

On the importance of topography, site quality, stock quality and planting date in a semiarid plantation: Feasibility of using low-density LiDAR



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ABSTRACT

Pine seedling survival and growth in eastern Spain have often been related to site preparation, planting date and seedling stock. However, in spite of the acknowledged importance of spatial heterogeneity in seedling performance, little is understood about how topography-related spatial patterns may modify seedling response to plantation, particularly on dry sites. We tested the hypotheses that growth and survival of *Pinus halepensis* seedlings are related to stock quality, plantation date and topographic conditions, as well as the spatial pattern of environmental variables using a spatially explicit design. The plantation treatment consisted of three seedling stocks, two plantation dates and two contrasted quality sites. Topographic features, such as slope, aspect, Compound Topographic Index and flow accumulation, were measured using GPS and low density LiDAR, with growth and survival monitored over a period of one and two years, respectively. The spatial pattern of the study variables was examined via spatial analysis by distance indices (SADIE). The relative importance of each topographic variable explaining the spatial pattern (local aggregation indices, v) of seedling response was examined using ordinary least squares (OLS) regressions. *P. halepensis* seedlings showed higher survival and growth in better sites and early plantations, but they were very similar between seedling stocks. A significantly greater proportion of seedlings survived in early date of plantation (54%) compared to medium date (36%), and in the favorable site (51%) versus the restrictive site (38%). Seedlings also grew significantly faster for those treatments during the first year. However, stock quality had few effects on survivorship and growth. All the topographic and seedling response variables exhibited an aggregated spatial pattern. Seedling survival was clearly associated with topographic patterns, particularly to those related to water availability (CTI and flow accumulation), indicating that on topographic-spatial scales, seedling response is driven by soil–water dynamics in Mediterranean ecosystems. The topographic morphology described by LiDAR was also closely linked to seedling response, thus suggesting the potential of these data to evaluate reforestation success. Accurate maps of topographic factors may indicate whether a plantation has a higher survival and growth potential and with routine reforestation planning activities such as soil preparation.

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1. Introduction

Forest plantations in Mediterranean areas are strongly limited by the inherent characteristics of this climate (with hot, dry summers and cold, rainy winters) (Archibold, 1995), but particularly by the low small-scale soil water availability, which is highly sensitive to the microenvironmental conditions (Snyder and Tartowski, 2006; Quero et al., 2011). Soils are also often poorly developed,

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shallow (20–40 cm), stony, poor in organic matter and sometimes with impermeable horizons (Puigdefabregas, 1998). In these areas, restoration projects often use soil preparation to improve root depth, increase soil infiltration and nutrient availability, reduce water runoff and control competing vegetation (Barberá et al., 2005; Palacios et al., 2009; Löf et al., 2012).

Previous studies aiming to improve woody seedling establishment in these areas have shown the effectiveness of using high quality seedlings (Puértolas et al., 2003; del Campo et al., 2007a,b, 2011; Oliet et al., 2009; Grossnickle, 2012), controlling for date of planting (Seifert et al., 2006; Palacios et al., 2009), implementing early growth promotion treatments (Navarro-Cerrillo et al., 2006; del Campo et al., 2011; Villar-Salvador et al., 2012) and mechanical soil preparation techniques (Thiffault and Roy, 2011), or their interaction effects (Palacios et al., 2009; Ceacero et al., 2012). In spite of the potential benefits of soil preparation, the direct effect on reforestation success is often unknown (Löf et al., 2012). Moreover, water flows at microsite scale are often closely linked to nutrient dynamics, water availability, and groundwater, so they can highly modify seedling growth and survival during dry periods (Cabin et al., 2002; Devine and Harrington, 2007; Bailey et al., 2012). Given this high variation among planting-sites, seedling performance due to topographic conditions has seldom been disentangled from other effects, such as seedling stock quality or planting date.

In natural conditions, seedling performance is typically influenced by the regeneration niche, i.e. the result of spatially structured microsite variables (Maestre et al., 2003); particularly soil properties, which are heterogeneous at small scale in Mediterranean areas (Gallardo et al., 2000; Maestre et al., 2003; Quero et al., 2011). Likewise, these microsite factors may exhibit complex interactions (Quero et al., 2008) and can vary widely in space and time, thus affecting growth and establishment (Maestre and Reynolds, 2006). Therefore, the spatial distribution of microsite variables, which usually take the form of gradients or patches, is often of a non-random nature and promotes the formation of clumped patterns to which plants respond differently (Maestre and Quero, 2008).

Although an increasing number of spatially explicit experimental designs is being used to examine aggregation patterns for plantation success (Maestre et al., 2003; Messaoud and Houle, 2006; Quero et al., 2011; González-Rodríguez et al., 2011), these designs are more focused on underlying ecological processes than their operational implementation in existing reforestation techniques. Therefore, when identifying the primary effects of a soil preparation treatment, a direct quantification of the influence of topography on seedling response is required. A greater understanding of the topographic factors limiting the growth and survival of forest plantations will help managers to design practices that optimize restoration success while minimizing costs.

The mismatch between the well-known ecology importance of topography and its practical implementation in reforestation techniques is likely due to reforestation topography, which is not accurately known because of the limited resolution of existing maps (Goodchild et al., 1993; Huang, 2002) (e.g., between 10,000 and 25,000 scale map). The accurate identification and mapping of topographic factors is therefore a key issue in the physically-based characterization of reforestation processes at seedling/sapling scale (Maestre et al., 2003; Ceacero et al., 2012). Reforestation topographic characterization has received little attention from researchers using modern geospatial analysis (Navarro-Cerrillo et al., 2006; González-Rodríguez et al., 2011; Quero et al., 2011). Aerial photography has occasionally been used in reforestation studies and new aircraft data with the required spatial resolution to evaluate small-scale reforestation development have recently become available. However, these methods are less effective in

smaller or more abrupt areas. Under these conditions, reforestation mapped by visual or computer interpretations of aerial photographs is often used, but have low resolution power for topographic interpretation. Hence, the generation of topographic data in reforestation areas with new-high-resolution techniques is needed. Light Detection and Ranging (LiDAR) is an active remote sensing technology that can be used to develop high-resolution topographic data over large areas. If accurate, LiDAR-derived maps could help to accurately identify topographic networks, flow paths, and topologic and morphometric features of microcatchments that facilitate reforestation success at operative levels (Lefsky et al., 2002; Wulder et al., 2012). These improved capabilities would facilitate topographic, local topographic morphologic information for parameterizing reforestation modeling. Standard LiDAR data generally lack the spatial availability to perform microsite detection at the local reforestation scale. However, if accurate, low LiDAR data could provide an opportunity for the on-going evaluation of topographic factors conditions at a cost-effective scale.

The goal of this study is to address the influence of topographic factors on a semiarid plantation and its interaction with the reforestation factors considered (stock quality, plantation date and site quality). Additionally, we have studied the feasibility of using low-density freely LiDAR data to identify those topographic factors. To achieve this objective, (1) we studied the spatial patterns of plant growth and survival of *Pinus halepensis* Mill. seedlings in relation to topographic characteristics; (2) simultaneously allowed for the effects of planting date (early vs. late), seedling stock quality (three qualities) and site quality (two contrasted site qualities); and (3) related the direct measurements of topographic conditions to those provided by low-resolution LiDAR in order to identify, map, and measure topographic conditions for reforestation practices in comparison with field topographic data.

