Evidence-based policy briefs Life adaptamed

ACTIONS C1, C2, C3, C4, C5 AND C6

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Junta de Andalucía
Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible

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Protection of key ecosystem services by adaptive management of Climate Change endangered Mediterranean socioecosystems

Deliverable product associated with actions C1, C2, C3, C4, C5 and C6.

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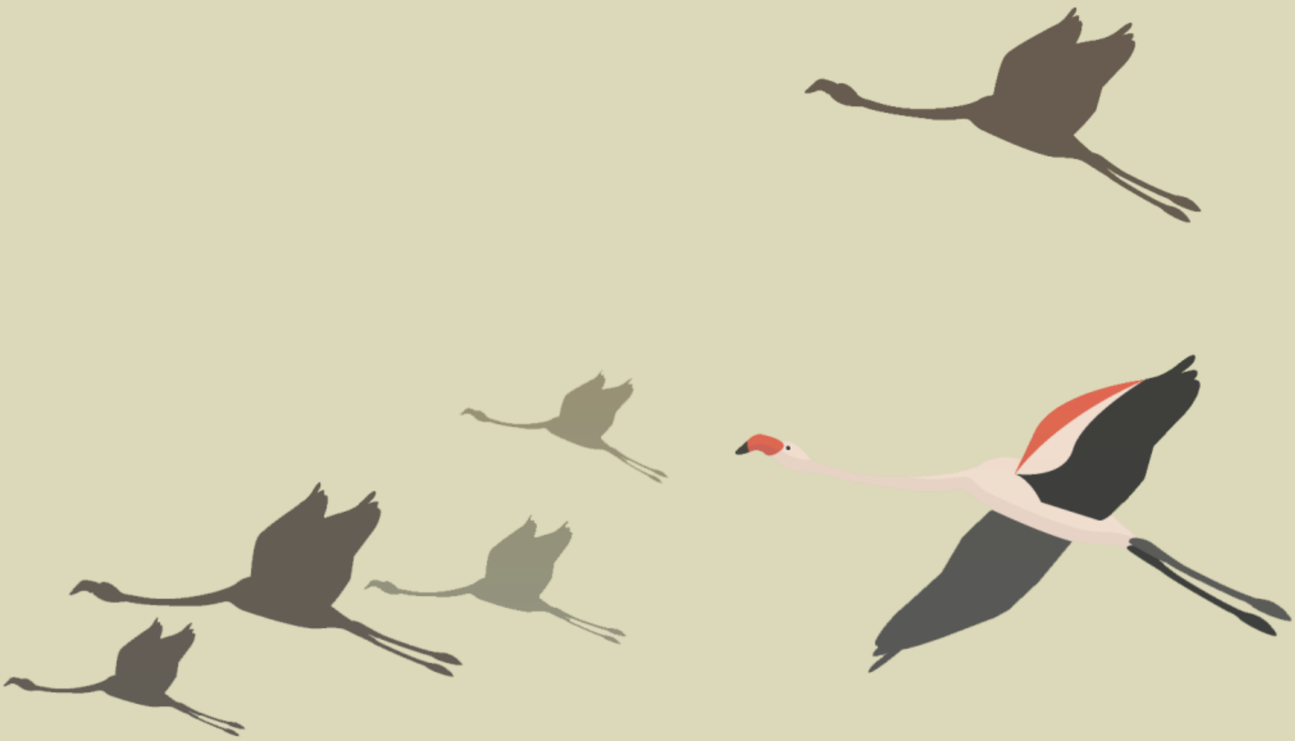


