Deliverable on establishment success of plantations:

Survival and Growth

LIFE16 ENV/ES/000159

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TECMINE After-LIFE. Action 1. MONITORING OF PLANT SURVIVAL AND GROWTH	
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Introduction

This report presents the work carried out during the After-LIFE period and the results obtained in relation to ACTION 1: MONITORING OF PLANT SURVIVAL AND GROWTH. This action aimed to continue the monitoring of plant establishment in terms of plant survival and growth, biodiversity and plant colonization in the main restoration unit (Geofluv West).

The methodology of this sampling followed the methods developed during LIFE TECMINE project which can be found in the Deliverable Action C2: "Establishment success of plantations: Survival and growth".

The **After-Life actions conducted** were:

1.- Monitoring of survival and growth in 2023 and 2025 of introduced species in the Unit.
2.- Assess natural colonization of new or introduced species, biodiversity determination, and soil protection in 2023.

This monitoring survey was carried out in the *Geofluv West* Unit composed of three differentiated Restoration Units (RU, Fig. 1)

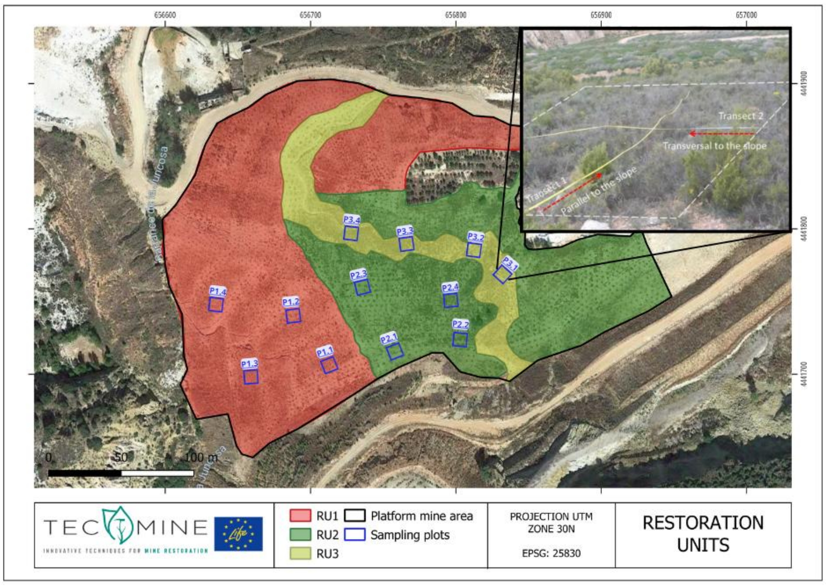

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Figure 1. Sampling plots distribution (100 m^2 each) through the study area for each RU (RU1: red; RU2: dark green; RU3: light green).

Abiotic conditions during the TECMINE After-LIFE period

To illustrate the degree of aridity in the restored area during the following years after restoration and relate it to the water stress experienced by plants during the six and a half years after plantation, we calculated the 6-month SPEI (Standardized Precipitation Evapotranspiration Index; Fig. 2) through the openly available CSIC website (https://spei.csic.es/spei_database). This SPEI-time scale effectively captures moisture conditions at seasonal level, such as the summer droughts or the growing seasons, which can correlate with the success or failure of restored plants.