2. Materials and methods

2.1. Study area

The field trial was conducted in two sites: Domeño (hereafter Site 1) (39°43'18" N, 0°56'6" W, 440 m elevation), and Castellano (hereafter Site 2) (39°45'50" N, 0°52'10" W, 900 m elevation), North Valencia (Eastern Spain). The climate in both sites is transitional from maritime Mediterranean to continental Mediterranean. Mean annual temperature and mean annual precipitation on Site 1 are 15.2 °C and 452 mm (83 mm in summer), respectively, with 83% of the rainfall occurring between October and May, while the values for Site 2 are 12.7 °C and 560 mm (105 mm in summer), respectively. The precipitation, temperature and soil moisture of both sites were recorded from November 2004 to February 2006 with a data logger (HOBO Pro Series 8 Temperature and relative humidity) located in both study areas and averaged on a daily basis. The soil on Site 1 is a xerorthent type and 60 cm deep (pH: 7.95, Electric Conductance EC: 2.24 dSm⁻¹), with 1.8% of organic matter, and 46% of coarse fragments. The soil on Site 2 is of the clay-loam xerorthent type, which is characterized by a shallow (<30 cm), rocky A horizon (80.2% coarse fragments), with 36% of clay and 43% of silt fractions, pH: 8.4, EC: 0.18 dSm⁻¹ and 7.5% organic matter, underlain by a C horizon of calcareous rock. The topography of Site 1 is more complex than that of Site 2, with higher mounds and remnants of old agricultural terraces. The landscape is a former *P. halepensis* forest affected by a fire in 1995, which consists of a mosaic of a few pines remaining on the overstory with shrub ground layers (*Thymus* spp., *Rosmarinus officinalis*), calcareous outcrops, and eroded areas with decapitated soils and rock surfaces.

2.2. Experimental design

In each site, a 100 m × 100 m experimental plot was established in a representative area. The soil preparation treatment was carried out in October 2004 and consisted in establishing contour curves every 3 m by mechanical holing with a retroexcavator. Planting was done by hand in a rectangular plot following a regular spatial pattern distribution (3 m × 3 m) in November 2004 (early date), and January 2005 (mid-date) with three types of seedling lots (stock quality, Table S1, Supplementary Information) in a three complete random block design. Each block consisted of 54 tree replications per factorial combination, giving a total of 972 seedlings per site (54 × 3 blocks × 3 stock quality × 2 plantation date), with a total of 1944 seedlings for the whole experiment. In each block, early and medium plantation dates were alternated on the contour lines, whereas the stock quality factor was fully randomized within each planting date line.

2.3. Seedling data collection

The three stocklots used in this work were chosen as representative of different commercially available stock qualities (del Campo et al., 2007b). Detailed information on the seedling quality attributes for each stock is available in a previous study (del Campo et al., 2007b, where stocklots FA, HT and GE correspond in this work to the notation of stock 1, 2 and 3, respectively; Table S1, Supplementary Information). At the time of planting in November 2004 and January 2005, all transplanted seedlings were tagged and their diameter (at ground level) and height (stretched distance from ground level to highest living bud) were measured. Seedling height, basal diameter, and survival were then measured monthly from March to November 2005, with a final measurement taken in December 2006. Seedlings were considered dead if their shoot was brown and shriveled. Growth rate was computed as the difference in height (H) and diameter (D) between planting date and 3 strategic assessments in the first year after planting (Apr-05, spring; Jun-05, before summer and Nov-05, after summer).

2.4. Topographic data collection

Topographic characteristics were measured in the field during spring 2005 for all seedlings ($N=1944$) at the reforestation sites and included localized topography of all planting sites using the Real Time Kinematic (RTK) satellite navigation technique with a Trimble R6 GPS (Trimble Navigation Limited, OH, USA). Horizontal and vertical accuracies under abrupt topographic conditions were up to centimeter-level using a base station, which was located on the nearest geodesic vertex for both sites.

For the topographic factor description, conventional leveling was used to survey the total study area, and a Digital Elevation Model (DEM) was developed for each site using Profile Extractor[®]; an extension of ESRI ArcView 3.3. The topographic features for each study site were computed using four variables as predictors of seedling survival and growth: (1) slope inclination (SLO); (2) aspect (ASP); (3) Compound Topographic Index (CTI) (also called Topographic Wetness Index), which represents a steady-state wetness index as a function of the upstream contributing area and the slope; and (4) Flow Accumulation Function (FLA), which defines the amount of upstream area draining into each cell. It is essentially a measure of the upstream catchment area (Teng et al., 2008) (Table S2 Supplementary Information). Higher CTI values represent drainage depressions, while lower values represent crests and ridges (Teng et al., 2008). These measurements were selected due to their importance in reforestation success (Fidelibus and Bainbridge,

1995), simplicity of evaluation, and comparability with LiDAR data (Brubaker et al., 2013). The information was converted to shapefiles and reprojected into UTM coordinates using ArcGIS 9.0. Most of the raster processing was done using Arc Hydro[®] within ArcGIS Spatial Analyst (ESRI Corp.).

2.5. LiDAR data acquisition and analysis

The LiDAR data were acquired from the Spanish National Plan of Aerial Orthophotography (PNOA), and collected in October 2009 using an Optech ALS50-II sensor, with a minimum laser pulse rate frequency of 45 kHz, a scan angle between 0° and ±5° and a scan rate of 70 Hz. The final density ranged from 0.5 points m⁻² in most of the area to 2 points m⁻² when the flights overlapped and/or the plane speed was slower. Vertical accuracy in terms of root mean squared error was less than 40 cm, and the planimetric error (x, y) was less than 36 cm.

The LiDAR point data were filtered to select bare-Earth estimates, which were provided in ASCII text files as x, y, z values with state plane coordinates. Filtering of ground hits was done using morphologic filter algorithm (Zhang and Whitman, 2005). The postings were converted to shapefiles and reprojected into UTM coordinates using ArcGIS 9.0 (ESRI Corp.). The LiDAR bare-Earth point data were used to generate a triangulated irregular network (TIN) for each of the two study areas and two DEMs were generated from the TINs at 2-m × 2-m grid-cell spacing. Contour maps were generated from the 2-m × 2-m DEMs for qualitative field evaluations and for deriving topographic network by the contour crenulation method. The same topographic network was evaluated including slope inclination and aspect. The Compound Topographic Index and flow accumulation were determined using Arc Hydro[®] within ArcGIS Spatial Analyst (ESRI Corp.) (Table S2 Supplementary Information).

2.6. Statistical analysis

The influence of planting date, seedling quality and site quality on survival from 3 to 48 months after planting was tested using a Cox proportional hazard (PH) model, which takes into account both seedling longevity and status (dead or alive) at the final assessment of survival (Cox and Oakes, 1984). This analysis has been employed in previous studies of tree seedling survival (e.g., Navarro Cerrillo et al., 2012), and is a suitable approach to evaluate survival patterns between treatments where the cumulative hazards over time (hazard functions) are generally proportional.

Seedling growth rate was separately analyzed with linear mixed models to examine the effects of planting date, seedling stock, and site quality in each sampling period in the first year after planting. Diameter increment and height increment were used as the dependent variables, with planting date, seedling stock, and site quality designated as fixed factors and block as a random factor. Models containing the three-way interaction and all two-way interactions of the fixed factors were assessed for each time period using Akaike's Information Criterion (AIC). The models were selected based on the lowest value of AIC, which indicates the optimal fit. Survival, growth rates, diameter and height were examined graphically to ascertain that the residuals were normally distributed and the variances were homogeneous. Height was subjected to log transformation to improve normality. The Cox PH regression was run in R with the survival package (Therneau and Lumley, 2009; R Development Core Team, 2011) and linear mixed models were run using the SPSS software package version 12.0 (Chicago, IL, USA; <http://www-01.ibm.com/software/es/analytics/spss/>).

2.7. Spatial patterns of topographic variables

To characterize the spatial patterns of the seedling growth (24 months after plantation) and survival (48 months after plantation), spatial analysis by distance indices (SADIE) was used to calculate spatial indices and test for statistical significance (Perry et al., 1999). The analyses were carried out with the free SadieShell v1.3 software (www.rothamsted.ac.uk/pie/sadie). The spatial pattern for each variable was assessed in terms of the aggregation index (I_a) and clustering index (ν). The aggregation index (I_a) provides information on the overall spatial pattern of each environmental variable. The spatial pattern is aggregated if $I_a > 1$, random if I_a is close to one, and regular if $I_a < 1$. The clustering index (ν) measures the degree of clustering of the data into patches (areas of high values of the target variable) and gaps (areas of low values). Given that ν is a continuous variable, data can be contoured by kriging in a two-dimensional map showing their spatial distribution. Points within patches have values of $\nu \geq 1.5$, whereas those within gaps have values of $\nu \leq -1.5$ (Perry and Dixon, 2002). The maps were produced by linear interpolation with Surfer v8 software (Golden Software Inc., CO, USA). For environmental variables, a separate SADIE analysis was performed per variable and plot site.

