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Assessing reforestation failure at the project scale: The margin for technical improvement under harsh conditions. A case study in a Mediterranean Dryland

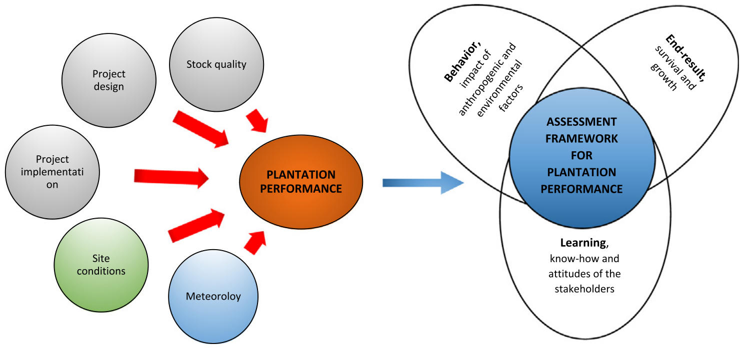
Antonio D. del Campo [a,b,*,1], Guillem Segura-Orenga [a,1], Inmaculada Bautista [a], Carlos J. Ceacero [c], María González-Sanchis [a,b], Antonio J. Molina [a,b], Javier Hermoso [d]

[a] Research Group in Forest Science and Technology (Re-ForeST), Universitat Politecnica de Valencia, Camino de Vera s/n, E-46022 Valencia, Spain
[b] Desert Leaves Foundation, Spain. https://desertleaves.org
[c] Departamento de Fisiología, Anatomía y Biología Celular, Universidad Pablo de Olavide, E-41013 Sevilla, Spain
[d] Consejería de Agricultura, Desarrollo Rural, Emergencia Climática y Transición Ecológica, Generalidad Valenciana. c/ Gregorio Gea, 27, Valencia, Spain

HIGHLIGHTS

- Full and comprehensive assessment framework for plantation performance assessment is developed.
- Evaluation is based on 3 levels to improve program outcomes: en-results (performance), behavior (drivers) and learning (know-how).
- Plantation mortality was high and varied with both site and species. Hardwoods and the juniper showed lower growth rates than pines
- Soil moisture and meteorology in the planting season gathered high importance on post-summer survival.
- Environmental variables, such as site quality and meteorological drought, showed increased importance on survival after 10 years.

GRAPHICAL ABSTRACT



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ABSTRACT

Poor reforestation outcomes imply failure to fulfill program goals and tend to erode institutional willpower and political momentum towards reforestation efforts, affecting both public and private support. However, program improvement in real reforestation projects is challenging, due to the conjunction of many different variables that mutually interact and feed back on each other inextricably. This study develops a comprehensive assessment framework for reforestation programs, for which technical and environmental information is gathered and related to indicators of performance in both the short- and mid-term. This assessment, tested on a case study, aimed to provide reliable end-results for survival and growth, revealed pitfalls in successful plantation establishment and taught us how to improve plantation performance and what the margin for this improvement was. The selected project was carried out on harsh site conditions, with different species, cultivation treatments and contractors, and was affected by the driest year on record. Plantation mortality was high and increased progressively

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* Corresponding author at: Research Group in Forest Science and Technology (Re-ForeST), Universidad Politécnica de Valencia, Camino de Vera s/n, E-46022 Valencia, Spain.
E-mail addresses: ancamga@upv.es.
URL's: https://desertleaves.org (A.D. del Campo), https://desertleaves.org (M. González-Sanchis), https://desertleaves.org (A.J. Molina).

[1] Co-first authors.

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Restoration improvement
Establishment
Survival
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Pinus sp.
Boosted regression trees model

over time, particularly in the short-term when the rate was 53% (rising to 83% after ten years), showing high variation between sites and species (*Pinus pinaster* and *Quercus faginea* died more than 94% after ten years while *Junipus phoenicea* only 40%). All the hardwoods and the juniper showed lower growth rate after ten years (average stem volume < 40 cm^3) than pines (stem volume > 470 cm^3). Technical variables (project planning and execution) had a relatively important impact on plantation performance in the first two years (11–29%), but decreased with time, whilst environmental variables (site and meteorological) were more important ten years after planting (>50%). In the short-term, soil moisture and meteorology during the planting season were identified as key factors that triggered the effects of both technical decisions (planting date and planting technique) and other environmental variables on performance. In the design phase, some decisions related to zoning, species selection and cultural treatments were related to poor performance. The results provide practical information and guidelines about all potential drivers of plantation performance and contribute to identify those aspects more related to success of forest restoration in Mediterranean drylands.

1. Introduction

In the United Nations Decade on Ecosystem Restoration, creation of more resilient and productive landscapes is an overarching goal in most programs, declarations and on-spot projects (Chazdon and Brancalion, 2019; Chazdon et al., 2020; Höhl et al., 2020). In particular, reforesting degraded drylands makes it possible to achieve many of the important commitments included in national and international agendas, such as sustainable development goals and the land degradation neutrality target, the Bonn Challenge and other agreements on desertification, climate change and biodiversity (Stanturf et al., 2014; Cunningham et al., 2015; Chazdon et al., 2017). However, the attainment of the environmental and socioeconomic targets pursued in reforestation projects is not straightforward, as out planted seedlings need to survive in a harsh environment to complete successful establishment (Burdett, 1990; Grossnickle, 2012).

Plantation failure is indeed one of the most important factors hampering the high hopes, political willingness and funding efforts in Forest Landscape Restoration (FLR). Failure may well be more common than success, which negatively affects FLR communication efforts (Suding, 2011; Höhl et al., 2020). The high percentage of mortality commonly found in dryland plantations has been the subject of previous attempts to identify the reasons in order to improve program effectiveness (Pausas et al., 2004; Del Campo et al., 2007, 2011; Ceacero et al., 2012; Navarro-Cerrillo et al., 2014). Early plantation failure may be due to a great many technical, environmental and administrative factors that need to be carefully broken down and analyzed (Margolis and Brand, 1990; Le et al., 2012, 2014; Lawson and Michler, 2014). Weather and climate conditions (such as extreme drought) after planting are the main causes of the high mortality of plantations in Mediterranean drylands (Rey Benayas et al., 2015; Del Campo et al., 2020). Mortality is also caused by improper decisions, either in the design (how the reforestation is conceived) or in the implementation (how it is achieved) of the project. Thus, the success of a plantation is a conjunction of both environmental conditions and the adequacy of the decisions, planning and actions included in the technical project and during execution. All these factors affect the capacity of the seedling to grow under the often-harsh physical environment of the reforestation site (Grossnickle and MacDonald, 2018). Each of these sets of factors or drivers includes a multitude of other involved and interrelated factors. In this work we have used the hierarchy of factor, subfactor and variable. Thus, plantation success must be studied in a context that explicitly takes into account this complexity and all possible interactions (Ceacero et al., 2012; Le et al., 2014).

Several management decisions can increase mortality in dryland plantations regardless of meteorology, such as shallow site preparation (Palacios et al., 2009; Löf et al., 2012; Smanis et al., 2021), unsuitable planting timing (McTague and Tiius, 1996; Pardos et al., 2003), pre-planting mishandling of plant stock (Edgren, 1984), careless execution of planting (Mullin, 1974; Long, 1991) or inadequate species selection (Suárez et al., 2011; Meli et al., 2014; Del Campo et al., 2020). Additional aspects involved in poor performance include inadequate ecological zoning (Klijn and De Haes, 1994; Ceacero et al., 2012, 2020), the lack of well-founded ecophysiological criteria when assigning aftercare cultural treatments such as tree shelters, soil amendments, etc. (Puértolas et al., 2010; Padilla et al., 2011; Del Campo et al., 2011) and poor stock quality (Del Campo et al., 2007, 2010; Grossnickle and MacDonald, 2018). Some of these factors can be addressed by quality controls (Long, 1991; Trewin, 2001; Navarro et al., 2009; Kankaanhuhta, 2014) such as those concerning the use of suitable provenances and plant stock with functional quality and controls on planting works.

Throughout the regeneration process, the different drivers with potential impact on indicators of plantation success are divided into anthropogenic (technical, socio-economic, institutional, policy, management) and biophysical drivers (Le et al., 2012). A key point when addressing plantation performance, through either quality controls or assessments, is that drivers are linked to the indicators used to measure project success within a framework that allows for complex arrays of variables that interact and feed back on each other fully (Le et al., 2014). Systems approach facilitates such a combination of inter-related parts, allowing for changes in operational environments and uncertain circumstances (Le et al., 2012). The evaluation approach must provide a measurable outcome of the actions taken (end results), which in turn leads to changes in the techniques and actions recommended (behavior) and finally to changes in the knowledge, know-how and attitudes of the stakeholders (learning), thus avoiding their discouragement (Kankaanhuhta et al., 2010; Melo et al., 2013). Protocols to assess and monitor restoration efforts need to adjust to the scale, biome and social-ecological particularities of each context (Navarro et al., 2009; Melo et al., 2013; Lazos-Chavero et al., 2016; Holl, 2017). Such a comprehensive framework must be able to assess progress in the resulting environmental and socio-economic benefits, if the program is to be judged successful, e.g. with more C fixed, ecosystem services restored, employment and local enterprises enhanced, etc. This is particularly important when dealing with uncertainties in the context of climate change, such as species adaptiveness, climate dislocation problems and other technical aspects (site preparation, planting densities, cultural treatments, etc.) that might need continuous re-assessment (Löf et al., 2019).

The main objective of this study was to develop and field-test a full and comprehensive assessment and evaluation framework for plantation performance, in order to better identify and address the drivers of plantation failure (Fig. 1). To this end, we tested a methodological approach that encompasses both technical and environmental factors in the assessment of a reforestation project. This assessment is intended to reveal pitfalls for successful plantation establishment in both the short- (1–2 years) and mid-term (10 years) by better assigning the relative importance of i) the decisions taken at the planning or design stage, ii) the execution of the work and iii) the environmental factors, such as weather constraints at planting and site quality. We used the overall analysis to find which aspects of the project should be changed

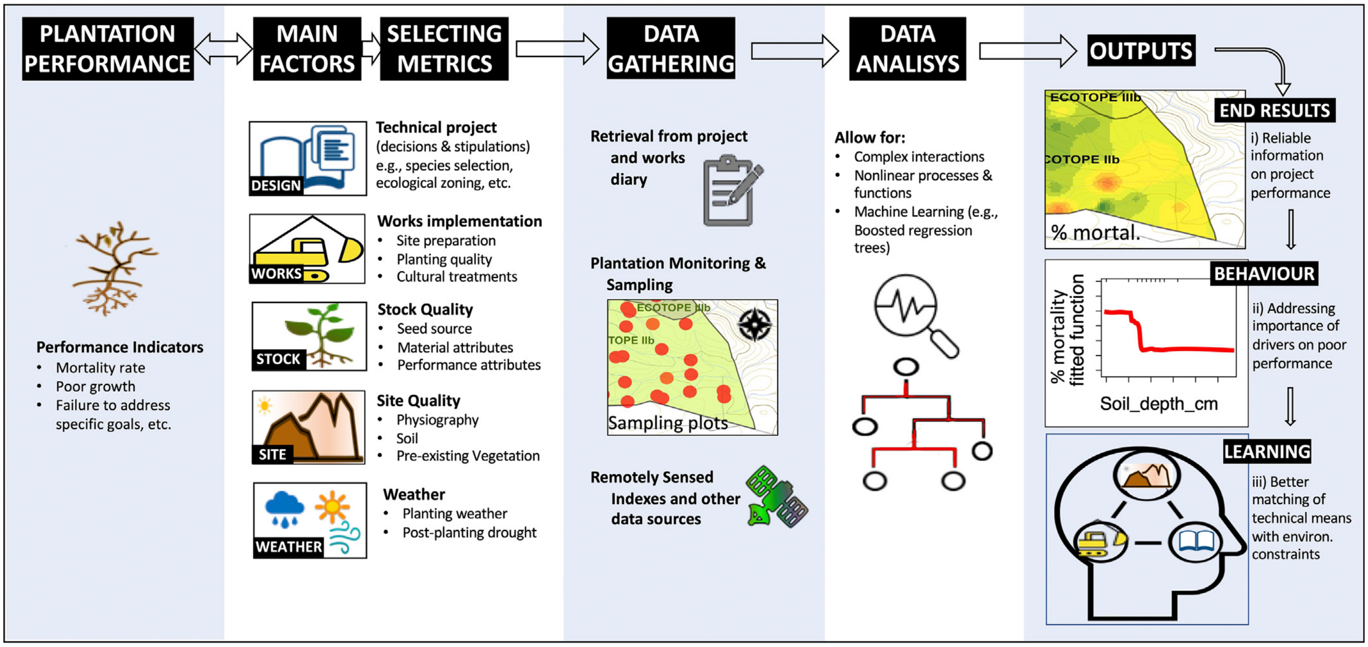


Fig. 1. Comprehensive assessment framework for reforestation programs: reforestation failure is addressed through a breakdown of both technical and environmental factors that provide information and data to feed complex non-linear models which output reliable end-results, understanding and capacity for improvement.

to improve plantation performance and what the potential margin for this improvement was. The selected case study is a complex real restoration project undertaken by a regional Forest Service that encompasses enough variation (environmental and technical) to provide a valid framework for achieving the study's aims. The project was carried out on harsh site conditions, with different species, cultivation treatments and contractors, and was affected by the driest year on record. Since the project was not intended for scientific research, this study does not aim to contrast different treatments through a well-balanced design. This is beyond the objectives of the study.

