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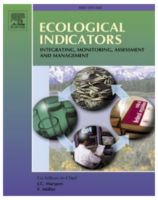

diveRpine: Diversification of pine plantations in Mediterranean mountains. An interactive R tool to help decision makers

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ABSTRACT

Forest plantations are an example of widespread land-use change shaping terrestrial ecosystems. They usually have high stand density, low tree diversity, and homogeneous structure. Their conversion into more natural forests, *i.e.* naturalization, to foment active regeneration, heterogeneous structure, high biodiversity levels, and high resilience to disturbances such as pests and fires, is urgently needed. More diverse and heterogeneous forest stands display greater resilience to global change, in addition to protecting the ecosystem services that mountainous pine-plantations provide.

We present *diveRpine* (**diveR**sification of **pine** plantation), an interactive application designed to show how the species richness (and therefore resilience) varies in pine plantations based on the mountain landscape configuration, the internal structure of the stand, and the composition of the dispersal vectors. The aim of the application is double. On the one hand, it would provide a guidance tool for natural resource managers that aid in the naturalization of forest plantations to recover the multifunctionality of these ecosystems. On the other hand, this tool could be a valuable teaching resource in ecology and conservation classes, since it has great value to explore virtual scenarios and demonstrate the process of prioritization of the management actions. The user can simulate different combinations and analyze how they would affect the tree-species richness in a specific pine plantation stand. It also allows the user to visualize some of the complex ecological processes that underlie the diversification of pine plantations in Mediterranean mountain areas. This tool provides a valuable aid for decision making, for example helping managers to decide whether or not to intervene in a certain pine stand, by projecting the most probable ecological succession under a specific scenario. Our diveRpine concept combining scientific rigor with simplicity of presentation and interpretation is applicable in any restoration context.

1. Introduction

Forest plantations are an example of widespread intensive and extensive land-use change shaping terrestrial ecosystems (Hobbs et al., 2006; Chazdon, 2008). To optimize the timber production, forest management typically focuses on growing even-aged, homogenous forest stands dominated by a few high-yielding and sometimes non-native species (Puettmann et al., 2009; FAO, 2010; West, 2014). However, such management can hinder other ecosystem services, such as carbon sequestration, soil protection, and aesthetic value, and can cause major losses in biodiversity (van Dijk and Keenan, 2007; Brockerhoff et al., 2008; Gundersen and Frivold, 2008; Edwards et al., 2012; Herbst et al., 2015; Triviño et al., 2015), and higher susceptibility to natural disturbances (Turner et al., 2013; Stritih et al., 2021). For instance, in Mediterranean Region, dense, monospecific pine plantations were originally planted to retain soil, but they now generate different ecological challenges, such as increasing the risk of high-intensity fire and hindering the development of native vegetation (Pausas and Fernández-Muñoz, 2012; Leverkus et al., 2019).

Converting forest plantations into more natural forests with active

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regeneration, heterogeneous structure, high biodiversity levels, and high resilience to disturbances such as pests and fires is urgently needed (Maestre and Cortina, 2004; Brockerhoff et al., 2008; Pejchar et al., 2008; Villar-Salvador, 2016; Lewis et al., 2019). In this respect, interest has surged in recent decades to restore monoculture afforestation, in an effort to foment biodiversity, the carbon sink capacity, and a greater resilience in the face of changing climates (Maestre and Cortina, 2004; Brockerhoff et al., 2008; Pejchar et al., 2008; Lewis et al., 2019; Stanturf and Mansourian, 2020, Chazdon and Guariguata, 2018). In a recent global synthesis using data from the world's major forest biomes, Hua et al. (2022) compared how the different forest restoration approaches deliver critical ecosystem services. They found that native forests consistently delivered better performance than plantations in the provision of three major ecosystem services (aboveground carbon storage, water provisioning and soil erosion control), with additional benefits for biodiversity. They also highlighted that the benefits of reforestation will be best achieved through the restoration of native forests rather than extensive plantation programs (Hua et al., 2022).

The role of planted forests as ecosystem services providers has attracted increasing attention (Brockerhoff et al., 2008; Brockerhoff et al., 2013; Bauhus et al., 2010; Vihervaara et al., 2012; Dai et al., 2017; Liu et al., 2018; Freer-Smith et al., 2019). Although the potential to enhance the ecosystem values of planted forests has been recognized for some time (Keenan et al., 1999; Lindenmayer et al., 2015), the need persists for developing tools and assessing frameworks to guide informed decision making (Zamora and Bonet, 2015; Sperry et al., 2019; Chazdon and Guariguata, 2018). Planted forests can be managed to be resilient ecosystems (Puettmann et al., 2013; Baral et al., 2016) that maximize the multifunctionality of the ecosystem services they provide (Bremer and Farley, 2010; Bravo-Oviedo et al., 2014; Cruz-Alonso et al., 2019; Freer-Smith et al., 2019).

From an applied perspective, it is critical to diagnose the natural recovery potential of a given plantation (García et al., 2020). Under suitable ecological conditions, the plantation can recover biodiversity and heterogeneity naturally (passive restoration) (Meli et al., 2017). On the contrary, if the ecological conditions are unsuitable, passive restoration will not suffice, and management actions will have to be taken to revitalize the naturalization process (Fernández et al., 2017). Here we present an interactive tool, **diveRpine** (*Diversification of Pine plantations*), which simulates the way in which species richness in pine plantations varies depending on the landscape, the internal structure of the plantation (past land uses, tree density), and the composition of the dispersion vectors (birds, mammals). This tool uses the information published in scientific journals in a synthetic and straightforward way, enabling the manager to visualize different scenarios and perform simulations based on solid field data interpreted in scientific contexts. The purpose of the application is to develop a decision-support tool that simulates the dynamics of forest ecological processes. The application projects the most likely ecological succession in each stand based on the ecological context, and visualizes the relative importance of the different ecological mechanisms involved in the process. The resulting scenarios help the manager to identify forest stands that most need intervention (active restoration), compared to other stands where intervention is unneeded (passive restoration). Thus, diveRpine enables the user to answer key management questions such as: What variables should be taken into account to naturalize plantations? When is it worth acting to naturalize pine plantations?.

Our work provides a comprehensive view of a diverse range of ecological implications of changing from a monospecific forest plantation to a more diverse forest structure, highlighting the broad ramifications of resulting biodiversity and ecosystem services (Baral et al., 2016; Felipe-Lucia et al., 2018; Liu et al., 2018).