A. Adaptive management of Andalusian Mediterranean pine forests in face of global change

Current Issues

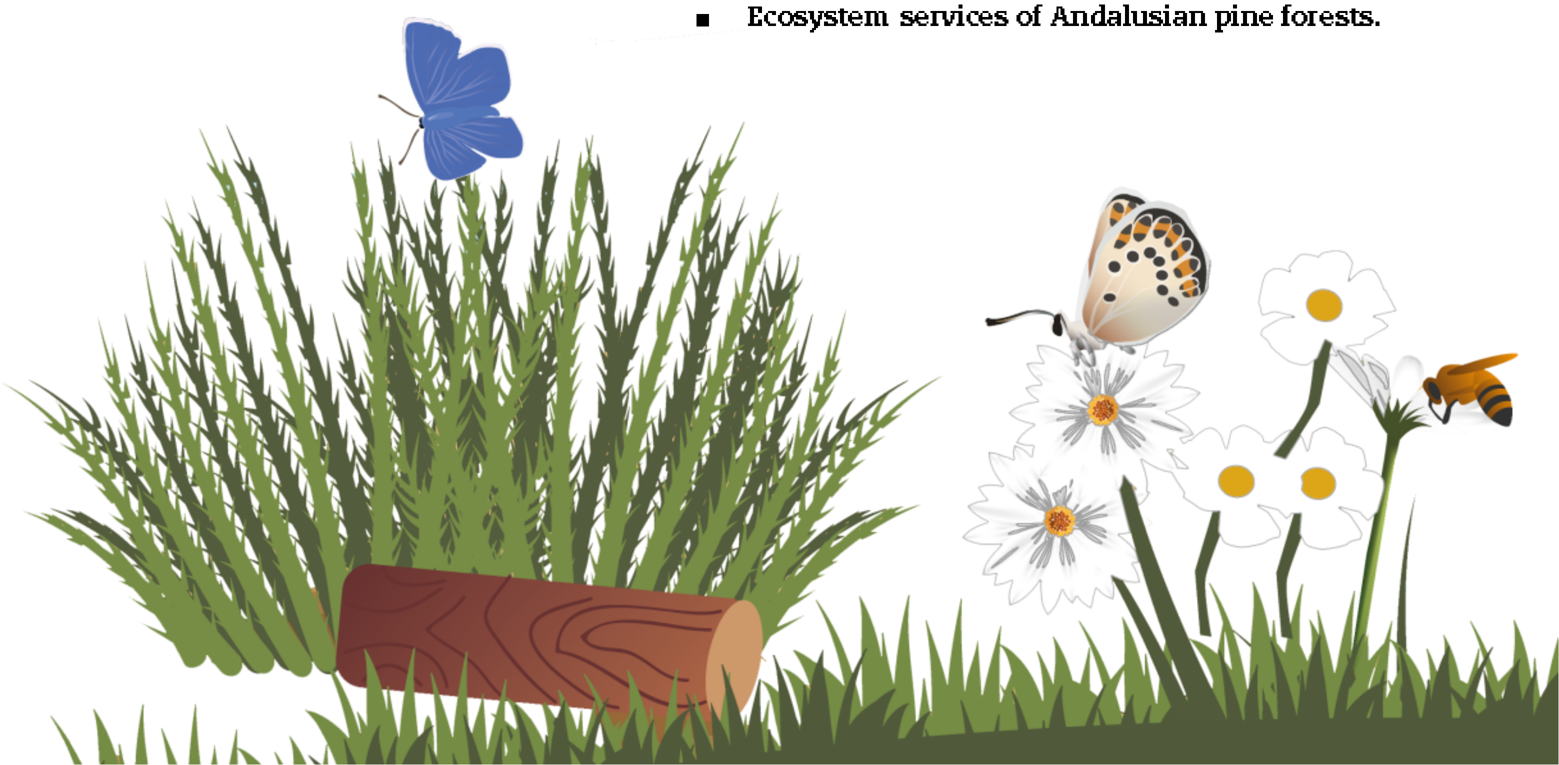
- The Andalusian Mediterranean pine forests group together a varied range of forest stands characterised by different species of pine, of both natural and artificial origin, which vary greatly depending on the local conditions of soil, altitude, sunshine and rainfall.
- Within this group, afforestations with pine species dominate, which are artificial stands at different stages of ecological integration, characterised by a high degree of homogeneity due to their coetaneity and regular distribution. These formations have a low structural diversity, often with little or no undergrowth and a homogenous understorey. Low biodiversity constrains the functionality of the ecosystem as well as its adaptive capacity, increasing its vulnerability to the effects of climate change.

Vulnerability

- The main threats are imposed by climatic variations related with recurrent droughts and the occurrence of extreme phenomena. All this contributes to outbreaks of major fires and the spread of new pests and emerging diseases.

Provisioning Services	Regulating Services	Cultural Services
Pine forests have always been a major source of resources, mainly raw materials and fuels. Main provisions are timber, firewood, resins, mushrooms, pasture, livestock and hunting production.	Are those that constitute immaterial services that derive into direct benefits for society. These include the fixation of atmospheric CO_2, the improvement of air quality and the generation of oxygen, the regulation of the hydrological cycle and the prevention of soil loss.	Consisting of intangible services associated with the human valuation of these services. They include recreational and leisure use, as well as a wide range of practices related to scientific and educational activities.

■ **Ecosystem services of Andalusian pine forests.**



Best management practices: adaptive forestry

1 Adaptive forestry to climate change is defined as a set of initiatives and measures aimed at reducing the vulnerability of forest ecosystems, ensuring their conservation, increasing their resilience, and safeguarding the provision of ecosystem services in the face of scenarios of change. The most general schemes define adaptive forestry actions along a gradient of intervention, including, from no-action, resistance, resilience to transformation.

2 Adaptive forestry in pine forests must combine the principles of classical forestry such as persistence, perpetuation and improvement of forest systems, guarantee of ecological and economic sustainability of management, multifunctionality and maximisation of services and goods, with the difficulties inherent to the adaptation of forest systems to climate change.

3 Adaptive silviculture of pine forests involves the reinforcement and conservation of natural stands together with the naturalisation of afforestations, seeking to reduce the density of trees when this is excessive by means of medium and high intensity thinning, provided that the stability of the stand allows it, in order to increase the structural heterogeneity and resilience of the remaining trees.

4 Carbon forestry refers to those actions that aim to optimise the carbon sequestration of forest ecosystems within sustainable forest management, which allows for achieving mitigation objectives of the ecosystem. An indispensable element for achieving the mitigation objective of an ecosystem is to know the carbon stocks present.

5 Adaptive forestry needs ecophysiologically based models, including key aspects such as biomass and biodiversity, in order to design management scenarios that, incorporating today's complex objectives of multifunctionality and protection of ecosystem services, together with existing uncertainty, can guide its actions.

6 The structural weakness of Mediterranean pine stands constrains any measure. Although silviculture indicates how to carry out thinning cycles for different species, the initial situation of a stand may make this approach inadvisable. For all these reasons, we consider necessary to implement adaptive silviculture based on flexible treatments, both on temporal and spatial scales, aimed at increasing the strength of the trees and their capacity to cope with pests, diseases and episodes of water stress or other types of pressures.