2. Materials and methods

2.1. Project design and site framing

The study examined a reforestation program carried out in 709 ha from autumn 2007 to mid-winter 2008 at “La Muela de Cortes” public forest, municipality of Cortes de Pallás (Valencia, Spain, 39°13′ N; 0°53′ W; 794 m a.s.l.; Fig. 2). The geomorphology of the area corresponds to a flat-topped mountain (butte) where parent material is a consolidated cretaceous limestone (and dolostone) with a haplic calcisol developed over it. The soil is shallow (<30 cm), very rocky and has a pale brown surface horizon, more reddish with depth, with substantial accumulation of lime, which provides an alkaline pH. Texture is clay-loam to silty-clay-loam and organic matter around 6% (see Section 2.3). Climate is dry sub-humid Mediterranean with annual precipitation of 510 mm (10% in summer; 1999–2019, Cortes de Pallás-Casa del Barón Met. station). Average annual temperature is 13.8 °C (2005–2019, adjusted for the site from Requena-Cerrito Met. station). The natural vegetation in this area consists of ephemeral grasses, shrubs and trees that form a sparse to closed canopy depending on site conditions and previous disturbance regimes. In the reforestation area, vegetation consisted mainly of xerophytic shrubs (*Rosmarinus officinalis, Quercus coccifera, Q. ilex, Ulex parviflorus, Thymus spp., Juniperus oxycedrus, J. phoenicea* and the grass *Brachypodium retusum*) and sparse pine trees (*Pinus halepensis* and *P. pinaster)* that survived the last wildfire in the early 1990's.

The technical document of the project states the goal (restoring the forest) and includes information and decisions such as site and climatic characterization, zonation in ecotopes (spatial units which are homogeneous as to vegetation structure, succession stage and the main abiotic site factors that are relevant for plant growth), species selection and mixture, site preparation, early growth promotion and protection treatments and how the plantation work should be carried out. The project was started in 2008–2009 and was awarded to a public company (TRAGSA), who in turn subcontracted to several local contractors.

Seven native species were selected in the technical project following auto-ecological and floristic approaches, including the most typical main and secondary species used in reforestation programs in Mediterranean areas (Vadell et al., 2016) (Table 1). Aleppo and Maritime pine were selected as the main species, whilst the rest were secondary (oaks) or accessory species, mixed differently according to the ecotope (Table 1). Sites were prepared either by backhoe (flat terrain) or by walking (steep slopes) excavator removing pre-existing natural vegetation and opening 40x50x50 cm (depth, width, length) pits. As stated in the project, all the species were planted with ventilated 60-cm-tall tree shelters, 5–10 g of hydrogel per spot, and stone cover on the ground around the plant.

To assess this factor in the comprehensive analysis pursued in this study, key decisions taken in the project were reviewed. We followed detailed checklists that help to eliminate subjectivity (Serrada et al., 2005; Dougherty and Duryea, 1991) and found that species mixture, site preparation (technique and plant density), ecotope subdivision and the use of tree shelters for conifers were arguable (Table 2) (Puértolas et al., 2010; Padilla et al., 2011). When dealing with just one single project, as in this case, the analysis of a particular variable depends only on the intrinsic variation of such a variable, thus narrowing the potential contribution of this factor. Given our limited scope for action in the project, planting without tree shelters was not possible except in an experimental plot with three reiterations (described in Del Campo et al., 2020, Fig. 2) within the boundary of the project, where both pines and the juniper were planted without shelter. Also, seedlings that had their tree shelters blown away by the end of 2008, due to windstorms and poor tethering, were included in this regard (Table 2).

2.2. Project implementation and reforestation sampling

This factor is commonly assessed by means of a network of sampling plots where quality control determines whether poor performance can

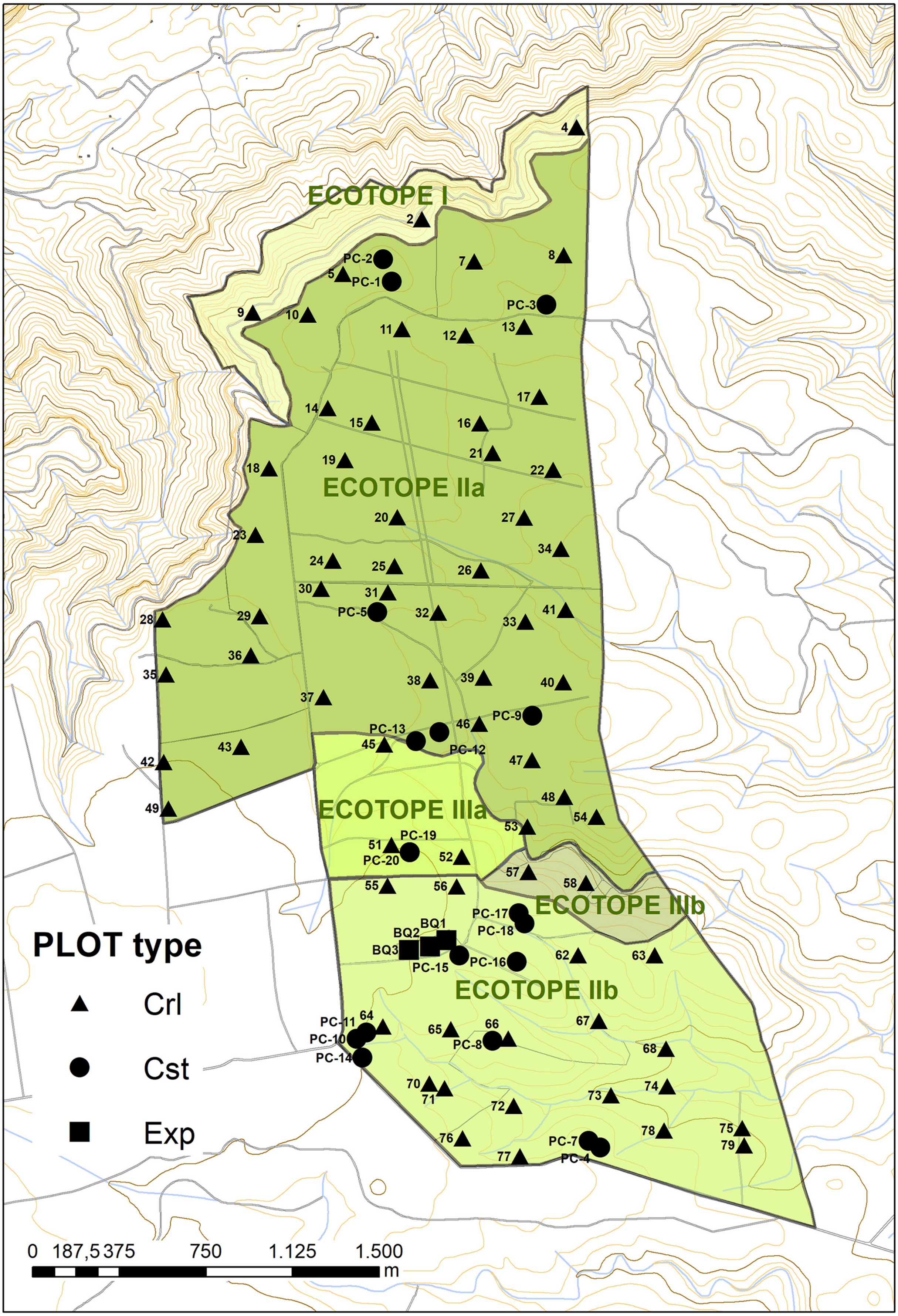


Fig. 2. Map of the reforested area with the zoning (ecotopes I, IIa, IIb, IIIa, IIIb) and layout of the sampling plots network, including 70 control plots (Crl, #), 19 contrast plots (Cst, PC-#) and three blocks or repetitions of an experimental plot located in a representative area (Exp, BQ-#).

be attributed to poor execution of the work (Matney and Hodges, 1991; Torres and Magaña, 2001). Field sampling is complemented by a work diary, which collects information relating to the different tasks, dates, crews, meteorological constraints, etc. Both elements were taken into account in this study. A network of 92 plots was laid within the boundary of the reforestation project (see below). Three different types of plots were considered: control plots ($n = 70$), contrast plots ($n = 19$) and experimental plots ($n = 3$) (Fig. 2). The only difference between control and contrast plots is that the latter are planted in the presence and under the indications of the work management. The experimental plots are three replicates of a statistical design aimed to test stock quality and species performance described elsewhere (Del Campo et al., 2020). The plot is the basic unit used here to gather most of the information (technical and environmental) of the reforestation and to process and analyze the data.

Instead of calculating the sampling intensity for just one single variable as a function of its variance, maximum admissible error and level of confidence (t statistic) (Matney and Hodges, 1991), a fixed percentage was considered more suitable here, as we were measuring many variables of a very different nature in an integrated fashion per plot. Systematic sampling used circular plots with a fixed area of 707 m^2 each (15 m radius) (Torres and Magaña, 2001), as these are easy to install and mark (one point). They also fitted better the lack of rows-and-columns arrangement in this reforestation (which would have been advised for a rectangular plot design). The number of plots was established from the ratio between sampling intensity (total area to be sampled) and the area of the sampling plot. In general, the lower the planting density, the larger the plots and the lower their number. Sampling intensity was set to be 1% of the total planted area, following Murillo and Camacho (1997). The plots were located at the vertices of an imaginary grid with a side of 100 m, with their coordinates generated with a GIS and entered into a GPS. Then, a sampling route was created with all georeferenced points. The first point (or plot) was chosen at random. The center of all plots was marked with a wooden stake with the plot number. A Vertex IV© ultrasound instrument was used to measure the radius, which was corrected with cos α (α being the angle of the slope in radians) whenever the slope was above 15%. For some variables (Tables 2 and 3) it was necessary to sample within the plot, in which case this was carried out at equidistant points falling on concentric circumferences from the central point.

The variables selected for the evaluation of project work were those related to planting (plant density, gang, date, soil moisture at planting and proper location of seedling in the spot), site preparation and cultural treatments (Table 2 and SM1). Site preparation took place between Sep-2007 and Jan-2008 and planting was done manually between Nov-2007 and early Feb-2008 by three planting gangs. An external contractor controlled the quality of site preparation, rejecting inadequate spots when they were too shallow. Part of the information gathered in this study comes from records in the work diary (e.g., planting gang or planting dates), whereas most variables were measured in the whole set of 92 plots (Table 2 and SM1). For those variables measured only in a subsample of plots, their value was calculated for the whole set whenever a goodness of fit of $r^2 > 0.6$ was achieved (linear regression or neural networks, see Section 2.6). The stock used in the plantation was grown for use in large-scale reforestation programs and matched the regional standards (Hermoso, 2017). Stock quality was only considered for Aleppo pine, as two stock lots from different forest nurseries were used in the plantation.

