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Mineral nutrition and growth of containerized *Pinus halepensis* seedlings under controlled-release fertilizer

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Abstract

Low, moderate and high rates (3, 5 and 7 g/l, respectively) of two controlled-release fertilizer (CRF) types, Osmocote 9–13–18 and Osmocote 17–10–10 were evaluated for their effects on production of containerized *Pinus halepensis* planting stock. Both formulations had similar patterns of nutrient release, with high release rates during the first 2–3 months, in contrast with minimum seedling uptake (determined by stem volume current increment). Shoot morphological attributes improved with increasing application rate regardless of formulation, though root growth was not affected. Shoot/root ratio was significantly affected by both factors, with the highest value (3.3 g/g) observed with Osmocote 17–10–10 at the 7 g/l rate. Needle N concentration was significantly affected by both rate and formulation, with 17–10–10 at the 7 g/l rate producing the highest value (18.5 mg/g). Needle P concentration was not affected by rate, and was low in all treatments (maximum of 2.2 mg/g), particularly in the 17–10–10 formulation, suggesting that P enrichment may be needed to improve its composition. Needle K concentration was significantly affected by rate, regardless of formulation. Absorption efficiency of N was near 40% in all treatments, although K and P recovery was lower. The CRF types used in this study may be useful for plant production of *P. halepensis*, promoting suitable morphological values and nutritional status.

Keywords: Slow-release fertilizers; Forest seedling nutrition; *Pinus halepensis*; Forest seedling quality; Nutrient recovery

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1. Introduction

Fertilization is one of the most important cultural practices for plant quality in reforestation, especially for seedlings produced in containers in which the limited volume seriously hinders their growth (Landis, 1989). Fertilization can accelerate shoot and root growth of plants, modify tissue nutrient contents and hence the amount of available reserves, improve post-transplant rooting and growth capacity, and increase resistance to water stress, low temperature and disease (Landis, 1985; van den Driessche, 1991, 1992; Timmer and Aidelbaum, 1996; Haase and Rose, 1997; Shaw et al., 1998; Malik and Timmer, 1998; Grossnickle, 2000). These properties are of vital importance for successful plant establishment under unfavorable conditions (Puttonen, 1997; Birchler et al., 1998).

The form of nutrient delivery can substantially influence seedling development. Application of water soluble fertilizers (fertigation) is currently the norm in forest nurseries. Nevertheless, the application of solid fertilizers to the substrate, particularly controlled-release fertilizer (CRF), represents a good alternative to fertigation under certain conditions. Similar growth rates have been observed in trials in which both types of fertilization were compared (Broschat, 1995; Oliet, 1995; Walker and Huntt, 1999, 2000; Puértolas et al., 2000). The duration of nutrient release for CRF types adapted to the forest industry has been extended to a period of 16–24 months, ensuring the supply of nutrients during the entire cropping cycle (Benson, 1997) and the possibility that nutrients will continue to release following field transplant (Reddell et al., 1999).

Consequently, CRF may provide an inexpensive and simple way to supply nutrients to forest tree seedlings in low-technology nurseries while allowing relative control of the supply during the growing period (Donald, 1991; Pueyo, 1992). Additionally, their field of application could be widened with the simultaneous use of products with different rates of release (Hicklenton and Cairns, 1992) or combined with fertigation (Cadahía and Fernández Herrera, 1992; Rey, 1997; Eymar et al., 2000).

One disadvantage of CRF is that, despite long durations of fertilizer release, proportionally greater quantities of nutrients are often released during the beginning of culture (Wright and Niemiera, 1987; Broschat, 1996; Huett and Gogel, 2000) when plants are small and nutrient requirements are low. This can rapidly exhaust the fertilizer and promote high salinity levels at this stage, which may cause root damage and limit seedling growth (Jacobs et al., 2003). This may limit nursery productivity when the objective is to grow either large or high N content seedlings (McNabb and Heser, 1997). There are many CRF product types available, differing not only in formulations but also in nutrient release rate dynamics. Despite similar longevity ratings, the intensity and pattern of nutrient release can be significantly different among polymer-coated CRF products (Cabrera, 1997; Huett and Gogel, 2000). The choice of CRF product and application rate must be suitable for the species and nursery growing conditions (Rose, 2002). Our current knowledge of the feasibility of controlled-release types, formulations and rates, as well as plant nutrient use efficiency under different CRF regimes is still rudimentary.

Pinus halepensis Mill. is one of the tree species common in the most arid habitats in the Mediterranean basin, and plays a critical role in the restoration of degraded lands and abandoned croplands in this region (Ne'eman and Trabaud, 2000). The present works was conducted to obtain information on the release of nutrients from different CRF types varying

in formulation and rates, and to analyze the effect of these treatments on *P. halepensis* seedling growth and nutritional status.

