Effects of Restricted Watering and CO₂ Enrichment in the Morphology and Performance after Transplanting of Nursery-grown Pinus nigra Seedlings

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Abstract. Extensive areas occupied by Pinus nigra forests in Spain have burned in recent years. Recovery of these forests depends upon reforestation. In this study, we analyze the combined effects of different treatments of water restriction and air enrichment with CO₂ on the performance of 2-year-old seedlings that will be planted in the field. An enriched CO₂ atmosphere might lead to more hardened seedlings by increasing specific leaf weight, the amount of solutes (nonstructural carbohydrates), and fine roots, thus promoting better water status (Wulfschleger et al., 2002). Different studies indicate that nursery treatments can influence the performance of seedlings after planting in the field (Bayley and Kietlka, 1996; van der Driessche, 1991a, 1991b), but there is still insufficient information about the field response of seedlings receiving different treatments and the effects (synergistic or not) caused by those treatments (Arnott et al., 1993; van der Driessche, 1992). The main objective of this study was to evaluate the combined effects of different treatments of irrigation and CO₂ enriched air for improving survival and growth of Pinus nigra seedlings transplanted into burned areas in Catalonia (northeastern Spain).

Material and Methods

This work was conducted in two different stages: a nursery assay and a plantation test in the field.

Nursery assay. The nursery assay was developed in a greenhouse located in Cabrilts Barcelona (2° 30' E, 41° 45'N). In September 1999, 1200 P. nigra seeds were sown in 300 -cm³ forest-pot containers of 17-cm³ cell upper surface and 18 cm high, filled with a substrate of 1 peat : 1 perlite mixture (by volume). In October 1999, 600 one-year-old P. nigra seedlings (1.0) and 600 two-year-old seedlings (2.0) were obtained from a commercial nursery (Olot, northeastern Spain) and were also placed in the greenhouse. Commercial seedlings were grown in 300-cm³ forest-pot containers filled with 3 peat : 1 vermiculite (by volume). Plant density in the greenhouse was 387 plants/m². Mean, minimum and maximum temperatures

Wildfires are among the most important natural disturbances in Mediterranean ecosys-
tems (Trabaud, 1987). However, during recent decades, the number and, especially, the surface area burned by forest fires has increased consider-
sably (Pitil et al., 1998). These larger and more intense wildfires are now affecting areas that have not so regularly burned in the past as fire-prone Mediterranean areas (Moreno et al., 1998). These areas are occupied by species that may lack an efficient postfire regeneration mechanism. This is the case of Pinus nigra Arnold, a pine widespread in middle-montane areas of the Mediterranean Basin. Due to the lack of serotinous cones and the early dispersal of seeds at the beginning of spring, this species does not have a seed bank after summer wildfires (Habrouk et al., 1999), and shows very low or no postfire regeneration (Retana et al., 2002; Trabaud and Camps-mant, 1991).

Due to this lack of successful regeneration, the only alternative to recover P. nigra forests is to reforest with seeds or seedlings of this species developed in nurseries. The first objective of nursery production is to obtain plants adequate for the area where they will be planted. In the Mediterranean region, water stress is the main limiting factor for plant life (Mitrakos, 1980). The almost complete absence of rainfall during the hottest months and its irregular distribution in the cold season can impair performance of forest plantations (Baeza et al., 1991; Vilagrosa et al., 1996). For this reason, plants needed for revegetation and restoration projects in Medi-
terranean climates should be plants adapted to low rainfall (Ararjó-Alves et al., 2000). Water requirements during establishment may be particularly high (Baeza et al., 1991), because seedlings have root systems that are not devel-
oped sufficiently to replace water lost through transpiration and because they are acclimatized to the environmental conditions of nurseries, which favor plant productivity rather than plant hardening (van der Driessche, 1991a, 1991b, 1992). The ecophysiological response of plants to harsh environmental conditions can be changed by acclimatization during nursery production or in the first stages in the field, after transplanting (Sachs, 1991). Thus, exposure of conifer seedlings to drought stress can increase their subsequent drought resistance (Kaushal and Aussenac, 1989). This resistance can be achieved by a series of morphological and physiological features that may, to a great extent, be conditioned in the nursery by certain cultural practices. Among these practices, application of restricted watering has been proved to promote osmotic adjustment and changes in cell wall elasticity (Royo et al., 2001; Savé et al., 1993, 1995; see Villar-Salvador et al., 1999), and increase root growth capacity (Ali Abod and Sandi, 1983).