2.3. Environment: ecological site factors

Environmental factors were separated into site- and meteorology-related variables (Table 3 and SM1). The site was subdivided into topographic, soil, vegetation cover and remotely sensed vegetation indexes (SVI). Meteorology comprised both planting weather and drought occurrence throughout the study period. It should be mentioned that some environmental factors are partially under technical control (e.g., site factors can be modified, proper planting weather can be chosen, etc.), whilst others are unpredictable and hard to modify (e.g., meteorological drought).

Topographic variables (aspect, slope and elevation, Table 3) were obtained with GIS software (QGIS3) for each sampling plot. Soil properties were obtained in a ramdom subset of 29 plots by collecting a composite sample in 5 different spots chosen at random from soil in the top 25 cm of the profile. Texture and organic matter were analyzed in this subset (Aparicio Navarro, 2010), and their values calculated for the remaining plots by means of an artificial neural network, using Landsat indexes as independent variables (MSI, NDMI, ARVI, NBRI, EVI2 and NDVI, Table 3). Then, organic matter ($r^2 = 0.61$), clay ($r^2 = 0.77$), sand ($r^2 = 0.61$) and silt percentages were extrapolated to the entire network of plots. By introducing sand and clay contents in Saxton and Rawls (2006) equations, hydro-physical properties of soil were calculated (Table 3). Also, soil moisture was monitored in all the plots in 9 field campaigns from Mar to Nov 2008 by means of a TDR (TDR-300, soil moisture meter, 10 cm rods, Field Scout, Spectrum Tech. Inc., 5 points/plot). The time-averaged value of each plot was used as a mean indicator of soil moisture per plot (SM_index, Table 3). Vegetation cover variables were obtained either directly on the spot by means of transect inventories (total cover and partial cover by species, Table 3) or indirectly with LiDAR data used to calculate forest structure variables (shrub cover and height, Table 3). Two available LiDAR flights (2009 and 2015) were used (PNOA, National Plan of Aerial Ortophotogrammetry, Spanish Government), with a final average density of 0.88 pulses/m^2 and vertical and planimetric (X, Y) errors less than 40 and 36 cm, respectively. Based on point classification by the National Cartographic Institute (ground, building, low vegetation, high vegetation, low points, overlap points and unclassified), the digital terrain model and the canopy surface model were created using Fusion v3.30 software. The metrics retrieved from both LiDAR flights were considered as static and independent indicators of site (plot) quality regardless of time. Remotely sensed vegetation indexes (SVI) were retrieved from Landsat surface reflectance images. Landsat 5 and 7 images were used to calculate ARVI, BSI, EVI2, GCI, GNDVI, MSI, NBRI, NDMI, NDVI, NDWI and SAVI indexes (Table 3) by using near-monthly scenes from December 2007 to November 2009, 2014 and 2018 (2014 was included due to the severe drought occurring that year and was used in the 10th-year assessment, see next section). The scenes were aggregated to the year and the maximum, minimum and average values of each index per sampling plot were computed (the bands have a spatial resolution of 30 m and the plot is 707 m^2).

2.4. Environment: meteorology

Meteorology was monitored by instruments installed in plot number 36, located on the center-left of the area (Fig. 2). Different sensors were arranged to measure precipitation (P, Davis 7852), temperature (T, Hobo S-THA-M002), relative humidity (RH, Hobo S-THA-M002) and soil moisture both in the unaltered soil (SM_soil, Decagon EC-20) and in the stirred soil of the planting spot (SM_spot, Decagon EC-10 and EC-20). Sensors were connected to a data logger (HOBO® Micro Station H21–002) and programmed to store data every 15 min. The value of soil moisture in this plot was used, together with the above-mentioned soil moisture index of each plot (SM_index), to correct and adjust a value of soil moisture at planting date for each sampling plot (Table 2 and SM1). Environmental conditions were monitored throughout 2008–2009 (soil moisture only in 2008) and averaged or totalized on a daily basis. T/RH series were gap-filled and lengthened up to 2019 by regressing the measured values on the corresponding series recorded at the SAIH Requena-Cerrito observatory ($r^2 = 0.85$ and $r^2 = 0.72$ for T and RH, respectively) (SAIH weather network). P data were taken directly from the SIAR network (Casa del Barón) due to the proximity of the station to the study site. Seasonal droughts in the three assessments (2008, 2009 and 2018, see 2.) were characterized as the maximum negative magnitude of the SPI index (McKee et al., 1993),

Table 1
Main characteristics regarding technical decisions of the reforestation project for the five ecotopes or intervention zones. Species: *Pinus pinaster* Ait. (Maritime pine, PIPR), *P. halepensis* Mill. (Aleppo pine, PIHA), *Quercus ilex* subsp. *ballota* (Desf.) Samp. (Holm oak, QUIL), *Q. faginea* Lam. (Lusitanian oak, QUFA), *Arbutus unedo* L. (Strawberry tree, ARUN), *Fraxinus ornus* L. (Flowering ash, FROR) and *Juniperus phoenicea* L. (Phoenician juniper, JUPH).

Ecotope	Area ha	Measures foreseen in the project	Species percentage					Density (plant/ha) foreseen/planted	Site preparation
			PIPR	PIHA	QUIL	QUFA	ARUN^a/FROR^b/JUPH^c		
I	49	Reforestation	36	50	6	2	6^a	850/782	Walking excavator
IIa	395	Reforestation	49	43	4	3	1^c	850/434	Backhoe exc.
IIb	202	Reforestation	50	40	5	4	1^b	850/358	Backhoe exc.
IIIa	44.5	Reforestation, scrub clearance, thinning/pruning small oaks	23	15	35	25	2^a	100/382	Backhoe exc.
IIIb	18.5	Reforestation thinning/pruning small oaks	29	64	5	2		500/304	Backhoe exc.

which measures anomalies of accumulated precipitation during a given period (3 months in this case).

Meteorological variables changed markedly over the time period (Fig. 3), with year 2008 (planting) being the wettest (730 mm), whilst years 2012 and especially 2014 were well below the average, with only 183 mm (less than 40% of the expected value) falling between Sep 2013 and Aug 2014. According to the 3-month SPI value, this drought lasted 15 months, peaked at −2.1 and had a magnitude of −14.8 (SPI units, Fig. 3), which highlights the considerable anomaly of this drought. In 2009, with 558 mm of total rainfall, there was a shorter dry spell between Apr 09 and Aug 09 (35% of the expected value). Mean annual temperature increased from 2014 onwards, averaging 13.3 °C and 15.1 °C for the first and second halves of the period studied, respectively (data not shown). Soil moisture (2008) was above wilting point in 2008 in the undisturbed soil (22%, assuming a bulk density of 1.27 g/cm^3) except for the summer months, as expected. The oscillations of soil moisture were, however, much more pronounced in the disturbed soil of the planting spots (Fig. 3).

2.5. Plantation performance monitoring

Monitoring of the reforestation was more intensive in late 2007 and 2008, with various assessments and measurements performed. The execution of the work was assessed between Nov-2007 and April-2008. Plantation performance was assessed by repeated measurements of height (H, cm), basal diameter (D, mm) and mortality after the first growing season (Jun-2008), after the first summer drought (Nov-2008), after the second year (Nov-2009) and after the tenth year (Jul-2018). Seedling mortality was assessed for all the seedlings within the 92 plots (mean number of seedlings and its standard deviation per plot was 30 ± 13), whereas growth was assessed in a ramdom subsample of 10–12 seedlings in a subset of 31 plots; each plant was individually labeled. For ease of representation, assessments in Jun-2008, Nov-2008, 2009 and 2018 are coded as 2, 3, 4 and 5, respectively. Stem volume (Vol, cm3) was calculated as an integrated metric of seedling size by using the formula for an elliptical cone, $V = (\pi D^2/4)H/3$, where D is the diameter and H is the height.

2.6. Data analysis

Variables were grouped into generic factors (technical and environmental) and subfactors (design, works implementation, site [topography, soil, SVI, vegetation cover] and meteorology). Non-linear statistical methods were used to frame the proposed methodology, although linear correlations (bivariate - Spearman), factor analysis and parametric and non-parametric ANOVA's were also used to further explore and reduce the dataset. In the ANOVA, data were examined to ascertain whether the variables were normally distributed and the

Table 2
Variables selected to assess the impact of technical-related factors (project design, project implementation and stock quality) on plantation performance. Superscripts refer to the method used for gathering the information (see Table foot-notes). Cat(): categorical variable (number of categories). Additional statistics for each variable are provided in Table SM1.

Factor	Variable	Mean	Units and description
Project design	%_SpX$^{(1)}$	14.3	% of a given species (X) in a sampling plot (X coded as 0: PIPR; 1: PIHA; 2: QUIL; 3: QUFA; 4: ARUN; 5: FROR; 6: JUPH).
	%_Notube_SpX$^{(1)}$	4	% of planted spots without tubes either for the whole sampling plot (all species integrated) or specifically in PIPR (X = 0) or PIHA (X = 1).
	Site_prep$^{(2)}$	–	Site preparation technique: Backhoe excavator, Walking excavator.
	Spot_Dens$^{(1)}$	436	Site preparation density per sampling plot (spots/ha).
	Ecotope$^{(3)}$	–	Zonation in homogeneous ecological classes or ecotopes (Table 1).
Works' implementation	Plant_Gang$^{(2)}$	–	Planting gang. Three planting crews (6–8 persons each) were hired.
	Plant_date$^{(2)}$	6/01	Planting date: 20-Nov-2007 (day 1, 39,406 in Excel© software) to 5-Feb-2008 (day 77, 39,483 in Excel©).
	Plant_Dens$^{(1)}$	405	Planting density (trees planted/ha).
	ΔDens$^{(4)}$	−31	Difference between Spot_Dens and Plant_Dens. Positive values: prepared spots were rejected after quality control. Negative values: planting done, erroneously, on ground marks made by the stabilizer legs of the excavator.
	SM_soil20_p$^{(4)}$	0.27	Soil Moisture (SM) m3/m3 at planting date (upper 20 cm of undisturbed soil).
	SM_spot10_p$^{(4)}$	0.18	Shallow SM m3/m3 in the planting spot at planting date (upper 10 cm of disturbed soil at the planting spot). Replacing "p" with a number "n" refers to the same variable after n days.
	REW_soil$^{(4)}$	0.33	Relative extractable water at planting date in undisturbed soil (upper 20 cm): (value at planting date - PWP)/(FC -PWP). FC (field capacity) and PWP (wilting point) as in Section 2.3. Negative values were allowed due to the theorical basis of FC and PWP calculations.
	REW_spot$^{(4)}$	−0.24	Relative extractable water at planting date of disturbed soil at planting spot (upper 10 cm). Same calculations as in REW_soil.
	Spot_rejec$^{(2)}$	7.7	% of prepared spots rejected during the quality control in a sampling plot before planting.
	StoneCover_size$^{(1*\#)}$	0.54	Size of stones used to cover the ground around a planted seedling (0: no stone cover; 0.5 inappropriate size and/or cover of stones around a seedling; 1: appropriate size and cover 10–20 cm ø).
	Proper_planting$^{(1*\#)}$	73.5° 0.96	Planting quality (Long, 1991): plug orientation (angle with the horizontal plane, 90°: correct) and firmness (0: poor; 0.5: fair; 1: correct/fault-free) in excavated seedlings.
	Spot_Basin$^{(1*\#)}$	0.96	Quality of the micro-basin around a planted seedling (0: absent/poor; 0.5: fair; 1: correct/fault-free).
Stock quality	SQ-PIHA$^{(1,2)}$	–	Stock Quality (only in PIHA, two stock lots were used).

$^{(1)}$ Direct observation/counting in sampling plots; $^{(2)}$ Query in works diary and/or provided by the works management; $^{(3)}$ Planning project, maps and GPS; $^{(4)}$ Spreadsheet calculation; * not available for the whole set of plots (92) and segregated in the analysis of importance. # sub-sampled ($n = 5$) within the sampling plot.

Table 3
Variables selected to assess the impact of environmental factors (site: topography, soil, vegetation cover and remotely sensed vegetation indexes or SVI; and meteorology) on plantation performance. Superscripts refer to the method used for gathering the information (see Table foot-notes). Additional statistics for each variable are provided in Table SM1.

