



Mechanical site preparation severity mediates one-year-survival response to summer drought in planted tree seedlings

Catherine Collet¹ · Chloé Agro¹ · Emila Akroume² · Jordan Bello³ · Alain Berthelot⁴ · Vincent Boulanger⁵ · Aurore Calas³ · Noé Dumas¹ · Jonathan Pitaud⁶ · Malaurie Puyal⁷ · Florian Vast¹

Received: 23 December 2023 / Accepted: 30 April 2024 / Published online: 16 May 2024
© The Author(s), under exclusive licence to Springer Nature B.V. 2024

Abstract

In face of future climatic conditions, methods to ensure the success of forest plantation in warm and dry conditions are required. Mechanical site preparation (MSP) prior to planting is widely used around the world to enhance seedling establishment success. Our study aimed at identifying, among a set of MSP methods that are used in practical forestry, which methods ensure plantation success under dry weather conditions.

We evaluated the combined effects of summer drought (estimated using the Standard Precipitation Index) and MSP severity (estimated using vegetation cover in the immediate seedling vicinity one year after MSP) on 1-year seedling survival. We used a network of 20 experimental sites established in France over a 10-year-period, and where seedlings were planted after various MSP.

In all treatments (severe MSP, moderate MSP, no MSP), seedling survival was higher in years with rainy summers than in years with dry summers. In rainy years, both moderate and severe MSP methods slightly improved the seedling survival rate (95%) compared to the unprepared control (88%). In dry years, seedling survival was similar after moderate MSP or with no MSP (50 and 54%, respectively), whereas it was much higher after severe MSP (79%).

In practical forestry, severe MSP appears as an option to enhance early seedling survival, especially when summer precipitations are lower than the seasonal average, whereas moderate MSP does not significantly improve seedling survival compared to an unprepared control, in all summer weather conditions.

Keywords Standard precipitation index · Climate change · Reforestation · Mechanical site preparation

Introduction

Global increases in temperature and drought, which are presently observed in western Europe and are expected to rise in the next decades (IPCC 2023), have multifold impacts on forest ecosystems, threaten their resilience, and call for adaptation actions in forest management (Lindner et al. 2014; Keenan 2015). Plantation of tree seedlings is a major tool to reinforce the resilience of forest ecosystems to current and future climatic conditions. It allows stand reforestation and restoration in all situations where natural regeneration from a seed bank or from sprouts does not provide the adequate material to meet the management objectives (Stanturf et al. 2001; McEwan and Steenkamp 2015).

Ensuring a high level of plantation success, even under hot and dry weather conditions, is a prerequisite to using plantation as a management measure to adapt forest ecosystems to future climatic conditions. Methods to plant tree seedlings have evolved in the last decades and have significantly improved plantation success (Chirino et al. 2009; Grossnickle 2018; South et al. 2023), but the risk of failure still remains high when rainfall is low and temperatures are high. There is ample evidence that hot and dry conditions during the growing season are deleterious to seedling establishment and planting success (Padilla and Pugnaire 2007). In drylands, characterized by repeated seasonal drought, plantation establishment is severely limited by long, dry periods that occur during the spring and summer (Pausas et al. 2004; del Campo et al. 2022). In addition, the analysis of interannual variation in plantation success in most forestry regions reveals that the average seedling survival rate varies from year to year and primarily depends on the severity of spring and summer drought, with dry years resulting in significantly lower seedling survival than wet years (Zwolinski et al. 1994). Across Europe, in the Mediterranean (del Campo et al. 2022), temperate (Boutte et al. 2023) and boreal (Luoranen et al. 2023) zones, plantation success becomes critical in dry years, especially for drought-sensitive species (del Campo et al. 2020). These observations underline the urgent need to develop plantation methods that ensure plantation success during dry years for different forestry regions, including regions that were not previously affected by recurring seasonal drought.

Silvicultural methods to improve plantation success in dry conditions aim at improving the water status of the newly planted seedling by increasing the amount of water available to the seedling or by enhancing seedling water uptake capacity (Chirino et al. 2009). Mechanical site preparation (MSP) prior to planting is widely used around the world to enhance seedling establishment success. In plantation sites with limited water supply, MSP may improve seedling water status by reducing the abundance of vegetation in the immediate vicinity of the seedling, therefore improving soil water availability in the seedling rooting zone, as well as by reducing soil resistance to root growth, thus facilitating root system development (Löff et al. 2012). Numerous studies have documented the beneficial effects of MSP on seedling survival and early growth, especially in dry conditions (Prévost 1992; Nilsson and Örlander 1995; Querejeta et al. 2001). Although it has not been clearly shown in the previous literature, the positive impact of MSP on seedling establishment is expected to increase with the intensity of drought during the growing season in all sites with limited water supply.

A variety of MSP methods, which differ in the equipment used and in their implementation in the field, have been developed worldwide in response to specific biotic and abiotic constraints, in order to match site characteristics with silvicultural objectives (von der

Gönnä 1990). MSP methods all create a disturbance around the seedlings but they markedly differ in the disturbances they induce. In the field of disturbance ecology, the severity of impact is an integrative indicator that has proven to be very useful to compare disturbances of different kinds (Roberts 2007; Kurth et al. 2020). It refers to the extent of the impacts that occur in the disturbed system (Frelich 2002; Iwasaki and Noda 2018) and is often measured as the proportion of biomass removed. Following the same conceptual approach, Chaves Cardoso et al. (2020) suggested examining site preparation methods through the lens of disturbance ecology and, more specifically, using the severity of impact as an indicator to understand the effects of different site preparation methods, as well as evaluating their suitability for various forest management goals. In previous works, Mattsson & Bergsten (2003) and Hjelm et al. (2019) used a severity index to compare MSP methods that differed in the equipment used and in their impact on the soil and the vegetation, and showed that the severity of the MSP method was positively related to early seedling performance and to long-term stand productivity.

