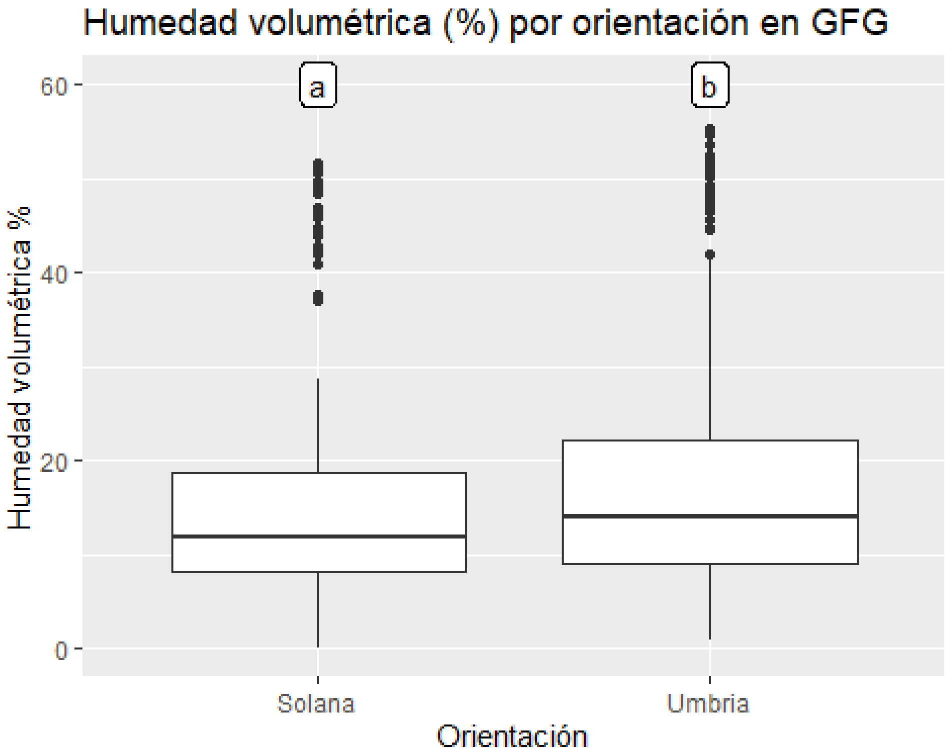
## ori             3  2295  93.8663  <.0001
```

Figure 18. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture between the different aspects. Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: Este: East; Oeste: West; Solana: South; Umbría: North.

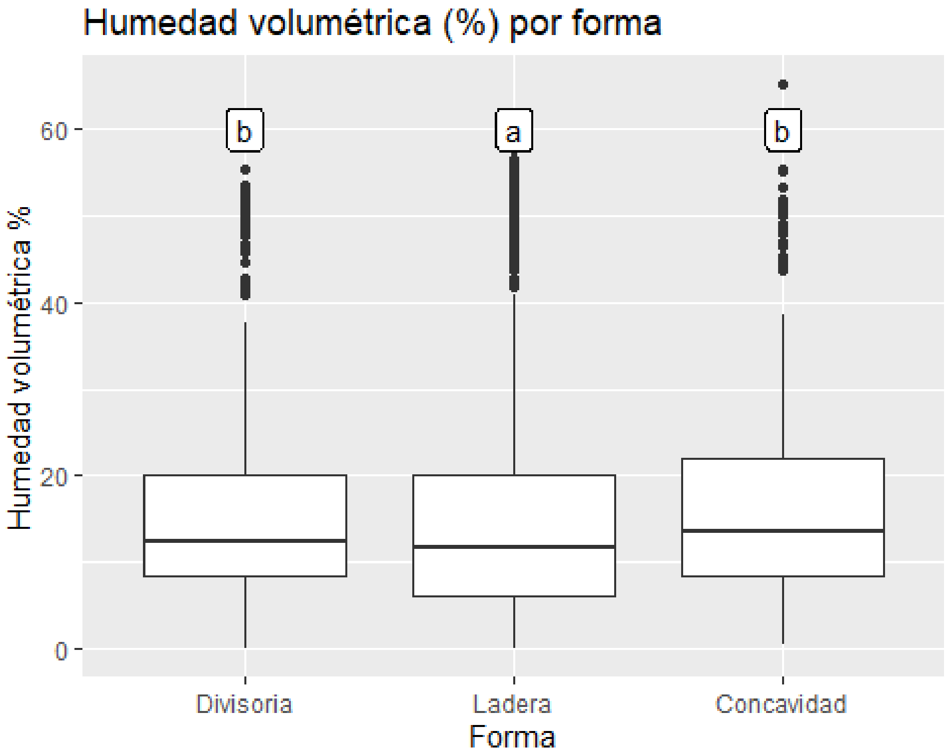
To isolate the effect of aspect from the effect of substratum, another Anova analysis was conducted with data from the treatment with colluvium substrate (GFG). Results show higher SMC in north-facing slopes than in south-facing slopes with statistical significance (Figure 19).