However, the most effective treatments for drought resistance in the nursery tend to produce the smallest seedlings (Royo et al., 2001, van der Driessche, 1991a). Since large seedlings usually have higher survival and growth than small seedlings under natural conditions (Eggell and Orlander, 1993; Lamhamedi et al., 1996, van der Driessche, 1991a), the second objective of nursery production should be to obtain plants of larger size than those grown with hardening treatments. To increase seed-
ing growth and compensate for the reduced growth of hardening treatments, one possibil-
ity is to complement them with applications of high CO₂ concentrations in the atmosphere of the nursery (Savé et al., 1998), because the general conclusion of a number of studies (see reviews in Curtis and Wang, 1998; Norby et al., 1999; Tingey et al., 2000) is that tree seedlings exposed to high CO₂ generally show enhanced growth due to increased carbon assimilation.

Thus, the combined effects in the nursery of drought stress and high CO₂ might improve both the hardening and productivity of tree seedlings that will be planted in the field. An enriched CO₂ atmosphere might lead to more hardened seedlings by increasing specific leaf weight, the amount of solutes (nonstructural carbohydrates), and fine roots, thus promoting better water status (Wulfschleger et al., 2002). Different studies indicate that nursery treatments can influence the performance of seedlings after planting in the field (Bayley and Kietlka, 1996; van der Driessche, 1991a, 1991b), but there is still insufficient information about the field response of seedlings receiving different treatments and the effects (synergistic or not) caused by those treatments (Arnott et al., 1993; van der Driessche, 1992). The main objective of this study was to evaluate the combined effects of different treatments of irrigation and CO₂ enriched air for improving survival and growth of Pinus nigra seedlings transplanted into burned areas in Catalonia (northeastern Spain).

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CO₂ concentrations were kept constant through increasing flux rates. During the experiment, ventilation rates ranged from 5.0 to 6.1 m⁻²s⁻¹ with a wind speed between 0 and 4 m·s⁻¹. The film cover of the three modules had 64% of transmittance, and the mean radiation received by the plants was 1772 W·m⁻²·d⁻¹.

1) CO₂ TREATMENT. A multitunnel greenhouse (a three-span tunnel type divided into three modules of 77 m² each) was used to test the effects of CO₂ on P. nigra seedlings. The air was enriched with a constant flow of pure industrial CO₂ (Carburos Metálicos, S.A.) through polyethylene vessels. One greenhouse module was flushed with this gas until 500 ppm CO₂ concentration was reached and the other one was flushed until a concentration of 750 ppm was reached. The third module was maintained at atmospheric CO₂ concentration (350 ppm; control treatment). The CO₂ concentration was measured by an infrared gas analyzer (IRGA) (LIRA model 3600; MSA, Spain) connected to a personal computer and controlled by a PLC OMRON C20K, an automatic device to control the opening and closure of the valves (Peñuelas and Ocaña, 1996). Water plus fertirigation was daily applied with microsprinklers. Nutrient solution was 8.22 mmol·L⁻¹ NO₃⁻, 0.9 mmol·L⁻¹ PO₄³⁻, 1.66 mmol·L⁻¹ SO₄²⁻, 4.20 mmol·L⁻¹ K⁺, 3.92 mmol·L⁻¹ Ca²⁺, 1.50 mmol·L⁻¹ Mg²⁺, and 1.28 mmol·L⁻¹ NH₄⁺. The pH was adjusted to 6.5.