The general objective of our study was to identify, among a set of MSP methods that are used in practical forestry, which methods ensure plantation success under dry weather conditions. These methods could then be recommended to forest managers to enhance plantation success. We focused on seedling survival during the first growing season. In many European countries, 1-year-survival is used as a criterion to evaluate planting success (Mataruga et al. 2023) and to prescribe refilling operations, which are very costly. Post-planting stress very often causes high seedling mortality rates during the first months, which may increase with adverse growing conditions (Grossnickle and Ivetić 2022). Environmental factors that determine seedling survival after one year differ from those that determine survival or growth over longer periods (2 to 5 years) (Cole et al. 2018; Dumas et al. 2021), and 1-year-survival must be specifically analyzed in studies aimed at improving plantation methods. Our study was performed in France, between 2011 and 2019, a period that was characterized by intense summer droughts in some years that caused extensive seedling mortality during their first growing season (Tallieu et al. 2022).

We used the severity of the disturbance to compare the effects of various MSP methods and to identify the methods that ensure a high rate of seedling survival in the first year. We classified the MSP methods according the severity of the disturbance they induce in the immediate vicinity of the seedlings into two classes: severe and moderate. We expected that MSP methods that induce severe disturbances because they provide better access to soil water to the newly planted seedlings would ensure greater plantation success than MSP methods that produce moderate disturbance. We hypothesized that (1) MSP improves 1-year seedling survival, compared to an unprepared control; (2) the improvement in seedling survival is higher under dry weather and soil conditions; (3) severe MSP methods are more beneficial to seedling survival than MSP with moderate severity; and (4) the benefit increase from moderate to severe MSP methods is higher under dry conditions. To test these hypotheses, we used a network of field experiments that evaluate the performance of various MSP methods used in plantation forestry in France, and we compared first-year seedling survival in plots with severe, moderate or no MSP.

M&M

Study sites

The field experiments were established at 20 sites in France, with latitudes ranging from 44°N to 49°N, and longitudes from 1°W to 8°E (Table 1). Soil texture ranged from sandy to clayey and soil moisture regime ranged from water-logged to dry soils. Field vegetation was dominated by various grass, fern, bramble or woody species, depending on the site. Annual minimum and maximum temperatures ranged between 5.7 and 8.0° and between 14.6 and 19.3°, respectively, and annual precipitation between 633 and 1183 mm.

The experiments were established between 2011 and 2019 to evaluate the performance of various MSP methods. The experiments started between one and nine years after clear felling, depending on the site. The vegetation was dominated by grasses or by ferns except in three sites with recent clear cuts where the main species in the neighboring vegetation also included tree or shrub species (Table 1). In all sites, vegetation was below 3 m height when the experiment started. The above ground part of the vegetation was shredded along the future planting lines, to make it easier for the MSP machines and the planters to access the planting spots. In each site, MSP methods were applied in autumn and the seedlings were planted within a few months, in the following winter or early spring. Between four and six MSP methods and an unprepared control were tested in each site. Treatments were not replicated within each site. Each experimental site compared a specific set of MSP methods, selected among the methods used locally in practical forestry. Methods differed in the type of tool (disc, ripper, tooth, plough) used, the machine (tractor, excavator) used, the type of preparation performed (scarification, trenching, mounding, plowing), the spatial extent of the preparation (along the planting lines or on spots around the seedlings), and in the severity of the disturbance they induced.

We evaluated the severity of the disturbance of each MSP method on the basis of its impact on neighboring vegetation in the immediate vicinity of the seedlings during the first growing season after MSP. In each MSP method plot of each experimental site, we measured vegetation cover on ten 1-m²-subplots surrounding the seedlings one year after site preparation, and we computed the ratio between the average vegetation cover measured in the treatment and in the control. These ratios ranged from 0.02 to 1. Each MSP method was tested in several experimental sites, and we estimated the severity of the disturbance of MSP methods as the mean value of the ratios computed in all experiments where the method was tested. MSP methods with a mean ratio below 0.3, i.e., methods that removed more than 70% of the vegetation cover compared to the unprepared control, were classified as very severe and referred to as “S” for “Strong”. MSP methods with a mean ratio above 0.3, i.e., methods that removed less than 70% of the vegetation cover compared to the unprepared control, were classified as moderately severe, and referred to as “M” for “Moderate”. The threshold value of 0.3 was chosen in order to obtain a balanced number of M and S plots in our dataset. Selecting a lower or higher value would have forced us to either eliminate some experimental sites and lower the total number of observations, or obtain a strongly unbalanced design. The unprepared Control was referred to as “C”.