```
##                numDF denDF F-value p-value
## (Intercept)         1   691 501.764  <.0001
## ori                 1   691  27.542  <.0001
```

Figure 20. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture between south and north aspects in colluvium covered slopes (GFG). Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: Solana: South; Umbría: North.

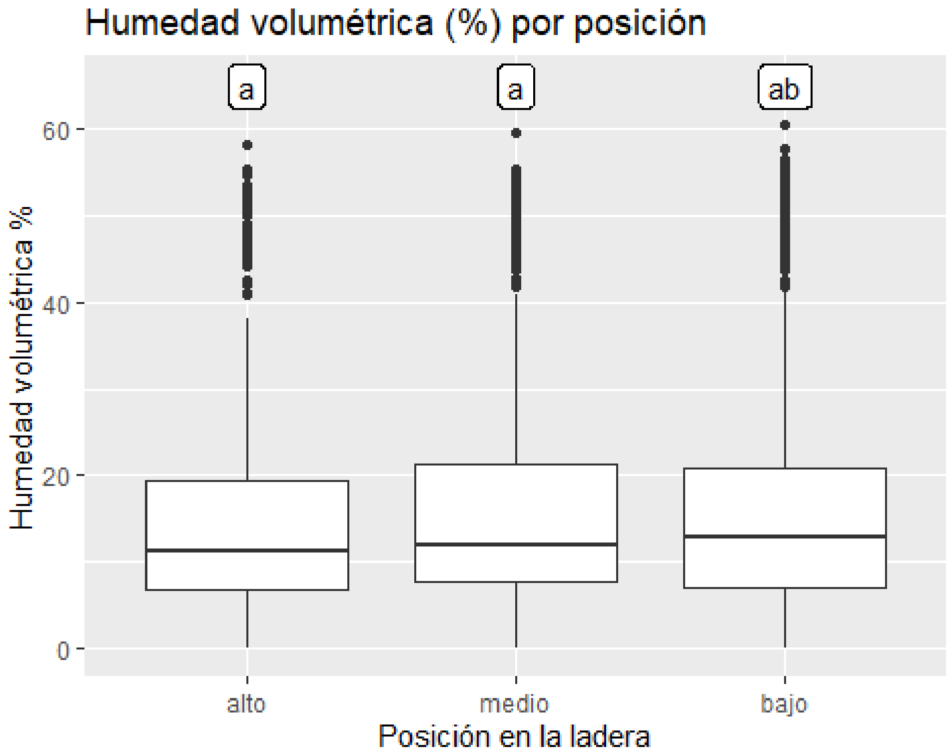
The effect of the type of GeoFluv landform on SMC has been analysed (Figure 21). There are statistically significant differences among the three landforms: divides and concavities have higher SMC values than hillsides.




```
##              numDF denDF  F-value p-value
## (Intercept)     1  2296 385.6349  <.0001
## forma           2  2296  35.5727  <.0001
```

Figure 21. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture among GeoFluv landforms. All GeoFluv treatments have been included in the analysis. Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: Divisoria (divide); Ladera (hillside); Concavidad (concavity).

SMC along the hillside position in all treatments has been analysed (Figure 22). Lower zones of the hillslopes have significant higher SMC than middle and upper zones.

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##              numDF denDF  F-value p-value
## (Intercept)     1  2296 387.2426  <.0001
## pos             2  2296   2.9521  0.0524
```

Figure 22. Results of the mixed linear model of repeated measures for the comparison of mean soil moisture along of the hillside position. Lower case letters indicate the statistical significance of the differences according to the post hoc analyses. F-value and p-value are indicated. The treatments are as follows: alto (upper); medio (middle); bajo (lower).