1.1. *Restoration of Mediterranean mountain pine plantations*

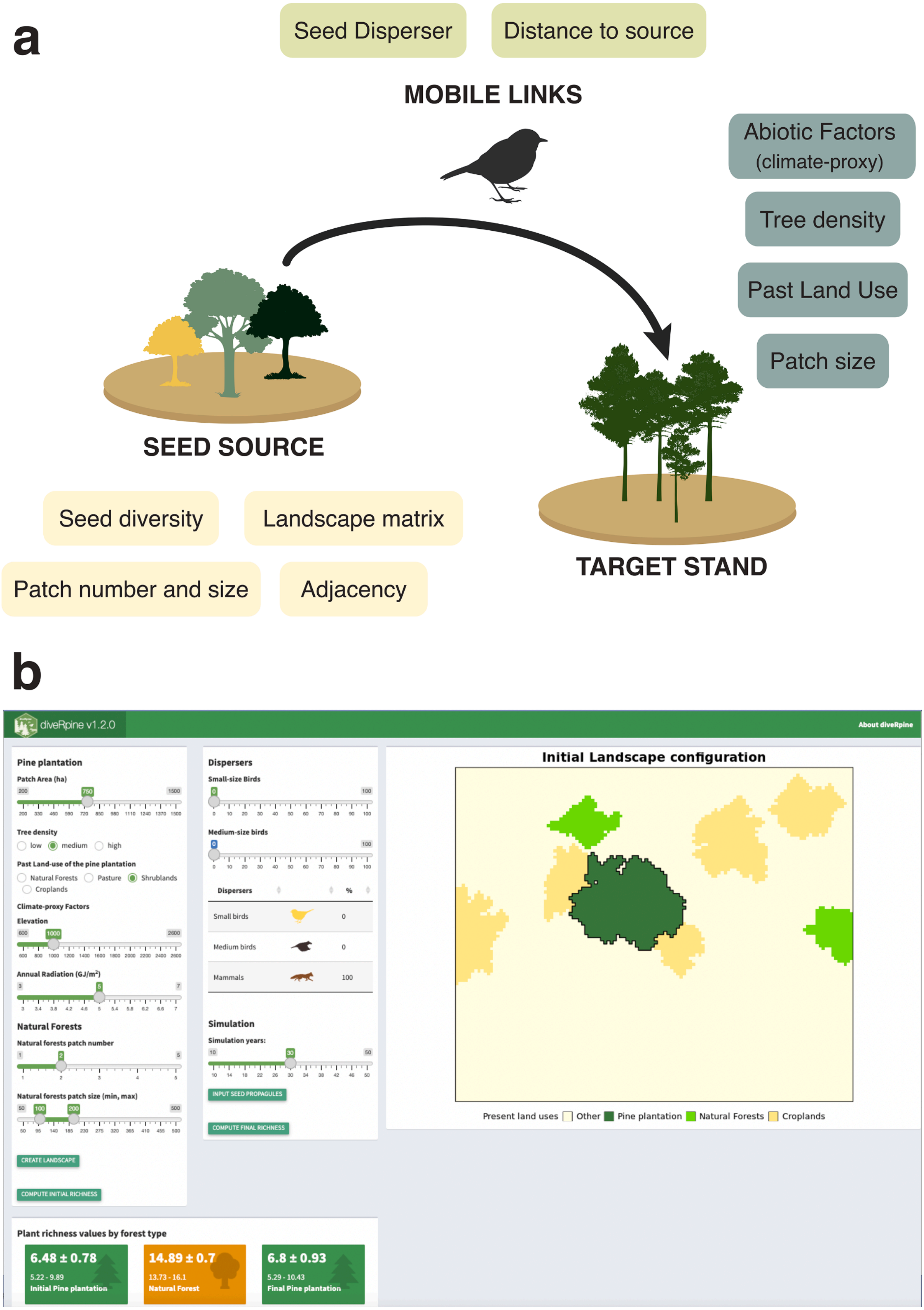
During the second half of the 20th century, many large reforestation projects were conducted in the south of Europe (Ortuño, 1990; Villar-Salvador, 2016). Several reforestation programs were undertaken in degraded areas where different pine species were planted (Pausas et al., 2004). This was particularly important for mountainous areas in which large areas were replanted with trees after the abandonment of croplands and pastures in habitats that could sustain extraordinary biodiversity and provide higher environmental quality (Gerard et al., 2010). Those afforestation efforts, focused on reducing erosion and increase the forest productivity (Pausas et al., 2004), resulted in huge areas of monospecific pine plantations which are prone to fires, diseases and drought dieback (Seidl et al., 2011; Villar-Salvador, 2016; Martín-Alcon et al., 2017).

However, in recent years there has been a need to diversify pine plantations in order to reduce their vulnerability to global change and to expand the provision of non-timber forest products (Miina et al., 2020). Several studies have demonstrated that compositional and structural diversification in forest stands bolsters stand stability under climate fluctuations and drought episodes (climate regulation; Linares et al., 2010; Choat et al., 2012; Morin et al., 2014). Similarly, greater structural heterogeneity strengthens resistance to natural disturbances such as wind and snow storms (Martín-Alcón et al., 2010; Jactel et al., 2017). The increase of compositional diversity (including genetic and phenotypic diversity) and structural diversity, fortifies resilience and functional redundancy in the forest and therefore a greater capacity to adapt to the environmental changes (Elmqvist et al., 2003; Paillet et al., 2010; Gamfeldt et al., 2013; Puettmann et al., 2013; Martín-Alcón et al., 2017 and references therein). The greater the diversity of functional traits in a forest, the greater the response capacity of the forest to disturbances (Sánchez-Pinillos et al., 2016).

2. The diveRpine tool

The application diveRpine was built using the R programming language (R Core Team, 2019), several packages (see https://ajpelu.github.io/diveRpine/articles/packages-used.html for a detailed list of the packages used), and Shiny technology (Chang et al., 2019). It simulates how the richness species comprising pine plantations varies depending on the landscape configuration, the stand structure and the composition of the dispersion vectors. The application consists of three conceptual modules (Fig. 1a) based on the concept of "mobile links" (Lundberg and Moberg, 2003) showing how species richness varies in pine plantations depending on: *(i)* the stand features (internal structure: land-use legacies, tree density; abiotic factors: climatic, topographical); *(ii)* the landscape configuration; and *(iii)* the disperser composition. The modules are supported by the results reported in scientific studies on pine forest naturalization and landscape ecology conducted mainly in the Sierra Nevada mountain (southern Europe) (*e.g.* Gómez-Aparicio et al., 2009, Matías et al., 2010, Zamora et al., 2010, González-Moreno et al., 2011, Navarro-González et al., 2013). We focus on the dispersion and recruitment of woody zoochorous plants, because they constitute a major component of Mediterranean woody flora whereas a large number of Mediterranean fleshy-fruited woody species are late successional (Herrera, 1995).

The establishment of the native forest species within pine plantations depends on both *in situ* land-use legacies as well as the distance to seed sources from remnant native forest fragments. In addition, other ecological factors intervene, such as internal spatial structure of plantation patches (Utsugi et al., 2006; Gómez-Aparicio et al., 2009; González-Moreno et al., 2011), vegetation type surrounding plantation patches (Hewitt and Kellman, 2002a; 2002b; Zamora et al., 2010), availability of seed-dispersal vectors (Zamora et al., 2010) or abiotic factors (Gómez-Aparicio et al., 2009; González-Moreno et al., 2011). The arrival of off-site propagules through organisms acting as mobile links is of special importance to plantations, where the internal resources for ecological succession are impoverished (Bengtsson et al., 2003; Lundberg and Moberg, 2003; Gómez-Aparicio et al., 2009). It is



Pine plantation

Patch Area (ha): 750 (200–1500)

Tree density: ○ low ● medium ○ high

Past Land-use of the pine plantation: ○ Natural Forests ○ Pasture ● Shrublands ○ Croplands

Climate-proxy Factors

Elevation: 1000 (600–2600)

Annual Radiation (GJ/m^2): 5 (3–7)

Natural Forests

Natural forests patch number: 2 (1–5)

Natural forests patch size (min, max): 100, 200 (50–500)

Dispersers

Small-size Birds: 0 (0–100)

Medium-size birds: 0 (0–100)

Dispersers		%
Small birds		0
Medium birds		0
Mammals		100

Simulation

Simulation years: 30 (10–50)

Plant richness values by forest type

6.48 ± 0.78	14.89 ± 0.7	6.8 ± 0.93
5.22 - 9.89	13.73 - 16.1	5.29 - 10.43
Initial Pine plantation	Natural Forest	Final Pine plantation

Fig. 1. a) The "mobile-links" conceptual framework used to develop diveRpine (drawing from Lundberg and Moberg, 2003). b) Screenshot of diveRpine showing the different components: modules (left side), the virtual landscape (right side) and the Plant richness values of pine plantations (initial values; final -after simulation- values) and natural forests (bottom-left).

crucial to place this recovery potential in a landscape context, and in a given time frame, in order to help the manager determine the consequences of acting or not (*i.e.* choosing *active* or *passive* restoration) (Fernández et al., 2017; Meli et al., 2017).