2. Materials and methods

2.1. Seedling production, fertilizer treatments and growing conditions

The experiment was conducted in the Agriculture Research and Training Centre of La Mojonera (longitude 2°41′W, latitude 36°47′N, elevation 160 m, Almeria, Spain). Plants were grown in 230 cm^3 containers, filled with a 3:1 (v/v) sphagnum peat moss—vermiculite growing medium in which fertilizer treatments were mixed. Fertilizer treatments consisted of three rates of two Osmocote® formulations (O.M. Scotts Co.). The formulations used were:

1. (1) Osmocote 9–13–18: 9N (6.1% NH_4-N and 2.9% NO_3-N)–5.7P–14.9 K.
2. (2) Osmocote 17–10–10: 17N (10% NH_4-N and 7.0% NO_3-N)–4.4P–8.3 K.

Each formulation had an equivalent stated nutrient release period: 12–14 months at 21 °C. Rates used for each formulation were 3, 5 and 7 g/l substrate (low, moderate and high, respectively). Amount of N supplied per seedling was 77.2, 128.7, and 180.2 mg with 9–13–18 at 3, 5 and 7 g/l and 145.9, 243.1 and 340.3 mg with 17–10–10 at 3, 5 and 7 g/l, respectively. Micromax (Scotts Co.), a solid mixture of microelements was added at 0.2 g/l for all treatments.

The six treatments (two formulations and three rates) were randomly arranged in four complete blocks, each treatment in each block represented by a tray of 70 containers. The trial was conducted in a polyethylene (0.2 mm thickness) greenhouse. Two *P. halepensis* seeds, collected at the natural pine forests in Sierra de Lucar, southeastern Spain (region of provenance 15, "Bética meridional", Gil et al., 1996), were sown per container on 9 November. Germination generally occurred within 30 days of sowing and germination rates were >95% in all cases, except for 17–10–10 at 7 g/l, which germinated at 92% (data not shown). Following germination, seedlings were thinned to one per container. On 23 May the trial was transferred, with the same block arrangement, to a shadehouse with 80% shading under the cloth. Mean daily temperature for the whole cropping period was 20.1 °C, mean maximum daily temperature was 26.1 °C, and mean minimum daily temperature was 14.1 °C.

Irrigation was generally applied three times per week, except during the winter months (two times a week). The volume of water supplied at each irrigation varied during the cropping cycle from 25 to 70 ml/seedling (18 ml/seedling average daily water supply). Irrigation water pH was 8.2, electrical conductivity at 25 °C (EC) was 0.56 dS/m, and chemical composition (mg/l) was NO_3-N 7.0, P 0.0, K 5.9, Ca 27.9, Mg 31.6, SO_4 72.0, Na 24.8, Cl 35.5, and CO_3H 183.0.

Monthly measurements of plant height and root collar diameter were conducted beginning in February on a sample of 10 plants per treatment replication, randomly selected and used throughout the experiment. Height and diameter data were transformed into the stem volume index, using the following formula: stem volume = $(1/3)\pi(1/4)(\text{root collar diameter})^2 \times$

height. Stem volume (SV) index provided a more accurate indicator of shoot development ($r^2 = 0.96$ for linear regression adjusted for shoot dry weight at lifting) than height or root collar diameter. Stem volume current increment (SVCI) for measurement i was calculated using the formula:

$$\mathrm{SVCI}_i = \frac{\mathrm{SV}_i - \mathrm{SV}_{i-1}}{t_i - t_{i-1}}$$

where t_{i-1} and t_i are days since sowing for measurement number $i-1$ and i, respectively. Stem volume current increment may reflect the nutrient demand during that period.

2.2. Monitoring seedling nutrition: leachates and saturation extract

To assess nutrient availability during the cropping cycle, leachates were collected using the pour-through technique (Landis, 1989; Niemiera and Leda, 1993; Groves et al., 1998) and analyzed, together with saturation extracts. Beginning in January, leachates were collected monthly after applying 230 ml of water per container, 1 day after irrigation. Ten plants per treatment in each block were randomly selected and used for leachate sampling throughout the experiment. Leachates from the 10 containers were composited for sampling (four samples per treatment), and were analyzed for pH and EC within 2 days of collection. In addition, NO_3-N, P and K were also determined at five sampling intervals (Fig. 1).

Substrate samples were taken at the middle and end of the growing period (July and November, respectively) from two containers per treatment in each block, and were composited to determine EC and concentration of NO_3-N, P and K from the saturation extract.

The analytical determinations were based on methods described by MAPA (1986), except the determination of NO_3-N which was conducted using potentiometry with selective electrodes (Sarro et al., 1985). The concentration of nitrates represents most of the total N leached due to active nitrification in the medium (Niemiera and Leda, 1993; Cabrera, 1997).