Different morphological and biomass allocation variables were measured for plants of each treatment before and five months after treatment application (in both cases, six plants per treatment were randomly selected). Biomass, expressed as a dry weight, was obtained after oven-drying to constant weight at 60 ºC for at least 48 h. Seedling root, stem and needle biomass were measured separately. Projected leaf area was determined for each plant with a digital analysis system (Delta-T Devices, Cambridge, U.K.). Total stem height (from ground to base of terminal bud) and basal stem diameter (with a digimatic caliper; 500 series, Mitutoyo, Japan) were measured. From these variables, different indexes were calculated: specific leaf weight (SLW, leaf weight/leaf area), leaf weight ratio (LWR, leaf weight/plant weight), leaf area ratio (LAR, total leaf area/plant weight), stem weight ratio (SWR, stem weight/plant weight), root weight ratio (RWR, root weight/plant weight), and root/shoot ratio (root weight/stem weight/leaf weight) (Coombs et al., 1985). Total root length and total root area were measured with a digital analysis system (Delta T Devices). Specific root length (SRL) was calculated as root length/root weight (Tagliavini et al., 1993).

At the end of the experiment and just before field plantation, five samples of five leaves of seedlings per treatment were saturated overnight at 7 ºC. Fresh weight was measured gravimetrically the next day at intervals of 30 and 60 min. Leaf dry weight was measured after drying at 60 ºC for 48 h. Cuticular transpiration was calculated as loss of water after stomatal closure (see Villar-Salvador et al., 1999).

This nursery experiment was conducted as a factorial experiment and analyzed as a completely randomized design, with three factors tested: age [seed, 1 year old (1:0) and 2 years old (2:0)], CO₂ concentration (ambient, 350, 500, and 750 ppm), and water level (control, 100%, and 50% of water supply). There were 100 1- and 2-year-old plants, and 200 plants of seed origin per treatment. Statistical analysis was performed with SAS (SAS Institute Inc., Cary, N.C.). Analysis of variance was used to test for the effects of age, CO₂, and water treatment on all measured and calculated variables. When necessary, data were normalized by a log transformation. The sequential Bonferroni method was used to control the group-wide type I error rate (Rice, 1989). The individual values of the different levels of each variable were compared with a posthoc test (Fisher’s protected least significant difference).

Field plantation. To assess the response to field conditions of the P. nigra seedlings grown under different greenhouse treatments, they were planted outdoors in the Castelllallat Mountains (41° 45’ to 42° 6’ N; 1° 38’ to 2° 1’ E, Catalonia, northeastern Spain). This area was affected by a wildfire in July 1998, which burned 14,300 ha covered extensively by P. nigra forests (84% of the surface). The soil of this area is a calcareous Mediterranean (according to the Thornwaite index), with mean annual temperature of 10 to 13 ºC and mean annual precipitation of 600 mm. The experimental plot (1.7 ha) was located in a burned forest of P. nigra with no regeneration of any tree species and barely covered by scattered shrubs and a herb layer dominated by Brechspodium retusum. The soil of the plot was a calcareous limestone.

Before plantation, soil ripping was carried out using a double teeth subsoiler mounted at the rear of a bulldozer, which opened parallel rips of 70 cm deep with 2.5 m between them. After site preparation, 60 1-year-old and 60 2-year-old plants of each greenhouse treatment (2 water levels × 3 CO₂ levels) and two ages [1 year old (1:0) and 2 years old (2:0) in the nursery] were randomly chosen and planted in the rips by assigning a random number before plantation to each of the 720 seedlings. No selection by size was carried out; seedlings were randomly chosen in the greenhouse. Seedlings were planted in the field at a density of 1400 seedlings/ha, a standard density value used in P. nigra afforestations (Espelta et al., unpublished data). We did not plant the third age treatment (seedlings arisen from seeds in the greenhouse) because they did not attain the minimum size recommended for planting. Seedlings were planted in March 2000, and their survival was monitored at the end of 2000 and 2001. Height at the end of 2001 and height growth during these 2 years in the field were measured for all surviving plants.