In each experimental site, we selected one S method, one M method, and the unprepared Control. In each site, we selected the S and M methods that were most commonly tested across the 20 experiments so as to avoid, whenever possible, methods that were tested in too

Table 1 Site characteristics: site number; geographical location (latitude and longitude were blurred and rounded to the nearest degree); MSP treatments applied; year indicates the first growing season after plantation; Standardized Precipitation Index (SPI) computed over June, July and August of the same year; planted species. MSP treatment codes are: 1: disk pulled by a tractor; 2: scalper mounted on an excavator followed by a ripper-disk trencher pulled by a tractor; 3: ripper pulled by a tractor; 4: plow pulled by a tractor; 5: ripper-scarifier mounted on an excavator; 6: ripper-scarifier-disk trencher mounted on an excavator; 7: scalper mounted on an excavator followed by a ripper-scarifier mounted on an excavator; 8: scarifier mounted on an excavator; 9: scarifier mounted on an excavator followed by a ripper-scarifier mounted on an excavator)

Site				Mechanical Site Preparation treatment		Year	SPI	Species
Number	Location	Soil texture /humus type	Vegetation : main species	Medium severity	Strong severity			
1	49°N 1°E	Sandy-loamy / dysmoder	<i>Pteridium aquilinum</i>	3	5	2014	2,01	<i>Quercus petraea</i>
2	49°N 1°E	Sandy-loamy / dysmoder	<i>Pteridium aquilinum</i> /		9	2011	1,21	<i>Pinus nigra</i> <i>Quercus petraea</i>
3	47°N 6°E	Loamy / hydromull	<i>Molinia caerulea</i>	2	8	2014	1,8	<i>Quercus petraea</i>
4	47°N 0°E	Loamy / hydromull	<i>Molinia caerulea</i>	2	7	2015	0,47	<i>Pinus pinaster</i>
5	49°N 3°E	Sandy-loamy / moder	<i>Calamagrostis epigejos</i>	3	5	2014	1,9	<i>Quercus petraea</i>
6	49°N 3°E	Sandy-loamy / hydromull	<i>Agrostis stolonifera</i>	3	5	2014	1,91	<i>Quercus petraea</i>
						2016	0,1	<i>Quercus petraea</i>
7	44°N 1°W	Sandy / mor	<i>Pteridium aquilinum</i>	4	9	2012	-0,8	<i>Pinus pinaster</i> <i>Quercus robur</i>
8	48°N 3°E	Sandy-loamy / mull	<i>Calamagrostis epigejos</i> and <i>Pteridium aquilinum</i>	3	8	2014	1,82	<i>Quercus petraea</i>
9	48°N 6°E	Loamy / mull	Mixture of grasses, shrubs and trees	3	5	2014	0,71	<i>Pseudotsuga menziesii</i>
10	49°N 8°E	Sandy / mor	<i>Pteridium aquilinum</i>	1	9	2012	1,14	<i>Pinus sylvestris</i>
						2013	-0,56	<i>Quercus petraea</i>
11	49°N 8°E	Sandy-loamy / hydromor	<i>Molinia caerulea</i>	1	9	2012	1,14	<i>Pinus sylvestris</i>
						2013	-0,56	<i>Quercus petraea</i>
12	49°N 8°E	Sandy-loamy / hydromor	<i>Molinia caerulea</i>	1	9	2012	1,14	<i>Pinus sylvestris</i>
						2013	-0,57	<i>Quercus petraea</i>

Table 1 (continued)

Site				Mechanical Site Preparation treatment				
Number	Location	Soil texture /humus type	Vegetation : main species	Medium severity	Strong severity	Year	SPI	Species
13	49°N 7°E	Loamy / hydromull	<i>Cala-magrostis epigejos</i>	/	6	2019	-1,71	<i>Quercus petraea</i>
14	46°N 2°E	Sandy / moder	<i>Cytisus scoparius</i>	/	5	2017	-0,35	<i>Pseudotsuga menziesii</i>
15	48°N 2°W	Loamy / hydromull	<i>Molinia caerulea</i>	1	9	2012	0,57	<i>Pinus sylvestris</i> <i>Quercus petraea</i>
16	48°N 2°W	Loamy / hydromull	<i>Molinia caerulea</i>	2	5	2016	-0,26	<i>Pinus pinaster</i>
17	44°N 1°W	Sandy / hydromor	<i>Molinia caerulea</i>	4	9	2012	-0,79	<i>Quercus robur</i>
18	49°N 6°E	Loamy / mull	Mixture of grasses	3	6	2018	-1,17	<i>Pinus sylvestris</i>
						2019	-1,23	<i>Pinus sylvestris</i>
19	48°N 2°W	Loamy / mull	<i>Pteridium aquilinum</i>	1	9	2012	0,47	<i>Pinus sylvestris</i> <i>Quercus petraea</i>
20	47°N 4°E	Loamy / mull	<i>Cytisus scoparius</i>	3	5	2018	-0,45	<i>Pseudotsuga menziesii</i>
						2019	-1,81	<i>Pseudotsuga menziesii</i>

few experiments. In three experiments, no M method was retained and in one experiment, no Control was available.