Conclusions

- Adaptation of Mediterranean pine forests, as a programmed and anticipatory activity, should not aim to perpetuate the current state of the system. It should provide a state in which the forest structure is as well adjusted as possible to the new environmental conditions, conserving adequate functioning and guaranteeing, as far as possible, the provision of the associated goods and services.

- To this end, adaptive silviculture is proposed, defined along a gradient of intervention, aimed at resistance, resilience or even forest transformation where necessary, based on the analysis of the particular conditions of each forest type system and taking into account aspects such as management objectives, structure, dynamics and functionality when designing treatments. Ecophysiologically based models allow thinning to be designed to improve the balance between water availability, carbon sequestration and soil protection, taking into account current and future scenarios.

b. Cork oak and Mediterranean scrubland formations of Doñana

- **Promote the development of forests that are more structurally and spatially heterogeneous, more diverse in specific composition and less vulnerable to disturbances.**
- **Facilitating recruitment through priming actions in favourable locations (availability of water and soil), the use of nurse structures and reducing overgrazing.**
- **Apply adaptive actions, designed to obtain feedback and address existing uncertainties, with clear objectives evaluated periodically, based on the results of a monitoring programme.**

1 Promoting heterogeneity and diversity

In order to enhance adaptation of forest ecosystems to climate change and reverse the historical processes of degradation, ecosystemic management is necessary. Management should focus on the increase of heterogeneity and diversity of the forest elements and its associated flora and fauna that both depend on the forest and, at the same time, sustains it by providing essential services. Open forestry, close to nature, which promotes natural processes, avoids major works and replaces it with less impacting and more flexible actions to unfavourable conditions, favours its intrinsic potential and enables essential adaptive responses to make forest ecosystems less vulnerable.

The aforementioned heterogeneity should be understood in a broad sense, including a diversification of ages, structures and types of reproduction; as well as the promotion of species and microhabitat diversity, associated with a wider range of regulated uses to ensure the sustainable provision of different ecosystem services. This requires renouncing the application of classical forestry criteria focused on favouring homogeneous stands in terms of spatial distribution, structure, size and age composition; and critically reconsidering some traditional uses (such as livestock and beekeeping), adjusting their extent and design to the carrying capacity of the ecosystems.

2 Facilitate recruitment

A key element to reverse the historical processes of degradation of the cork oak forest and fully developed scrubland in Doñana is a forest management focused on the safeguarding of recruitment and natural rejuvenation of the tree layer, promoting the longevity of the reproducers still present and the generation of heterogeneity in the shrub layer. This facilitates the creation and occupation of forest recruitment niches. To this end, it is essential to reduce herbivory pressure, through a combination of short-term local measures (exclosures to favour the creation of recruitment 'hotspots' and 'islands of diversity', applying selective plantations) and others of longer duration and scale (reduction and/or rotation of livestock pressure, combined with proactive management of wild ungulate populations based on demographic models and herbivore plant dynamics). These practices can be complemented by the development of more detailed techniques for selective plantations, incorporating the identification of microhabitats and periods favourable to recruitment and identifying appropriate structure and/or nurse plant designs.

3 Apply adaptive designs

Collaborative active management (adaptive co-management) establishes a management setting that accepts the uncertainties inherent to decision-making in the management of natural resources and processes. To this end, it explicitly frames its decisions within a structure of shared learning, based on the continuous evaluation and generation of knowledge. The aim is to establish a dynamic management that allows for the evaluation of continuously updated results and choose between the most robust alternatives, avoiding interventions that may trigger non-return effects, and explicitly seeks to combine efficient action with effective learning.

Establishing adaptive management processes involves introducing procedures that facilitate learning, understanding and constructive collaboration by and between all stakeholders. Decision-making processes should therefore be participatory and should be supported by procedures that ensure transparency and equitable access by all stakeholders to all available knowledge and data.

c. Control of *Phytophthora cinnamomi* in cork oaks (*Quercus suber*)

- **Take measures to prevent their spread from affected areas, within a management framework that builds resilience to disturbances and the impact of climate change.**
- **Use control measures adjusted to the characteristics of the forest cover, including trunk-injected Fosetyl-Aluminium applications to reduce the impact on affected trees.**
- **Maintain a monitoring programme to identify new outbreaks of infection and regularly evaluate the actions taken within an adaptive management framework.**

1 Prevent spreading and increase resilience

Climate change increases the incidence and impact of pests and diseases such as the oomycete *Phytophthora cinnamomi* infections of the cork oak, a key species in Mediterranean forest formations. As many of pests and diseases mutually favour each other, the vulnerability of current forest formations is multiplied. The control and spread of *P. cinnamomi* starts with an accurate mapping of its local distribution. In affected areas, soil tillage should be avoided, good soil drainage should be ensured and high stocking rates should be avoided. In addition, the movement of people, vehicles, machinery and animals from areas where *P. cinnamomi* is present should be limited. For this purpose, access must be done after cleaning (disinfestation) of footwear, tools, and wheels of vehicles and machinery. Finally, in general, in any forest area, materials used for restauration and plantations, including plants and root balls, must be free of this pathogen, as well as any other exotic species. For this reason, sowing instead of planting should be considered in sensitive areas.

These control measures should be framed within an ecosystemic management based on increasing heterogeneity and diversity of forest formations, which is essential to enhance resilience to disturbances. Heterogeneity should be understood in a broad sense, including the spatial, vertical and age structure diversification of different forest species, while increasing the diversity of species and associated habitats. Forestry that stimulates heterogeneity and natural processes, coupled to a range of uses that carefully respect the sustainability of ecosystem functions and services, will result in a greater adaptive capacity of forest ecosystems to face unfavourable conditions and enable adaptive responses essential to reduce their vulnerability to diseases and pests.