2.8. Relative importance of topographic variables affecting the spatial pattern of growth and survival

The effect of spatial distribution on the observed pattern of topographic variables was examined using Statistical Analysis for Macroecologists package-SAM (Rangel et al., 2010). To explore the relative importance of each topographic variable (slope, aspect, Compound Topographic Index and flow accumulation) that explains the spatial pattern (local aggregation indices, ν) of seedling response, ordinary least squares (OLS) regressions of pattern was performed against each of these factors.

Since spatial data are generally spatially autocorrelated, the value of seedling response variables occurring in a certain area is very likely to be similar to those in the direct vicinity, and spatial measurements cannot be considered independent. The failure of data to meet the fundamental statistical assumption of independence will result in an overestimation of the degrees of freedom. Consequently, statistical inferences about variables predicting seedling response will generate a bias in the type I errors (e.g., accepting significant differences when these are actually absent). To correct for spatial autocorrelation in regression residuals, the effective number of degrees of freedom were calculated according to Dutilleul's method (Brehm et al., 2007), and adjusted P -values (Padj for R^2) were considered based on the effective degrees of freedom. The variance inflation factor between the independent variables included in our models was below four, suggesting the absence of collinearity problems (Chatterjee and Price, 1991). To explore multivariate relationships for seedling response in terms of survival and final size, multiple linear regressions were computed. All possible linear regression models containing the different variables were evaluated, with the clustering indices (ν) of final height, final diameter and survival as dependent variables and slope, aspect, Compound Topographic Index and flow accumulation as independent variables from both the Total Station and LiDAR data. The 15 models generated with our independent variables were ranked according to the second-order Akaike information criterion (AIC_c), and calculated as described in Fotheringham et al. (2002). The AIC_c of each model was then transformed to ΔAIC_c , which is the difference between the AIC_c of each model and the minimum AIC_c found for the set of compared models. ΔAIC_c values above 7 indicate that a model has a poor fit relative to the "best" model (i.e., the model with the lowest AIC_c), whereas values below

Table 1
Average height and diameter (\pm S.E.) (cm) of *Pinus halepensis* seedlings by planting date, site quality, and seedling stock type.

	Date since planting					
	Early date			Medium date		
	Stock 1	Stock 2	Stock 3	Stock 1	Stock 2	Stock 3
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
Diameter (mm)						
June2005	3.85 \pm 0.06	3.41 \pm 0.05	3.15 \pm 0.04	3.36 \pm 0.04	3.41 \pm 0.05	3.21 \pm 0.05
Nov200512	5.04 \pm 0.15	4.54 \pm 0.17	4.41 \pm 0.14	4.37 \pm 0.12	3.96 \pm 0.11	4.36 \pm 0.13
Height (cm)						
June2005	16.01 \pm 0.29	16.12 \pm 0.21	14.77 \pm 0.24	20.86 \pm 0.32	14.67 \pm 0.33	12.28 \pm 0.19
Nov200512	19.56 \pm 0.52	19.34 \pm 0.42	19.59 \pm 0.69	22.56 \pm 0.52	16.12 \pm 1.19	15.57 \pm 0.46
					Site 1	Site 2
					3.49 \pm 0.04	4.04 \pm 0.12
					2.79 \pm 0.04	3.66 \pm 0.11
					22.90 \pm 0.31	25.47 \pm 0.70
					3.50 \pm 0.04	4.52 \pm 0.15

2 indicate that models are indistinguishable (Johnson and Omland, 2004). The ΔAIC_c values were also used to obtain the Akaike weights of each model (w_i) following Burnham and Anderson (2002). This parameter provides evidence that the model is actually the best explanatory model. Akaike's weights were also used to define the relative importance of each predictor across the full set of models evaluated by summing the w_i values of all the models that included the predictor of interest, taking into account the number of models in which each predictor appears (Burnham and Anderson, 2002). The larger this sum, the more important a given variable is relative to the other variables used in the same models. Multi-model analyses were carried out with SAM 4.0 software (Rangel et al., 2010).

3. Results

3.1. Survival and growth rates

The percentage of seedlings surviving 24 months after plantation varied across treatments, ranging between 51% and 38% (site quality), 54% and 36% (planting date), and 42% and 47% (stock quality) (Fig. 1). According to the Cox PH regression, percent survival varied significantly between sites ($\chi^2 = 13.991$, $P < 0.001$, Fig. 1A) and planting date ($\chi^2 = 6.914$, $P = 0.009$, Fig. 1B), which showed a notably similar pattern of decreasing survival in every sampling period. Seedling survival at the end of the study was higher in early plantation date (54%) compared to middle date (36%). As regards seedling quality stock, survival was similar for the three stock types (42–47%, $\chi^2 = 2.418$, $P = 0.129$, Fig. 1C), and the differences were not significant.

Initially, the diameter increment was significantly related to site quality, planting date and seedling stock (spring: $F = 227.5$, $P < 0.0001$; $F = 8.9$, $P = 0.003$; $F = 14.3$, $P < 0.0001$, respectively) (Table 2). After summer, the diameter increment was significantly related only to site quality and planting date and the seedling stock effect disappeared. The interaction treatment had a significant effect on diameter increment for site \times planting date and planting date \times stock in the spring assessment ($F = 79.0$, $P < 0.0001$; $F = 5.6$, $P = 0.004$) and for all two-way interactions of the fixed factors after the summer assessment (Table 2). In post hoc comparisons, Site 1 showed greater diameter growth rates in spring and after summer assessments (Fig. 2). During the monitoring periods, diameter increments were significantly greater in the early date treatment than in the medium date treatment. Among seedling stock treatments, the lower diameter growth rate was always observed in stock 3 in contrast with stock 2. Stock 1 showed an intermediate behavior. After summer, no significant differences were observed in the seedling stock for the first monitoring year (Fig. 2).

In the spring assessment, the height increment showed significant differences only for seedling stock ($F = 4.6$, $P = 0.01$). However, after summer, the height growth rate was significantly related to site quality, planting date and seedling stock (Table 2). The interaction treatment had a significant effect on height increment for site \times planting date in the spring assessment ($F = 14.7$, $P < 0.0001$) and for planting date \times stock in the assessment before summer (Table 2). According to post hoc comparisons, Site 1 showed greater height growth rates in the assessments before and after summer (Fig. 2). The early date treatment only showed greater height growth rates after summer, whereas no significant differences were observed in the measurements taken in spring and before summer. Finally, with regard to the seedling stock factor, stock 2 always showed the lowest height increment in contrast to stock 3 in spring and stock 1 before and after the summer period (Fig. 2).