Factor	Variable	Mean	Description
Site_Topography	m.a.s.l.$^{(1)}$	777	Elevation, m
	Aspect$^{(1)}$	119	Aspect, degrees (0° = north, counterclockwise)
	Slope$^{(1)}$	5.3	Slope, %
Site_Soil	Soil_depth$^{(2,\#)}$	35.5	Average soil depth (cm) in a plot (n = 5–10), manual auger.
	SM_index$^{(2)}$	14.2	Soil Moisture index: average SM (TDR, %) in planting spot (disturbed upper 10 cm) during 2008 ($n = 45$ per plot).
	OM$^{(3)}$	6.3	Organic matter, %
	Clay$^{(3)}$	39	Clay, %
	Silt$^{(1)}$	37	Silt, %
	Sand$^{(3)}$	24	Sand, %
	Porosity$^{(1)}$	52	Porosity, % (with sand and clay contents, Saxton and Rawls, 2006).
	PWP$^{(1)}$	22	Permanent wilting point, % (Saxton and Rawls, 2006).
	FC$^{(1)}$	37	Field capacity, % (Saxton and Rawls, 2006).
	Ks$^{(1)}$	0.28	Saturated Hydraulic conductivity, mm/h (Saxton and Rawls, 2006).
	AW$^{(1)}$	15	Available water, % (Saxton and Rawls, 2006).
	BD$^{(1)}$	1.28	Bulk density, g/cm^3 (Saxton and Rawls, 2006).
Site_Vegetation cover	Elev_P95$^{(1)}$	0.75	Height of vegetation above ground (percentile 95%, LiDAR 2009 and 2015), m.
	fcc05$^{(1)}$	5	Fraction of canopy cover above 0.5 m plane (LiDAR 2009 and 2015), %.
	Int_mean$^{(1)}$	135, 2009 14, 2015	Mean intensity of the Lidar returns (LiDAR 2009 and 2015). Related to stoniness on surface (> intensity on rocks). Dimensionless and varying with flight characteristics (different value and range in each flight).
	Cover_invt_%$^{(2*)}$	61	Total plant cover in field inventories, %.
	XXXX_cvr_%$^{(2*)}$	4.5	Plant cover, %, of the species XXXX in field inventories, % (XXXX stands for BRRE: *Brachipodium retusum*; ULPA: *Ulex parviflora*; QUIL: *Quercus ilex*; CICL: *Cistus clusii*; PIHA *Pinus halepensis*). Only species with significant correlations mentioned in this Table.
Site_SVI	ARVI$^{(1)}$	0.08	ARVI: Atmospherically Resistant Vegetation Index. (Kaufman and Tanre, 1992).
	BSI$^{(1)}$	0.16	BSI: Bare Soil Index. Values range between −1 and 1 (> value indicates a > cover of bare soil). The BSI is more reliable in situations where the vegetation covers less than half of the area (Rikimaru et al., 2002).
	EVI2$^{(1)}$	0.42	EVI2: Enhanced Vegetation Index 2. Used to measure vegetation greenness. More sensitive in areas with dense vegetation (Jiang et al., 2008).
	GCI$^{(1)}$	1.2	GCI: Green Chlorophyll Index. Useful for monitoring the impact of seasonality and environmental stresses (Gitelson et al., 2003).
	GNDVI$^{(1)}$	0.33	GNDVI: Green NDVI. Commonly used to determine water and nitrogen uptake into the plant canopy (Gitelson et al., 1996).
	MSI$^{(1)}$	1.6	MSI: Moisture Stress Index. The values of this index range from 0 to more than 3, with the common range for green vegetation being 0.2 to 2 (Rock et al., 1986).
	NBRI$^{(1)}$	0.06	NBRI: Normalized Burn Ratio Index. Takes advantage of the NIR and SWIR, which are sensitive to vegetation changes, to detect burned areas and monitor the recovery of the ecosystem (Key and Benson, 1999).
	NDMI$^{(1)}$	−0.11	NDMI: Normalized Difference Moisture Index. Developed by Gao (1996). Soil contributions to NDWI are mostly negative, whereas green vegetation contributions are positive. -1 to 0 is a bright surface with no vegetation or water content; >1 represents water content.
	NDVI$^{(1)}$	0.23	NDVI: Normalized Difference Vegetation Index.
	NDWI$^{(1)}$	−0.33	NDWI: Normalized Difference Water Index.). Thresholds: < 0.3 are for non-water; ≥ 0.3 for water. (Gao, 1996; McFeeters, 1996; Xu, 2005)
	SAVI$^{(1)}$	0.25	SAVI: Soil Adjusted Vegetation Index.(Huete, 1988).
Meteorological	Temperature$^{(2)}$	7.8	Maximum (Tmx), Mean (T) and Minimum (Tmn) temperatures during the planting day, °C. Recorded at plot#36.
	RH$^{(2)}$	77	Relative Humidity on the planting day. Recorded at plot#36.
	P_10days$^{(2)}$	0.8	Cumulative 10-day rainfall, mm, at planting date (planting day = 5th day). Recorded at plot#36.
	ET_10days$^{(1,2)}$	8.2	Cumulative 10-day evapotranspiration, mm, at planting date (planting day = 5th day). Hargreaves method (temperature from plot#36 and solar radiation from Requena-Cerrito Met. Station).
	SPI3mo_MxMag$^{(1)}$	−7.5	Maximum magnitude of the 3-month drought SPI index (McKee et al., 1993) between two consecutive assessments of mortality.

$^{(1)}$ Calculated by using specific databases, software and/or spreadsheet. $^{(2)}$ Direct observation/counting in sampling plots; $^{(3)}$ Inferred from data gathered in a subset of plots; * not available for the whole set of plots (92) and segregated in the analysis of importance; $^{\#}$ sub-sampled within the sampling plot. In the meteorological set, no spatial variability was taken into account.

variances homogeneous. When these assumptions were violated a non-parametric Mann-Whitney *U* test and the Moses test were used to test for differences between groups. Artificial Neural Networks (ANN) calculated soil properties by means of the MLP (Multilayer Perceptron Network) in SPSS 22.0 (IBM Corp., 2013).

The different factors, subfactors and variables (i.e., predictors) were related to plantation performance indicators (mortality and growth in height, diameter and stem volume) through boosted regression tree (BRT) models performed in R software (R Core Team, 2015) using the "gbm" package (Ridgeway, 2017; Elith and Leathwick, 2017). BRT is a machine learning technique that has provided clear evidence of strong predictive performance and reliable identification of relevant variables and interactions in ecological studies (Elith et al., 2008). The relative importance (RI) or contribution of predictors was assessed. RI measures the number of times a predictor variable is selected for splitting, weighted by the squared improvement in the model as a result of each split, averaged over all trees and scaled so that the sum adds to 100 (Elith et al., 2008). The higher the RI, the stronger the influence of the predictor in the response variable. For those predictors with higher RI, partial dependency plots (PDP) were produced by using the same package in R. In the case of mortality, these analyses were done for 2008 ($n = 92$), 2008–2009 ($n = 184$) and 2008–2018 ($n = 276$). In the last two cases, some variables remained constant in a plot over time (e.g., design, work implementation), whilst the variables with temporal variation (SVI and drought) changed with the assessment date. Growth was studied for the lapses of early (2008–2009) and mid-term (2008–2018) growth. In this case, a temporal variable (months since planting) was added to allow for the direct relationship between growth and time. The analyses employed a Gaussian distribution family, learning rates of 0.05–0.0001, tree complexity of 4–15, and bag fractions of 0.5–0.75. The minimum number of trees was in most cases above 1500. In the fitted models, the correlation coefficient was used for

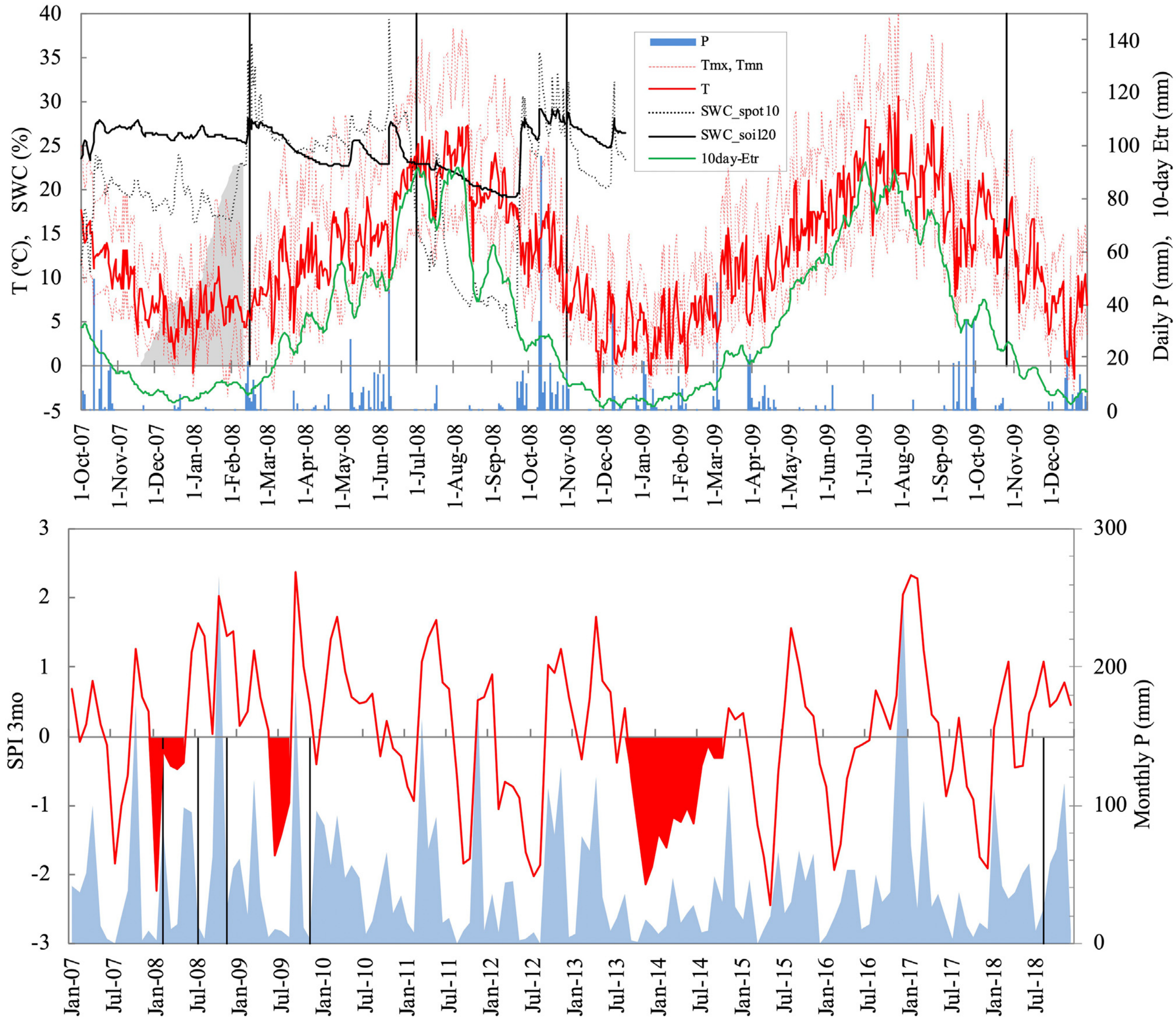


Fig. 3. Environmental and climatic variables during the first two years (up) and 10 years of the study period (bottom): daily (up) and monthly (bottom) precipitation (P, mm), maximum, minimum and average daily temperature (Tmx, Tmn and T respectively), cumulated 10-day evapotranspiration (10 day Etr, mm), soil water content of both the undisturbed soil and the planting spot (SWC, %) and the 3-month value of SPI drought index (red areas indicate the most severe drought between two consecutive assessments). Vertical black lines indicate the assessment dates. Planting season is also showed as the shaded gray area in upper panel left (representing cumulated number of plants x 10,000 on the left y-axis). SPI < -1.5 has probability of 2.7% and drought is severe; SPI < -2.0 has 1.7% probability and drought is extreme. Detailed plots presented as Figure SM1.

goodness of fit. The results of this analysis provide the RI of the set of predictors for the response variables (mortality and growth).