2.3. Morphological variables and mineral nutrition at lifting

Eleven months after sowing, seven plants per treatment in each block were randomly selected (total of 28 plants per treatment) for destructive sampling. Roots were separated from the growing medium using pressurized water and plants were then dipped in distilled water for 5 min prior to chemical analysis (Landis, 1985). Plant height and root collar diameter were then measured, together with the number of lateral branches. The different plant fractions were separated (needles, stem and roots) and oven-dried at 65 °C for 48 h to determine dry matter contents.

Tissues of each fraction (needles, stem and roots) from each seedling were later combined for each treatment replication in a composite sample (four samples per treatment and fraction in total) to determine mineral nutrient concentrations. Nitrogen was determined using a Leco analyzer (model CHN-600, USA); P and K were determined by atomic emission spectrophotometry (spectrometer ICP model 400, Perkin Elmer, USA).

2.4. Analysis of data

Data were analyzed using analysis of variance (ANOVA) for a randomized complete block design with four blocks. Analysis of leachates, saturation extracts and SVCI data was made by one-way ANOVA (six treatments were considered). Data from plant morphological attributes and nutritional status were subjected to two-way ANOVA where formulation (two levels) and rate (three levels) were main factors. Any significant formulation × rate interaction was noted in the text. In all cases, the treatment mean for each block was the experimental unit, although the number of sampling units comprising the experimental unit varied with the parameter estimated: the experimental unit used for SVCI and morphological data analysis was the mean measurement (computed from individual seedlings) for each treatment within a block; leachate, saturation extract and mineral nutrition data were analyzed from a composite sample for each treatment within each block. When a significant effect of rate was found on element mass content, a regression model was fitted to quantify the relationship. For comparing element recovery percentages in plant tissue, data were arcsine transformed (Steel and Torrie, 1989).

3. Results

3.1. Leachates and saturation extract

Leachate pH values ranged from 8.04 to 8.57 (similar to the irrigation water), except for those samples extracted in May, in which pH values were on average one point lower for all treatments (data not shown). Significant differences among treatments for pH levels were only found during April, June and September, with 17–10–10 at 7 g/l having the lowest values.

The electrical conductivity of the leachates generally increased over time (Fig. 1). Treatments differed significantly at each sampling point, with the largest EC values nearly always corresponding with the high rate (7 g/l) of both fertilizers. The 7 g/l rate of 17–10–10 had the highest EC values throughout the study (excepting the first sample in January).

The concentration of NO_3-N in the leachates was lower than that of the irrigation water (7 mg/l) from April onwards, except for the 17–10–10 at 7 g/l treatment (Fig. 1). This treatment released significantly more NO_3-N during most of the periodic samplings, with a maximum value of 14.6 mg/l in April, followed almost always by the 17–10–10 at 5 g/l treatment (Fig. 1). The maximum values of leached P occurred at the first sampling, with the 9–13–18 fertilizer releasing at the highest rate (ANOVA, $P < 0.001$, Fig. 1). This significant difference was maintained for the 5 and 7 g/l rates of this formulation during the entire cycle except on the final sampling, in which the same rates of 17–10–10 showed higher release rates. Potassium decreased in the intermediate phases of the cropping cycle (Fig. 1). The 9–13–18 at 7 g/l always released the greatest amounts of K (ranging from 15 and 36 mg/l), nearly always followed by 9–13–18 at 5 g/l or 17–10–10 at 7 g/l. A clear increase in K concentration was observed in September.

The ANOVA test of the electrical conductivity of the saturation extract showed very significant differences between treatments at each measurement ($P < 0.001$). In both for-