Users can modify the parameters of several variables in each module (Fig. 1b) by simulating different situations in which to perform the management action, and evaluate how they affect the species and structural diversity within the target pine plantation. The results of the simulations can be expressed by numerical value (increase in species richness), and also displayed spatially in a virtual scenario (Fig. 1b).

2.1. *How does diveRpine run?*

diveRpine is designed so that it can be run both locally and also online (see https://sl.ugr.es/diveRpine). The recommended option is to download the package and run it locally (the use of RStudio is recommended). Two simple steps are needed to run diveRpine:

1. Download and install the latest version of diveRpine package typing (run once):

```
# install.packages(“devtools”)
devtools::install_github(“ajpelu/diveRpine”)
```

2 Run the app:

```
library(“diveRpine”)
run_diveRpine()
```

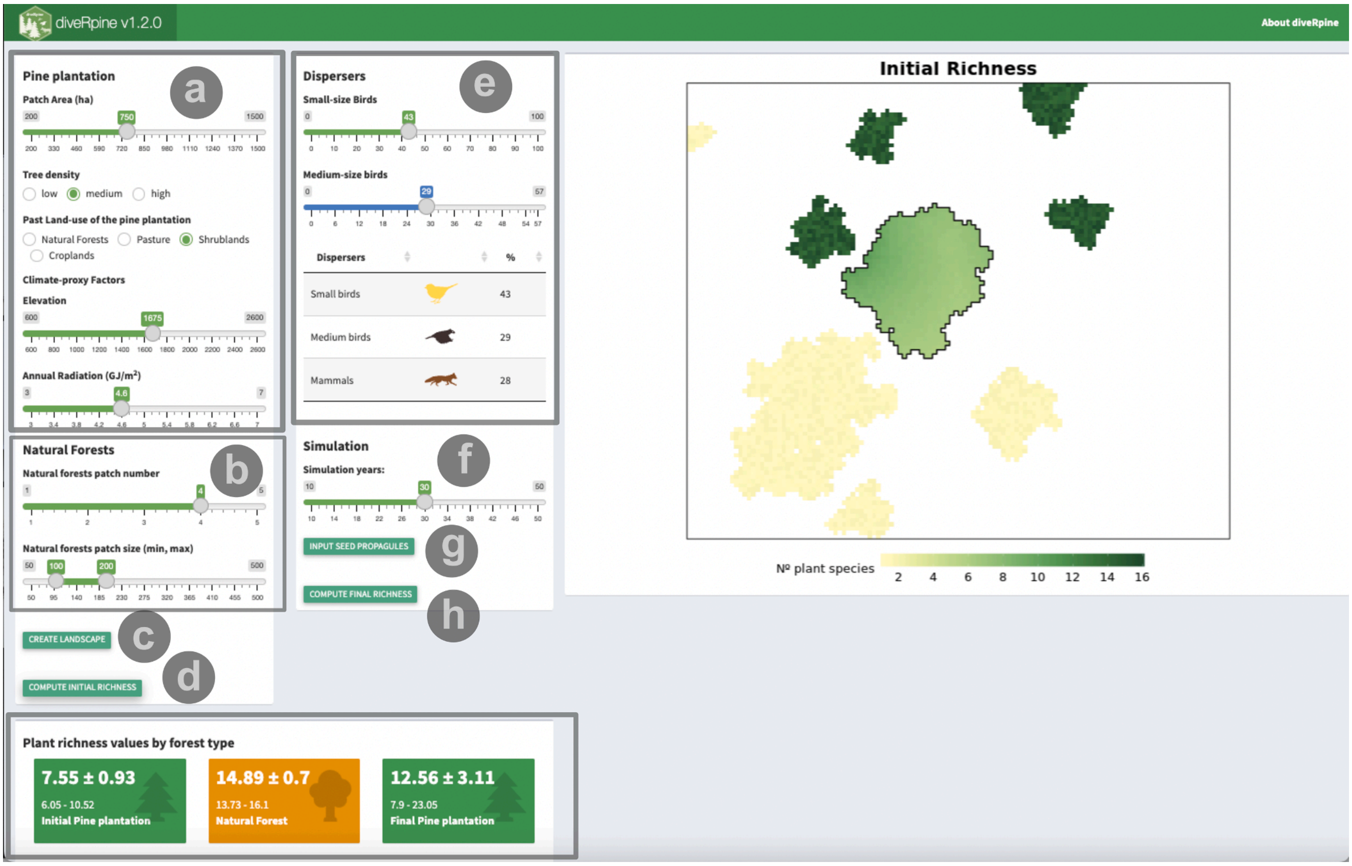
Then, a browser will open with the application ready to be used. A introductory tutorial with the steps explaining how the diveRpine works is then launched. Below, we explained a simple case of how to diveRpine works.

The first step is to set the features of the target pine plantation, defining patch size, tree density, past land use and climate-proxy factors (Fig. 2a). Then, the landscape is configured by determining the number and size of patches of natural forest (Fig. 2b). With this, diveRpine generates a virtual landscape with the characteristics specified by the user (Fig. 2c). The map with the created landscape can be visualized at the right side of the application. When the users click the button “Compute initial richness”, diveRpine computes the initial richness value in both the natural vegetation patches and the target pine plantation (Fig. 2d). These values are expressed numerically (bottom-left side in the Fig. 2) and can also be visualized spatially (right-side in the Fig. 2). The next step is to configure the composition of the disperser community. The user specifies the percentage of small- and medium-sized bird dispersers, and the remaining percentage corresponds to mammals (Fig. 2e). A table with the selected composition of the dispersal community is shown. Then, diveRpine computes a proxy of the seeds input, by computing the amount of propagules that can enter a pine plantation in a year, taking into account all the previous characteristics specified by the user (Fig. 2g). Finally, the simulation years are specified (Fig. 2f) and the final richness in the pine plantation computed (Fig. 2h).

We briefly describe how each module making up the application works, and the scientific results supporting them. A more detailed description of the modules, the code of the tool and a tutorial, is available at https://ajpelu.github.io/diveRpine/, which also includes a description of all the functions used in the app (see https://ajpelu.github.io/diveRpine/reference/index.html).