3. Results

3.1. Out-planting mortality and growth over time

Excluding the experimental plots, where all the species were equally represented, the frequencies observed for the seven species planted in the remaining 89 plots were very close to those foreseen in the planning project (sampled values were 46.4, 42.1, 5.8, 3.9, 1.1, 0.3 and 0.4% for PIPR, PIHA, QUIL, QUFA, ARUN, FROR and JUPH, respectively, whilst the designed percentages were 46.2, 41.4, 6.4, 4.6, 0.5, 0.3 and 0.6%, respectively), which validates the sampling.

Average plantation mortality of all species increased progressively over time from the second assessment in Jun 2008 (3.6 ± 4.5%) to the fifth in Jul 2018 (82.6 ± 13.3%), with interim values of 25.9 ± 17.6% in Nov 2008 and 52.6 ± 21.5% in Nov 2009 (Fig. 4). Mortality varied with the species, with both Juniper and Aleppo pine showing below-average mortality, whilst the two oaks and the Maritime pine suffered above-average mortality from the very beginning of the plantation. The Flowering ash and the Strawberry tree performed quite well until the second year, but mortality sharply increased for both species in the final assessment in 2018 (Fig. 4).

Together with temporal variability, mortality also showed marked spatial variability across the area (Fig. 5), with no clear spatial pattern except for a central strip in the fourth assessment (Nov 2009), where higher mortality was glimpsed, although it had faded away by the last assessment (Fig. 5, center and right). Ecotope IIa registered the highest mortality in the first two years (35% and 60% in assessments 3 and 4, respectively), whereas in ecotope IIIa mortality ranged between 9% (2008) and 39% (2009). After ten years, mortality in all the ecotopes ranged between 80 and 87%, except in ecotope I (north-facing), which had 70% dead plants. These overall figures result from a combination of the performance observed in the two main species, i.e. Maritime and Aleppo pines. Both species showed similar mortality in the 3rd

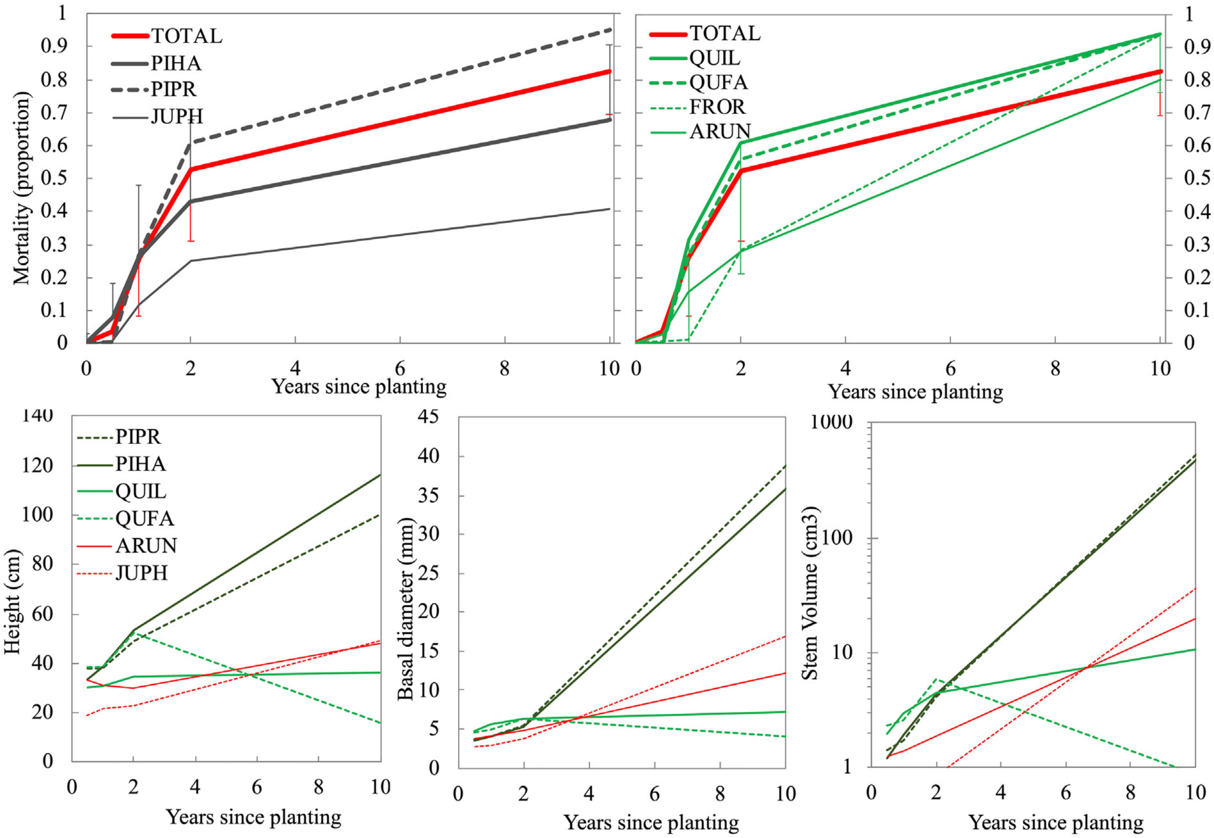


Fig. 4. Plantation performance along the 10-year's period in the five assessments carried out presented as proportion of mortality in conifers (top left) and hardwood species (top right), and as growth in height, basal diameter and stem volume (bottom). Aleppo pine (PIHA), Maritime pine (PIPR), Phoenician juniper (JUPH), Holm oak (QUIL), Lusitanian oak (QUFA) and Strawberry tree (ARUN) and Flowering ash (FROR). Bars correspond to standard deviations (presented only in mortality for Total, Aleppo pine and Holm oak for simplicity).

assessment (Nov 2008), but thereafter their mortality trends diverged markedly (Fig. 4, Fig. SM2).

Growth performance was assessed in 31 plots, where both pines showed the highest growth increments, especially for stem volume at the end of the study (> 450 cm^3/plant on average) (Fig. 4). All hardwoods and the juniper (no ash was found in this subsample) showed lower growth rates than pines and, in some cases, the 10-year value was even lower than at planting time, as observed for the oaks. This

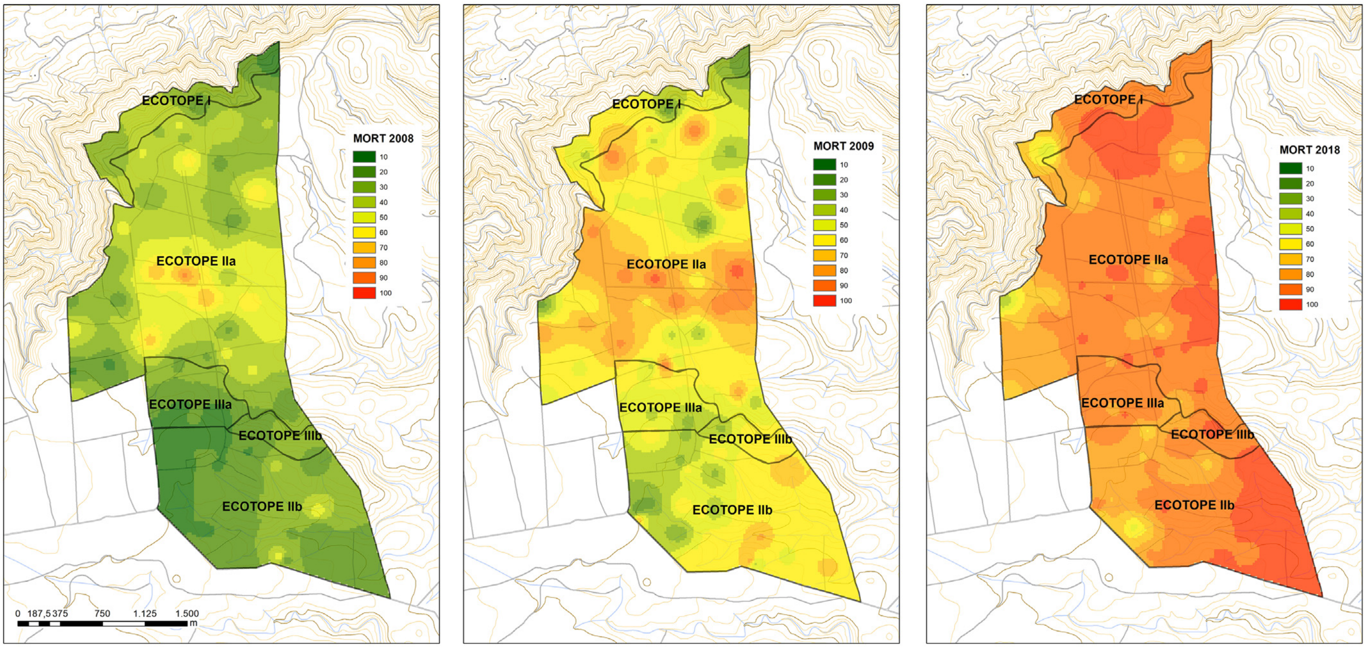


Fig. 5. Spatial representation of total mortality (%) averaged across species according to the assessments performed after the first (left), second (center) and tenth (right) year of outplanting. Dots represent the network of plots (control plots, contrast plots and experimental blocks) distributed within the five ecotopes of the project.

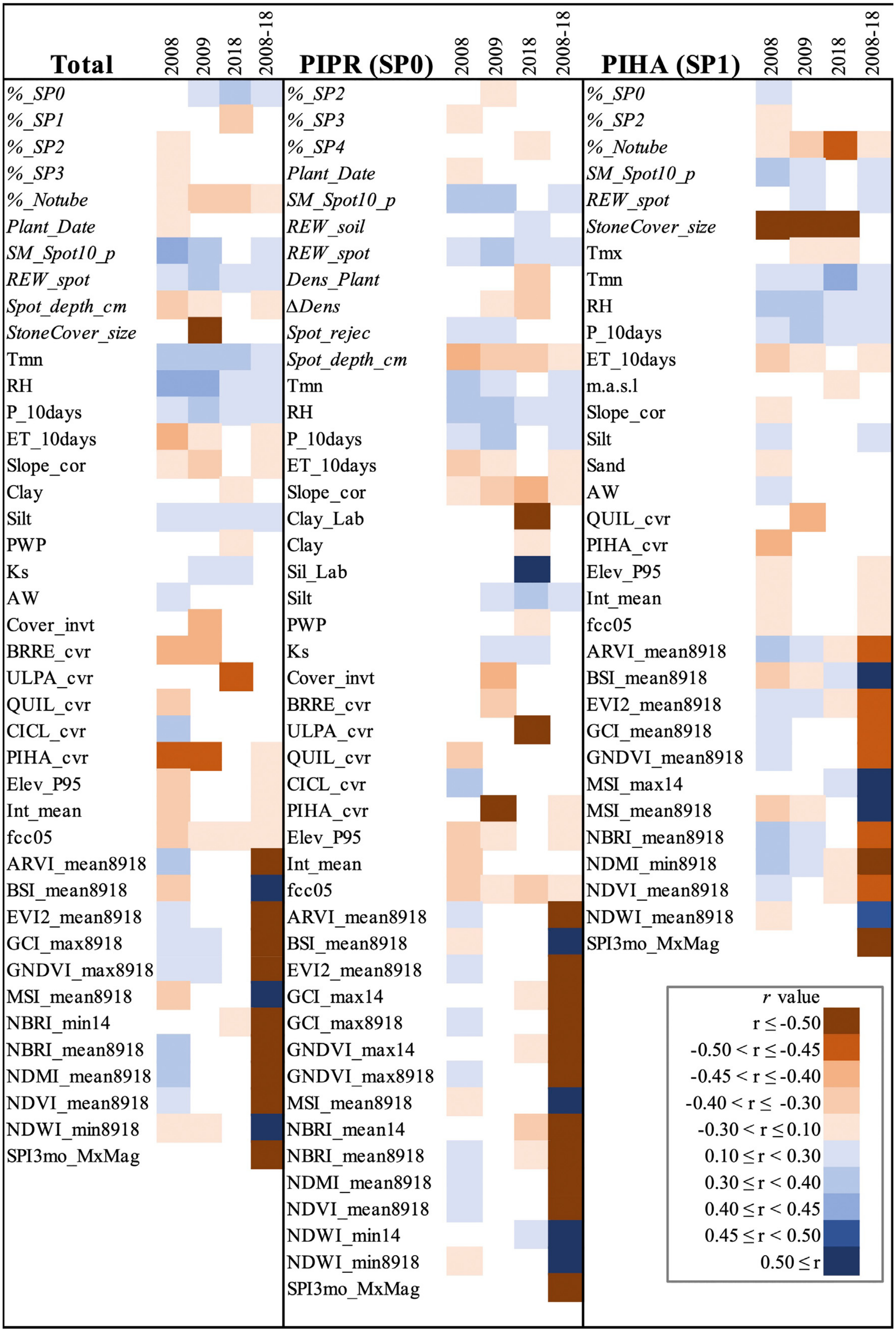


Fig. 6. Significant correlations of different plantation variables (technical, in italic style, and environmental) to plant mortality after the first year 2008 (3), the second year 2009 (4), the tenth year 2018 (5) and for the ten year's period (3–5). Figures following a SVI refer to the year (8:2008; 9:2008; 14:2014; 18:2018. 2014 values were considered in 2018's mortality assessment only if they added nonredundant information). See Tables 2 and 3 for explanation on the variables of the plantation.