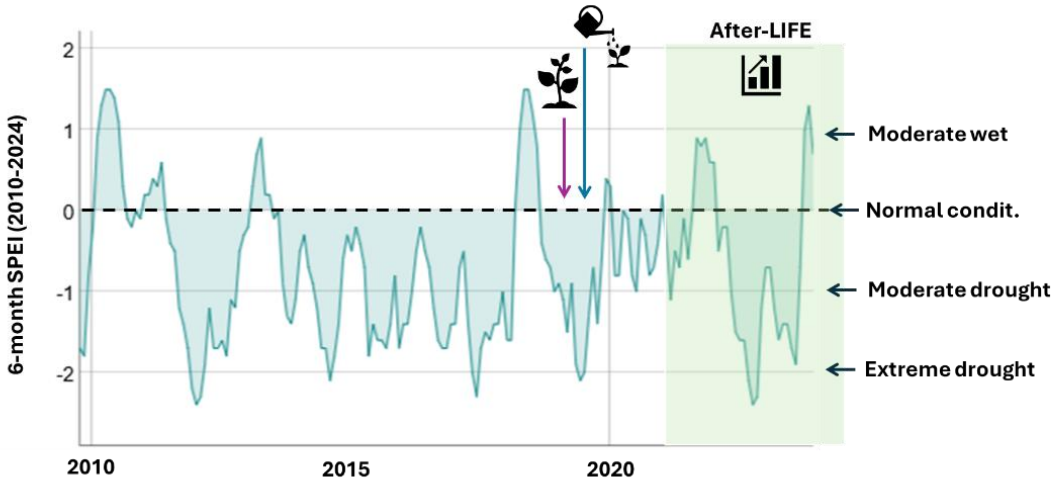

Figure 2. Evolution of 6-month SPEI index from 2010 to 2024, including plantation time (April-19) and the After-LIFE monitoring period (until 6 years after plantation).

Right after plantation (April-19) the area experienced an extended and severe drought-period (SPEI< -1.5) that conditioned the implementation of an emergency watering. Fortunately, the irrigation applied during the early stages after plantation ensured enough soil water content for plants uptake, and the following years, until 2022, the water availability conditions were good enough to allow root development and plant establishment. During the After-LIFE, nevertheless, especially during 2023 and part of 2024, the aridity conditions reached even SPEI values significantly lower than -2, which is considered extreme aridity conditions. These harsh water availability conditions greatly limited plant growth rates. Surprisingly, survival rates remained almost stable during the After-LIFE period (see survival data below).

Inter-annual variation in rainfall from 2021 to 2024 shows a fluctuating pattern from 570 mm in 2021, the minimum values around 280 mm in 2023 (i.e. the extreme aridity conditions), and up to 780 mm in 2024 (Fig.3). These values corroborate SPEI data and show the high variability in the soil water availability for the introduced plants. However, the low values registered in 2023 were not related to an increase in mortality rates, which remain the same rates and point out that the survival of seedlings is increasingly independent of climatic conditions, especially water availability.

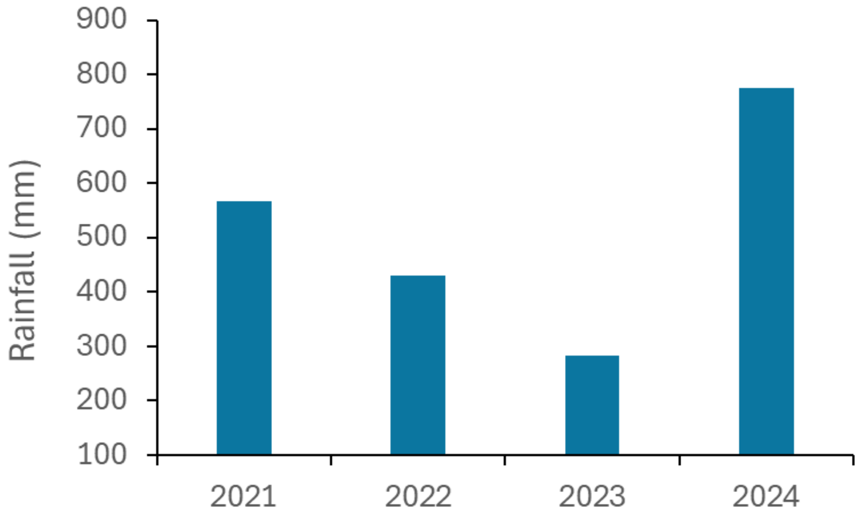

Figure 3. Annual cumulated rainfall during the afterlife period. Data from the ongoing 2025 are not considered to avoid the inclusion of incomplete-year information.