2.2. *Target stand (pine plantation)*

In this module the user specifies the size, the internal structure of the target pine plantation (tree density), and the abiotic variables (climate-



Pine plantation
Patch Area (ha): 750 (200–1500)
Tree density: ○ low ● medium ○ high
Past Land-use of the pine plantation: ○ Natural Forests ○ Pasture ● Shrublands ○ Croplands
Climate-proxy Factors
Elevation: 1675 (600–2600)
Annual Radiation (GJ/m²): 4.6 (3–7)

Natural Forests
Natural forests patch number: 4 (1–5)
Natural forests patch size (min, max): 100, 200 (50–500)

Dispersers
Small-size Birds: 43 (0–100)
Medium-size birds: 29 (0–57)

Dispersers		%
Small birds		43
Medium birds		29
Mammals		28

Simulation
Simulation years: 30 (10–50)

Plant richness values by forest type

7.55 ± 0.93	14.89 ± 0.7	12.56 ± 3.11
6.05 - 10.52	13.73 - 16.1	7.9 - 23.05
Initial Pine plantation	Natural Forest	Final Pine plantation

Fig. 2. Display of the diveRpine tool. Letters indicated the different modules of the application. See text for details.

proxy factors) that influence the richness and diversity of species that these ecosystems can harbour (Gómez-Aparicio et al., 2009; González-Moreno et al., 2011; Navarro-González et al., 2013). The first step is to select the size of the target pine plantation. The range values for size of the pine-plantation patch in diveRpine were defined considering the size of the existing pine-plantation patches in Sierra Nevada (Pérez-Luque et al., 2014; 2019).

2.2.1. Tree density

Tree density has a negative effect on the diversity and total species richness in pine plantations, decreasing these as the density of the plantation increases (Gómez-Aparicio et al., 2009). Higher tree density blocks light, and therefore reduces the diversity of plant species. In addition, in very dense pine forests, the flow of seeds is hindered for both wind-dispersed and bird-dispersed species. For example, the Eurasian jay (*Garrulus glandarius*), one of the most active dispersers in Mediterranean mountain pine-oak forests, prefers to visit less dense stands (Gómez, 2003).

Users can choose among three levels of tree density: low density (<500 trees/ha), medium density (500–1500 trees/ha), and high density (>1500 trees/ha). It has been shown that tree density is a key variable affecting plant richness in pine plantations, which decreased monotonically along the density gradient (Gómez-Aparicio et al., 2009). The tree-density threshold was based on data from Forest Inventory conducted in Sierra Nevada (Pérez-Luque et al., 2014).

2.2.2. Land-use legacies

Most of the afforested pines in Mediterranean mountains were planted in areas degraded by intensive human use (*e.g.* mountain croplands, pastures), or in shrublands or natural forests that were replaced by these conifer plantations (Pausas et al., 2004). The past land use affects the richness of species that inhabit a pine plantation (Navarro-González et al., 2013). For example, the number of recruits of *Quercus* sp. species found in a pine plantations depends on the past land use, and on the distance to the seed source (Navarro-González et al., 2013; González-Moreno et al., 2011). There is a gradient of intensity of use, so the more intense the past use before reforestation, the lower the probability of finding recruits of *Quercus* species at present (Navarro-González et al., 2013).

In this module, users specify the intensity of human use before the afforestation. The gradient of human use from highest to lowest is: cultivation, pasture, scrubland, and natural forest.

2.2.3. Climatic effect

Climatic conditions are important determinants of species richness, particularly in mountainous regions. Gómez-Aparicio et al. (2009) found an effect of climate conditions on potential species richness within pine plantations. Using 19 variables related to climatic and topographic conditions, they applied a principal components analysis, and found that elevation and annual radiation were the variables most correlated with the first two axes (explaining 83.3 % of the variance). diveRpine implements a module considering the climate-proxy factors of the target pine-plantation. Specifically the users could specify-two proxy-variables: elevation and global annual radiation. The effect of elevation follows a gaussian curve, where total species richness peaked at middle altitudes, whereas that the relation with radiation is linear with a decreasing in richness with increasing radiation (Gómez-Aparicio et al. (2009).

2.3. Landscape configuration

Landscape characteristics determine the functioning of certain ecological processes. The richness of species under pine plantations varies according to the number of natural vegetation patches (seed source) and the distance to them (González-Moreno et al., 2011). Thus, the greater the number of patches of natural forest, the greater the probability of native species propagules reaching the target pine plantation. On the other hand, the amount and diversity of seeds provided by a seed source depends on its size (natural forest patch size) and specific composition. The distance to the seed source affects the process of seed dispersal (Hewitt and Kellman, 2002a; 2002b). Shorter distances to the natural vegetation patches boost the probability of propagules entering afforested stands (Gómez-Aparicio et al., 2009; González-Moreno et al., 2011). The degree of adjacency of the patches of natural vegetation also affects the amount of seeds that penetrate the pine plantations (Zamora et al., 2010), so the greater the area of adjacency, the greater the entry of seeds, and therefore the greater the probability of new species establishing themselves in these plantations.

The user chooses the number of the natural vegetation patches (up to 5 for computational simplification), and their sizes (as a value range). Range values of size for the natural vegetation patches were specified according to real data of the natural forests existing in Sierra Nevada mountain region (Pérez-Luque et al., 2014; 2019). Once the user specified the number and size of the natural vegetation patches, diveRpine randomly generates a distribution of the different vegetation patches around the target pine plantation (Fig. 3a).

2.4. Computation of initial richness

diveRpine computes the initial plant richness of the target pine plantation (at a pixel scale) using the function `initRichness` (Table 1), considering the input parameters provided by the user and the configured landscape. It also generates a map with the initial richness (Fig. 3b) and the average values for the entire target pine plantation. For each pixel *j* of the pine plantation the initial richness value is computed as

$$Richness_{init,\,j} \quad Potential\,Richness \times fc \tag{1}$$

where *PotentialRichness* is a random value coming from a range of values obtanied from references in our study area (8.82–13.34 number of species) (Gómez-Aparicio et al., 2009; Pérez-Luque et al., 2014); and *fc* is a correction factor computed as:

$$\begin{aligned} fc = {} & w_{\text{past}}\cdot f(\text{past Land Use}) + w_{\text{dist}}\cdot f(\text{Seed source distance}) \\ & + w_{\text{treeden}}\cdot f(treeDensity) + w_{\text{clim}}\cdot f(\text{Climate-proxy}) \end{aligned} \tag{2}$$

which corrected the richness values according to the distance to seed source, the tree density, and the past-land use of the pine plantation. Different weights (w_{past}, w_{dist}, $w_{treeden}$ *and* w_{clim}) can be specified for each one of the previous factors. In diveRpine, we specified $w_{past} = 0.2$, $w_{dist} = 0.35$, $w_{treeden} = 0.25$, and $w_{clim} = 0.2$, according to the importance of each factor on the species richness (see Gómez-Aparicio et al., 2009; Navarro-González et al., 2013; Pérez-Luque et al., 2014).