Finally, we selected nine MSP methods across the 20 experimental sites. The four M methods were: (1) disk pulled by a tractor (five experimental sites; mean ratio between vegetation cover in the treatment and in the control: 0.86); (2) scalper mounted on an excavator followed by a ripper-disk trencher pulled by a tractor (three sites; mean ratio: 0.38); (3) ripper pulled by a tractor (seven sites; mean ratio: 0.84); and (4) plow pulled by a tractor (two sites; mean ratio: 0.34). The five S methods were: (5) ripper-scarifier mounted on an excavator (seven sites; mean ratio: 0.23), (6) ripper-scarifier-disk trencher mounted on an excavator (two sites; mean ratio: 0.29); (7) scalper mounted on an excavator followed by a ripper-scarifier mounted on an excavator (one site; mean ratio: 0.13); (8) scarifier mounted on an excavator (two sites; mean ratio: 0.29); and (9) scarifier mounted on an excavator followed by a ripper-scarifier mounted on an excavator (eight sites; mean ratio: 0.14). The MSP methods are fully described in Online Resource 1. Vegetation cover after one year averaged 84% in the Control, and 59% and 19% in all methods pooled from treatments Moderate and Strong, respectively.

The experimental sites were planted with different tree species: pines (*Pinus sylvestris* L., *Pinus nigra* var. *corsicana* (Loudon) Hyl., *Pinus pinaster* Aiton), oak (*Quercus petraea* (Matt.) Liebl., *Quercus robur* L.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco).

Seven sites were planted with two species, and 13 with one species. Six sites were refilled the following year because of high seedling mortality in some treatments. We planted one-year-old containerized (container size varied between 110 and 400 cm³) pine seedlings (measured height ranged between 10 and 20 cm), two or three-year-old bare root (1+1 or 1+2) oak seedlings (category: 30/60–50/80 cm), and two or three-year-old bare root (1+1 or 1+2) Douglas fir seedlings (category: 30/60 cm). Pines were planted between November and March, oaks between December and March, and Douglas fir in April or May.

In all forests with a high density of wild ungulates, the experimental sites were fenced or the seedlings were individually protected against browsing. Pine and Douglas fir seedlings had been chemically treated against *Hylobius abietis* in the nursery or after planting.

We considered each (site x MSP method x species x year) combination as an observation. In total, 77 observations were available for our study.

Measurements and data

In each site and each treatment, between 95 and 388 seedlings of each planted species were selected and tagged immediately after planting. In the following winter, all seedlings were examined and their status (alive or dead) was recorded. In the six sites that were refilled, both the initial and the refilled seedlings were measured and were considered as different observation sets. Seedling survival rate after one growing season was computed for each observation.

We estimated meteorological summer drought in each site and each year using the Standardized Precipitation Index (SPI) computed over 3 months (June, July, August) (McKee et al. 1993). SPI correlates well with plantation success (Del Campo et al. 2021). In a study that used data from 10,404 planting sites in conditions (geographic area, calendar years, planted tree species and MSP methods) that encompassed the conditions of our study, Talieu et al. (2022) showed that SPI computed over June, July and August was a good estimator of seedling mortality in the first year after planting. SPI values for all sites and all years were extracted from the Météo-France SAFRAN database, where SPI values are computed over an 8 km x 8 km grid and use a 30-year period (1981–2010) to estimate the long-term rainfall distribution (Soubeyroux et al. 2012).

Statistical analyses

First, we analyzed the crossed effects of MSP and summer drought on seedling survival using a beta regression. We then ran a full model, where treatments (3 levels: S, M, C) and SPI estimated in each site and each year (continuous factor) were the predictors, and seedling survival estimated in each observation was the response variable. We performed a likelihood ratio test, which indicated that the interaction between the two predictors was statistically significant (p -value=0.024). As a consequence, three reduced models were separately fitted for treatments C, M and S, where SPI was the predictor and seedling survival the response variable. We used the logit function as a link function in all models.

Second, we used Wilcoxon signed rank tests to estimate whether treatments M and S induced higher seedling survival than treatment C, in the same site and same year. Unilateral paired tests were performed separately for treatments M and S, and separately for years with summer rain above (SPI>0) and below (SPI<0), the median long-term precipitation. We

also tested whether treatment S induced higher seedling survival than treatment M in the same site and same year using the same tests.

All data treatments and statistical analyses were performed using the R environment (Cribari-Neto and Zeileis 2010; R Core Team 2023).

Results

In all three treatments, average seedling survival in the first year progressively decreased as SPI decreased from 2 (very rainy year) to -1.8 (very dry year) (Fig. 1): it decreased from 89 to 34% in the unprepared control, from 97 to 32% in treatment M, and from 94 to 75% in treatment S. Parameters of the beta regression models expressed in the logit link are given for treatment C [intercept=0.59 (std-err: 0.21); slope=0.81 (std-err: 0.19)]; M [intercept=1.25 (std-err: 0.17); slope=1.25 (std-err: 0.16)]; and S [intercept=1.82 (std-err: 0.20); slope=0.46 (std-err: 0.15)].