Results:

1.- Evolution of seedling survival

During the TECMINE After-LIFE monitoring we conducted two field surveys to evaluate plant survival rates at mid-term after plantation. First survey took place in July-23 (4.5 years after plantation) and the second survey in May-25 (~6.5 years after plantation), at the end of the TECMINE After-LIFE monitoring period.

Despite the limiting abiotic conditions during the After-LIFE period, average survival rates of the introduced seedlings in the last field sampling (2025), was around 75%. Regarding each restoration unit: final survival rates were 74%, 78% and 72% for RU1, RU2 and RU3, respectively. The results after 6.5 years showed high survival rates and an overall restoration success (Fig. 4).

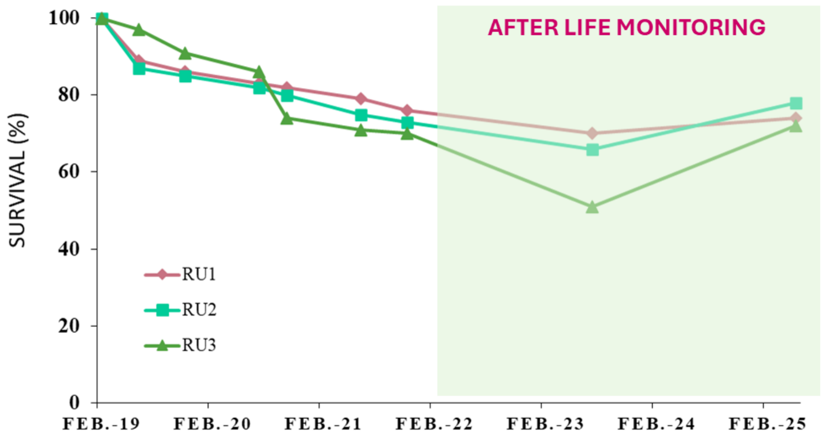

Figure 4. Survival dynamics across time in the restored area (Geofluv West area) of the TECMINE project for each Restoration Unit: dark pink-diamonds=RU1; light green-square=RU2; grey- triangle= RU3.

Among species, the best performing species in survival were *Brachypodium phoenicoides, Dorycnium pentaphyllum,* and *Salvia rosmarinus* (former *Rosmarinus officinalis*) in RU1, *Juniperus phoenicea* in RU2*,* and *Lonicera etrusca and Crataegus monogyna,* all of them with survival rates above 90% (Fig. 5). Oppositely, the species that clearly performed below our expectations was *Pinus nigra*, in RU3, that had very poor plant-quality conditions from the nursery. This supposed survival rates below 20%. Additionally, *Psoralea bituminosa*, in RU1, neither accomplished fully successful expectations with survival rates between 40 and 50% as consequence of 2023 drought (Fig. 5).

According to the figure 4, in the survival campaign in 2023 we detected a slightly decrease in survival rates in RU1 and RU2. This drop was especially notable for plants introduced in RU3. This artefact could be attributed to the resprouting capacity of many of the introduced species, that dried out the leaves and the above ground biomass during the extremely drought 2023 and recover from roots when soil water conditions enhanced. Furthermore, some of the metallic labels used to taggle the plants were lost after more than 6 years, especially in plants from RU3. Thus, the number of individuals sampled 2025 could have slightly varied from the previous field surveys.