2 Control measures with fosetyl-aluminium

Control of *P. cinnamomi* is complicated due to the longevity of its resistant spores in soil and the fact that low inoculum densities in soil (>61 cfu/g) are sufficient to produce infections that trigger disease symptoms when environmental conditions are suitable. Trials with Fosetyl-Aluminium injected directly into the trunk have given positive results. This treatment does not prevent possible infection of the roots, although there are indications that it may reduce the incidence in the rhizosphere and increase the natural defence mechanisms of the tree, inhibiting the growth of the pathogen. Treatment needs to be accompanied with monitoring to assess the long-term effects, which are currently unknown.

3 Regular monitoring and follow-up

Monitoring of the health condition of cork oaks can be based on regular assessment of leaf condition and mortality of a representative sample of individuals. Identification of the presence of *P. cinnamomi* should be carried out using regular soil and root sampling, allowing detection by laboratory culture. This monitoring should represent an essential element of prevention and control actions for this exotic pest, using it proactively to evaluate and refine these actions, improving their effectiveness and correcting unexpected or counter-intuitive effects. To this end, we recommend including such actions in an adaptive co-management framework, which establishes a management method that accepts the uncertainties inherent to decision-making and introduces procedures that facilitate learning, understanding and constructive collaboration by and between all stakeholders.

d. Management of Z. lotus shrublands: a groundwater-dependent ecosystem

Conservation problems

Z. lotus is a shrub native to the arid zones of the Mediterranean basin, whose northern limit is mainly in the Arid Iberian southeast and the semi-arid plains of Cyprus and Sicily. It is an ecosystem engineer species that gives rise to scattered shrub thicket formations (wild jujube matorrals), considered by the European Commission as a priority habitat for conservation (5220*). This priority status is due to its reduced range and distribution area within the Natura 2000 Network, the current pressures and threats on the habitat, and the relict character of *Z. lotus* in the European continent.

Z. lotus formations have experienced a significant decline in recent decades throughout arid areas of Europe. This decline is particularly relevant in the southeastern Iberian Peninsula, where land-use changes threaten the most important populations.

1. The expansion of intensive agriculture and urbanisation in the range of wild jujube matorrals has led to an extreme reduction and fragmentation of the habitat, which currently occupies only 5% of its potential area in the southeastern Iberian Peninsula. This pressure is of particular importance since research showed that it reduces the arrival of pollinators, the dispersal capacity of propagules, the number of adult reproductive individuals and the availability of appropriate sites for recruitment. In addition, overexploitation of aquifers is altering the groundwater bodies on which the habitat depends. Along with these traditional pressures, the development of large tracts of solar platforms can pose a serious threat, just where they have not been occupied by intensive agriculture.
2. The synergy between climate change and land-use changes poses a severe threat to this ecosystem due to its nature as a facultative phreatophyte. Increasing summer temperatures impose higher transpiration rates on the plants. In addition, the groundwater extraction for agriculture and the torrential rains are reducing the recharge of the aquifers. Finally, as the soil dries out, wild jujubes are forced to mobilise more water from the deep layers of the vadose zone or even from the aquifer, which implies less nutrient mobilisation and less capacity for the soil microbiota for nutrient cycling. These processes affect the ability of *Z. lotus* patches to act as islands of fertility islands in the arid landscape matrix.
3. Biological invasions can be relevant in some ecosystem locations, such as the coastal plain of the Cabo de Gata-Níjar Natural Park, the main remnant of the ecosystem in Europe. In this area, the old industrial crops of *Agave sisalana* and *A. fourcroydes* show an invasive behaviour in the sandy areas. The result is a profound modification of the ecosystem structure and the desiccation of the most superficial soil layers, directly affecting the diversity and abundance of steppe fauna and short-rooted scrub species. Furthermore, other invasive species such as *Pennisetum setaceum* and *Lantana camara* have been described in wild jujube matorrals of Sicily and Cyprus, which shows the risk of biological invasions in the biogeographical region.

Management recommendations

To advance in the protection and enhancement of wild jujube matorrals resilience and the ecosystem services they provide, we propose management actions that integrate the knowledge acquired during the project's development, and the research carried out by the scientists.

1 Groundwater dependence

Identifying phreatophyte vegetation in the absence of surface water is particularly difficult. This difficulty contrasts with the urgent need to protect groundwater-dependent ecosystems in arid zones. We have shown that *Z. lotus* is a facultative phreatophyte that determines the whole ecosystem's structure and function. Thus, maintaining groundwater integrity is critical for preserving this ecosystem of conservation concern (habitat 5220*). In this regard, we have to consider management and conservation plans within the framework of the European Water Framework together with the Habitat Directive. These plans should be extended beyond the Cabo de Gata-Níjar Natural Park boundaries to guarantee the integrity of the ecosystem in its whole range. Furthermore, it is urgent to characterize the degree of dependence of the aquifers on the remnant patches that persist in the southeastern Iberian Peninsula to establish appropriate aquifer management measures in an area with groundwater overexploitation.