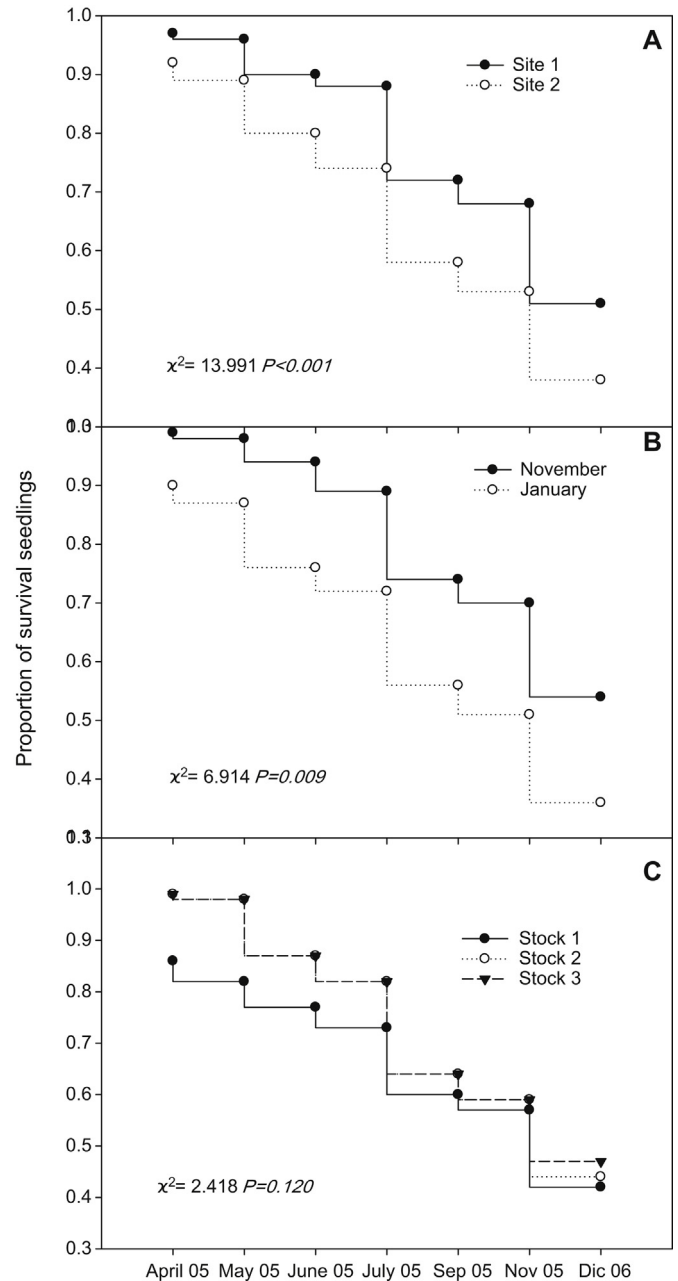


Fig. 1. Cox proportional-hazards regression model comparing survival between 3 and 24 months after planting, with the following factors: (A) site quality (Site 1 deep-non rocky soils and Site 2 shallow-rocky soils), (B) date of planting (November 2004, early season, and January 2005, mid-season), and (C) stock quality (Table S1, Supplementary Information).

3.2. Spatial pattern of survival and growth

The results of the SADIE analyses are summarized in Table 3, and graphic information on the characteristics of spatial clusters is shown in Figs. 3 and 4. A strong aggregation of seedling response (survival and growth) at the site level and for planting date was confirmed by a large and significant value of I_a ($I_a > 1.5$, $P < 0.05$).

Survival in Site 1 and early plantation (November) exhibited the highest aggregation index ($I_a = 1.92$; $P_a = 0.002$). The clustering index maps [ν] (Fig. 3) showed patches and gaps (zones with ν greater and less than 1.5 and -1.5 , respectively). The aggregation pattern for survival persisted for medium plantation (January)

Table 2
Linear mixed models at each sampling period for increment in diameter and height of *Pinus halepensis* seedlings with the following fixed effects: site quality, planting date (early and medium), and seedling stock. Random effect: Block. The structure of fixed main effects and interactions reflect model selection based on Akaike's Information Criterion.

Time period (Planting date to)		Spring (April)		Before summer (June)		After summer (Nov)	
Dependent variable	Fixed effect	F	P	F	P	F	P
Diameter increment	Location	227.543	<0.0001	1.948	0.163	4.007	0.046
	Planting date	8.967	0.003	140.735	<0.0001	27.820	<0.0001
	Seedling stock	14.395	<0.0001	12.363	<0.0001	1.656	0.192
	Location × planting	79.010	<0.0001	0.111	0.739	7.243	0.007
	Location × stock	1.328	0.265	0.681	0.506	4.295	0.014
	Planting × stock	5.649	0.004	2.603	0.075	4.730	0.009
	Location × planting × stock	1.543	0.214	0.163	0.849	1.550	0.213
Height increment	Location	0.096	0.757	22.762	<0.0001	35.862	<0.0001
	Planting date	0.307	0.579	0.396	0.529	8.277	0.004
	Seedling stock	4.627	0.010	5.705	0.003	5.935	0.003
	Location × planting	14.770	<0.0001	0.009	0.925	0.018	0.893
	Location × stock	0.880	0.415	1.141	0.320	0.568	0.567
	Planting × stock	0.507	0.602	4.736	0.009	1.772	0.171
	Location × planting × stock	2.609	0.074	0.998	0.369	0.506	0.603

($I_a = 1.74$; $P_a = 0.001$) (Table 3). Moreover, spatial aggregation in plant survival was also detected in Site 2 for both plantation dates ($I_a = 1.89$, $P_a = 0.026$ and $I_a = 1.55$, $P_a = 0.086$) (Table 3).

The aggregation pattern of height and diameter was stronger on both site qualities and for both plantation dates, with a higher and

statistically significant value of I_a for height ($I_a = 3.02$, $P_a = 0.002$ and $I_a = 2.46$, $P_a = 0.089$ for early plantation and two sites) than diameter ($I_a = 1.42$, $P_a = 0.02$ and $I_a = 2.04$, $P_a = 0.057$ for early plantation and two sites) (Table 3), but close to a random pattern at medium plantation in Site 1 ($I_a = 1.00$, $P_a = 0.407$). The spatial pattern was