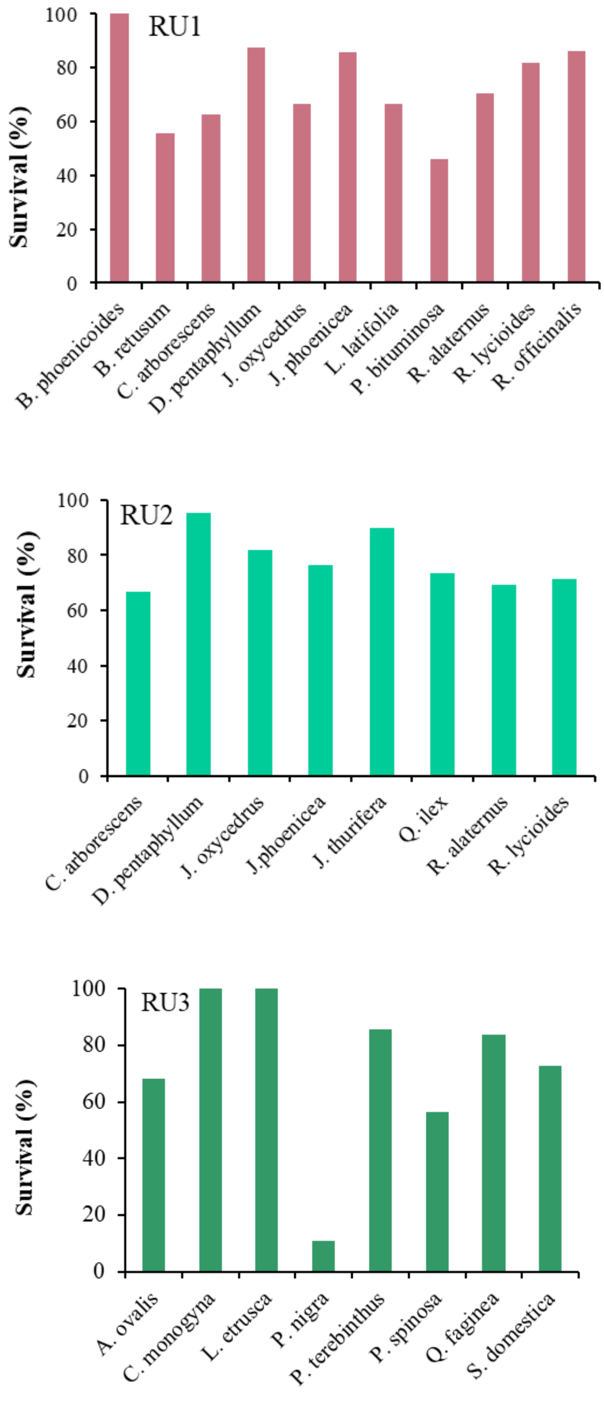

Figure 5. Survival rates (%) by species at the end of the After-LIFE monitoring of the TECMINE project (May 2025) in each Restoration Unit: RU1 , RU2and RU3 .

2.- Analysis of plant growth

Seedlings growth rates were in general low. Species growth rates were affected by both abiotic and biotic factors. In the one hand, regarding abiotic factors, some species were especially affected by the low water availability during 2023. Thus, the growth rates were variable depending on the species and the RU restoration unit (Fig. 6). Some species such as *Colutea arborescens* or *Sorbus domestica* showed higher growth than the rest of the species. In the other hand, some other species were specially affected by predation (by roe deer or wild boars) showing slightly lower values than previous samplings. This damage was specially marked in species such as *Sorbus domestica, Quercus ilex and Rhamnus alaternus.*