To study differences of survival between planted seedlings of different ages, CO₂ and irrigation treatments, models obtained from multi-way contingency tables were analyzed. When the goodness-of-fit was p > 0.05, data were considered to fit the model in question.
The best model was considered to be the most parsimonious acceptable ($p > 0.05$) one. These analyses were carried out with the program STATISTICA for WINDOWS. A two-way analysis of variance was used to test the effects of CO$_2$ and water treatment on final height and height growth of seedlings. To control the group-wide type I error rate, the sequential Bonferroni method was used (Rice, 1989). The individual values of the different levels of each variable were compared with a posthoc test (Fisher’s protected least significant difference).

**Results**

**Nursery assay.** The effects of age, CO$_2$ treatment, and irrigation on morphological and biomass allocation variables of *Pinus nigra* seedlings in the nursery essay are summarized in Table 1. The age of seedlings influenced all variables considered (Table 2). Seedlings increased in size from recently emerged seedlings to 1- and 2-year-old seedlings for most variables considered. Seedlings of different ages also differed in the variables related to resource allocation, because LWR, LAR, and SRL decreased from recently emerged to 1- and 2-year-old seedlings, while SWR, RWR, and SLW showed the opposite pattern.

The increment of CO$_2$ increased total biomass, leaf biomass, and leaf area of *P. nigra* seedlings (Table 3). High CO$_2$ concentration also increased root length, although the interaction age × CO$_2$ treatment was significant for this variable and for SRL (Fig. 1). Root length increased with CO$_2$ in recently emerged and in 1-year-old seedlings, but not in 2-year-old seedlings.

There was no significant evidence that the decrease in water supply affected total biomass (Table 1), but it reduced stem height, leaf area, leaf biomass, and stem biomass (Table 3). A consequence, LWR decreased, while R/S ratio and RWR increased (Table 3). However, there was a significant interaction between age × irrigation for some of the variables considered (Fig. 2). Leaf area increased with irrigation for recently emerged seedlings but not for older ones. This also led to an increment of LWR and LAR for these young seedlings but not for older ones. Root length and SRL also increased with irrigation in recently emerged and, to a lesser extent, in 2-year-old seedlings, but decreased in 1-year-old seedlings.

According to Table 1, age of plants was also the only factor significantly affecting cuticular transpiration of *P. nigra* seedlings. Plants of seed origin and 1-year-old showed higher values than 2-year-old plants (Table 2). The other factors and the different interactions were not significant.

**Field plantation.** Mean survival of *P. nigra* seedlings one season after their transplant to the field was 75%. According to the best model obtained in the analysis of the multivariate contingency table of survival data, survival of *P. nigra* seedlings was not influenced by the experimental treatments previously received in the nursery, neither varying regimen of CO$_2$ fertilization, but did depend on seedling age (log-linear analysis, $G^2 = 14.8$, $p = 0.789$, df = 20). Survival was higher in 2-year-old seedlings than in 1-year-old seedlings (81% vs. 69% of seedlings alive). Two years after planting, seedling survival was only 51%. Again, there were no differences in survival among CO$_2$ or water treatments, but survival still depended on seedling age (56% and 44% for 2-year-old and 1-year-old seedlings).

Seedling height 2 years after planting was significantly affected by seedling age and the CO$_2$ treatment in the greenhouse but not by the irrigation level applied in the greenhouse (Table 4). Two-year-old seedlings were taller than one-year-old ones (23.2 ± 0.4 vs. 18.2 ± 0.5 cm). Seedlings receiving 550 ppm achieved higher heights than those receiving 350 ppm in the greenhouse.
height (22.0 ± 0.7) than seedlings receiving 750 ppm (19.4 ± 0.5 cm), while those of 350 ppm (20.5 ± 0.7 cm) did not show differences with the other two treatments. Similarly, height growth also depended on seedling age and CO2 treatment but not on irrigation level (Table 3). The interaction between CO2 enrichment and water regime was significant (Fig. 3a). 100%-watered seedlings were taller than 50%-watered seedlings in the 750 ppm treatment, but no differences were found in the 550 ppm treatment. The age × CO2 interaction was also significant (Fig. 3b). Height of 1-year-old seedlings was higher in those that had received higher CO2 enrichment, while 2-year-old seedlings showed the highest value in the intermediate CO2 level.