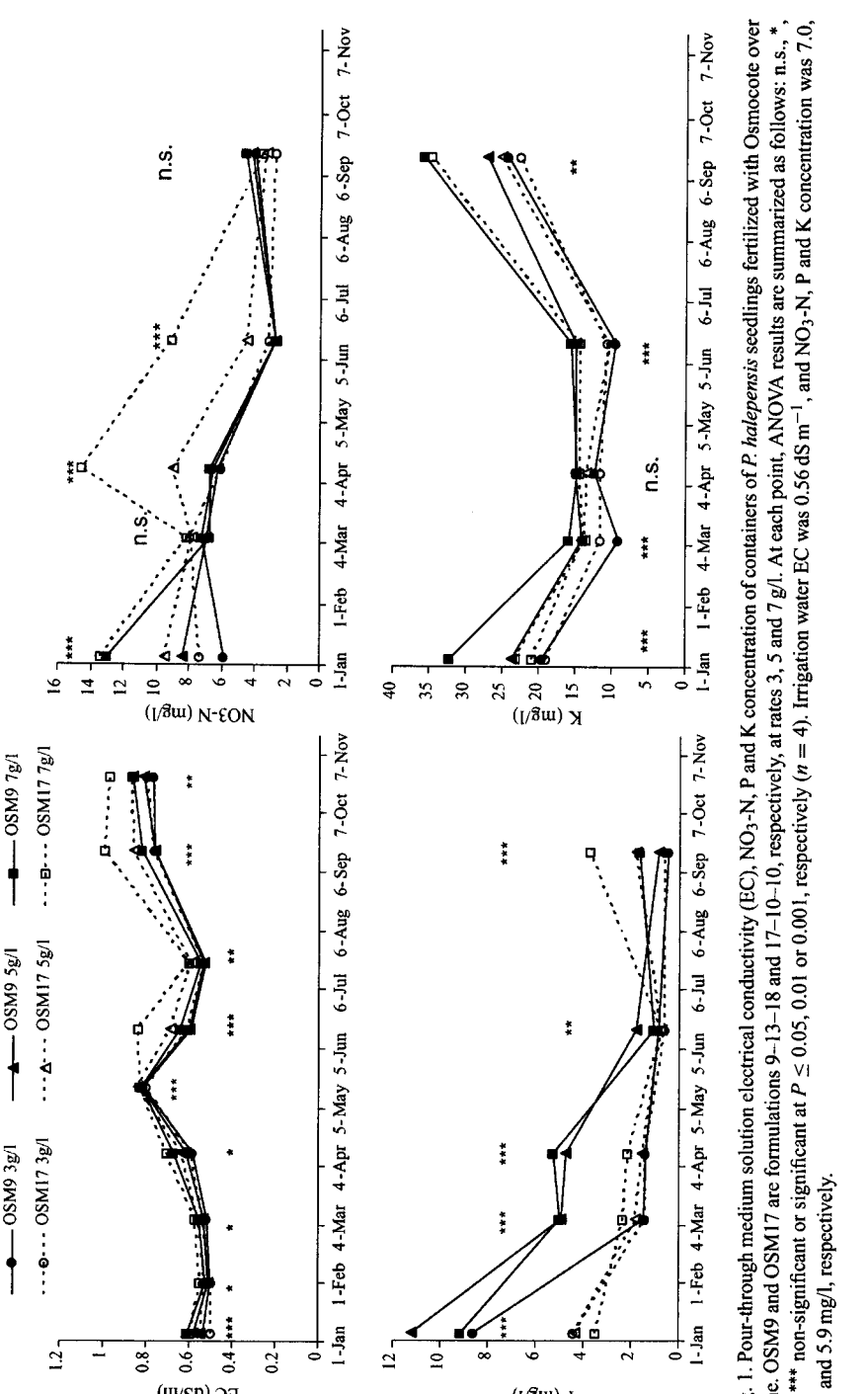

Fig. 1. Pour-through medium solution electrical conductivity (EC), NO_3-N, P and K concentration of containers of *P. halepensis* seedlings fertilized with Osmocote over time. OSM9 and OSM17 are formulations 9–13–18 and 17–10–10, respectively, at rates 3, 5 and 7 g/l. At each point, ANOVA results are summarized as follows: n.s., *, **, *** non-significant or significant at $P \leq 0.05$, 0.01 or 0.001, respectively ($n = 4$). Irrigation water EC was 0.56 dS m^{-1}, and NO_3-N, P and K concentration was 7.0, 0.0 and 5.9 mg/l, respectively.