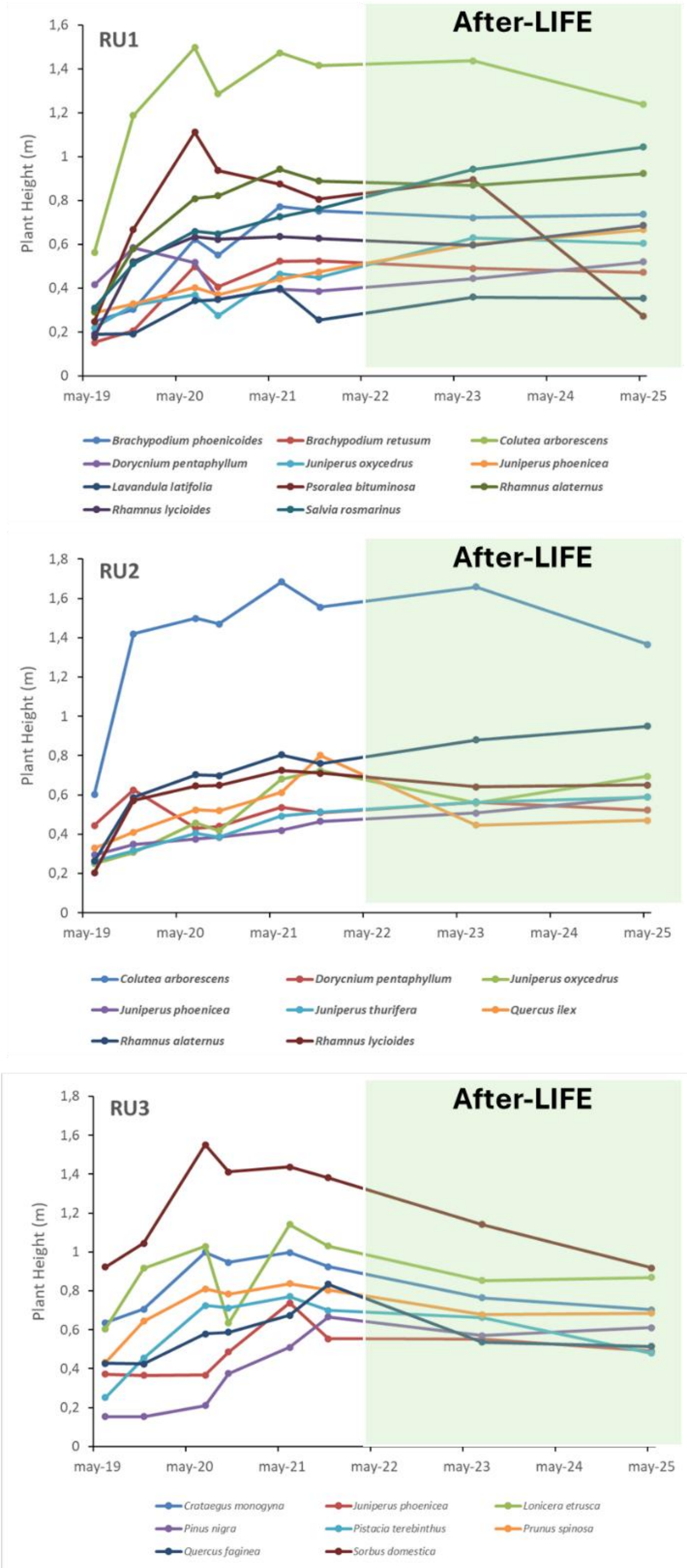

Figure 6. Average seedling height over time for each planted species. The period covers from the nursery to the After-LIFE survey (July 2023) for each Restoration Unit: RU1, RU2 and RU3.

3.- Natural colonization, biodiversity, and soil protection

Although during the TECMINE After-LIFE period only survival and growth monitoring were agreed upon, in July 2023 we assessed the evolution of some other key indicators of restoration success that were part of the master's thesis of Katty L. Duchicela from the University of Alicante, that was carried out within the framework of TECMINE After-LIFE. Such evaluated indicators were the evolution of natural plant colonization, biodiversity indexes and soil protection.

Regarding vegetation, 4.5 years after restoration the plant cover in the three restoration units was around 66% on average. This meant a 4% increase in two years, from 2021 to 2023. This increment meanly corresponded to the plant cover found in the RU2, while the other two restoration units RU1 and RU3 decreased by 11% and 7% respectively (Fig. 7). Nevertheless, these small reductions in plan cover were very low and not statistically significant. In both cases, the restoration units RU1 and RU3 had similar decreasing trends possibly due to the high solar exposure for RU1 and the enlargement of a gully observed in situ in RU3 which belongs to the valley bottom area.