Tree density of the pine plantation has a negative effect on the plant diversity, and on the total plant species richness (Gómez-Aparicio et al., 2009). The potential richness of a pine plantation is affected as a function of tree density as follows (see Equation 3 of Gómez-Aparicio et al., 2009):

$$f(treeDensity) = exp\left[-\frac{1}{2}\left(\frac{tree\,Density - 0.22}{1504.1}\right)^2\right] \tag{3}$$

Climate-proxy variables affect to plant richness within pine plantation. Higher plant richness were found at middle elevation (1400–1600 m.a.s.l.) (Gómez-Aparicio et al. (2009). Plant richness decreasing roughly linearly with increasing radiation (Gómez-Aparicio et al. (2009). The effect of climate-proxy conditions on the potential richness within pine plantations were implemented in diveRpine using the following equation (see Equation 2 of Gómez-Aparicio et al. (2009):

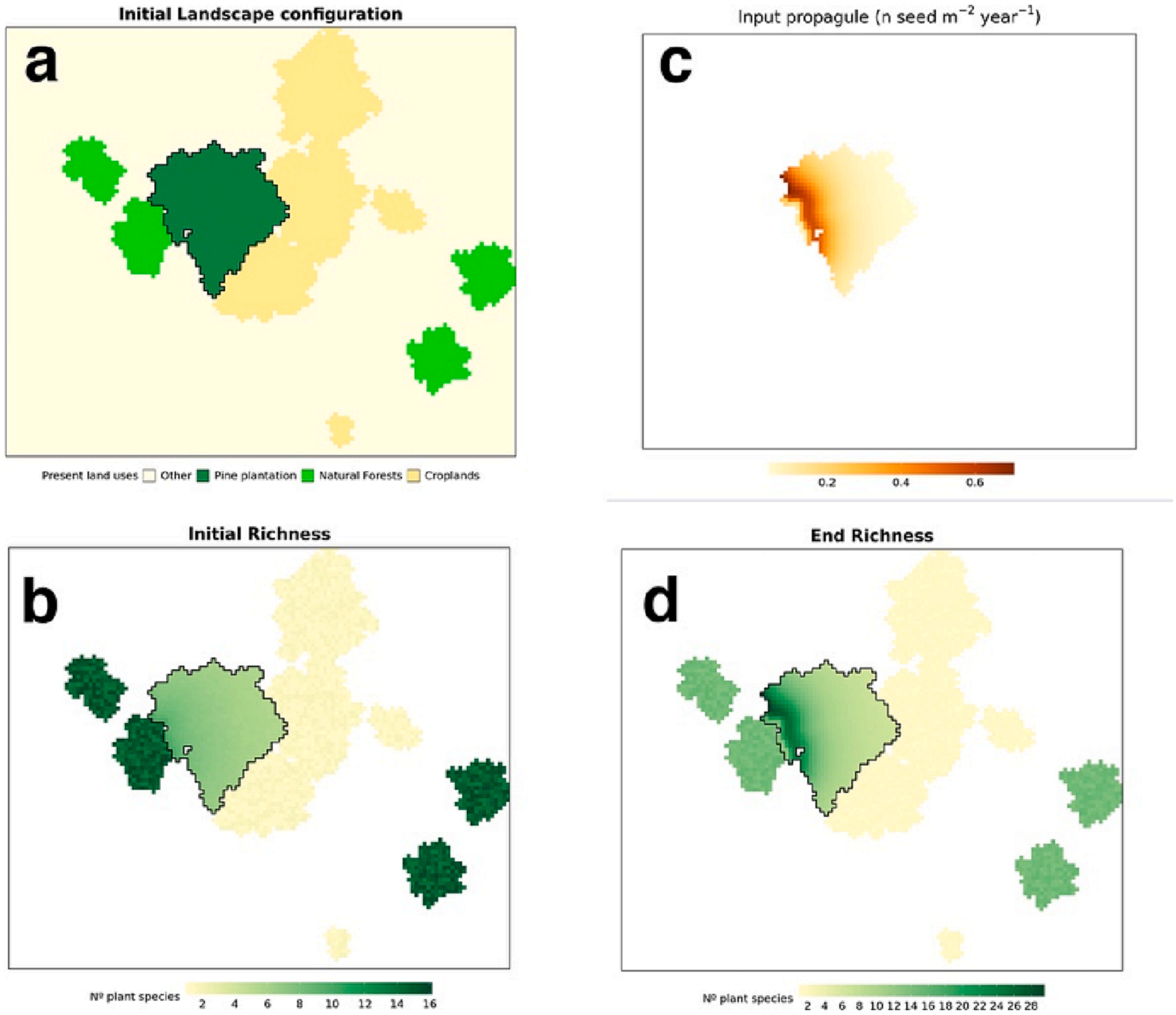


Fig. 3. Different output maps generated by diveRpine. Landscape configured by the user (a). Initial richness of the landscape configured (b). Potential input propagule into pine plantation (c), and Final richness of the landscape after simulation (d).

$$f(\text{Climate-proxy}) = exp\left[-\frac{1}{2}\left(\frac{Elevation - 1557.16}{644.89}\right)^2\right] \times \exp\left[-\frac{1}{2}\left(\frac{Radiation}{13.24}\right)^2\right] \quad (4)$$

Seed dispersal depends on the distance from the seed source (Hewitt and Kellman, 2002b). In pine plantations, the presence and abundance of species other than pines is determined, among others, by the distance to the seed source (González-Moreno et al., 2011). In our study area, natural oak forests are the most influential in terms of distance to the seed source (González-Moreno et al., 2011). Shorter distances could increase the pool of species in the pine plantations and reduce the evenness of plantation communities. González-Moreno et al. (2011) found that the relationship between distance to the source and diversity observed in mountain pine plantations of our study area follows the equation:

$$Diversity = 1.7605 - 0.0932\sqrt{\sqrt{distance}} \quad (5)$$

So, diveRpine computes for each pixel of pine plantation, the minimum of the distances between the centroid of the pixel and the edge of each natural forest patches. Then the seed source distance effect is scaled from 0 to 1.

$$f(Seed\ source\ distance) = 1.7605 - 0.0932\sqrt{\sqrt{min\left(dist_{pine-natural\ forests}\right)}} \quad (6)$$

The richness value of a plantation is also conditioned by their past land-use (Navarro-González et al., 2013). Different past land-use intensities affected the available oak recruit bank, so higher degradation levels associated with more intense past land uses modulated the biological legacies in current pine plantations (Navarro-González et al., 2013). The probability of finding recruits of *Quercus* species within a pine plantation follows a gradient from higher values for less intense past-use (*e.g.,* oak forests) to lower values for highly degradation past land-use (*e.g.,* croplands). Using the data of probability of finding regeneration from Navarro-González et al. (2013), diveRpine assigns a rescaled value (*i.e.,* $f(pastLandUse)$) according to the following gradient: Natural forests (0.9999) > Shrublands (0.4982) > Croplands (0.0279) > Pasture (0.0001).

The values of species richness existing in the seed sources (natural forest) are selected from a range of values (13.72–19.66) based on data from forest inventories carry out in our study area (Gómez-Aparicio et al., 2009; Pérez-Luque et al., 2014).

Table 1

Description of the main diveRpine R functions. For each function a brief description, the default values, and the references on which it is based are shown. Detailed description at https://ajpelu.github.io/diveRpine/reference/index.html.