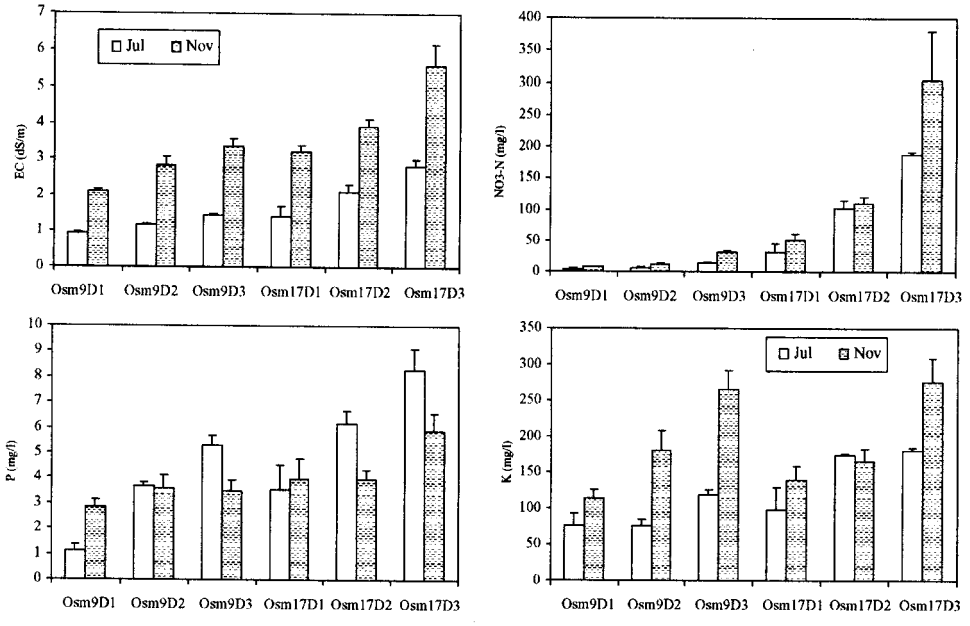

Fig. 2. Electrical conductivity (EC), concentration of NO_3-N, P and K in the saturation extract (+S.E., $n = 4$) of the growing medium from vegetative period (July) and end of the growing period in the nursery (November). OSM9D1, D2, D3 and OSM17D1, D2 and D3 are rates 3, 5 and 7 g/l of Osmocote 9–13–18 and Osmocote 17–10–10, respectively.

mulations, EC values increased with application rate (Fig. 2) and the EC of 17–10–10 was higher than that of 9–13–18 (for equivalent rates) in both July and November. The EC at the end of the cropping cycle (November) was approximately double that of July for all treatments. The EC of November for 17–10–10 at 5 and 7 g/l rates was 3.9 and 5.5 dS/m, respectively. The NO_3-N concentration in the saturation extract increased with rate in both formulations, and was higher in the 17–10–10 than in the 9–13–18 formulation (Fig. 2); the ANOVA test showed significant differences between treatments ($P < 0.001$ at both measurement dates). In November, NO_3-N levels for 17–10–10 at 7 g/l treatment were 305 mg/l compared to 7 mg/l for 9–13–18 at 3 g/l. The concentration of NO_3-N in the saturation extract increased between July and November.

The concentration of P in the saturation extract for the 17–10–10 formulation (Fig. 2) was significantly higher than the 9–13–18 formulation at the first extraction in July (ANOVA, $P < 0.001$). This confirmed higher P release rates for this formulation from June on, as observed in the pour-through leachates (Fig. 1); the 9–13–18 formulation still had lower P extract concentrations in November (compared with the same application rates), although differences were less pronounced (Fig. 2). Values for P in November were lower than those of July for both formulations at 5 and 7 g/l rates. Potassium concentration was higher at the end of the cropping cycle than during summer (Fig. 2), and a positive and significant rate response was observed for both formulations at each measurement (ANOVA, $P < 0.001$). Maximum concentrations of K were found for 17–10–10 at 7 g/l, both in July and

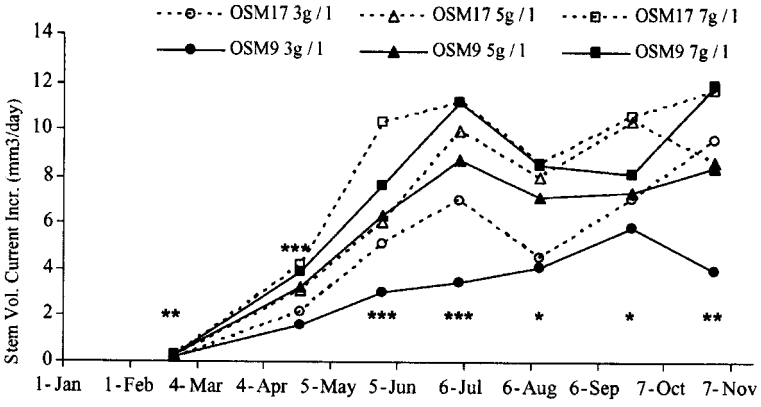

Fig. 3. Stem volume current increment of seedling during nursery culture as affected by CRF treatment. OSM9 and OSM17 are formulations 9–13–18 and 17–10–10, respectively, at rates 3, 5 and 7 g/l. At each point, ANOVA results are summarized as follows: *, **, *** mean significant at $P \leq 0.05$, 0.01 or 0.001, respectively ($n = 4$).

November, although this formulation had a lower initial supply of K than the 9–13–18 at 7 g/l.

3.2. *Nursery growth analysis and morphological attributes at the end of culture*

The current increment of stem volume showed an increasing pattern until 10 August (Fig. 3), reflecting a decreasing in SVCI for all treatments in July and part of August. The SVCI increased again after the second half of August, reaching the highest values at the final measurement (30 October).

Each periodic measurement of SVCI showed significant differences among treatments, with 17–10–10 at 7 g/l always having the highest values (Fig. 3). SVCI always increased with increasing rate of fertilizer application.