2 Reforestation actions

The overall survival rate of the seedlings planted during the project has been relatively low, directly related to the arid conditions and the plants' difficulty accessing groundwater, mainly during the summer. Nevertheless, the moderate survival rates of *Z. lotus* seedlings in the first year indicate that their irrigation during the first summer was favourable, although not enough to acquire the necessary root biomass at depth to reach deeper and wetter soil layers. Therefore, we propose that in future plantings of *Z. lotus*, seedlings of at least three years old with well-developed roots should be selected. In addition, they should be planted at a depth of at least 15 cm to minimise the effects of desiccation of the first soil layers, facilitate reaching moist layers, and periodically remove seedlings that emerge in their vicinity to avoid competition. This procedure will require many resources to carry out a plantation with these characteristics and a more controlled subsequent maintenance (eliminating competing seedlings and summer irrigation).

3 Removal of invasive species

The mechanical extraction methods used to eliminate agaves have been very effective due to their low cost and the rapid recovery of the scrub and grasslands after the intervention with heavy machinery. However, once this action has been carried out, it is essential to focus on the medium and long term control of the resprouting of invasive species. The monitoring actions indicate that the most effective propagation mechanism for the invasion of *A. fourcroydes* and *A. sisalana* is the production of shoots from rhizomes and stolons, which re-colonize the gap left by the adults-only one year after their removal. Accordingly, medium- and long-term efforts to control the invasion should focus on eliminating such shoots rather than on removing prominent reproductive individuals (as they will die after flowering) or collecting bulbils (very unlikely to root and survive in such arid conditions). Furthermore, the recovery of fauna (birds and soil insects) almost immediately after removing the agaves justifies that controlling these invasive species represents an appropriate management technique for the ecosystem.

4 Maintain and create islands of biodiversity to support sustainable agricultural production

We have found that *Z. lotus* thickets harbour an important diversity of insects beneficial for agriculture throughout the project. Accordingly, it may be instrumental in revealing to the local society this critical ecosystem service to create and maintain habitat patches in an area where agricultural expansion represents a persistent threat. Indeed, in the canopy of the shrub formations, we found a high abundance of species valuable to combat the most common agricultural pests in the area, such as the flower thrips (*Frankliniella occidentalis*) and the whitefly (*Bemisia tabaci*). This fact implies that the maintenance of natural vegetation islands with *Z. lotus* among the agricultural landscape constitutes a powerful ecological tool that improves, in the long term, the natural biological control and ultimately reduces the entry of pests inside the greenhouses.

5 Narratives of ecosystem services for the valorisation of the ecosystem by society

The experience gained in the identification and dissemination of ecosystem services provided by wild jujube matorrals from the study of the functional characteristics of *Z. lotus* leads us to propose the promotion of ecosystem narratives based on research and the transfer of scientific knowledge as an essential measure for ecosystem conservation in a highly anthropised landscape. Furthermore, outreach actions can help understand the importance of preserving habitat 5220. An example of this is the "climate change route" that we have created within the project framework, a trail with information on the functions and services of the wild jujube matorrals that run along the coastal plain of the Cabo de Gata-Nijar Natural Park. This trail shows the value of *Z. lotus* as an indicator of the impact of climate change on aquifers. It has been well received by local ecotourism companies, which are already operating it.

E. Soil management and conservation in arid zones to ensure the provision of key ecosystem services

Conservation issues

The capacity of soils to provide ecosystem services depends on the environmental controls acting on the territory and management decisions. These decisions are critical in arid areas, where poor soil management leads to severe desertification—on the contrary, efforts to recover degraded areas can positively impact climate change mitigation. Given the enormous global importance of drylands, it is essential to understand how dryland soils respond to these types of decisions.

A key aspect of understanding the role of soils in the provision of ecosystem services is understanding the effect that ecological and socio-cultural processes have on essential ecosystem functions, such as regulation of the hydrological cycle, carbon sequestration, or maintenance of biodiversity. This fact implies exploring the role of the rhizosphere and microorganisms and the presence of soil conservation structures, such as dry stone walls ("balates"), tillage, or plant cover planting, on these functions. Vegetation cover and distribution significantly impact the spatial variability of soil organic matter. On the other hand, soil structure and texture are among the main controls on its water retention capacity. The developed actions were designed to assess the effects of three management decisions in arid zone crops (restoration of crop terraces, low-intensity tillage, and planting of green covers) on the provision of critical ecosystem services (soil carbon storage, water availability for plants, and habitat maintenance for biodiversity) in arid zone crops: restoration of crop terraces, low-intensity tillage, and planting of green covers. Such experiences can lead to the design of new and better management practices for traditional Mediterranean agroecosystems, both to increase their role in climate change mitigation and to develop cultivation practices that require less water and contribute to the maintenance of biodiversity.

Halting and reversing soil degradation is a priority for the transition to sustainability, but this requires various approaches appropriate to the type, extent and degree of soil degradation. Abandoned crops represent, in this sense, an element of the landscape managed to ensure the maintenance of essential ecosystem functions and services. For example, after agricultural abandonment in mountain areas of arid zones, there is a degradation of the stone walls ("balates") that support the crop terraces, resulting in soil degradation processes that may become irreversible. On the other hand, once the slopes have been stabilized, there are processes of scrubland stabilization that can increase the carbon stored but, on the other hand, decrease the soil's water recharge capacity. Conversely, the conversion of natural areas to rainfed crops increases water recharge but reduces carbon storage, while irrigated crops lessen the provision of both services.

Management recommendations

1 Restoration of stone walls ("balates") of former cultivation terraces prevents soil degradation and monitoring indicators.