Table 4

Summary of the Boosted Regression Trees (BTR) models fitted for plantation mortality and growth for all the species together and separately for the two pines (PIPR and PIHA) as the main species. Mortality was modeled at the end of the first (2008), second (2008–09) and tenth year (2008–18). Growth in height (H), diameter (D) and stem volume (Vol) was modeled for the first two years (2008–09) and for the entire period (2008–2018). In BRT, the measure of model fit is the total % deviance explained and model predictive performance (the mean cross-validation (c-v) correlation coefficient of observed vs predicted values derived from 10 folds). se: standard error of the coefficients.

	Model	Trees (No.)	Mean total deviance	Mean residual deviance	Estimated c-v deviance (se)	Training data correlation	C-V correlation (se)
Total	Mortality 2008	3150	303.3	1.88	177.7(35.6)	0.99	0.70(0.05)
	Mortality 2008–09	3300	556.4	0.19	192.5(24.8)	1.00	0.82(0.02)
	Mortality 2008–18	2450	851.2	3.85	192.5(14.3)	0.99	0.88(0.01)
PIPR	Mortality 2008	4500	0.058	0.017	0.043(0.009)	0.90	0.58(0.09)
	Mortality 2008–09	2250	0.095	0.001	0.044(0.004)	0.99	0.75(0.023)
	Mortality 2008–18	1450	0.126	0.003	0.032(0.003)	0.99	0.87(0.016)
PIHA	Mortality 2008	2050	0.049	0.005	0.033(0.005)	0.97	0.61(0.05)
	Mortality 2008–09	2000	0.063	0.005	0.037(0.005)	0.97	0.67(0.033)
	Mortality 2008–18	2100	0.084	0.002	0.039(0.003)	0.99	0.74(0.016)
Total	D.Growth 2008–09	700	0.977	0.56	0.705(0.037)	0.82	0.71(0.043)
	D.Growth 2008–18	1300	9.88	1.93	2.67(0.23)	0.94	0.92(0.011)
	Vol.Growth 2008–09	850	1.51	0.85	1.02(0.07)	0.76	0.69(0.032)
	Vol.Growth 2008–18	1200	152.3	47.48	58.64(11.06)	0.80	0.81(0.032)
	H.Growth 2008–09	750	175.18	82.6	120.8(9.81)	0.74	0.56(0.031)
	H.Growth 2008–18	3750	24.93	10.2	13.1(0.27)	0.90	0.84(0.019)

pattern indicates that either the seedlings are dying from the top (i.e., resizing their shoot part) or that only smaller seedlings survived (thus lowering the sample's average).

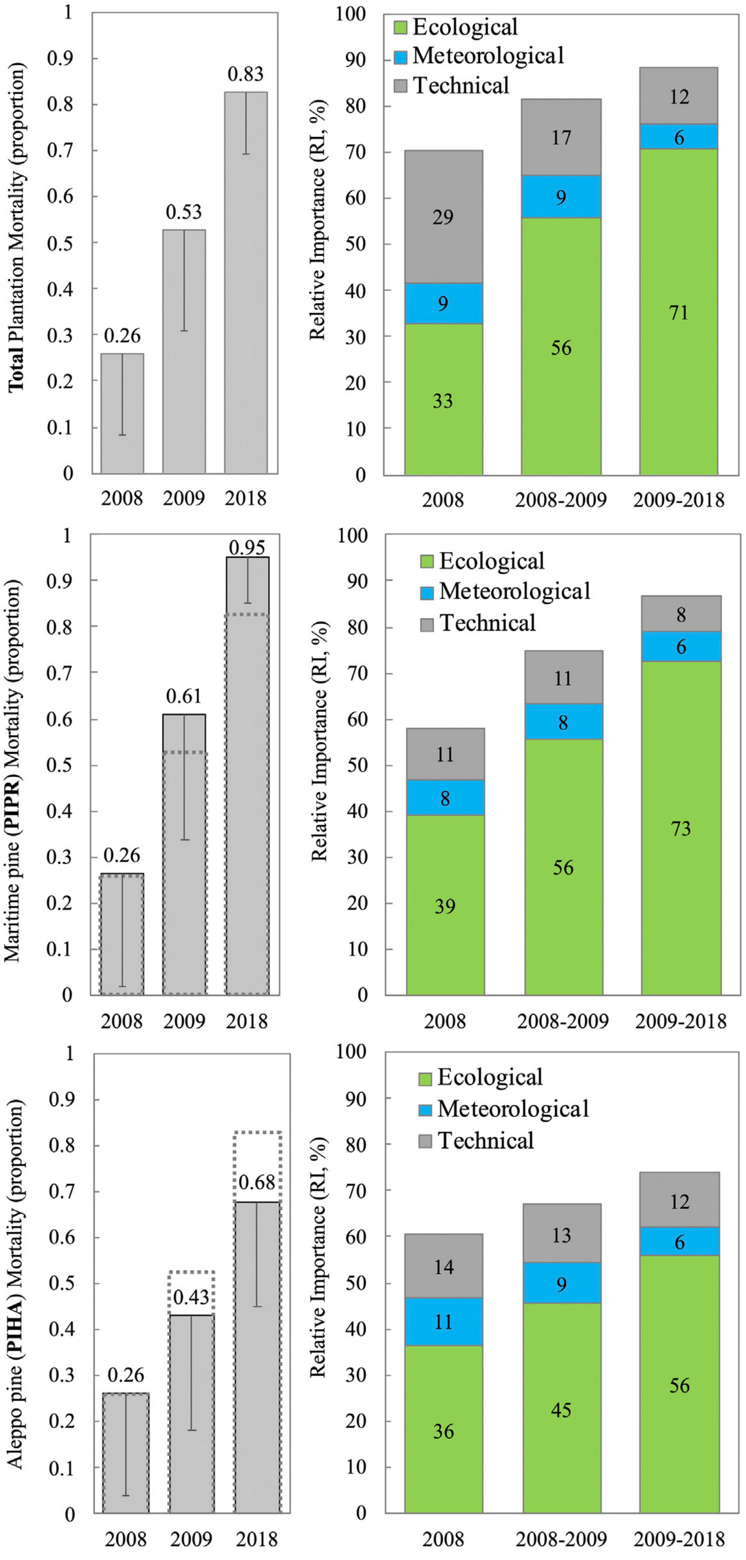
3.2. Relative importance of technical and environmental factors in plantation performance

Both technical and environmental variables correlated significantly with plantation mortality in the single-year analyses (2008, 2009 and 2018) and for the 10-year trend (2008 to 2018) (Fig. 6). In general, technical variables correlated with mortality more in the early assessments and showed no change in their correlation, regardless of the year or time lapse being considered. Some correlations are worth highlighting: the higher the proportion of Maritime pine in a plot, the greater the mortality. Something similar can be said for tree shelters (especially in Aleppo pine). There were more significant correlations with technical variables in Maritime pine than in Aleppo pine. Worth mentioning is the positive relationship between shallow soil moisture at planting time (at the planted spot) and mortality. Along these lines, meteorological variables at planting time also showed counter-intuitive signs in their correlations (e.g. relative humidity, temperature, evapotranspiration and rainfall, Fig. 6). Correlations with SVI stood out when the temporal lapse was considered, i.e., when the values of mortality for 2008, 2009 and 2018 were correlated with the corresponding SVI values (mean) of each year. The spatial variation of SVI across the plantation also correlated with mortality in the single-year assessments, although with alternating signs between the early assessments and the last one. Finally, the drought index (SPI), which only has temporal variation (same value for all plots on the same date), correlated strongly with the temporal evolution of mortality ($r = -0.72$; $p < 0.01$).

BRT models were fitted to assess the RI of the factors and variables involved in plantation performance, obtaining cross-validation correlations above 0.56 in all cases and training data correlation generally above 0.90 (Table 4). In all cases, the performance of the models improved when the whole period of 10 years was taken into account. In the analysis of mortality, its first year's value (25%) was explained by technical and environmental factors equally, with weighted RI of 33 and 38%, respectively (Fig. 7). Zonation (ecotopes, 16%) and project work (planting date, planting density and soil moisture at planting time, all accumulating an RI of 8.6%) were the technical factors most involved in this early response (Table 5). However, their importance halved by the second year (16.5%) and further dropped to 12% after ten years, when total mortality was 83%. In these cases, zoning remained the most influential predictor in this set (Table 5) given the higher mortality observed in ecotopes IIa and IIb (Figs. 5 and 7).

In the environmental set, on the one hand, meteorological variables held modest RI values (ranging 5–10%), which dropped to about 6% (accumulate for the meteorological factor) at the end of the survey (Fig. 7). 10-day P and RH of the planting day were the most commonly selected predictors, with a counter-intuitive pattern between rainfall and mortality standing out (positive relationship, Fig. SM3). On the other hand, site-related or ecological factors showed higher RI than technical ones regardless of the date and the analysis performed (in Total plantation, Maritime pine and Aleppo pine, Fig. 7). Within the different subfactors, soil variables (e.g. soil depth and sand content) held more importance in the first year's assessment, whilst the SVI gained much more RI over time, given their concomitant temporal variation that other variables lack. The roles of specific soil-related predictors in Maritime pine are highlighted, such as soil depth, which must be above 30–35 cm in order to improve survival (partial dependance plots, Fig. SM3). With time, SVI gained RI, whilst the remaining factors steadily lost it in spite of the better fit of the models obtained (Fig. 7). The SVIs selected in the models differ between the second and the tenth year's assessments, with indexes such as BSI and MSI (with an interpretation inverted relative to NDVI-type indexes) holding more importance in 2009 (wet year), whilst the NDVI-type vegetation indexes (NBRI, ARVI, EVI2) acquired greater importance at the end of the study after the severe drought (Table 5). This pattern was also observed for the linear correlations, as mentioned above (Fig. 6).

Growth variables also showed higher dependence on ecological site-related factors than on other factors (Fig. 8). The species and the time since planting were most important in plantation growth, adding up to between 10% and 22% of RI, depending on the variable and the lapse of time being considered. The greater RI of species than of time in height growth was seen clearly, even for the mid-term lapse (partial dependance plots, Fig. SM4). The RI of the work on plantation growth was scattered among many different variables with little individual contribution from specific predictors (less than 2% in all cases). Soil, topographic and vegetation cover variables, with the height of the pre-existing scrub reaching the maximum RI value of just 3% in the early diameter growth, were found to be similar. However, the SVI proved to be very important in explaining plantation growth, especially EVI2 and GCI, with ARVI and NBRI following them in cumulative RI (Fig. SM4). It is notable that, in most cases, the relationship between these indexes and growth reflects a competition effect, with higher values in the indexes indicating less plant growth, especially in 2008–2009, when, for instance, volume growth was primarily affected by EVI2 values below 0.4 (Fig. SM4).