At the end of the growing cycle, no formulation × rate interaction was found for any morphological parameter (data not shown). Root collar diameter, shoot height and shoot dry weight were positively affected by fertilizer application rate ($P < 0.010$). The number of lateral branches was marginally affected by application rate ($P = 0.055$).

Although the CRF formulation did not result in significant differences for most growth parameters, shoot dry weight was higher for all rates of 17–10–10 fertilizer (Fig. 4). There were significant effects for both rate and formulation on shoot/root ratio (S/R, $P = 0.008$ and 0.041, respectively).

3.3. *Mineral nutrient concentration, content and uptake efficiency*

No significant fertilizer × rate interaction was found among all nutrients considered on tissue concentration (Table 1). Both formulation and rate significantly affected N concentration in all tissues, except formulation for stem (Table 1). At equivalent application rates, Osmocote 17–10–10 produced higher values for N concentration than 9–13–18 (Fig. 5). There was also a direct effect of fertilizer rate on N concentration. The maximum needle N

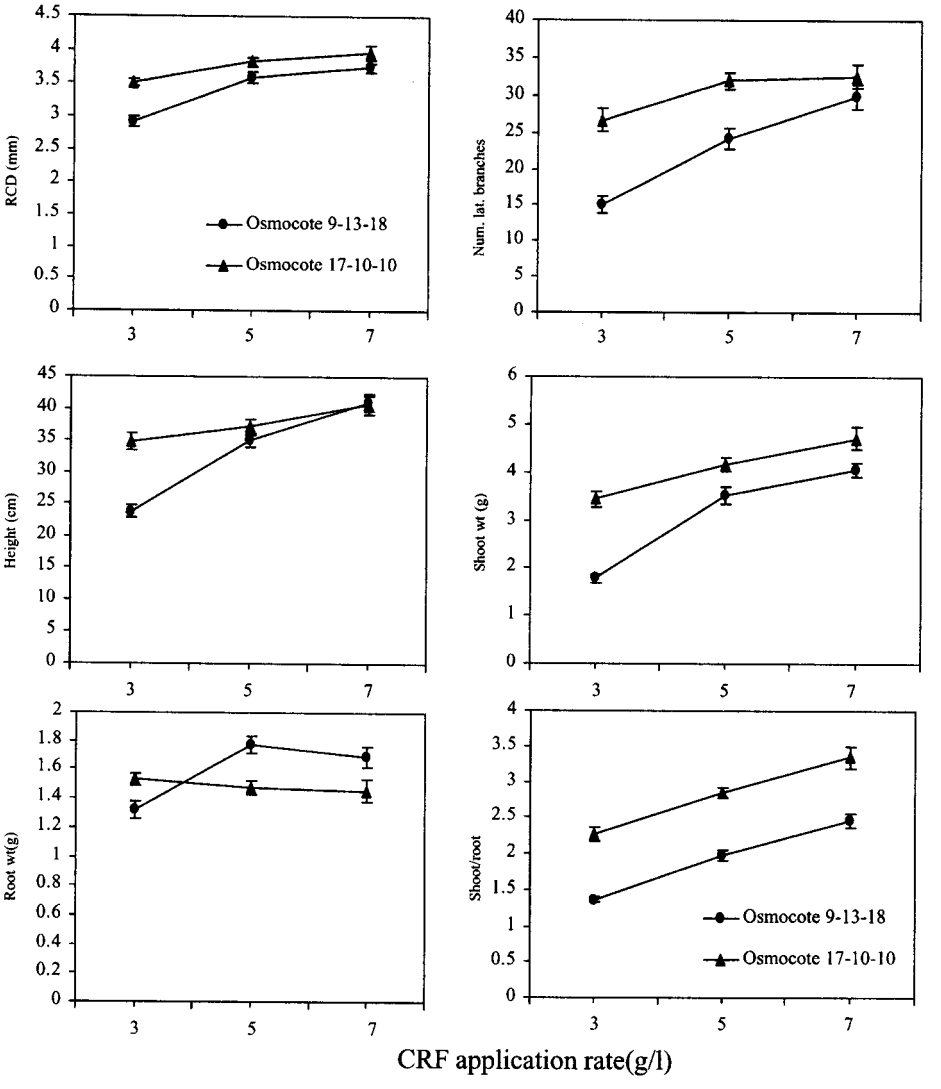

Fig. 4. Morphological attributes of containerized *P. halepensis* seedlings aged 11 months as affected by controlled-release fertilizer application (fertilizer rates 3, 5 and 7 g/l) and formulation (Osmocote 9–13–18 and Osmocote 17–10–10): RCD = root collar diameter (mm); num. lat. branches = number of lateral branches; mean and standard error ($n = 28$).

concentration (18.5 mg/g) occurred in the 17–10–10 at 7 g/l and the minimum (11.9 mg/g) in the 9–13–18 at 3 g/l.