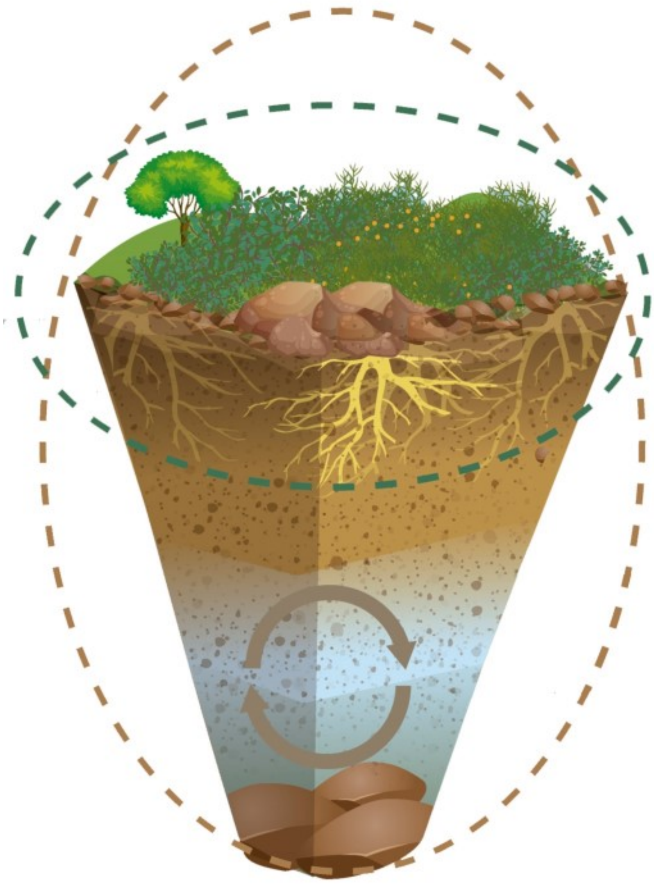
Balates are retaining walls built in dry stone to create terraces irrigated by gravity or flooding. They also serve as a defence against runoff and soil degradation and a refuge for fauna in their hollows. The work carried out shows that the reconstruction and maintenance of these swales improve soil conditions by controlling erosion, promoting the accumulation of organic matter and soil biological activity, and increasing its carbon sequestration capacity. This improvement was observed in spatial comparisons (areas with swales vs without swales) and temporal comparisons (before and after swale restoration). On the other hand, we propose an indicator for monitoring these improvements in soil condition, which is derived from the annual dynamics of soil respiration. We have verified that degraded soils show little difference between the maximum yearly peak of soil respiration and the minimum. On the contrary, well-conserved soils show high seasonal differences for this indicator (significant differences between the top and minimum peak soil respiration).

2 Low-intensity tillage and green cover planting

The tillage actions show that this soil management practice affects the redistribution of soil pores, resulting in an improvement in the soil's water storage capacity. In addition to the positive impact of this action on the water regulation function, tillage, even at low intensity, leads to the mineralization of organic matter. Therefore, this management action leads to a decrease in soil carbon stock (reducing its contribution to climate change mitigation), at least in the short term. Therefore, when the management objective is the maintenance of crops for food provision, this action is very relevant. However, tillage maintained over time can lead to degradation processes. On the other hand, to recover the biological activity of soils after tillage, we tested the planting of cover crops. These covers mineralization of organic matter can enhance the carbon, nitrogen, and phosphorus cycles. However, the plant input must be more intense for this to occur.

3 Revealing the contribution of protected areas to climate change mitigation through soil conservation

Protected areas represent 12% of the land surface and are usually conceived as the best biodiversity and landscape conservation tool. Despite this extension and being a critical piece in the conservation policies of the countries, they are rarely considered a means to combat desertification or advance towards neutrality in soil degradation. As we have seen, well-conserved soils in protected areas can help mitigate climate change by zoning appropriate uses and restoring structures that prevent soil degradation and maintaining healthy ecosystems. This role of protected areas is even more relevant in the case of arid areas, such as the Cabo de Gata-Níjar Natural Park. Dryland soils contribute significantly (approximately one third) to global biodiversity and soil organic carbon stocks and can contribute significantly to global food production and climate change mitigation. Furthermore, these soils are precious for carbon storage due to their high carbon residence time.



F. Adaptive management for the protection of ecosystem services under climate change in Mediterranean high mountain shrublands.

Conservation issues

The juniper shrubland of Sierra Nevada have been subjected to various types of anthropic disturbance for centuries, causing a regression in their distribution area. These alterations have caused a considerable reduction and fragmentation of the distribution area of juniper in Sierra Nevada, aggravating its regeneration problems in the current context of climate change. The objective set within the framework of the Life Adaptamed project has been the recovery of high mountain juniper habitat. The planned restoration actions are based on knowledge of the natural regeneration of juniper in high mountains (nature-based solutions) and on traditional land uses, using traditional irrigation channels to consolidate and expand juniper populations in the high mountain .

Management recommendations

We concluded from our data that any management involving burning or clearing juniper scrub in the high mountains of Sierra Nevada result in bare soils for many years, even for several decades, after the disturbance. The arid Mediterranean summers, exacerbated during the last few decades due to longer drought episodes, has practically collapsed the regeneration capacity of the junipers, diminishing its distribution area in the high mountain area of Sierra Nevada along with clearing and burning events. Current climatic limitations also hampers attempts to actively restore junipers. Fires and clearings of junipers additionally generate the loss of vegetation cover, increased soil erosion, as well as an decrease in the diversity of endemic herbaceous species. Where a juniper tree disappears, in the best case scenario, dwarf scrubs appear, with a significant loss in the provision of certain ecosystem services of the high mountains. Therefore, the most effective and least costly way to conserve and manage juniper groves and their traditional provisions is to conserve those that still exist rather than to attempt to recover those that have already been lost, especially in the current context of climate change.