Predictor set	2008	2008-09	2008-18
	Total plantation		
Ecol. Topography	6.5	5.9	2.8
Ecol. SVI	9.5	36.9	59.3
Ecol. Veg. cover	6.7	5.6	3.1
Ecol. Soil	10.1	7.4	5.4
Meteorological	8.9	9.3	5.7
Project design	17.8	8.9	6.5
Project works	10.8	7.6	5.5

Predictor set	2008	2008-09	2008-18
	Maritime pine (PIPR)		
Ecol. Topography	3.8	3.6	1.8
Ecol. SVI	6.8	34.7	58.7
Ecol. Veg. cover	15.0	7.5	4.6
Ecol. Soil	13.4	10.0	7.5
Meteorological	7.9	7.6	6.2
Project design	4.2	2.8	2.3
Project works	6.6	8.7	5.8

Predictor set	2008	2008-09	2008-18
	Aleppo pine (PIHA)		
Ecol. Topography	7.7	7.2	5.3
Ecol. SVI	20.1	25.1	39.3
Ecol. Veg. cover	2.6	5.7	5.3
Ecol. Soil	5.9	7.4	5.9
Meteorological	10.6	8.8	6.3
Project design	6.4	3.7	3.5
Project works	7.2	8.3	7.7
Stock Quality	0.2	0.6	0.4

Fig. 7. Relative importance (weighted values, %) that the different factors/subfactors (or sets of predictors) had on plantation mortality (represented on the left). Results are presented for different temporal assessments (2008, 2008–09 and 2008–18) and either for the total plantation mortality (up) or for the main species of the project (PIPR, center, and PIHA, bottom).

4. Discussion

The case study selected is an example of a typical reforestation project on public land in Mediterranean Spain. It is aligned with both the technical and the environmental set-ups that usually frame these projects (Vadell et al., 2016). The intrinsic complexity of real projects like this may hinder successful implementation of plantation improvement efforts (Le et al., 2014). Most scientific literature is conceived within an experimental framework in which some important drivers of plantation performance are controlled or neutralized. In real projects, however, there is a conjunction of technical and environmental factors that profoundly interact and feedback on each other, such as project stipulations

Table 5
Relative importance (RI, %) of the highest-ranked predictors (RI > 5%) in the BRT models fitted for mortality (Table 4) after one (2008), two (2008–09) and ten years (2008–18) of outplanting. RIw represents the RI weighted with the cross-validation correlation.

Mortality	2008			2008–2009			2008–2018		
	Predictor	RI	RIw	Predictor	RI	RIw	Predictor	RI	RIw
TOTAL	Ecotope	22.4	15.8	MSI_min	10.8	8.8	NBRI_max	19.7	17.4
	Plant_date	7.5	5.3	BSI_min	9.2	7.5	ARVI_min	13.7	12.1
	Slope	5.3	3.7	NDMI_max	5.7	4.6	EVI2_min	6.7	5.9
	P_10days	5.1	3.6	Ecotope	5.6	4.6			
PIPR (SP0)	Soil_depth	17.0	9.8	MSI_min	7.0	5.3	EVI2_min	15.0	13.0
	Ecotope	6.9	4.0	BSI_min	6.3	4.7	NBRI_max	9.7	8.4
	Elev_P95 (09)	6.9	4.0	Soil_depth	6.0	4.5	MSI_max	7.5	6.5
	Elev_P95 (15)	6.2	3.6	NBRI_max	5.7	4.3	ARVI_min	6.8	5.9
				EVI2_min	5.7	4.2			
PIHA (SP1)	Ecotope	8.7	5.3	MSI_min	6.0	4.0	ARVI_mean	10.6	7.8
	Slope	6.5	3.9	Slope	5.2	3.5	ARVI_min	7.5	5.6
	m.a.s.l.	5.9	3.6	RH	5.1	3.4			
	T	5.5	3.3						
	RH	5.2	3.2						

(technical agreement between contractor and developer), staff and task management, large areas with varying site conditions and with different actions/jobs to execute in narrow time windows, weather uncertainty, etc. In this respect, the specific results of this case study are highly specific and irrelevant beyond its local scale. In line with the objectives of this study, we consider it more fruitful to ground the discussion in how the methodological framework explained has the potential to improve reforestation results by making it easier to identify and understand key pitfalls that need to be addressed in order to improve plantation success and future technical decision-making. As stated in the introduction to this project (Kankaanhuhta et al., 2010 and references therein), the evaluation method can be based on three hierarchical levels in order to achieve continuous improvement in program outcomes: end-results, behavior and learning.

4.1. End-results: poor performance of the plantation

The results in this study were analyzed for two different time windows. In the short term (establishment phase), when meteorological constraints were almost absent (only a short, acute drought between April and August 2009), mortality can be considered as mid-to-high, with about one quarter of the plantation dead by the first year, and more than half in the second year. In the mid-term, this trend worsened due to an exceptional, severe drought.

Of the two main species, Aleppo pine's 2-year survival (57%) showed the same overall mean in this case to that reported for the species under similar conditions (del Campo et al., 2007), although growth results differed somewhat in this case (53 cm and 5.3 mm for 2-year height and diameter, respectively) from the 2007 one (overall means of 24.7 cm and 5.5 mm for 2-year height and diameter, respectively). In the mid-term, other studies (Pausas et al., 2004; del Campo et al., 2008) reported, after 7.5–11 years of outplanting, survivals of 40–65% (32% here), height of 2.1 m and basal diameter of 8.7 cm (1.26 m and 3.6 cm in this study for 10-year height and diameter, respectively). These figures highlight the bad performance of the species in this program. One key point to bear in mind is that these values differ considerably in our experimental plot (10-year values for survival, height and diameter were, respectively, 70%, 1.4 m and 5.5 cm). Maritime pine presented even worse

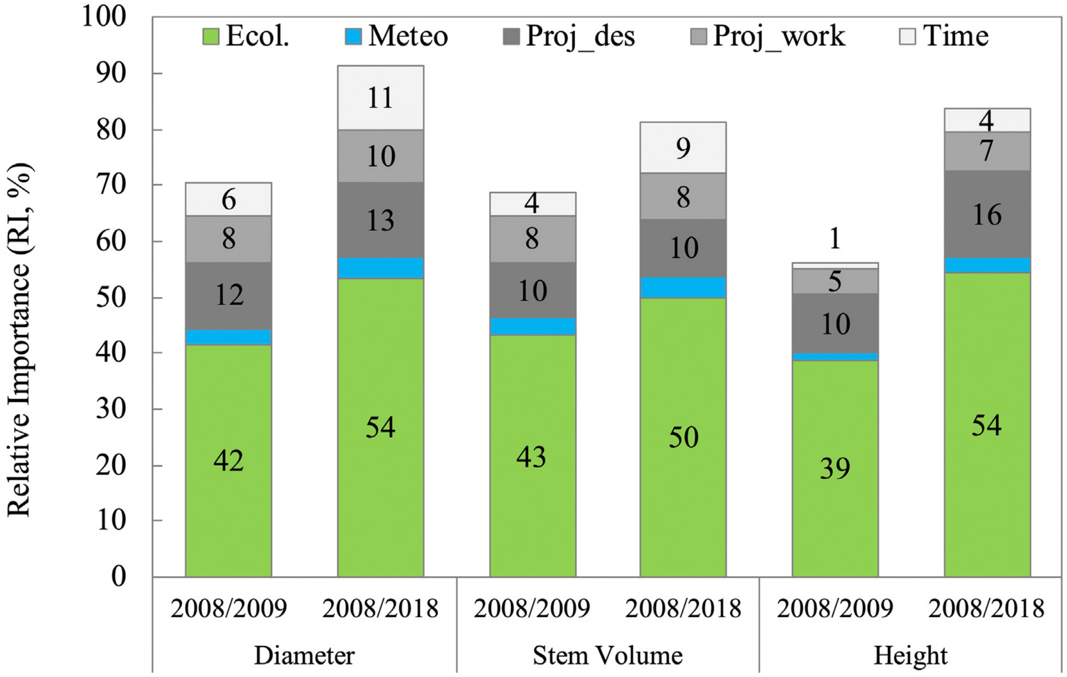


Fig. 8. Relative importance (RI, %) of different sets of factors on diameter, stem volume and height at early (2008–2009) and mid-term (2008–2018), as obtained from the BRT models. Partial dependence of the 4 highest-ranked predictors (higher relative importance in the BRT models) are presented in Figure SM4.

results in this plantation when compared with the literature (del Campo et al., 2020 and references therein), as its early survival was just 39% (50 ± 37% overall mean in the reference) and less than 5% after 10 years, with 1.0 m height and 3.8 cm in diameter. These values are somewhat lower than in the experimental plots (del Campo et al., 2020): survival, 11%; height, 1.1 m; diameter, 6.2 cm. The poor performance in this typical reforestation project can be extrapolated to similar programs in the Valencian region and Eastern Spain, where 5700 ha were reforested in 2008, at an average cost of ca. 2000 €/ha (MAPA, 2019).

4.2. Behavior: understanding the impact of technical and environmental factors on plantation performance

The question arising from the end-results is, why was mortality so high and how much of it can be addressed through technical means? To respond, we need to look into the technical and environmental factors that most impacted mortality according to the fitted models (behavior) and learn how to address these factors by technical means (learning).

Ecotope and planting date were more important than the rest of the technical variables (Table 5). Planting date is a transient variable that needs to be further examined to reveal the underlying factors explaining its relationship to mortality, so that practical advice can be given. Mortality was below average for early and late planting dates (Fig. SM3), but increased above the average for the middle dates, peaking around January 8-10th. As planting date is related to planting weather and the critical factors that affect the loss of water in the plant (Long, 1991), i.e. temperature, relative humidity (or vapor pressure deficit), wind speed and soil moisture, it must be addressed jointly with these factors. However, either the correlations (Fig. 6) or the partial dependence plots (Fig. SM3) showed contradictory relationships between mortality and planting weather (e.g. RH, P_10days, ET_10days and SM_spot10_p). The temporal evolution of all these variables is given in detail in Fig. 9, showing light rainfall events around mid-January (< 3 mm in 10 days), less evapotranspiration on those rainy days and a slight increment in shallow soil moisture (SM_spot10_p). However, this was far from being a generalized and durable wetting of the soil profile sufficient to enhance root growth (Burdett, 1990). In fact, soil was dry during the second half of the planting window before a series of rainfall events in February rewetted it (Fig. 3). Thus, the peak of mortality for plots planted on January 8–10 could be explained by that dry spell and not by the meteorological conditions at planting. Linear correlations between mortality 3 (Nov-2008) and spot moisture after “d” days of planting (SM_spot10_d, with d ranging between 1 and 22) were highest for the lapse between 17 and 20 days ($r < -0.50^{**}$, see Table SM2). When these new variables (SM_spot10_d, d = 17, 18, 19, 20) were included in the BRT models, they accumulated a RI of 20% on the first year's mortality (see Table SM3 and Fig. SM5). Hence, the factor that might have triggered high mortality when long lapses (> 15 days) of dry soil follow the planting date, likely was the inability of the seedlings to successfully establish under such conditions, i.e., to develop enough root system to overcome summer drought (see soil moisture series and mortality in Fig. 9).