**Discussion**

During the nursery assay, age, water regime, and atmospheric CO2 concentration modified the morphological traits of seedlings (Table 1). As expected, all variables related to size (height, diameter, and biomass) increased with age. Moreover, biomass allocation to roots (R/S, RWR) or stems (SWR) also increased with age, while allocation to leaves (LWR) decreased. This pattern of biomass allocation, in which older plants allocate less to leaves and more to support tissues than younger plants, has been commonly reported in the literature (Tissue et al., 1997). Older seedlings also exhibited a higher specific leaf weight (SLW) and a lower cuticular transpiration rate. Both trends involve a progressive increase in the sclerophyll of leaves (Edwards et al., 2000), probably due to larger concentrations of secondary and structural compounds not involved in the photosynthesis process in older seedlings (Cornelissen et al., 1999). These morphological and physiological characteristics could promote some advantages, such as increased leaf longevity, increased carbon gain per unit investment, and high water use efficiency (Freitas, 1997; Turner, 1994).

Atmospheric CO2 concentration significantly affected total biomass, leaf biomass, leaf area, and root length of seedlings. Total biomass was higher for 750 than for 550 ppm (e.g., 28% and 16% respectively, in comparison with seedlings grown at ambient CO2). This enhancement of above-ground growth has been perhaps the most common manifestation of the effect of CO2 on seedlings of many species (Broadmeadow and Jackson, 2000; Curtis and Wang, 1998; Norby et al., 1999), including *Pinus* species (Tissue et al., 1997), where aerial biomass may increase 40% to 60% with increasing CO2. On the other hand, in our study, the impact of elevated CO2 on roots was small, and the increase of root biomass found in other studies (Norby et al., 1999; Tingey et al., 2000) was not confirmed in the case of *P. nigra* seedlings. Root length and SRL increased with CO2 in recently emerged and in 1-year-old seedlings but not in 2-year-old seedlings (Fig. 1). This pattern could be related to the fact that containers may affect root growth in the larger plants, as has been previously shown in other studies using container-grown plants (Tingey et al., 2000). The causes of this effect remain unclear, but it has been attributed to physical restrictions of growth leading to a hormonal response (Sage, 1994) or the inability of roots to absorb enough water and nutrients to fulfill requirements of the aerial part, causing water stress (Will and Teskey, 1997).

The reduced water regime applied affected stem height and biomass and leaf area, with values being 14% to 18% lower for low-watered plants. On the contrary, no effects in root biomass or area were found. Altogether, these variations lead to an increment of R/S and RWR under the reduced water supply treatment. These morphological traits, coupled with a low cuticular transpiration rate, confirm the positive effects of reduced irrigation to increase the potential hardening process in plants (Grossnickle et al. 1991; van der Driessche, 1991a, 1991b), which could confer a higher drought resistance to seedlings (Savé et al., 1993). In the case of several morphological traits (leaf area, LAR, LWR, root length, and SRL), there was an interaction between age of seedlings and irrigation. Differences between irrigation treatments were higher for recently emerged seedlings than for older ones, pointing out that the effects of hardening treatments should be applied when plants are young because they have higher levels of morphological plasticity than older ones. In spite of the separate effects reported for CO2 and water regime, none of the

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**Table 4. ANOVA test of effects of age (1-year-old and 2-year-old seedlings), CO2 treatment (350, 500, and 750 ppm), and irrigation (100% and 50% of water supply) in the greenhouse on height and height growth 2 years after planting of *Pinus nigra* seedlings. Total sample size was 252.**