Name Function	Description	Default values	Supporting references
plot_landscape	This function creates a "virtual" landscape composed of different patches: the target pine plantation; natural forests; croplands; and shrublands. User can set several parameters: - *Target pine plantation*: patch size, tree density, past land use - *Landscape configuration*: number and size of natural forests patch	Patch-size values of target pine plantation and natural forest come from a range based on data from study area. The distribution and size of the cropland and shrubland patches depend on the available space in the virtual landscape (*i.e.* after establishing the distribution of the natural forests and the target pine plantation) and is based on the coverage values of those classes for the study area.	Pérez-Luque et al., 2014; Pérez-Luque et al., 2019
initRichness	Compute the richness values of each pixel after the landscape configuration was done. Richness values on target pine patch depends on: - Target stand structure: tree density, patch size, past land use, climate-proxy variables - Distance to seed source (landscape matrix)	Richness values for each of the patch classes (*i.e.* pine plantation, natural forests, shrubland and crops) are calculated considering the range of possible values for the study area	Gómez-Aparicio et al., 2009; Mendoza et al., 2009; González-Moreno et al., 2011; Navarro-González et al., 2013; Pérez-Luque et al., 2014
input_propagule	Compute the propagule input from each patch to pine plantation target using three classes of dispersers. Quantity and quality of seed dispersion are influenced by: - Seed sources: seed diversity in seed source patch, and patch size. - Disperser: percentage of each disperser - Landscape configuration	Three classes of dispersal were considered: small birds (*e.g. Erithacus rubecula, Sylvia melanocephala*); medium birds (*e.g. Garrulus glandarius*); and mammals (*e.g. Vulpes vulpes*)	Gómez, 2003; Zamora et al., 2010; Matías et al., 2010; Jordano et al., 2007

2.5. Dispersal community

We considered three groups of dispersal vectors, characterized mainly by the dispersal distance and by the quantity and quality of the seeds they disperse:

- *Small-sized birds,* with maximum dispersal peak is between 0 and 50 m, and rarely exceed 100 m (Jordano et al., 2007; Zamora et al., 2010).
- *Medium-sized birds*, which disperse 50 % of the seeds over distances of more than 100 m. This group includes the Eurasian jay, which covers dispersion distances of up to 1000 m (Gómez, 2003; Pons and Pausas, 2007) and have a maximum dispersion distance of between 250 and 400 m, although this depends heavily on the landscape (Gómez, 2003).
- *Mammals* have highly variable dispersal kernels, but they disperse over greater distances (even more than 1500 m). They have maximum dispersal rates of around 650–700 m, and can also introduce non-native seeds due to their large dispersal distances (Jordano et al., 2007; Matías et al., 2010).

Dispersal patterns and distances were established based on work performed mainly in Mediterranean mountain plantations (Gómez, 2003; Jordano et al., 2007; Matías et al., 2010; Zamora et al., 2010). The user selects the percentage of each disperser group (Fig. 2e) and diveRpine computes the amount of propagules that can potentially be introduced in the target pine plantation by year (see below).

2.6. Potential propagule input to the plantation

For each pixel of the target pine plantation, the potential input of propagules is computed according to *(i)* the distance from the seed source, *(ii)* the richness of the seed source (natural forests), and *(iii)* the disperser. Since each disperser has different dispersal kernel (Fig. 4), potential propagule input depends strongly on the disperser type and on distance between seed source and the pine plantation pixel. According to literature, propagules input by birds and mammals in mountain pine plantation of our study area representing 3.7 and 0.2 seeds m^{-2} yr^{-1} respectively (Zamora et al., 2010).

diveRpine also considers the adjacency between each of the natural forest patches and the target pine plantation. It is known that the higher the adjacency between the natural forest and the pine plantation, the lower the limitation of the propagule entry dispersed by birds, specifically (see Zamora et al., 2010):

$$seed\ limitation = 0.733 - 0.0039 \times adjacency \tag{7}$$

with *seed limitation* values range from 0 to 1, and *adjacency* as percentage of pine-plantation perimeter in contact with native vegetation. diveRpine computes the adjacency of pine-plantation with each of the natural forest patches, and applies a correction factor to the entry of propagules into pine plantation as follows:

$$adjacency_{correction\ factor} = 1 + \frac{seed\ entry - seed\ entry_0}{seed\ entry_{100} - seed\ entry_0} \tag{8}$$

where $seedentry = 1 - seedlimitation$, and $seedentry_0$ and $seedentry_{100}$ corresponds to the seed entry for no adjacency and full adjacency respectively. For those patches with adjacency, the potential dispersion by birds increases according to the adjacency correction factor (see Zamora et al., 2010).

Once computed the potential entry of propagules for each of the disperser type, diveRpine weights the total propagule input into pine plantation according to composition of the disperser community selected by users (Fig. 2e), and then generated a map with the quantity of propagules input by year into the pine plantation (Fig. 3c).

2.7. Computation of final richness

Finally, the user can select the length of the simulation (Fig. 2g), and diveRpine estimates the quantity of propagules input into each pixel of the pine plantation. Then, the app calculates the final richness by considering the initial richness values, the propagule input, and

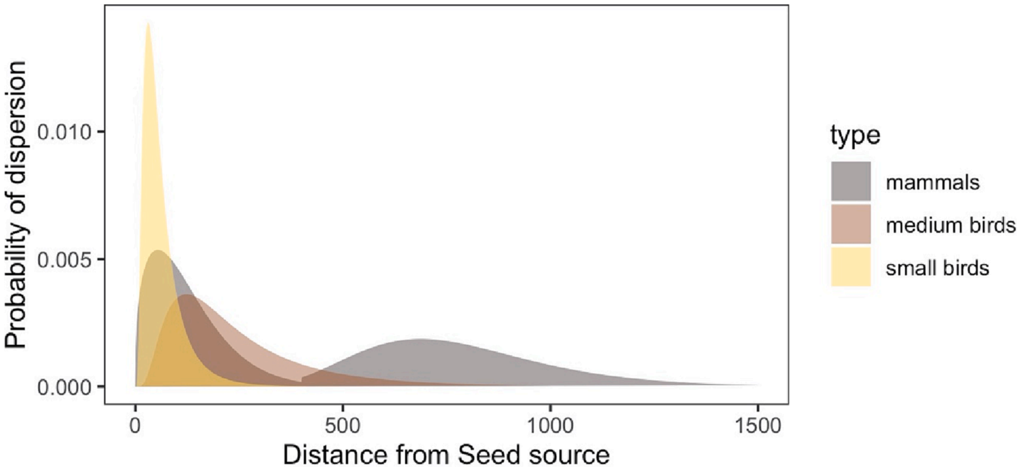


Fig. 4. Dispersion kernels used for each disperser in diveRpine. See potential_dispersion (Table 1) function for more details.

assuming the existence of plant establishment constraints. For this purpose, a general value of limitation to seedling establishment was assumed following values provided for several studies in this mountain region (Mendoza et al., 2009; Matías et al., 2011a; Matías et al., 2011b; Quero et al., 2011). diveRpine generates a map with the end richness (Fig. 3d) and the average values for the entire target pine plantation are shown.