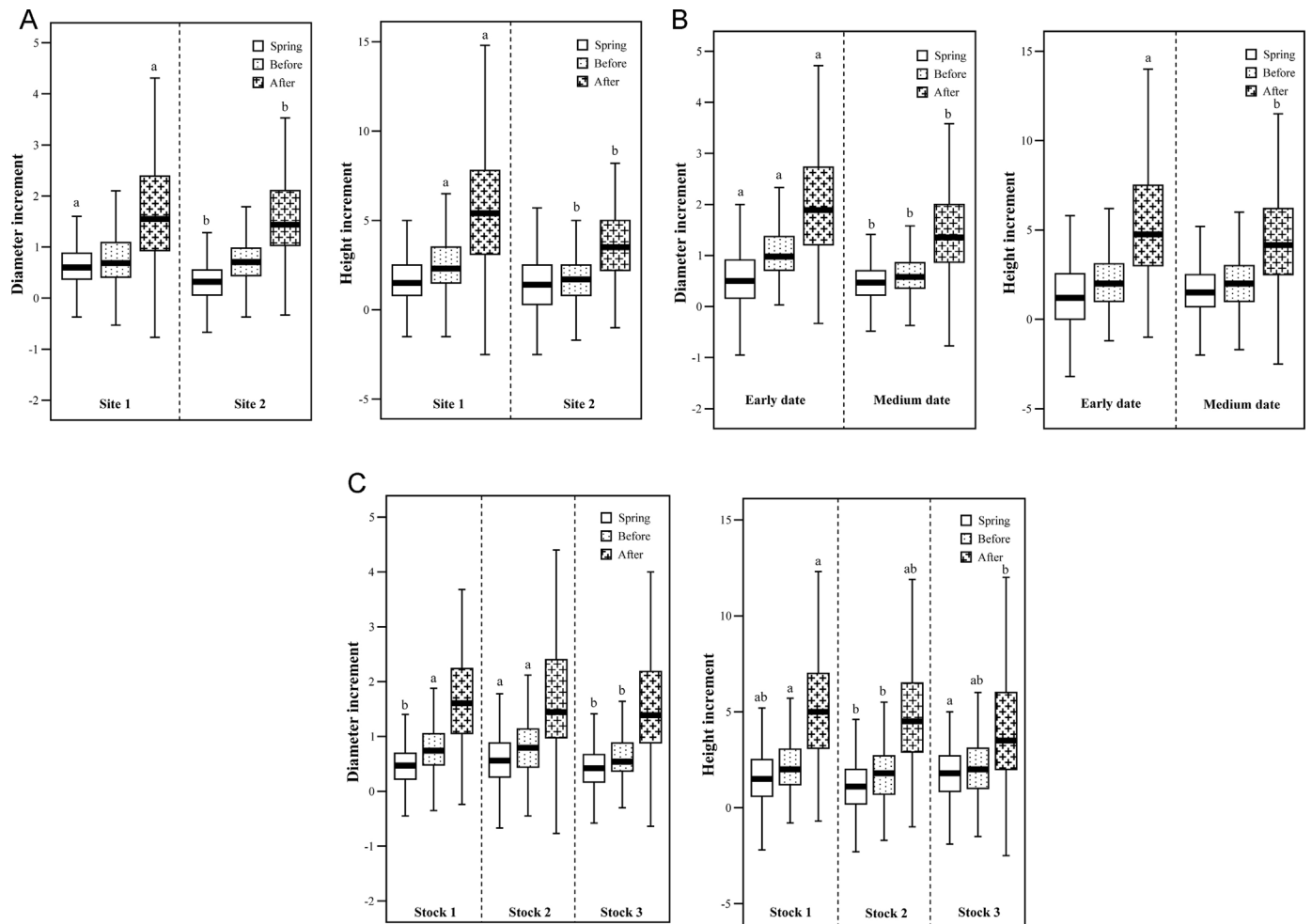


Fig. 2. Increments in diameter (mm) and height (cm) measured above individual seedlings according to: (A) site quality (rocky and non-rocky soils), (B) planting date (early and medium), and (C) seedling stock. Different letters represent significantly different post hoc differences between the respective treatments at alpha = 0.05 based on a linear mixed model for a given sampling period (spring-April, before summer-June and after summer-November).

Table 3

Results of SADIE analysis and descriptive statistics of seedling response related variables at the two sites. P_a values are derived from a randomization test (5967 permutations). I_a , aggregation index. Mean \pm SD for each location are also shown.

Variable	Site 1				Site 2			
	Date of planting	I_a	P_a	Mean	Date of planting	I_a	P_a	Mean
Survival (%)	Early	1.92	0.002	59.40 \pm 6.34	Early	1.89	0.026	49.12 \pm 6.85
	Medium	1.74	0.001	43.88 \pm 8.93	Medium	1.55	0.086	28.12 \pm 3.63
Height (cm)	Early	3.02	0.002	21.58 \pm 0.56	Early	2.46	0.089	19.55 \pm 0.50
	Medium	1.67	0.007	19.16 \pm 0.56	Medium	1.72	0.167	17.73 \pm 0.64
Diameter (mm)	Early	1.42	0.02	4.71 \pm 0.13	Early	2.04	0.057	4.12 \pm 0.13
	Medium	1.00	0.407	4.51 \pm 0.12	Medium	2.52	0.020	4.04 \pm 0.12

Table 4

Best-fitting regression models of seedling response according to topographic predictor variables obtained by Total Station. The best model within each set is presented, ranked according to their second-order AIC (AICc) value, ΔAIC_c , difference between the AICc of each model and that of the best model, and w_i , Akaike weights. AICc measures the relative goodness of fit of a given model; the lower its value, the more likely it is that this model is correct. Unshaded cells indicate variables that were not included in a particular model. Slope inclination (SLP), aspect (ASP), Compound Topographic Index (CTI) and flow accumulation (FLA).

Variable	CTI	FLA	ASP	SLP	R^2	AIC _c	ΔAIC_c	W_i
Site 1								
November								
Height					0.24	2850.89	0	0.70
					0.24	2852.63	1.74	0.29
					0.20	2868.88	17.93	<0.001
Diameter					0.34	1415.91	0	0.97
					0.32	1423.00	7.09	0.028
					0.28	1446.08	30.17	<0.001
Survival					0.23	423.34	0	0.95
					0.21	429.31	6.0	0.04
					0.17	447.21	24.0	<0.001
January								
Height					0.60	5374.42	0	0.38
					0.60	5375.02	0.59	0.28
					0.59	5375.86	1.43	0.18
Diameter					0.52	4138.21	0	0.36
					0.52	4193.75	0.53	0.28
					0.52	4194.42	1.20	0.20
Survival					0.42	133.92	0	0.94
					0.42	135.93	0.81	0.29
					0.36	136.89	2.55	0.15
Site 2								
November								
Height					0.38	6150.10	0	0.36
					0.38	6150.32	0.21	0.32
					0.38	6152.08	1.98	0.13
Diameter					0.49	4494.25	0	0.54
					0.49	4496.12	1.83	0.21
					0.48	4497.31	3.02	0.12
Survival					0.48	262.15	0	0.70
					0.48	270.93	1.86	0.27
					0.47	271.87	8.71	0.009
January								
Height					0.71	4780.32	0	0.56
					0.71	4781.11	0.79	0.37
					0.71	4781.01	5.70	0.03
Diameter					0.69	4255.89	0	0.72
					0.69	4257.74	1.89	0.28
					0.67	4286.04	30.14	<0.001
Survival					0.70	-29.27	0	0.69
					0.68	-27.63	1.63	0.30
					0.66	-1.02	28.24	<0.001