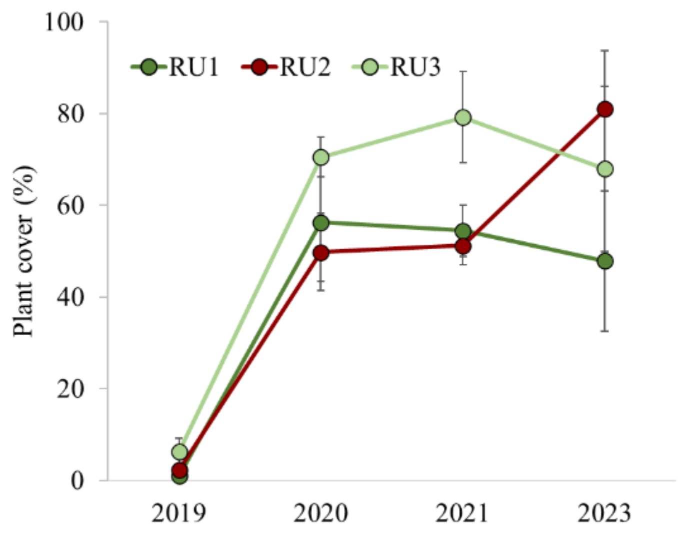

Figure 7. Plant cover (herbaceous + woody species) in each Restoration Unit: RU1 (upper plot), RU2 (middle plot) and RU3 (lower plot). Values represent means ± SE.

In relation to sown species for quick soil protection in early stages after plantation (*Lotus corniculatus, Melilotus officinalis and Dactylis glomerata*), the absolute plant cover significantly changed over time, depending on the species. In the July-23, their cover had considerably decreased in all restoration units (Fig. 8), which favoured the natural colonisation of native species. In fact, this early herbaceous cover aiming at soil protection, and the later decrease facilitating natural colonization (secondary succession), completely accomplished the goals of this restoration action. By May-25 the presence of these species was almost residual. *M. officinalis* has completely disappeared, *D. glomerata* was rarely found in some bottom areas of RU2 and RU3 while *L. corniculatus* could be generally found but in much lower presence than previous surveys.

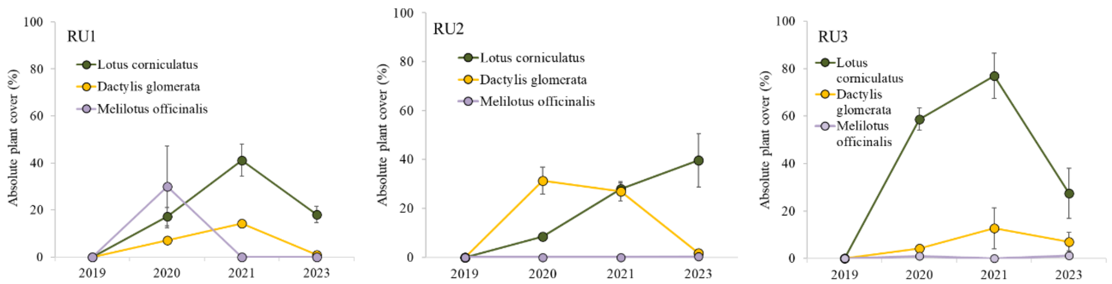

Figure 8. Absolute plant cover of the sown herbaceous species (*Lotus corniculatus*, dark green; *Dactylis glomerata*, yellow; *Melilotus officinalis*, grey) during the different monitoring periods (2019, 2020, 2021 and 2023). Values are means ± SE.

Regarding plant diversity, 4.5 years after plantation (July-2023), 20, 33 and 27 non-introduced species were found within restoration units RU1, RU2 and RU3, respectively. In the 2025´s field survey, the presence of native species colonizing the restored areas was even higher with species such as *Thymus vulgaris, Ononis natrix, Santolina chamaecyparissus* or *Genista Scorpius* among many others. Although diversity and species richness indices were higher in RU2 (Fig. 9a, Fig. 9b, Fig. 9c) we did not find significant differences between restoration units (95% CIs overlap) which is positive as it was not intended to have differences between them.