The effect of treatments on P concentration depended on the specific tissues. Whereas the effect of formulation was only significant in needles, the effect of rate was clearly significant in roots (Table 1). The 9–13–18 treatment showed higher P concentration in needles than the 17–10–10 (Fig. 5). The maximum value of P concentration (2.2 mg/g)

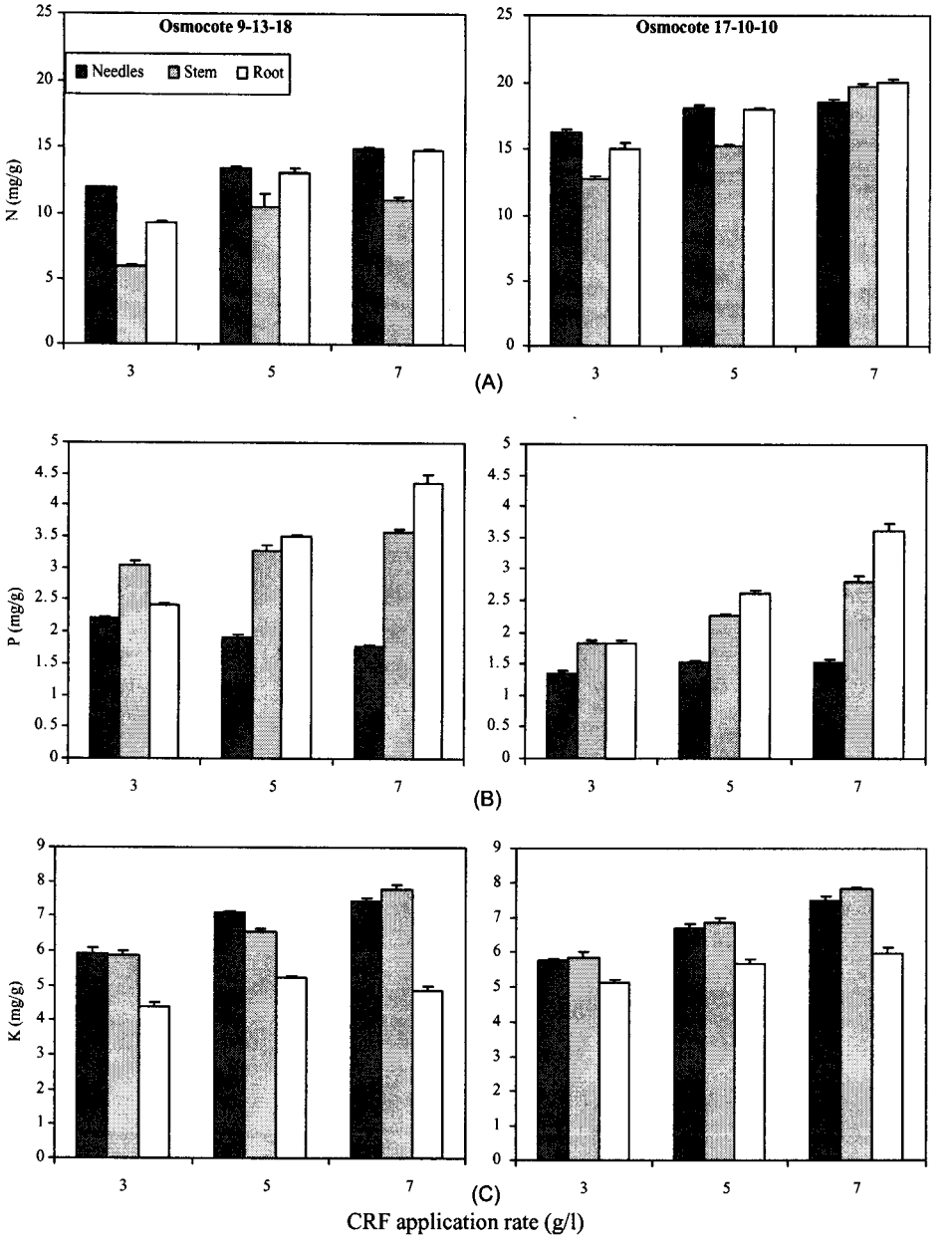

Fig. 5. Needles, stem and root concentration of N (A), P (B) and K (C) of containerized *P. halepensis* seedlings aged 11 months as affected by controlled-release fertilizer application (fertilizer rates 3, 5 and 7 g/l) and formulation (Osmocote 9–13–18 and Osmocote 17–10–10). Bars are standard error ($n = 4$).