<table>
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<tr>
<th>Source of variation</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
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<td>Age (A)</td>
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<td>272.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>CO2 level (C)</td>
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<td>5.4</td>
<td>0.005</td>
<td>4.1</td>
<td>0.018</td>
</tr>
<tr>
<td>Irrigation (I)</td>
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<td>0.875</td>
<td>1.0</td>
<td>0.323</td>
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<tr>
<td>A x C</td>
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<td>1.0</td>
<td>0.369</td>
<td>5.4</td>
<td>0.005</td>
</tr>
<tr>
<td>A x I</td>
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<td>0.9</td>
<td>0.346</td>
<td>1.5</td>
<td>0.222</td>
</tr>
<tr>
<td>C x I</td>
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<td>1.4</td>
<td>0.252</td>
<td>5.8</td>
<td>0.003</td>
</tr>
<tr>
<td>A x C x I</td>
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<td>0.380</td>
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<td>Error</td>
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</table>
almost entirely to water stress, as all dead seedlings presented brown-drought leaves with no signs of herbivory or pest attack (personal observation). Concerning the experimental factors as-sayed, age was the only significant factor affecting survival in the field, because the survival rate was 13% higher in 2- than in 1-year-old plants. As 2-year-old plants were the ones that exhibited lower cuticular transpiration (lower SLW) coupled with a lower leaf area ratio, this result confirms the paramount importance that some morphological traits may have to reduce water lost and to increase the successful establishment of seedlings (Egnell and Ørlander, 1993). In contrast, neither water regime nor CO2 enrichment modified survival of P. nigra seedlings after transplant in the field. Water shortage imposed in the nursery, although causing reduction in stem height and leaf area, did not modify leaf characteristics (such as sclerophyll) and did not promote enough hardening to enhance seedling survival. In spite of the lack of major effects of CO2 enrichment or water reduction treatments on seedling survival in the field, it is important to note that some differences in height growth and final height among the different treatments applied still remained 2 years after plantation (Table 4). Interestingly, seedlings previously grown under 500 ppm CO2 achieved the overall better results. In view of the absence of major differences in architecture and biomass partitioning of seedlings grown under 500 or 700 ppm of CO2 (Table 3), better growth of the former could be due to some ecophysiologically advantageous (e.g., higher assimilation rates) of intermediate CO2 enriched seedlings (Wallschlegler et al., 2002). On the other hand, considering the similar results obtained in the survival of seedlings, using larger plants in restoration projects might help to reduce soil erosion, increase water retention, and provide a better visual landscape quality (Biel, 2002).

The adoption of reduced watering regimes may be useful to reduce excessive water waste in the nurseries and to increase plant survival in the field (van der Driessche, 1991a). However, from our results we cannot conclude that the nursery treatments applied, neither water shortage nor CO2 enrichment, lead to important variations in plant survival. Two aspects would require further analysis. On the one hand, the irrigation levels tested (100% vs. 50%) may not have been sufficiently different to change drastically the morphological and physiological traits of P. nigra seedlings and determine their success in field conditions. Future studies should include more severe treatments of water reduction to force seedlings hardening. On the other hand, it remains unclear if a longer application of the experimental treatments to recently germinated seedlings (those that showed the highest response) would allow them to develop similar high-specific leaf area and lower cuticular transpiration rates than those exhibited by 2-year-old seedlings. In spite of the lack of effects of CO2 enrichment in seedling survival, it is important to stress the promising result that, for a similar survival rate, seedlings grown at 550 ppm of CO2 were larger after transplant than control plants. This result could improve the targets of the restoration process. Since reclamation of large burned areas requires the production of a large number of vigorous seedlings in a short time (Baiza et al., 1991; Vilagrosa et al. 1996), we feel that new strategies in landscape restoration under Mediterranean environmental conditions would benefit from further research on the combined effects of hardening by water stress and CO2 enrichment on the production of nursery seedlings.

**Literature Cited**


Minakos, K.A. 1980. Theory for Mediterranean plant-
science 9:89–97.
Savé, R., C. Biel, R. Domingo, M.C. Ruiz-Sánchez, and A. Torrecillas. 1995. Some physiological char-
Taglaviini, M., L.J. Veto, and N.E. Looney. 1993. Measuring root surface area and mean root diam-
eter of peach seedlings by digital image analysis, Tree Physiol. 13:740–749.