DISCUSSION

The most relevant finding of the moisture study is the confirmation that Geomorphological Restoration by the GeoFluv method presents higher moisture levels than conventional restoration. In other words, the supply of water to the plants is higher and the control of the water cycle by the ecosystem is greater. This is very relevant for mining restoration in Mediterranean and semi-arid climates, where water deficit is the first limiting factor for the success of revegetation (Bochet & García-Fayos, 2004). On the other hand, the greater control of the water cycle by the soil and GeoFluv topography also implies a lower emission of runoff into natural watercourses, i.e. a lower hydrological impact (off site effects) (Martín-Moreno et al. 2016).

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. Indeed, on overburden, the GeoFluv topography (divide, hillside, valley) does not offer more water than the straight slope. This leads us to conclude that the selection of the substrate and its management must be a priority objective in mining restoration. Relating this result to that obtained in the erosion study (Action C 1.1) it could be said that the topography controls more rill erosion and the substrate more runoff generation (water availability for plants).

In this sense, we found that the colluvium substrate has had similar SMC levels as the natural soil of the reference ecosystem (entisol with ochric epipedion), which indicates its good hydric properties. Colluvium has good physical properties such as higher water infiltration, higher water holding capacity and lower erodibility than overburden. In our study site, it is composed of limestone fragments and a fine matrix of sand, silt and clay, with a loamy texture that allows a balance between optimum drainage and accumulation of water and nutrients, decreasing soil erosion (Martín-Duque et al., 2010).

The aspect factor also influences SMC, with more water available in the shady areas than in the sunny areas as it is well known (Feng et al., 2019). However, the effect of aspect is diluted depending on the type of substrate and topography, which have a greater control on soil water content.

Knowing the spatial distribution of soil moisture is very relevant for revegetation design in Mediterranean quarries (Merino-Martin et al 2012). The selection of species and their spatial distribution must be conditioned by the availability of water. On the one hand, the general pattern of increased moisture in the lower part of the reliefs has been verified. On the other hand, it has been found that in GeoFluv reliefs, moisture is concentrated in the concavities, being higher in them and in the dividers than in the hillsides. This pattern can be taken into account for revegetation design in GeoFluv landscapes.

In order to improve the availability of water in the soil for plants the priority action is to carry out a good selection and management of the substrate. In the Mediterranean mountain environment, colluvium is an excellent starting material. It is also effective to form a GeoFluv topography with divides, hillsides and concavities where soil moisture is unevenly distributed, which favours environmental heterogeneity and thus biodiversity (Garbarino et al 2018) far from the uniformity present in conventional slopes (Rehounkova et al., 2011). Not forgetting that GeoFluv topography reduces the formation of rills and thus the loss of water from the slopes.

CONCLUSIONS AND FURTHER CONSIDERATION

- Geomorphological Restoration by the GeoFluv method presents higher moisture levels than conventional restoration (baseline), and this difference increases over time. That means that, the supply of water to the plants is higher and the control of the water cycle by the ecosystem is greater.

- Substrate selection and management is the key activity to optimize water supply to plants.

- Colluvium is an excellent starting material to develop functional soils, with a capacity to supply water to plants similar to soils of the reference ecosystem (topline). We strongly recommend its use as a first measure to optimize water supply to plants.

- Topography management with GeoFluv results in a variety of landforms with differences in soil moisture content (higher in the concavities and divides and lower in the hillsides as well as higher in the lower parts of the reliefs). This spatial pattern of soil moisture has to be taken into account for revegetation design in GeoFluv landscapes and, on the other hand it may favour environmental heterogeneity and biodiversity. Action C 1.1. has also found that GeoFluv landforms control rill erosion development.

- Soil moisture monitoring is a good approach for the evaluation of the water cycle in mining restorations.

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