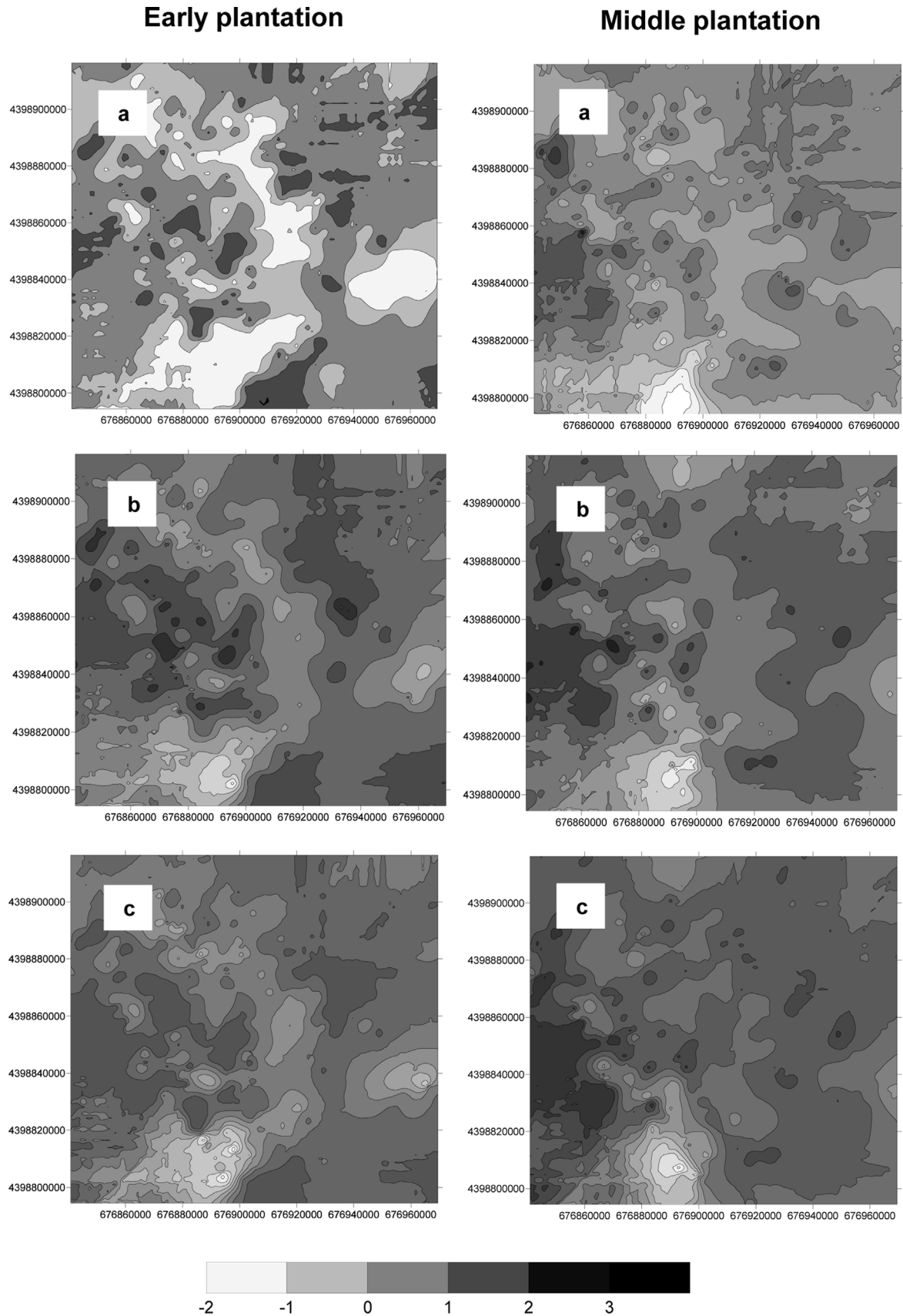


Fig. 3. Maps of SADIE index of clustering for seedling response on Site 1. Panels in the left and right columns show the analysis for early and middle plantation date, respectively. (a) survival; (b) final height; (c) final diameter. The maps show patches and gaps. Patches are areas where values of the studied variable are above the mean ($\nu > 1.5$, named ν_i by convention) and are represented by different shades from dark gray to black. Gaps are areas where values of the studied variable are below the mean ($\nu < -1.5$, named ν_j by convention) and are represented by different shades from light gray to white.

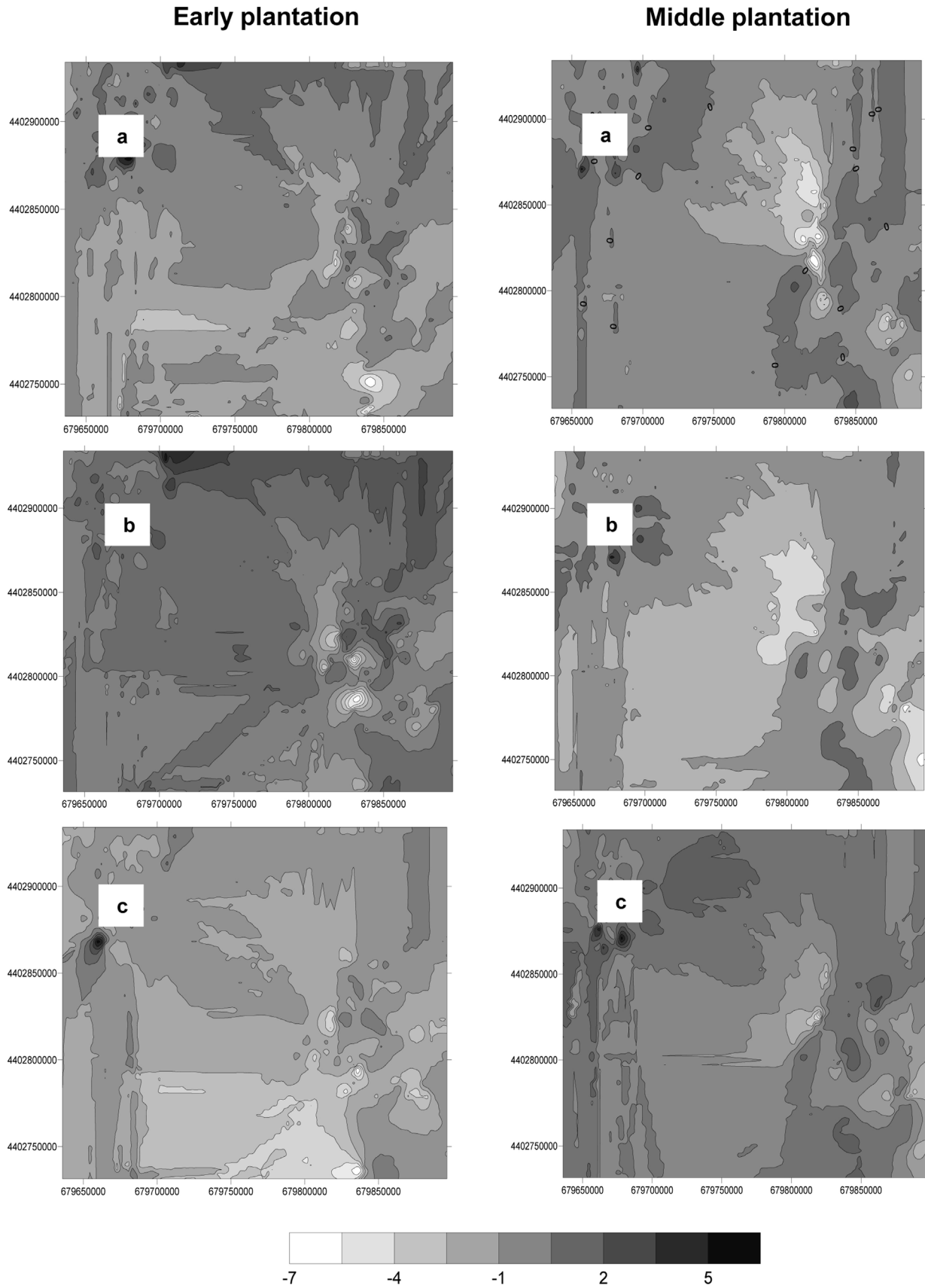


Fig. 4. Maps of SADIE index of clustering for seedling response on Site 2. Panels in the left and right columns show the analysis for early and middle plantation date, respectively. (a) survival; (b) final height; (c) final diameter. The maps show patches and gaps. Patches are areas where values of the studied variable are above the mean ($v > 1.5$, named v_i by convention) and are represented by different shades from dark gray to black. Gaps are areas where values of the studied variable are below the mean ($v < -1.5$, named v_j by convention) and are represented by different shades from light gray to white.

Table 5
Best-fitting regression models of seedling response according to topographic predictor variables obtained by low density LiDAR data. The best model within each set is presented, ranked according to their second-order AIC (AIC_c) value, Δ AIC_c, difference between the AIC_c of each model and that of the best model, and w_i , Akaike weights. AIC_c measures the relative goodness of fit of a given model; the lower its value, the more likely it is that this model is correct. Unshaded cells indicate variables that were not included in a particular model. Slope inclination (SLP), aspect (ASP), Compound Topographic Index (CTI) and flow accumulation (FLA).

Variable	CTI	FLA	ASP	SLP	R^2	AIC _c	Δ AIC _c	w_i
Site 1								
November								
Height					0.89	2066.88	0	0.72
					0.89	2068.77	1.89	0.28
					0.85	2178.31	111.43	<0.001
Diameter					0.89	726.77	0	0.99
					0.89	737.01	10.23	0.006
					0.86	822.60	95.82	<0.001
Survival					0.92	-385.96	0	0.73
					0.92	-383.93	2.03	0.26
					0.89	-291.42	94.53	<0.001
January								
Height					0.81	5109.44	0	0.67
					0.81	5110.88	1.44	0.32
					0.76	5183.68	74.23	<0.001
Diameter					0.90	3644.82	0	0.68
					0.90	3646.30	1.48	0.23
					0.88	3706.87	62.04	<0.001
Survival					0.95	-752.71	0	0.39
					0.95	-750.87	1.83	<0.001
					0.93	-600.19	152.51	<0.001
Site 2								
November								
Height					0.46	6098.60	0	0.72
					0.46	6100.59	1.98	0.26
					0.44	6111.41	12.80	0.001
Diameter					0.52	4472.78	0	0.56
					0.52	4473.94	1.16	0.31
					0.51	4477.05	4.27	0.006
Survival					0.48	265.44	0	0.47
					0.48	265.46	0.01	0.47
					0.47	271.34	5.90	0.02
January								
Height					0.56	4924.36	0	0.68
					0.56	4926.43	2.07	0.24
					0.55	4930.33	5.97	0.03
Diameter					0.48	4442.24	0	0.64
					0.48	4444.28	2.04	0.23
					0.47	4446.91	4.67	0.06
Survival					0.54	138.95	0	0.47
					0.53	139.40	0.44	0.38
					0.53	141.74	2.79	0.11

also characterized at this level; with the clustering index maps [ν] (Figs. 3 and 4) showing patches and gaps (zones with ν greater and less than 1.5, respectively).