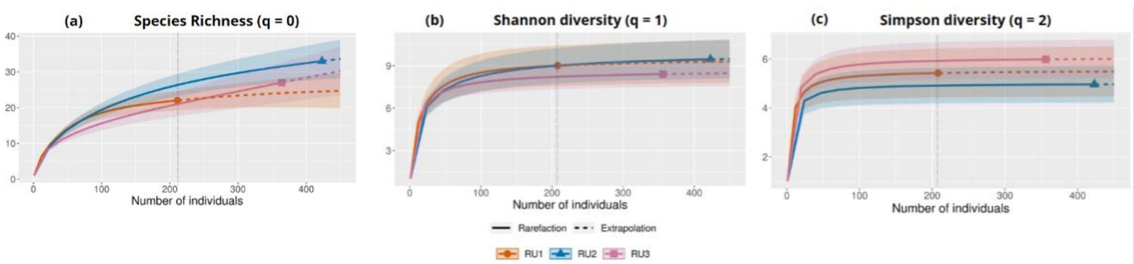

Figure 9. Diversity indices. In the curves: rarefaction (solid lines) and extrapolation (dashed lines) and in the mark (triangle, circle or square) the number of individuals observed. (a) shows species richness in each area (q=0). (b) Shannon index (q=1) and (c) the Simpson index (q=2). (Orange circle = Restoration Unit

RU1), (Blue triangle = Restoration Unit RU2), (Pink square = Restoration Unit RU3). The grey dashed vertical line indicates the number of individuals considered when assessing the indices.

Furthermore, it is important to highlight that only 6.5 years after restoration, we found many introduced species with flowers and fruits and new individuals recruited. It was specially marked in herbs species like *Brachypodium retusum* and *B. phoenicoides*, shrub species such as *Salvia rosmarinus*, *Dorycnium pentaphyllum, Lavandula latifolia, Colutea arborescens, Rhamnus alaternus, Prunus spinosa*, but it also happened in some tree species like *Amelanchier ovali*s or *Juniperus phoenicea*. In fact, new recruiment of introduced species is considered one of the best indicators of restoration success.

CONCLUSIONS:

1. The successful results achieved in the project regarding species establishment are due to both, a thorough initial characterization of the restoration area and an effective restoration design. This design incorporates a combination of accurate species selection, nursery cultivation practices, and field techniques to enhance plant establishment.
2. During the After-LIFE monitoring period, that covered 6.5 years after restoration, we found high survival rates (around 75%) regardless of abiotic conditions, even in the most unfavourable scenarios, like RU1. The application of low-cost restoration field techniques such as micro-catchments, instead of more expensive irrigation scheduling, the addition of organic amendments and irrigation at critical periods during the early stages after planting, enhanced the probability of seedling survival and growth.
3. The growth of species follows expected development patterns, with some species growing faster than others. Numerous species have been reported to undergo fructification and flowering and, in certain instances, recruit new individuals from these fructified species. However, some negative effects on growth have resulted from the combination of biotic (animal predation) and abiotic factors (drought period during 2023).
4. Achieving early plant cover is crucial for preventing soil degradation and promoting the recovery of key ecological processes. After 4.5 years, the average plant cover was over 60%, a value much higher than the 30% threshold for effective soil protection. Additionally, by that time, there was a significant presence of dead biomass -such as plant debris and necromass- that has integrated into the soil, thereby increasing its

fertility. Similarly, species diversity increased over time, enhancing ecological conditions and facilitating the recruitment of new native plants. Beyond plant cover, other elements that cover the soil, such as stones, litter, and organic waste (including organic strips), also played a vital role in increasing soil surface roughness. This, in turn, promoted seed germination and the establishment of new native colonizing species.

5. According to our expectations, plant cover of sown species declined after 6.5 years after seeding treatments and some species have almost completely disappeared. It is a sign of a good species selection, characterized by a fast growth during early stages after restoration to ensure soil protection from erosion and after that time, gradually disappear to allow the entry of natural colonization.

6. We also want to emphasize the importance of quality control through step-by-step supervision, along with the implementation of a monitoring plan to detect critical deviations. This enabled urgent actions during the restoration process when needed and facilitated the evaluation of long-term results. The watering treatments applied during the first year, prevented the effect of the extreme drought conditions, allow the normal development of rooting system and significantly enhanced species survival. Consequently, the plants were able to cope with subsequent years of severe drought, such as in 2023, and this drought had minimal impact on species survival.