After rainy summers (SPI>0), survival rates ranged between 64% and 100% in all treatments pooled. Seedling survival averaged 88, 95 and 95%, in treatments C, M and S, respectively. Unilateral paired Wilcoxon tests indicated that seedling survival was significantly

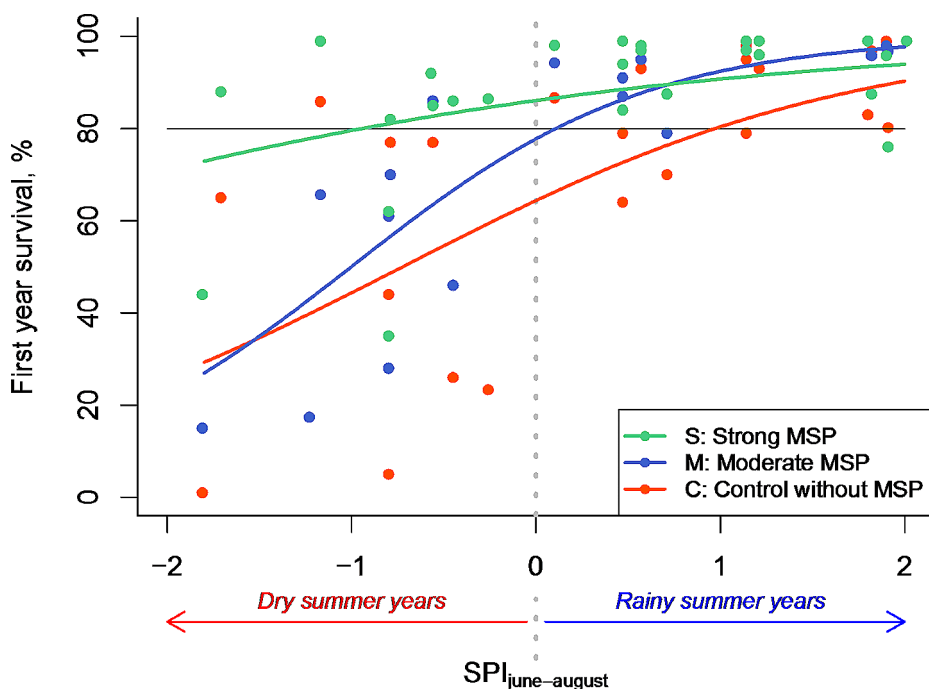


Fig. 1 Seedling survival in the first year after planting in relationship to the Standardized Precipitation Index computed over 3 months (June, July and August of the first year after planting) for two types of mechanical site preparation methods differing in their severity (S=Strong, M=Moderate) and for an unprepared treatment without mechanical site preparation (C=Control), measured in 20 experimental sites in France. The thin horizontal line represents the threshold value of seedling survival (80%) generally used to refill plantations in France. The dotted vertical line corresponds to the median value of the precipitation index

higher in both treatments M and S, compared to treatment C, but that treatment S was not higher than treatment M (p-values of 0.0053, 0.0016 and 0.45, respectively).

After dry summers ($SPI < 0$), seedling survival variability within each treatment was much higher than in rainy years, and survival rates ranged between 0% and 100%. Seedling survival averaged 50, 54 and 79%, in treatments C, M and S, respectively. Unilateral paired Wilcoxon tests indicated that treatment S was significantly higher than treatment C (p-value < 0.0001) and treatment M (p-value = 0.015), but that treatment M was not significantly higher than treatment C (p-value = 0.15).

Discussion

Impacts of MSP on seedling survival in interaction with summer drought

Our study showed that MSP enhances first-year seedling survival of species used to a large extent in European planted forests (sessile oak, Douglas fir, several pine species). It also showed that the increase in seedling survival following MSP is more pronounced when the summer is dry. These observations support our first and second hypotheses and agree with a large body of literature (Löf et al. 2012).

In years with rainy summers, early seedling survival in plots without MSP was high. MSP brought a slight but significant improvement and was similar for moderate and severe MSP. Seedling survival rates in plots without MSP decreased sharply as the amount of summer rain decreased, as previously shown by Zwolinski et al. (1994). In dry summers, seedlings planted after severe MSP had higher survival rates than those planted without MSP or with moderate MSP. All together, these observations partly invalidate our third hypothesis since severe MSP was more beneficial to seedling survival than moderate MSP only in dry summers, and they support our fourth hypothesis since the benefit from severe MSP, compared to moderate MSP, was higher in years with summers drier than normal.

The novelty of our study was to analyze the interaction between MSP severity and drought intensity. In rainy years, moderate MSP resulted in the same seedling survival rates as severe MSP, whereas in dry years, moderate MSP led to the same rates as the control without MSP. The interaction we observed between MSP severity and drought intensity suggests that moderate and severe MSP not only differ in the severity of their impact on the seedling environment but also in the type of impact they induce. MSP may improve seedling survival through the reduction of competition with neighboring vegetation, insect or rodent damage, soil compaction or soil water logging, and the various MSP methods differ in their impacts on these constraints (Löf et al. 2012). The relative importance of the constraints for seedling survival depend on the climatic conditions, soil characteristics and biotic interactions prevailing in the plantation site, and the impact of a MSP method on seedling survival in a specific set of environmental conditions may be indicative of which constraints are primarily affected by the MSP method.

In our study, moderate MSP was effective at reducing constraints that limited seedling survival in years with rainy summers (competition for nutrients and light from neighboring plants, biotic damage mediated by neighboring plants, allelopathy caused by neighboring plants, soil constraints), but could not significantly reduce constraints that limited seedling survival in years with dry summers (the same constraints as above, plus competition for

water from neighboring plants). Constraints not related to drought were probably limited, as suggested by the magnitude of the gain in survival brought by MSP in rainy years (+ 7%). These constraints probably also occurred in dry years as well but could not be detected because they were small compared to the high variability in survival observed in these years. This observation may explain the absence of statistically significant effects of moderate MSP in dry years, compared to the unprepared control. A larger number of observations would be required to test their effect.