3.3. Relative importance of topographic variables affecting the spatial pattern of growth and survival

Four topographic variables obtained from the Total Station and LiDAR data were incorporated in the OLS regression to predict survival and growth patterns. As expected, most of the topographic variation explaining seedling response was spatially structured. The effects of each topographic predictor on seedling survival and growth were established by standardized regression coefficients of full OLS models, in which these effects were measured after taking into account the spatial structures defined by the SADIE variables (Tables 4 and 5).

Regarding the Total Station data for the more favorable site (Site 1), the early plantation date showed the lowest partial coefficients

related to CTI, FLA and ASP ($R^2 < 0.34$) (Table 4). More importantly, standard OLS regression showed R^2 values usually higher than 0.4 in the rest of cases. In contrast, the more restrictive site (Site 2) and later plantation dates showed a stronger significant positive coefficient with CTI, FLA and SLO ($R^2 > 0.69$) (Table 4), indicating that most of the variation in seedling response can be explained by the combined effects of topographic predictors.

Moreover, when using LiDAR data predictors, the overall explanatory power of these full models was generally high ($R^2 > 0.46$), indicating that most of the variation in seedling response could be explained by the combined effects of topographic predictors (Table 5), with the overall effect of aspect in these metrics being much smaller. For the more favorable site quality (Site 1), early and medium plantation dates showed the strongest partial coefficients related to CTI, FLJ and SLO ($R^2 > 0.89$). For the more restrictive site (Site 2) and later plantation dates, a significant positive coefficient was found for CTI, FLJ and ASP ($R^2 > 0.46$) (Table 5), indicating that most of the variation in seedling

Table 6

Relative parameter importance values for seedling *Pinus halepensis* response data set, for models with $w_i > 0.0001$. Slope inclination (SLO), aspect (ASP), Compound Topographic Index (CTI) and flow accumulation (FLA).

Variable	CTI	FLA	ASP	SLP	CTI	FLA	ASP	SLP
	Field data				Low LiDAR data			
Site 1								
November								
Height	1	1	1	0.29	0.28	1	1	1
Diameter	1	1	1	0.97	1	1	1	0.99
Survival	1	0.95	1	1	1	1	1	0.73
January								
Height	1	0.66	0.43	1	1	1	0.32	1
Diameter	1	0.43	0.35	1	1	0.76	0.32	1
Survival	1	0.40	0.26	1	1	1	1	0.71
Site 2								
November								
Height	1	0.47	0.26	0.30	1	0.99	0.72	0.99
Diameter	1	0.33	0.76	0.99	1	0.90	0.60	0.97
Survival	1	0.98	0.98	1	1	0.99	0.49	0.95
January								
Height	1	1	0.41	1	1	0.93	0.27	0.99
Diameter	1	1	0.28	1	1	0.88	0.29	1
Survival	1	1	0.30	1	1	0.87	0.61	0.98

response can be explained by the combined effects of similar topographic predictors than when using Total Station data (Table 6). Consequently, although some variation was found regarding the importance of the topographic variables used in the models, the LiDAR topographic data had a stronger relationship with seedling response variables and performed better than the field topographic model according to the AIC values.

4. Discussion

We examined whether spatial variation in topographic variables is a relevant factor for *P. halepensis* seedling establishment in Mediterranean ecosystems. This trial showed that seedling survival and growth varied between two quality contrasted sites, and that a strong random component was linked to spatial patterns of topographic variables. Some studies have shown how survival and growth responses are modified by nursery and field treatments in the same experiment (Seifert et al., 2006; Palacios et al., 2009; del Campo et al., 2011; Villar-Salvador et al., 2012), the relationship of survival and growth responses to topographic variables (González-Rodríguez et al., 2011). Our results showed that date of planting and site quality features can significantly affect the survival and growth of *P. halepensis* seedlings, and that these variables have to be considered jointly with the spatial patterns of topographic variables. Additionally, low density LiDAR data can be used to integrate main topographic features and performed better as the field model to evaluate the effect of spatial pattern on seedling response.

4.1. Seedling survival and growth among plantation treatments

The hypothesis that *P. halepensis* seedlings will experience higher survival and growth in better site quality and early plantations due to the earlier establishment of roots, shoots and leaves was supported. Site quality and planting date were the variable with the greatest influence on plant survival after one growing season, followed by seedling quality stock, as indicated by the Cox regression model. The percentage of seedlings established 24 months after planting was higher for early plantation (54%) than medium plantation (36%). However, the proportion of seedlings that survived until the end of the study was very similar between

seedling stocks (~40%) (Fig. 1). It is important to highlight the variation in survival rates of stock 1 in both sites and for both planting dates: in Site 2 (less favorable site), final survival on early and medium dates was 63% and 5%, respectively, while in site 1 (more favorable site) it was 67% and 42%, respectively. In calculating the average of both percentages, a similar value is obtained to that of the remaining stocklots, which presented much more balanced survival rates between dates (data not shown). This performance of stock 1 is the result of an interaction between stock quality and plantation date, which was not detected by the Cox analysis but in the growth analyses. Stock 1 presented a high N concentration, which has been positively related to survival and growth (Oliet et al., 2009; Villar-Salvador et al., 2012), thus explaining the early date (November) results. On the other hand, temperatures were abnormally low in the region in late January (just after the medium date planting), reaching -8°C in the study area. Low temperatures are known to affect plant tissues with high N that can prolong the vegetative stage and increase the probability of cold injury (Royo et al., 2001; Puértolas et al., 2003).

Planting at the beginning of the Mediterranean winter period significantly increased survival, growth and early establishment success, as reported across a range of Mediterranean species (Turner et al., 2006; Palacios et al., 2009; Potts et al., 2010). This response has been linked to the promotion of deeper root growth; improved cold tolerance, altered soil moisture profiles, and less transplanting stress for seedlings planted at an early date, particularly during the summer drought period (Schiller and Cohen, 1998; Lloret et al., 1999; Potts et al., 2010). One of the major ecological factors acting on afforestation performance under Mediterranean climate is water availability (Ceballos et al., 2004; Nainggolan et al., 2012) and early plantation effectively increased water availability for the establishment process and cold tolerance in stock 1. Particularly in these conditions, the planting date could be a key factor affecting establishment. Early seedling plantation allows seedlings to access additional soil water content (Potts et al., 2010), which might reduce the spring and summer internal water stress that seedlings undergo in later plantings (Villar-Salvador et al., 2012). Thus, together with soil preparation, the careful selection of planting date seems to play an important role in the success of reforestation projects (Palacios et al., 2009).

In line with earlier research on conifer seedlings, plantation date and seedling stock quality had a positive influence on the growth of *P. halepensis* compared with later plantations (Palacios et al., 2009). Seedling height was greater at early dates and in the more favorable site. At least initially, early plantation seedlings had higher growth rates than later plantation seedlings, and were quickly able to take advantage of the early growth presented during the winter months. They invested in rapid vertical growth, which enabled them to obtain a height advantage over later plantation seedlings that persisted until the end of the study (Table 1, Fig. 2). The comparison of diameter increment values between treatments showed reduced seedling growth for later plantations, as well as more restrictive site (Site 2) and low-growth seedling stocks one year after planting. This growth effect can be partially attributed to the lower transplanting stress for seedlings in those treatments since they underwent a longer growth period after the time of planting, as it was in the case of later date plantation. Better site quality conditions and seedling stock also showed faster growth at the end of the trial, probably because those plantation factors allowed for better initial growth, in particular after the first summer (Table 1). As regards the date of plantation, during the first growing season there was a two-month difference in the duration of the total growing season between the early and medium date of plantation. Thus, the seedlings planted on the early dates had 2 months which favored their vegetative growth, mainly of their

roots. In contrast, the medium-date seedlings were planted in a much less favorable period, which limited their capacity to uptake the scant water reserves available in the soil during the following prolonged drought period (Metcalf and Grubb, 1997). Moreover, this initial advantage in growth persisted and resulted in greater seedling survival.