SUPPLEMENTARY INFORMATION

Figure S1. General view of restoration unit RU1 during the After-LIFE monitoring (July-23). Plant cover in this unit is lower than in RU2 and RU3. However, we found high survival rates of introduced seedlings.

Figure S2. General view of restoration unit RU2 (July 2023), with high degree of plant cover.

Figure S3. Transects display in RU2. We assess every 20 cm soil cover, species richness and abundance.

Figure S4. Detailed image of *Rhamnus alaternus* fructification (left) and new recruitments of *Colutea arborescens* (right).

plantation).

Figure S5. Detailed image of soil cover under vegetation. 4.5 years after restoration, we found significant presence of organic matter and plant debris that are being incorporated into the soil, increasing fertility, and composing step by step a real soil that started from sterile mining tails.

Figure S6. Example of *Sorbus domestica* with good growth in RU-3 by June 2025 (6.5 years after plantation).

Figure S7. General view of all the Geofluv West restored area.

Figure S9. General view of the RU-2 by June 2025. Note that introduced *Lotus corniculatus* has almost disappeared and other herbaceous species such as *Bromus* sp. are currently dominant. It can also be appreciated the high diversity of plant morphotypes indicating a high diversity of species.

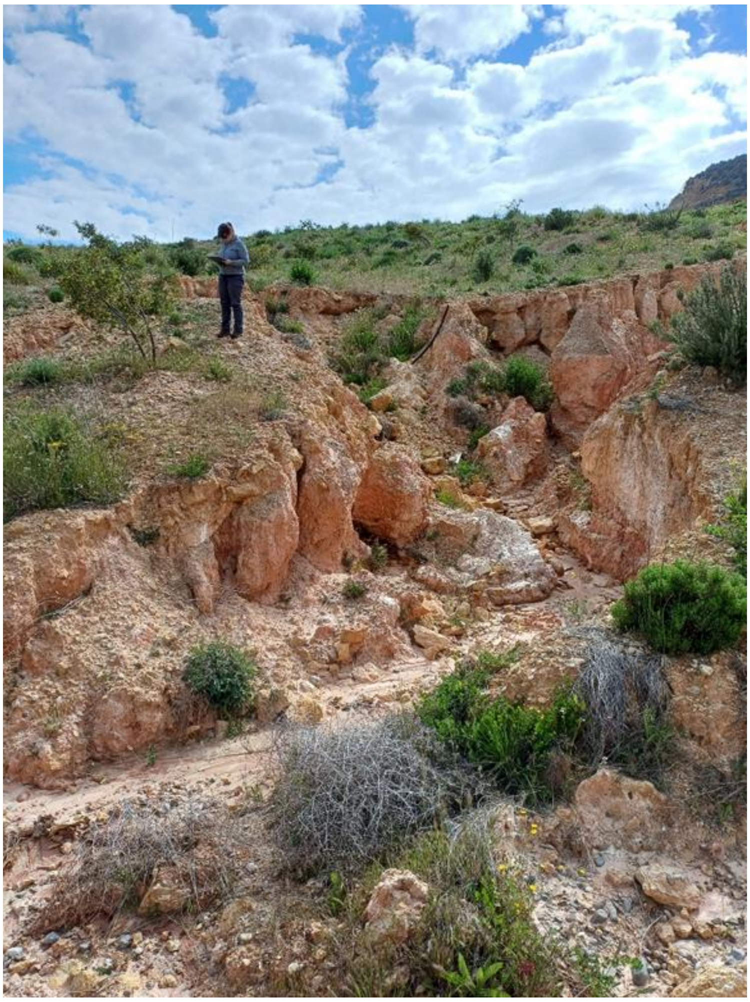

Figure S10. Big gully developed in the RU-1 because of flow concentration from upper parts of this unit. This highlights the relevance of creating a good geomorphological design avoiding steep slopes and promoting materials and textures in the soil surface to favor soil infiltration.