3. Case study

Sierra Nevada (southern Spain) is a mountain region where pine plantations dominated the forest cover. These plantations were established mainly during the period 1950–1980 on highly degraded, extensive agricultural landscapes abandoned after the Spanish Civil War (1936–1939) (Arias-Abellán, 1981; Mesa Garrido, 2019). They were planted to palliate the extreme erosion of their watersheds, some of these having the highest erosion rates in the Iberian Peninsula (Mesa Garrido, 2019). Those management actions, however, generated large afforested areas highly vulnerable to pests and worsening droughts, while other perturbations such as fire were exacerbated climate warming (*e.g.* Hódar and Zamora, 2004; Choat et al., 2012; Sánchez-Salguero et al., 2013). Currently, pine plantations in this mountain region occupy about 42,000 ha (representing about 80 % of its forest coverage), composed mainly of a single pine species (Bonet et al., 2016; Mesa Garrido, 2019). The density of the plantations currently ranges from 100 to 2100 pines/ha (Bonet et al., 2016). The restoration of those pine plantations is being a priority task for the managers of this mountainous region (Bonet et al., 2016), and many efforts have been invested in the last two decades to transfer scientific knowledge to the management of these pine forests (Aspizua et al., 2016; Zamora and Bonet, 2015).

4. Discussion

We applied the use of diveRpine as tool that aid to decision makers in the restoration of those pine plantations to maximize the provision of the ecosystem services (Fig. 5). Assuming that we want to restore a target pine plantation. The first step is to infer the ecological health status of the target pine plantation, by means of analyze each one of the modules. One possible situation is a plantation with a very good ecological health status of all modules where the plantation can naturalize by itself by means of passive restoration (Fig. 5b), because: 1) the stand of the plantation has vegetation legacies (seeds, roots, stolons); 2) the density of the plantation is not very high and allows light to penetrate the undergrowth, favoring germination and establishment; 3) the plantation is surrounded by natural vegetation providing propagules; 4) abundant populations of mobile links can disperse the seeds within the plantation; and 5) the size (small) and proximity (near) of the stands is ideal for the work of the mobile links be effective. If all the modules of the vegetation recovery process are optimal, then a flow of seeds will become established from the stands of native vegetation into the plantations by mobile links. Germination results and forms a diverse recruitment bank in species, with age structures and a spatial distribution that will first foment intermingling and eventually lead to the replacement of the planted trees (Zamora et al., 2010). The first utility of the application is, therefore, to identify the stands that have the most options to recover diversity and heterogeneity by themselves in a reasonable period of time (*e.g.* less than 10 years), reaching diversity values similar to those of stands of surrounding natural vegetation. In these stands, the management work would be limited to monitoring whether this naturalization process is actually taking place without human intervention. This monitoring also serves to check whether the simulation offered by the model fits the reality of the field, which also represents an exercise in validating the simulation.

Another opposite situation could be that some modules do not offer an optimal situation for natural recovery, acting as a “weak link” throughout the process. In such cases, the speed of natural recovery will be sluggish and will force the manager to decide whether or not it would be beneficial to act and, if so, in what specific way (Fig. 5c, d). Of the modules considered, the ones in which the manager is in fact able to act are: 1) management of tree density in the plantation, making controlled cuts, this being the case of traditional management in forestry practice; 2) improvement of the health status of disperser populations, especially if they are species of hunting interest, as in the case of many species of zoochorous birds. Another area where it can act is in maintaining the state of health of the stands of native vegetation that are close to the plantation, ensuring that they flower and fruit in abundance. The other modules, although also important (*e.g.* landscape configuration, intensity of the past land-use change) are further from the real possibilities of management.

The application diveRpine offers as output the number of species reached after a given time and the spatial heterogeneity of their distribution based on their proximity to the propagule sources. It also helps to identify the most limiting module. If this module can be managed (*e.g.* clear cutting, the conservation of seed dispersal populations and propagule sources surrounding the pine plantation) then the manager must decide the most suitable action. On the contrary, if several limiting modules are prohibitively expensive to handle, then the option is to take no action, leave the stand as it is, and wait a much longer time for a naturalization process that, due to its duration (decades), would go beyond the usual medium-term management plans. In this case, the inaction choice would represent a limit option when 1) the natural recovery possibilities are minimal, or 2) the actions affecting one of the