Zoning in ecotopes aims to group homogenous site factors (Klijn and De Haes, 1994; Ceacero et al., 2012, 2020) into reforestation that will receive the same treatment or set of actions (e.g., site preparation, species mixture, cultural management, etc.). The high impact of ecotopes on mortality here is because ecotope IIa (which includes about 55% of the plots) exceeded average mortality in the first two years (mortality 3 was 35.5% in IIa vs. 13.5% on average in the other four ecotopes). Either technical or site-related factors (or both) could be behind such poor performance, although technical decisions were not so different in IIa when compared with another ecotope such as IIb (Table 1). Ecological factors, on the other hand, were assessed for differences between ecotopes; first, a factor analysis reduced the number of ecological variables to 11 factors that explained 89% of total variance; then, either parametric or non-parametric ANOVA's were performed on each extracted factor categorized by ecotope (not shown). Only the factor integrating LiDAR-derived variables was significantly different between IIa and IIb. However, those variables showed little RI in the BRT models of mortality fitted for both Total and Aleppo pine (in Maritime pine, the ecotope held less RI on mortality) (Table 5, Fig. SM3). Further examination of the plots that exceeded mortality 3 in IIa revealed that they were planted in mid-late Jan 2008 and averaged 44% mortality, whereas the plots planted in IIb on the same dates averaged only 23% mortality. The only difference detected in this subsample of plots (those planted in Jan 10–22 in IIa and IIb) was the planting gang, with gang FSA planting IIb, whilst gang MFB did IIa (Fig. 9, shaded and solid red dots). This predictor was not associated with mortality in the BRT analysis. A non-parametric test (Mann-Whitney U) indicated significantly less mortality 3 (Total, PIPR and PIHA) for gang FSA (Fig. SM6); and the Moses test showed a significantly different range in two variables of planting quality according to the gang: plug orientation and firmness, which were higher in FSA (78° and 1.0 respectively) than in MFB (72° and 0.9) (Table SM4). Loose planting (failure to firmly close the top of the planting spot) and “L”-shaped plugs (caused by hand planters pushing seedlings into shallow planting holes) are among the most important causes of early mortality (Long, 1991) and could be the reason for the early mortality at IIa, a factor that was only relevant under the above-mentioned drying soil conditions, pointing to an interaction. Planting quality variables were examined in only 22 plots (subsampled in 5 seedlings per plot, i.e. a total of 110 excavated seedlings) and hence were not considered in the BRT analyses due to low sample size. However, following this reasoning, they should be fully considered in future studies.

Another point needing attention is the different performances of the two pines, which had contrasting mortality rates, with Maritime pine (PIPR) much higher. A reasoned discussion of the functional traits driving the establishment of the seven species in the experimental plots was given elsewhere (Del Campo et al., 2020). In this paper, the total results are a rough average of the performance of both pine species (nearly 90% of sampled seedlings). BRT showed high RI of soil-related variables in the performance of PIPR, which is known to prefer acidic or neutral soils, although it may tolerate alkaline soils when the substrate contains a large proportion of dolomite (Ruiz de la Torre, 2006). The geological map of Spain (IGME, 2003) shows transitional zones between micrites (limestones) and coarse-grained dolostones in this area, which would explain higher soil sensitivity in this species than in PIHA. The presence of Mg^{+2} ions in dolostone increases the proneness of this rock to weathering and dissolution due to the greater solubility-product of $CaMg(CO_3)_2$ (dolostones) than of $CaCO_3$ (limestones) (Hajna, 2003; Johnston, 1915), thus originating deeper soils, a variable that scored the highest RI on PIPR mortality 3 (Table 5). By the same token, the weathering process creates silty-clay soils with clay contents generally increasing with depth to the detriment of silt (Durn, 2003), which correlated positively with mortality (Fig. 6). These facts would explain the species-specific differences in soil properties reported in this paper and suggest higher habitat marginality in the case of PIPR.

Other technical aspects that correlated negatively with mortality (especially in Aleppo pine) were the absence of tree shelter and the presence of stone cover around the planted seedling (Fig. 6). The latter variable (only sampled in a limited number of plots) is related to soil moisture. The surface rock fragment cover has been shown to have implications for the soil water content and its spatial and temporal distribution pattern (Kader et al., 2017; Luna et al., 2018). In semiarid areas, Jiménez et al. (2017) showed that the rock fragment cover improved soil moisture only at 10 and 20 cm in depth so that could be more suitable for species with superficial root systems, such as *Pinus*. In the case of tree shelter, the interception of radiation has a negative impact on root growth in heliophilous species such as Aleppo pine (Puértolas et al., 2010; Padilla et al., 2011), an effect that would have been more acute under severe drought. The different survival rates between the

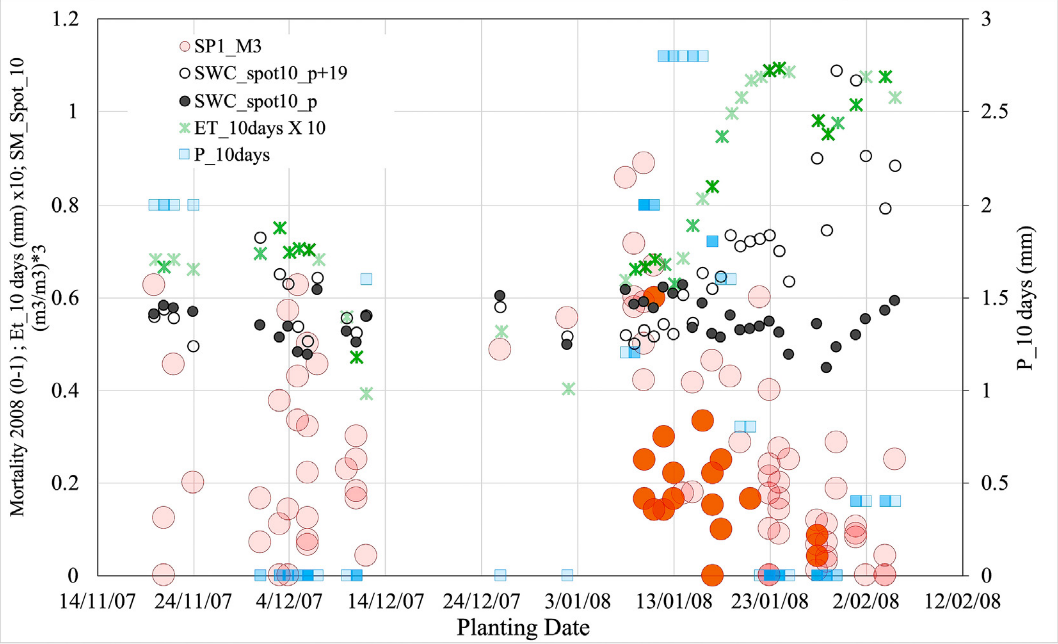


Fig. 9. Temporal progress of planting in each of the 92 sampling plots (x-axis) showing the first year's mortality of Aleppo pine (SP1_M3, left y-axis). Plots planted by gangs FSA and MFB are shown as solid and shaded red large dots respectively. Shallow soil moisture at the planting spot either on planting date (solid small dots) or 19 days later (empty small dots) and cumulated precipitation (blue squares) and evapotranspiration (green asterisks) in ten days are also shown. Note that units of soil moisture and evapotranspiration have been rescaled as indicated in the y-axes.

experimental plot (planted without tubes) (Del Campo et al., 2020) and the overall reforestation, and the stronger correlations after 10 years (Fig. 6) led us to hesitate on this variable. The BRT analyses undervalued this predictor. However, on redoing them only for the 10-year assessment (instead of for the 2008–2018 lapse, i.e. removing the temporal component), the RI of tree shelter rises to 29% as the first-ranked predictor (Tables SM5, SM6 and Fig. SM7). Therefore, although the technical factors showed greater impact in the short- than in the mid-term, our results suggest that environmental events such as the extreme drought recorded here can reveal, several years later, the impact of inappropriate technical measures that would otherwise remain concealed.

Previous experience underlines the importance of properly matching technical means to ecological factors and constraints that usually vary greatly in space and time. This variability has overarching importance in dryland reforestation (Vallejo et al., 2012) and needs to be addressed. In this study, remotely sensed vegetation indexes (SVI) and cover provided reliable indicators of plantation performance with increasing importance (RI) over time, as such spatial-temporal variation could be clearly seen. They were able to reveal dynamic plant-plant interactions between pre-existing vegetation and the planted seedling, first highlighting a competition effect in mortality 4 (2009, wet period) and then a facilitation effect in the mid-term assessment, after the severe drought of 2013–2015 (Table 5, Figs. 6, SM3, SM4). Less covered areas showed less mortality in 2009 and the SVI's that were more closely related to bare soil (BSI and MSI) gained in importance, whereas the NDVI-type indexes (mostly NBRI, ARVI, EVI2) were more important in the mortality models in the mid-term. Plant-plant interaction (i.e., planted seedling-preexisting scrubs) shows that open areas had better survival than those with thicker shrub cover (scrub removal for planting affects about 1 m^2). However, under drought, site conditions are harsher in open areas and facilitation might govern the response of the plantation. General assessments have demonstrated that competition is more important under less arid conditions (first two milder years in our study), whilst facilitation is needed under high-aridity conditions (Berdugo et al., 2019). Similar assertions have been reported for the specific case of reforestation (Gomez-Aparicio, 2009). The increasing importance of SVI in the 2008–2018 models was based on their ability to catch this dynamic behavior of the interactions (competition vs. facilitation) more efficiently than the SPI drought index, which showed no rise in 2018's mortality despite the severe drought experienced.

4.3. Learning how to improve plantation performance (conclusions)

The links used in this paper to join the different elements of reforestation (e.g., the measures foreseen in the project, different species, varying site conditions, planting, changing weather, etc.) can provide a solid pathway to improving plantation performance and the learning process that should be further developed and validated on other reforestation projects.

The implementation of the work was a major factor in this project, though less so than meteorological and design factors. A proper planting technique and a better coupling of weather-planting dates, together with their interaction, are key variables that assume greater importance when dry conditions prevail. On the design side, decisions on zonation, species selection and after-planting care treatments need better understanding of the species' eco-physiological traits, especially those related to drought avoidance/tolerance, and the matching of these traits to the site and after-planting care treatments.

Environmental factors must be at the very basis of both the design and the implementation of reforestation programs. Our study has confirmed that site variables with direct impact on the water balance at the planting spot need special attention, above all slope (aspect) and elevation, through their influence on evapotranspiration, and soil depth, through its influence on water storage and availability. The profound role of these ecological factors in plantation performance needs to be addressed by better identifying favorable microsites, rather than large ecotopes. SVI's are useful for this purpose. In addition, technologies such as remote sensing and LiDAR can lead to customized zoning and subsequent technical decisions, such as better assignment of species (and mixtures) and after-planting care treatments, or their proper deployment on the spot. For instance, one should optimize the planting date according to microclimate variation within the area and the eco-physiological strategy of the species being planted (as plants with isohydric behavior are more resistant on a drying soil than anisohydric species). This argues that precision forestry technologies and tools, to support site-specific reforestation, are required and management should be fine-tuned to suit ecotope conditions (shrub cover, soil type, topography, soil rock fragment content, etc.) (Dash et al., 2016; Choudhry and O'Kelly, 2018; Ceacero et al., 2012, 2020).

As well as this, a comprehensive assessment methodology encompassing the complex project-works-site-time is crucial in order to integrate (first) all potential drivers of plantation performance and to identify (second) those aspects more related to success. For this, analytical tools that allow insight into complex ecological interactions and processes such as non-linear models (Elith et al., 2008), complemented by traditional methods, can help identify relevant variables and interactions, fitting non-linear functions that relate these to successful field performance. The use of these techniques does not avoid, however, the need for expert judgement as a key component in this framework, as various direct and indirect variables selected as predictors need to be translated into basic plant resources (Guisan and Zimmerman, 2000) in order to address properly the key factors governing reforestation performance.

CRediT authorship contribution statement

This research is part of a reforestation improvement program carried out in the Valencia region since year 2002. The program has been supported by several contracts and agreements between Polytechnic University of Valencia and the Valencian regional Government (Consejería de Medio Ambiente). All authors have contributed to the research and work presented in this article. Dr. del Campo is the lead of the research program, who has been involved in all phases of the work, from its development and design objectives, to the final version of the work (including field campaigns and lab work, data analyses, elaboration of the draft and writing of the article). By the same, Guillem Segura, has been actively co-working with Dr. del Campo from the beginning (2007) as a PhD student and its contribution to the work includes data acquisition and validation, formal analysis, data curation and writing the manuscript. Dr. Bautista did all the work related to soil sampling and analyses in the Lab. Dr. Ceacero has been involved in the manuscript writing stage, both the original and final drafts, the creation, analyses and presentation of the published work, its review and its editing. Drs. González-Sanchis, Bautista and Molina have collaborated with the writing, review and editing of the manuscript, providing insights and helpful critical reviews and commentaries. They have also contributed to creation of the published work, specifically visualization. Dr. Hermoso has been involved in funding acquisition, management and coordination responsibility for the research activity, planning and execution, including mentorship external to the core team.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148952.

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