Severe MSP was as effective as moderate MSP to reduce constraints that limited seedling survival in rainy years. In addition, severe MSP significantly increased survival rates in dry years, showing that severe MSP efficiently alleviated drought constraints (i.e., mainly competition for water from neighboring plants).

Indicator of MSP severity

As expected from previous work in the field of disturbance ecology (Peterson and Anderson 2009; Royo et al. 2016), the severity of impact was successfully used to compare MSP methods with distinctive features: they differed in the type of tool and prime mover used, and in the type and the spatial extent of the preparation performed. The severity index (vegetation cover in the immediate seedling vicinity one year after MSP) performed well because (1) following MSP, vegetation cover positively correlates with other indicators of MSP intensity such as the extent of soil disturbance (Chaves Cardoso et al. 2020); (2) vegetation control is one of the primary effects of MSP (Löff et al. 2012); (3) in our study, vegetation cover could be estimated with good accuracy; and (4) in our study, we explored a large gradient of vegetation cover values (ranging from 3 to 100%).

Recommendations for management

We observed a strong decrease in seedling survival when summer drought increased, which is in full agreement with the long-term monitoring of plantation success in France (Tallieu et al. 2022; Boutte et al. 2023). In our study, we were not able to observe species-specific responses due to the small number of experimental sites available but, in their long-term monitoring, Tallieu et al. (2022) showed that some species (including *Quercus petraea* and *Pseudotsuga menziesii*.) are very responsive to summer drought, while others (including *Pinus sylvestris*, *Pinus nigra* and *Pinus pinaster*) show constant survival rates irrespective of summer drought. These observations provide robustness to our results since our results apply to tree species that show a wide range of responses to summer drought. Similarly, due to the limited number of experimental sites, we were not able to observe any impacts of vegetation or soil type, although these factors are known to have primary effects on seedling response to MSP (South et al. 2023), and forest managers should use their own expert knowledge to translate the results of our study to specific site conditions.

In our study, the average survival rate in plots without MSP was 50% in dry years, which is well below the threshold value of 80% used in many European countries to define planting success (Mataruga et al. 2023). In rainy years, seedling survival was above the threshold in most plots without MSP (13 out of 17 plots). All together, these observations reaffirm that the main issue for forest managers in France is to ensure plantation success during dry years

for species that are most susceptible to summer drought, in order to avoid the extra costs due to plantation refill.

In rainy years, a positive and statistically significant effect of MSP on seedling survival was observed, irrespective of MSP severity. However the magnitude of the effect was small (+7%) and its ecological or practical significance (sensus Dixon and Pechmann (2005) and Wei et al. (2015) is questionable. Previous studies performed on *Pinus taeda* L. (South et al. 2023) suggest that the benefit of MSP during the rainy years that we observed in our study was too small to substantially increase stand value at harvest and, therefore, could be considered as negligible.

In dry years, severe MSP made it possible to significantly increase seedling survival, and the magnitude of the effect (+30%) is large and, most probably, significant for the forest practice. Most plots that received severe MSP showed a survival rate above 80%. In practical forestry, these plots would avoid the expense of refilling operations. In comparison, many plots in the control and in the moderate MSP treatment were below the threshold value and would need to be refilled. Applying a severe MSP method reduces the number of plantations to be refilled after a dry summer by 60%, compared to applying a moderate or no MSP.

MSP has a financial cost that must be balanced against its beneficial effect on seedling survival. In our study, severe MSP methods used tools mounted on medium sized (7 to 8 tons) or large (20 to 22 tons) excavators, whereas moderate MSP methods (except for treatment #2) used tools pulled by tractors. Using an excavator instead of a tractor approximately doubles the working time (Puyal et al. 2022) and the financial cost (Suadicani 2003) of the preparation. In rainy years, there is no benefit to using excavators that perform severe MSP instead of tractors that perform moderate MSP because they are more costly and do not improve early seedling survival. On the contrary, in dry years the benefit of using excavators may be high because they increase seedling survival, although they are more costly.

Finally, we also need to consider environmental impacts of MSP, when recommending appropriate methods. There is a growing emphasis on the maintenance of soil fertility and biodiversity, prompting forest managers to select silvicultural methods that preserve both soil and biodiversity. In our study, MSP severity, which was found to be related to seedling survival, was assessed in the immediate seedling vicinity (1-m²-subplots surrounding the seedlings), which corresponds to the rooting zone of the newly planted seedlings and the potentially competing neighboring plants. We must stress that our results do not suggest that implementing a MSP method beyond the area (along the planting line or throughout the entire stand area) would further improve seedling survival. Therefore, implementing MSP on a larger surface area (along the planting line or throughout the entire stand area) should be decided cautiously, given its demonstrated strong and lasting environmental impact, particularly on soil structure and fertility. Intermittent MSP methods that implement a severe preparation around the planted seedlings while leaving the rest of the surface area in the stand undisturbed, appear to be a good option for forester managers looking to ensure high seedling survival while simultaneously preserving the environment.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11056-024-10050-0>.

Acknowledgements The authors heartily thank Léon Wehrle, Sébastien Harnist, Lindsay Godard and Erwin Thirion (INRAE), Didier François, Gwénaëlle Gibaud, Jérôme Piat, Quentin Girard, Lucie Arnaudet, Erwin Ulrich and Claudine Richter (ONF), Jean-Yves Fraysse, Mathilde Duverger and Xavier Montagny (FCBA),

and Christophe Vidal (IDF-CNPF) for their invaluable help when designing, establishing and running the 20 experimental sites.