The dry summers, characteristic of the Mediterranean climate, make active restoration of junipers very difficult. Any project of this type must take into account that, although the viability of seeds in natural populations is very low and seedlings are very sensitive to summer drought, their survival capacity increases considerably when they overcome the bottleneck of the first years of life. Therefore, given the climatic uncertainty, we recommend plantations to be carried out both with seeds, which allow to carry out a considerable number of sowings in a wide range of microhabitats without the need for prior soil preparation, and with seedlings, which have a greater survival success than sowings, but are much more costly to obtain. In the latter case, restocking should be done with well-developed seedlings that have well lignified stems. Such seedlings are difficult to obtain in high numbers from nurseries, adding additional complications for restoring actions.

If sowing is done in an exceptionally rainy year, germination and seedling establishment success obtained will be high. Nevertheless, if the year is dry or very dry (as is becoming increasingly common), germination success and seedling survival will be very low or non-existent. In these same dry climatic conditions, planting seedlings in suitable locations and with a water-holding bench will give better results than sowing seeds. Planting should be done in autumn, after the first rains and before the ground begins to freeze. Seedlings should be transported with a root ball for planting in high mountain microhabitats where survival is most likely, particularly suitable are bases of boulders and sites near watercourses. We do not recommend planting in spring, because the transition from winter to summer is very fast in high moun-

tain areas and the soil dries out very quickly, so seedlings do not have time to develop their root system and die. Seed sowing, on the contrary, can be done in spring or autumn, although when done in autumn we replicate the natural phenology of seed dispersal.
The old mountain ditches can play an important role as avenues for the reforestation of juniper groves, creating a mosaic of "restoration windows" on the mountain slopes. However, livestock pressure should be regulated over a number of years in the restored areas along the ditches. An excess of livestock leads to massive mortality of seedlings through trampling. Nevertheless, an absolute exclusion of herbivores by fencing encourages excessive grassland growth, especially in the wetter areas, which could eliminate juniper seedlings competitively.

As we can not foresee what the weather will be like in the year of the planting action nor that of the following years, our recommendation is: 1) to sow and plant in the best microhabitats of the high mountain (under rocks, under junipers and next to irrigation ditches); 2) to sow and plant several years in a row, in order to increase the probability that at least part of the sowing and planting will occur in a year of favourable weather. This obliges us to plan restoration actions in the long term. Planning should include both the provision of an adequate quantity of seeds and nursery plants, and the necessary monitoring of the sowing and planting success in the field.
Once sowing or planting has been carried out, it is essential to carry out periodic monitoring to determine the causes of seedling mortality, especially those that can be controlled.

Summary of recommendations

Based on our knowledge of the ecology of the junipers of Sierra Nevada, we offer several basic recommendations for the conservation and restoration of junipers under current climatic conditions:

1. Strict conservation of the juniper populations and individuals (*Juniperus sabina* and *Juniperus oxycedrus*) that still exist in the high mountain areas. The extreme longevity of the individuals guarantees the persistence of the populations in the current hostile climatic environment, as long as the established junipers are conserved. This recommendation is incompatible with additional clearing actions for tracks or ski slopes, which would require the uprooting of junipers.

2. Maintenance of the traditional "careo" (herding cattle) ditches to provide additional soil moisture during the summer to help the regeneration and natural expansion of the juniper groves and their associated plant community. The "careo" ditches act as true green infrastructures in the high mountains, favouring the regeneration of juniper throughout Sierra Nevada.

3. Monitoring of the conservation status of juniper-scrub groves of Sierra Nevada, their altitudinal expansion dynamics and their capacity to occupy new plots such as abandonned cultivated terraces, tracks or ski slopes, using remote sensing in combination with in situ field assessment. Such monitoring should be carried out along the entire altitudinal gradient of the juniper groves and on all slopes of Sierra Nevada, focusing on the upper altitudinal limit, which is where the least information is currently available and where climate change may have the greatest impact.

4. Strict conservation of bird species that disperse juniper seeds, especially in the current situation where their populations are severely reduced compared to 30-40 years ago. Any human activity that drives these birds away during their short stay in the juniper groves of Sierra Nevada must be avoided.

5 Implementation of restoration actions with long-term planning and monitoring of the results following an adaptive management model that allows us to learn from the results obtained. These actions should consider the need to carry out sowing and planting for several years in a row, expecting at least one climatically favourable year. The information obtained, together with all the scientific information already available, will allow us to design and develop a decision support tool similar to the one we have already developed for the management of pine reforestation in Sierra Nevada (**diveRpine** (*Diversification of Pine plantations* https://ajpelu.github.io/ 910 diveRpine/).

6 Both sowing and planting activities, as well as the monitoring of dispersing birds, can be incorporated into citizen science projects that serve to involve society in the conservation problems and impacts that threaten the juniper groves in Sierra Nevada.

7 Actions for conservation and restoration of the juniper groves in Sierra Nevada must be done within a collaborative platform that, based on the transfer of scientific knowledge, promotes joint design, learning and participation, bringing together the efforts of environmental managers and technicians, researchers and citizens.

8 Communication and dissemination actions should be developed to inform the public about the uniqueness of these high mountain ecosystems, the importance of their conservation and the necessity to invest resources in their management and protection.