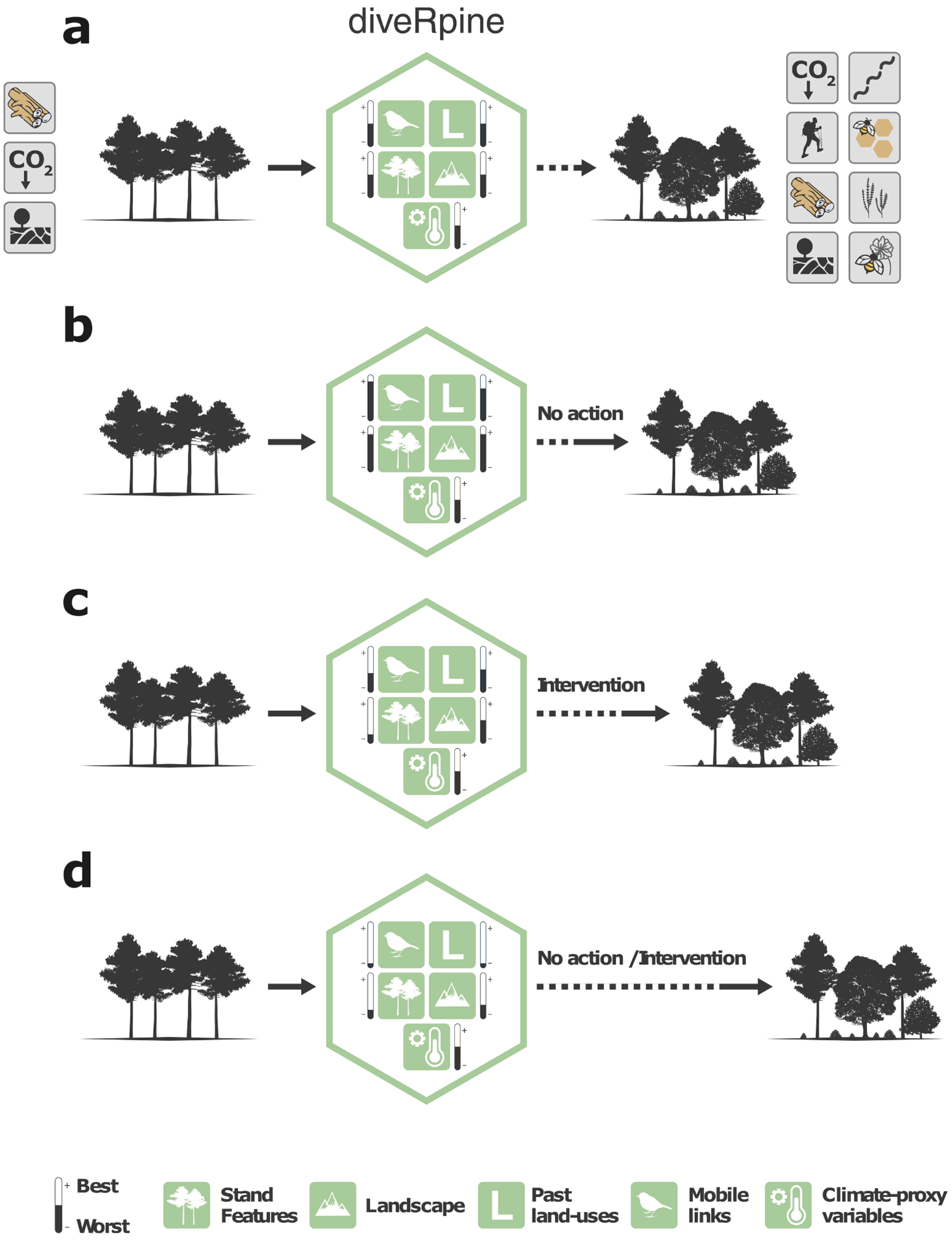


Fig. 5. Study cases showing how diveRpine could help to choose a given forest-management action depending on the features of the target pine plantation, landscape configuration, and disperser community. Initially (a) a dense, homogeneous and generally monospecific stand provides few ecosystem services (*e.g.* regulation: soil erosion, carbon sequestration; provisioning: timber production). The goal is to achieve greater diversity (composition) and heterogeneity (vertical and spatial structure) in the stand. This will also have more multifunctionality and thereby provide more ecosystem services (*e.g.* climate regulation, pest regulation, recreational values, pollination). Under optimal conditions (b) (*i.e.* low tree density, heterogeneous landscape with nearby patches of natural forest, healthy populations of seeds dispersers, etc.), the diversification would follow a natural course, and thus no action (passive restoration) would be the best management option. On the contrary, under suboptimal conditions (d) (*i.e.* high tree density, isolated pine plantation, poor community of dispersers, and scarce natural sources of propagules) the manager must decide whether the action merits the investment. If the target pine plantation has some optimal conditions (c) (*i.e.* intermediate values of tree density with several natural forest patches providing seeds) the app could help the manager to decide whether action would help diversify the pine plantation and therefore broaden the range of ecosystem services.

modules do not guarantee a recovery, because the plantation will very likely be replaced by another type of vegetation more in line with current ecological conditions. This is common in pine afforestation in Mediterranean mountains, usually severely limited by current climatic conditions. Under these conditions, the best long-term alternative would be to switch from the traditional monospecific forest plantation model to a more diverse forest structure dominated by shrubs (Matías et al., 2010), and thereby pursue the broad range of biodiversity and ecosystem services (Evy et al., 2016; Soliveres et al., 2016; van der Plas et al., 2016; Gross et al., 2017).

The manager should know how to translate forestry activities into a panoply of ecosystem services. That is, the manager can act on the composition (eliminating or planting some species instead of others) and structure (performing controlled thinning) of the plantation. These actions have functional consequences in ecological processes (*e.g.* thinning allows more light to enter the undergrowth, stimulating the germination of seeds and the growth of saplings). Each of field-target variable on which the management could act, must qualitatively and quantitatively support an ecological function and service. Then these changes, must be linked to expected implications for the provision of ecosystem services and the possible trade-off (Dai et al., 2017).

5. Concluding comments

Tools and assessment frameworks still need to be developed in order to guide informed decision making (Lindenmayer et al., 2015, Chazdon and Guariguata, 2018). Taking into account this premise, and considering the existing scientific information, we have developed diveRpine, which compiles the available scientific knowledge of pine plantations in Mediterranean mountains area, make it available for natural resource managers in a synthetic and friendly way to assist in the decision-making process.

Many tools have been developed to guide and inform decision making in the practice of forest restoration, with some focused on steering process-oriented decisions and assessing readiness for particular types of restoration actions, whereas others are used to perform quantitative assessments and develop scenarios for restoration outcomes, given a set of data layers (see reviews in Chazdon and Guariguata, 2018; Orazio et al., 2017; Segura et al., 2014). There are also an emergence of a large number of complex models to describe dynamics in forest ecosystems at different levels, from stand-scale empirical simulators to more complex process-based models operating at landscape scale (He et al., 2017; Seidl, 2017; Scheller, 2018). However decision support tools are ineffective without a clear objective in mind and without a framework for action. In addition, many of these tools require substantial initial investments in terms of time for the preparation of the input data (Suárez-Muñoz et al., 2021). In their review, Chazdon and Guariguata (2018) found that relatively simple tools, well-documented and validated, are more likely to be adopted by policy makers. diveRpine synthesizes the results of different complex models, and generates an intuitive, simple and user-friendly decision support tool for managers which are interested on respond to the key question of how to renaturalize pine plantations.

Our approach directly linked science to management: first, we have transformed ecological data into scientific information, and then we have used this information to develop a support tool for management decision making. With diveRpine, we aid managers to answer key questions such as when and how to manage forest plantations, or when is better apply passive restoration.

We are aware of some limitations of diveRpine. For instance, in its current version, it is limited for use in a specific area of the territory, and with a default equations and values that modelized how the plant richness varies within mountain pine plantation. But the users could modify the package functions to implement other equation for other forest plantations (see detailed manual in the app website). The novelty of our application is its conceptual and methodological approach. Conceptually, our support-decision tool is innovative by equipping managers to envisage the consequences of their decisions within a framework of the naturalization of pine plantations. diveRpine is a powerful tool to support decision making in the real world, working with key variables linked to the provision of services. From a methodological point of view, it is presented in a user-friendly format, so that decision making is based on the best possible scientific information processed with an easy-to-use tool. Methodologically, diveRpine used the most relevant scientific information on restoration of pine plantations (derived from scientific publications), and has generated an easy way to evaluate how different scenarios can modify the richness of a plantation, and therefore its multifunctionality. It uses a visualization framework based on open source and the all the code could be used and customize.

In addition, diveRpine has a substantial value as an academic resource, since it could be used as an aid applied to conservation and restoration focused management advices in the context of the Mediterranean pine plantations. This tool would also be a valuable teaching resource in both undergraduate and graduate ecology and conservation classes. The tool has great value to explore virtual scenarios and demonstrate the process of prioritization.

Although it has been developed with information from Mediterranean mountains, and particularly from Sierra Nevada, the conceptual and analytical approach allows diveRpine to be applied to others forests plantation in any other biome. The problem is the same everywhere: to convert forest plantations into more natural forests with active regeneration, heterogeneous structure, high biodiversity levels and carbon sink capacity, and high resilience to disturbances such as pests and fires (Maestre and Cortina, 2004; Brockerhoff et al., 2008; Pejchar et al., 2008; Villar-Salvador, 2016; Lewis et al., 2019). From the perspective of nature-based solutions, the way to solve the problem is also the same: to take advantage of the natural resilience of ecosystems, which depends essentially on the aspects considered in diveRpine: landscape configuration, the internal structure of the plantation (past land uses, tree density), and the composition of the dispersion vectors (birds and mammals). diveRpine uses common ecological process present in other ecosystems, such as seed sources, dispersers and target patches (mobile links, Lundberg and Moberg, 2003). In this respect, birds and mammals of diverse taxonomic origin act functionally in the same way as mobile links in contrasting ecosystems or the world (Garcia et al., 2010; García et al., 2011; Carlo et al., 2013).

The key issue is to have the data and scientific information of the relevant modules. Generally, the scientific information is available, but sometimes it is disseminated and it is not effectively highlighted. In addition, it is often necessary to make an effort to integrate and synthesize this scientific information in order to effectively transfer it to management. The more complete this information is for a given plantation in a given environment, the more reliable the scenarios and subsequent simulations will be.

CRediT authorship contribution statement

Antonio J. Pérez-Luque: Writing – original draft, Visualization, Software, Validation, Supervision, Methodology, Data curation, Conceptualization, Investigation. **Regino Zamora:** Conceptualization, Data curation, Investigation, Supervision, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code and data are available at https://ajpelu.github.io/diveRpine/

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