Author contributions All authors contributed to the study conception and design, to material preparation and data collection. Analyses were performed by CC. The first draft of the manuscript was written by CC, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the French Ministry in charge of forests (“Soutien au Pôle Renfor” annual grant), France Bois Forêt (grants 16RD496 and 17RD696), the Grand-Est region (“IPLor” grant), and the Fonds National pour l’Aménagement du Territoire (“IPLor” grant).

Data availability The datasets generated during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

References

- Boutte B, Husson C, Saintonge FX (2023) Quelle a été l'évolution des taux de succès des plantations de l'année au cours des quinze dernières années ? in: Expertise collective CRREF « Coupes Rases et Renouvellement des peuplements Forestiers en contexte de changement climatique », Rapport scientifique de l'expertise, editors: Landmann G Paris: GIP ECOFOR, RMT AFORCE (mai 2023) 624–635
- Chaves Cardoso J, Burton PJ, Elkin CM (2020) A disturbance Ecology Perspective on Silvicultural Site Preparation. *Forests* 11:1278. <https://doi.org/10.3390/f11121278>
- Chirino E, Vilagrosa A, Cortina J et al (2009) Ecological restoration in degraded drylands: the need to improve the seedling quality and site conditions in the field. In: Forest management. Grosberg, Editor, pp 85–158
- Cole E, Lindsay A, Newton M, Bailey JD (2018) Eight-year performance of bareroot Douglas-fir and bareroot and plug western larch seedlings following herbicide applications, northeast Oregon, USA. *New Forest* 49:791–814. <https://doi.org/10.1007/s11056-018-9653-5>
- R Core Team (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>
- Cribari-Neto F, Zeileis A (2010) Beta regression in R. *J Stat Softw* 1–24
- del Campo AD, Segura-Orenga G, Ceacero CJ et al (2020) Reforesting drylands under novel climates with extreme drought filters: the importance of trait-based species selection. *For Ecol Manag* 467:118156. <https://doi.org/10.1016/j.foreco.2020.118156>
- Del Campo AD, Segura-Orenga G, Bautista I et al (2021) Assessing reforestation failure at the project scale: the margin for technical improvement under harsh conditions. A case study in a Mediterranean Dryland. *Sci Total Environ* 796:148952. <https://doi.org/10.1016/j.scitotenv.2021.148952>
- del Campo AD, Segura-Orenga G, Molina AJ et al (2022) On the need to further refine stock quality specifications to improve Reforestation under climatic extremes. *Forests* 13:168. <https://doi.org/10.3390/f13020168>
- Dixon PM, Pechmann JHK (2005) A statistical test to show negligible trend. *Stat Rep* 86:1751–1756
- Dumas N, Dassot M, Pitaut J et al (2021) Four-year-performance of oak and pine seedlings following mechanical site preparation with lightweight excavators. *Silva Fenn* 55. <https://doi.org/10.14214/sf.10409>
- Frelich LE (2002) Forest dynamics and disturbance regimes. Cambridge University Press, p 266
- Grossnickle S (2018) Seedling establishment on a forest restoration site – an ecophysiological perspective. *REFOR* 110–139. <https://doi.org/10.21750/REFOR.6.09.62>
- Grossnickle SC, Ivetic V (2022) Root system development and field establishment: effect of seedling quality. *New Forest* 53:1021–1067. <https://doi.org/10.1007/s11056-022-09916-y>