G. Recommendations for the management of the oak groves of Sierra Nevada

Impacts of global change and conservation issues

- In the past, oak forests have suffered intense anthropic pressures that have led to a reduction in their distribution area, their floristic composition and the modification of their structure due to shrub encroachment. At present, these formations are highly vulnerable to climate change in the warmer regions of their distribution area. We share the hypothesis that oak and holm oak forests have to adapt to new climate change scenarios, in a context of abandonment of traditional silvicultural practices. To this end, we propose to focus forestry to pursue an increase in heterogeneity and diversity of oak forest as the key to achieving the purpose of adaptation.

- If we want to ensure the future of oak groves, we will have to manage them actively, under sustainability criteria, facilitating their adaptation to new climatic conditions. For example, under the assumption of more frequent drought episodes, a less dense oak grove (with fewer trunks per hectare) will be more resilient, since trees and plants will compete less for resources such as water. In contrast, increasing the resilience of these formations will require practices that favour biodiversity, both interspecific and intraspecific. Adaptation actions must be considered, but without losing sight of the fact that the situation of many oak forests is the result not only of changes in climate, but also of anthropogenic changes and their interactions. A first step in planning management actions is the identification and assessment, in a scientific context, of the different impacts of global change on oak forests.

- **It is especially important to pay attention to:**

Droughts

To assess how droughts are affecting growth, production and survival of stands. In the case of Sierra Nevada oak forests, it has been observed that, due to their location, they are highly resilient to drought events.

Wildfires

The abandonment of oak stands management increases the risk of fire, due to the accumulation of horizontal biomass (shrub encroachment), which is particularly important in this species due to its excellent regrowth capacity. In addition, the promotion of recreational activities (cultural services) may lead to an increased risk of accidental fires.

Pests and emerging diseases

Many oak and holm oak stands may be affected by the proliferation of pests and diseases due to rising temperatures. Identification of defoliator and gall insect communities in the oak forest is a key step in assessing the health status of forest stands.

Phenological changes

Different ecological processes are modifying their phenology due to the increase in temperature. It is important to study changes in the flowering and fruiting phenology of oak groves in order to be able to diagnose their reproductive capacity, and therefore their potential for natural regeneration.

Changes in the composition of communities

The plant and animal communities associated with oak and holm oak forests change according to seasonal qualities, its state of development and the evolution of the stands that generally provides shelter for a large number of species of flora and fauna. The resulting forest must provide adequate vegetation cover, without excessively large clearings, nor being too dense, which would diminish its vitality due to competition between trees, as well as increasing risks of wildfires.

Management recommendations

Adaptive management of oak forests should seek three broad objectives: to ensure their functionality, to provide goods and services, and to increase their resilience.

1 The role of oak and holm oak forests as **carbon sinks** will be promoted. To this end, an attempt will be made to maintain an adequate biomass, both aboveground and on the ground, by increasing the basal area of the stand with as few individuals as possible. Thus, as an indication, final densities of 400-900 ind/ha are recommended, contributing to a basal area between 28-36 m2/ha. Low densities (close to 500 ind/ha) with high basal areas (above 30 or 35 m2/ha), which could correspond to a tall canopy, may imply a higher probability of regeneration by seeds, which in turn would increase the resilience of the stand in the long term. For this reason, actions should be aimed at reducing competition between trees and favouring the growth of individuals that are set aside, seeking their maximum vegetative strength and health.

2 In any case, the maintenance of **biodiversity** of the oak woodland will be encouraged. Thus, when carrying out silvicultural management, care must be taken to respect the associated plant species as much as possible, particularly the presence of individuals of other tree species (e.g. yew, holly, rowan, whitebeam, maple, etc.) as well as other shrub or herbaceous species. It is therefore not advisable to clear scrub. In addition, it is advisable to leave dead wood in situ, as it creates micro-habitats for numerous species that take direct advantage of it or use it as shelter. It has been proven that there are a large number of saproxylic fungi species responsible for the decomposition process of wood, lichens and mosses, as well as saproxylic insects, which are directly dependent on the existence of dead wood. Therefore, in case of natural disturbances such as wind, avalanches or wildfires, it is recommended not to remove fallen trees from the area. If the surrounding forest stands are in good condition, this dead wood does not represent any danger to the health of the forest, as most saproxylic insect species do not consume live wood. We propose forestry to focus on increasing heterogeneity and diversity of the oak forest through selective thinning combined with rejuvenation thinning. When designing management actions, it will be essential to use the available historical information, especially to select and protect the best stands for seed production. The intensity of actions will be adapted to the characteristics of each stand, favouring where possible the formation of forest patches and mixed stands.

Conclusions

- Silvicultural actions should be aimed at obtaining a forest formation diverse in species and ecological functions, as resilient as possible to the wide range of disturbances it may face in a scenario of global change (droughts, temperature increases, increased incidence of forest pests, fires, etc.). To this end, in general, a high specific diversity of tree and shrub species, reproductive stands that do not compete with each other and that can produce acorns, an irregular age distribution (where different cohorts coexist), with presence of coarse dead wood, as well as trees with good vegetative strength and an adequate phytosanitary condition should be promoted. In locations with a high risk of soil loss, the combination of sexual or asexual reproduction may be advisable (scrubland). Low scrubs provide an important service of erosion regulation due to its complex and dense root system that holds on and protects the soil, which is why it is recommended to conserve in the worst locations of slopes or areas with scarce soils.

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