As regards plant quality, considerably fewer differences in survival rates were observed for different stock qualities than for seedlings planted on different dates or different sites. Many studies have shown that plant quality plays a central role in survival and out-planting growth, although others have not found any clear relation between plant quality and post-transplant response (Navarro-Cerrillo et al., 2006; Palacios et al., 2009). This open debate is due to the difficulty of assessing the effect of plant quality on the establishment of plantations as an isolated variable but jointly with the environmental factors and the plantation techniques employed. The results observed in our study showed a similar seedling response among stock types, having a weak power of association with seedling and growth survival when this was considered as an isolated factor.

4.2. Spatial pattern of response variables

Beyond measuring the effects of current nursery and plantation techniques, a full evaluation of seedling response patterns requires an understanding of the site-topography heterogeneity. Seedling response variables tended to show spatial gradients, whereas survival and growth showed some areas of higher values. Spatial patterns of survival and growth show that seedling response is related to a fine-scale spatial pattern of environmental variables on forest plantations (Figs. 3 and 4, see also Quero et al., 2011). These spatial patterns were generally within the expectations for Mediterranean domain and scale (Gallardo et al., 2000; Maestre et al., 2003; Valladares and Guzmán, 2006). Furthermore, the present study shows that the small-scale spatial heterogeneity of topographic features varies between sites. Thus, the more favorable site in terms of survival (Site 1) was characterized by lower slopes that resulted in a broader, more continuous spectrum of topographic variables (e.g., water runoff, slope and aspect). In contrast, the less favorable site was characterized by a higher structural complexity that resulted in more heterogeneous topographic conditions.

A relationship between fine-scale patterns of topographic variables and fine-scale patterns of survival and growth was observed (Table 3), reinforcing the idea that, at site-spatial scales, seedling response is driven by micro-topographic patterns (Maestre et al., 2003). Seedling survival and growth were clearly associated with topographic patterns following the overall pattern of Mediterranean plantations, in which water-related topographic predictors (Compound Topographic Index and flow accumulation) are the most important, reinforcing the idea that, at topographic-spatial scales, seedling response in Mediterranean ecosystems is driven by soil–water dynamics (e.g., Querejeta et al., 2001; Maestre et al., 2003). These variables may explain patterns by a simultaneous effect of topographic heterogeneity and available water, although the effects of slope and aspect cannot be ruled out (Gómez-Aparicio et al., 2004). A more complex set of explanations may be required when comparing sites, which may partially be the result of combining a very large number of heterogeneous soil and topographic conditions leading to different microsite responses. The effects of site heterogeneity, measured as topographic relief, were significant in our analyses and probably much greater than previously detected for microsite scales (e.g., Querejeta et al., 2001; Maestre et al., 2003). In contrast, the effects of topographic relief, expressed as slope and aspect, were not significant (lower coefficients

of determination for the original OLS regression) probably because these variables involve a more indirect, short-term effect in seedlings. However, seedling response was better explained by topographic variables on the restrictive site, with generally higher coefficients of determination (for the original OLS regression) than observed in the favorable site, indicating that topographic effects were not as strong here. The lack of a clear relationship between slope and aspect spatial variation and the spatial variation of seedling response may have been due to the effect of field topographic measures (i.e., Total Station topographic sampling bias). However, these variables are included in some models, and were significantly correlated with seedling response (Table 4).

4.3. Use of LiDAR in topographic descriptions

One reason for the scarce use of topographic features in reforestation projects is the limited spatial resolution of the available cartography. Other factors may also contribute to the limited use of topographic features, such as the complexity of data processing or data accessibility. These problems may be overcome by using low resolution LiDAR data to evaluate topographic conditions at reforestation scale as we have done in this work. The ability of the LiDAR-derived Digital Elevation Model to identify the same predictor variables as field data shows that topographic variables may be measured accurately at selected sites using LiDAR data.

Indeed, Brubaker et al. (2013) recently showed that LiDAR has the capacity to characterize surface roughness and microtopography. In this study, LiDAR topography patterns were used to define seedling response. It is important to note that the explanatory power of the LiDAR topography patterns was much higher than previous analyses at field scale, indicating the more complex resolution of this information (James et al., 2007; Brubaker et al., 2013). Topographic heterogeneity cannot be easily defined at the plantation scale, since it involves topographic conditions at spatial and temporal hierarchical scales, as reflected in the SADIE patterns (Quero et al., 2011).

The topographic morphology described by LiDAR was also closely linked to seedling response, thus indicating the potential of these data for evaluating reforestation success, which should be based, in part, on an accurate examination of topographic features. For example, the monitoring of water flow along hill-slope (expressed as CTI and flow accumulation) was strongly reflected using LiDAR data and seedling response. Accurate maps of topographic microsites based on topographic details may accurately forecast whether a given plantation has a higher survival and growth potential, considering routine reforestation planning activities such as soil preparation.

LiDAR technology can greatly improve topographic maps prior to reforestation actions as well as topographic analyses such as water use efficiency use at levels of precision not previously possible with standard cartography data. If possible, data accuracy should also be improved to enable the identification of local geomorphic features that are diagnostic of reforestation features as shown in this work. Several adjustments to LiDAR data collection and processing could improve the topographic mapping results. The data used in this study have relatively sparse point densities ($0.5 \text{ points m}^{-2}$) by current LiDAR commercial standards. Data on the average density between 1 and 2 points m^{-2} are now increasingly available from government agencies. Higher-resolution LiDAR data can improve the resolution of DEMs and contour maps, and could improve the sensitivity of the topographic data to abrupt changes in slopes. Despite this more complex approach underlying seedling response at site scale, different species have different requirements in terms of microsite use and response to topographic conditions, and differences in their spatial

patterns may help elucidate general processes driving variations in seedling response. As discussed above, using the low-density LiDAR data approach suggested in this work to analyze spatial patterns in seedling response may be very informative in improving our understanding of reforestation success.

5. Conclusions

Planting date and site quality have been shown to be factors determining survival response of *P. halepensis* in a reforestation carried out in the Mediterranean area. However, given the low survival rates of many afforestation programs in Mediterranean forests, a better understanding of the spatial interactions between topographic features and seedling response is increasingly needed at plantation scales to insure sustained restoration activities. Therefore, as pointed in this study, a full evaluation of seedling response patterns requires, beyond measuring current reforestation techniques effects (e.g., planting date, seedling quality and soil preparation), the understanding of the topographic dynamics, which are closely linked to water flow. Although these more complex processes underlying plantation success are difficult to model at small spatial units (i.e., micro-topographic), we believe that this information can be useful to improve our understanding of restoration in Mediterranean areas.

Detailed topographic data can contribute to explaining the spatial pattern of seedling response as the main topographic variables can be clearly identified, measured, and mapped at project scale. LiDAR data provides a relatively fast and efficient way to survey topographic details over large areas. Low LiDAR-derived data successfully identified and characterized the topographic features in the two study areas. The capacity of LiDAR-derived data to interpret seedling response is similar to that of high-precision topographic data. This evaluation capability should be of increasing importance for reforestation projects. As LiDAR technology becomes more economical and the analysis and products more refined, applications of the technology will expand. This capability should improve the use of topographic information for the interpretation of potential plantation response related to seedling response.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecoleng.2014.03.011>.

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