- Hjelm K, Nilsson U, Johansson U, Nordin P (2019) Effects of mechanical site preparation and slash removal on long-term productivity of conifer plantations in Sweden. *Can J Res* 49:1311–1319. <https://doi.org/10.1139/cjfr-2019-0081>
- IPCC (2023) Summary for policymakers. In: Lee H, Romero J (eds) *Climate Change 2023: synthesis report. Contribution of Working groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core writing Team. IPCC, Geneva, Switzerland, pp 1–34. doi: <https://doi.org/10.59327/IPCC/AR6-9789291691647.001>
- Iwasaki A, Noda T (2018) A framework for quantifying the relationship between intensity and severity of impact of disturbance across types of events and species. *Sci Rep* 8:795. <https://doi.org/10.1038/s41598-017-19048-5>
- Keenan RJ (2015) Climate change impacts and adaptation in forest management: a review. *Ann for Sci* 72:145–167. <https://doi.org/10.1007/s13595-014-0446-5>
- Kurth VJ, D'Amato AW, Bradford JB et al (2020) Assessing the ecological impacts of biomass harvesting along a disturbance severity gradient. *Ecol Appl* 30:e02042. <https://doi.org/10.1002/eap.2042>
- Lindner M, Fitzgerald JB, Zimmermann NE et al (2014) Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management? *J Environ Manage* 146:69–83. <https://doi.org/10.1016/j.jenvman.2014.07.030>
- Löf M, Dey D, Navarro RM, Jacobs DF (2012) Mechanical site preparation for forest restoration. *New Forest* 43:825–848
- Luoranan J, Riikonen J, Saksa T (2023) Damage caused by an exceptionally warm and dry early summer on newly planted Norway spruce container seedlings in nordic boreal forests. *For Ecol Manag* 528:120649. <https://doi.org/10.1016/j.foreco.2022.120649>
- Mataruga M, Cvjetković B, De Cuyper B et al (2023) Monitoring and control of forest seedling quality in Europe. *For Ecol Manag* 546:121308. <https://doi.org/10.1016/j.foreco.2023.121308>
- Mattsson S, Bergsten U (2003) *Pinus contorta* growth in northern Sweden as affected by soil scarification. *New Forest* 26:217–231. <https://doi.org/10.1023/A:1024425205712>
- McEwan A, Steenkamp J (2015) Silviculture modernization in the South African forestry industry. In: *Atti del Secondo Congresso Internazionale di Selvicoltura=Proceedings of the Second International Congress of Silviculture. Accademia Italiana di Scienze Forestali*, pp 822–826
- McKee TB, Doesken NJ, Kleist J The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, 17–22 January 1993, Anaheim, California, 6p
- Nilsson U, Örlander G (1995) Effects of regeneration methods on drought damage to newly planted Norway spruce seedlings. *Can J Res* 25:790–802. <https://doi.org/10.1139/x95-086>
- Padilla FM, Pugnaire FI (2007) Rooting depth and soil moisture control Mediterranean Woody seedling survival during drought. *Funct Ecol* 21:489–495. <https://doi.org/10.1111/j.1365-2435.2007.01267.x>
- Pausas JG, Bladé C, Valdecantos A et al (2004) Pines and oaks in the restoration of Mediterranean landscapes of Spain: new perspectives for an old practice – a review. *Plant Ecol* 171:209–220
- Peterson CE, Anderson PD (2009) Large-scale interdisciplinary experiments inform current and future forestry management options in the U.S. Pacific Northwest. *For Ecol Manag* 258:409–414. <https://doi.org/10.1016/j.foreco.2008.12.029>
- Prévost M (1992) Effets du scarifiage sur les propriétés du sol, la croissance des semis et la compétition: revue des connaissances actuelles et perspectives de recherches au Québec. *Ann Des Sci Forestières* 49:277–296
- Puyal M, Agro C, Collet C et al (2022) Productivité horaire de la préparation mécanisée du site avant plantation: premiers résultats du réseau Pilote. Internal Report INRAE, p 66
- Querejeta JJ, Roldán A, Albaladejo J, Castillo V (2001) Soil water availability improved by site preparation in a *Pinus halepensis* afforestation under semiarid climate. *For Ecol Manag* 149:115–128
- Roberts MR (2007) A conceptual model to characterize disturbance severity in forest harvests. *For Ecol Manag* 242:58–64. <https://doi.org/10.1016/j.foreco.2007.01.043>
- Royo AA, Peterson CJ, Stanovick JS, Carson WP (2016) Evaluating the ecological impacts of salvage logging: can natural and anthropogenic disturbances promote coexistence? *Ecology* 97:1566–1582. <https://doi.org/10.1890/15-1093.1>
- Soubeyroux JM, Kitova N, Blanchard M et al (2012) Sécheresses des sols en France et changement climatique. Résultats et applications du projet ClimSec. *La météorologie* 78:21–30
- South DB, Starkey TE, Lyons A (2023) Why healthy Pine seedlings die after they leave the nursery. *Forests* 14:645. <https://doi.org/10.3390/f14030645>
- Stanturf JA, Schoenholtz SH, Schweitzer CJ, Shepard JP (2001) Achieving restoration success: myths in bottomland hardwood forests. *Restor Ecol* 9:189–200
- Suadicani K (2003) Site preparation and planting in a *Picea abies* shelterwood stand. *Scand J for Res* 18:247–259

- Tallieu C, Collet C, Renaud JP, Pitaud J (2022) Conception d'indices météorologiques pour prendre en compte le risque de sécheresse estivale dans la garantie de reprise des plantations. Internal report INRAE, p 70
- von der Gönna MA (1990) Fundamentals of mechanical site preparation. Br Columbia Ministry Forests. 29 p
- Wei L, Villemey A, Hulin F et al (2015) Plant diversity on skid trails in oak high forests: A matter of disturbance, micro-environmental conditions or forest age? For Ecol Manag 338:20–31. <https://doi.org/10.1016/j.foreco.2014.11.018>
- Zwolinski J, South DB, Barber BL (1994) Drought and survival of loblolly pine seedlings after planting. Eighth Biennial Southern Silvicultural Research Conference, Auburn, AL, Nov. 1–3. 419–423

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Catherine Collet¹  · Chloé Agro¹ · Emila Akroume²  · Jordan Bello³  ·
Alain Berthelot⁴ · Vincent Boulanger⁵ · Aurore Calas³ · Noé Dumas¹  ·
Jonathan Pitaud⁶ · Malaurie Puyal⁷ · Florian Vast¹

✉ Catherine Collet
catherine.collet@inrae.fr

¹ Université de Lorraine, AgroParisTech, INRAE, Silva, Nancy F-54000, France

² Office national des forêts, Recherche Développement et Innovation, Dôle F-39100, France

³ Office national des forêts, Recherche Développement et Innovation,
Boigny-sur-Bionne F-45760, France

⁴ FCBA, Charrey-sur-Saône F-21170, France

⁵ Office national des forêts, Recherche Développement et Innovation, Fontainebleau
F-77300, France

⁶ Office national des forêts, Recherche Développement Innovation, Champenoux
F-54280, France

⁷ Office national des forêts, Recherche Développement et Innovation, Compiègne
F-60200, France