Table 1
Significance (ANOVA, *P*-value, $n = 4$) of main effects (formulation and rate) and their interaction on N, P and K concentration of *P. halepensis* seedling needles, stem and root at the conclusion of the study (month 11)

Effect	Nitrogen	Phosphorus	Potassium
Needles			
Formulation (F)	0.012	0.046	0.693
Rate (D)	0.020	0.685	0.011
F × D	0.756	0.116	0.848
Stem			
Formulation (F)	0.052	0.053	0.871
Rate (D)	0.043	0.092	0.025
F × D	0.579	0.713	0.956
Root			
Formulation (F)	0.015	0.099	0.147
Rate (D)	0.003	0.001	0.147
F × D	0.918	0.872	0.650

Actual data is shown in Fig. 5.

occurred in 9–13–18 at 3 g/l and no direct relationship with rate was observed for either formulation. Phosphorus concentration was always lower in needles than in stem and roots, in which a positive response to increasing application rate was found for both formulations (Fig. 5). The 9–13–18 formulation resulted in higher P concentrations in both stem and roots compared to the 17–10–10 formulation (Fig. 5).

A significant (and increasing) effect of application rate was observed for needle K concentration, but not of CRF formulation (Table 1 and Fig. 5) despite nearly double the initial K concentration in the 9–13–18 fertilizer as compared to the 17–10–10.

No significant fertilizer × rate interaction was found among all nutrients considered on mass content (data not shown). Both rate and formulation also significantly affected total N content ($P = 0.002$ and 0.020, respectively). Nitrogen content significantly increased with rate and, within the same rate treatment, N contents were always higher in the 17–10–10 formulation than in the 9–13–18 (Table 2). Nitrogen recovery in plant tissue (100 × (N content/N applied)) was significantly affected by the rate × formulation interaction ($P = 0.050$). While rate did not affect N recovery within the 9–13–18 formulation, N recovery significantly decreased with rate for 17–10–10 (data not shown). Fertilizer application rate significantly affected P and K contents ($P = 0.004$ and 0.001, respectively); total P and K contents significantly increased with the applied rate (Table 2). Formulation or rate did not significantly affect the percentage of recovered P. Formulation affected K uptake efficiency ($P = 0.007$), with 17–10–10 having a higher efficiency than 9–13–18 (Table 2).

4. Discussion

EC and NO_3-N, P and K concentrations in leachates, were higher at the start of the growing period, probably due to the effect of initial nutrient release into the substrate during the first weeks (Landis, 1989; Huett, 1997), without yet being balanced by plant uptake or drainage.

Table 2
Plant N, P and K mass content and percentage recovery (100·× (element content in plant/element applied)) in plant tissue of containerized *P. halepensis* seedlings as affected by controlled-release fertilizer formulation and application rate (means ± 1 standard error)

	N content (mg)	N recovery[a] (%)	P content (mg)	P recovery (%)	K content (mg)	K recovery (%)
Formulation						
9–13–18	59.3 ± 6.3	45.5 ± 1.7	13.0 ± 1.3	16.1 ± 0.7	30.5 ± 3.1	14.2 ± 0.5
17–10–10	97.3 ± 6.0[b]	42.3 ± 2.7	11.2 ± 0.9	18.5 ± 1.0	35.4 ± 2.2	31.5 ± 1.9[b]
Rate						
3 g/l	53.4 ± 9.2	46.1 ± 3.4	7.7 ± 0.4	18.2 ± 1.5	22.1 ± 2.1	25.6 ± 4.9
5 g/l	82.2 ± 6.3	46.0 ± 2.5	12.8 ± 0.9	17.8 ± 0.9	35.1 ± 1.4	23.2 ± 2.9
7 g/l	99.2 ± 7.6	39.6 ± 2.0	15.8 ± 0.8	15.8 ± 0.8	41.8 ± 1.3	19.7 ± 2.4
Regression coefficient (adjusted R^2)[c]	11.5 (0.42)		2.0 (0.70)	n.s.	4.9 (0.74)	n.s.

[a] A formulation × rate interaction occurred for N recovery, precluding statistical analysis of these main effects.
[b] Differences between formulations.
[c] Linear regression parameters: regression coefficient and adjusted R^2.

The subsequent decrease in nutrient concentration for almost all treatments (Fig. 1) was probably due to plant uptake associated with crop development (Groves et al., 1998), and also to the nutrient release pattern of the fertilizer. As shown by some authors (Broschat, 1996; Huett and Gogel, 2000), polymer-coated CRF can release nutrients unevenly, with the highest rate at the early part of the release period irrespective of temperature. Huett (1997) and Cabrera (1997) suggested that this may be caused by imperfections in the coating of some fertilizer granules.

After the April sampling, the NO_3-N concentration fell below values of the irrigation water in all treatments except for 17–10–10 at 7 g/l (Fig. 1). This suggests absence or very low concentrations of this element in the substrate solution (Andersen and Hansen, 2000) due to a higher demand for N than that released by the fertilizer. The observed values for NO_3-N concentration were low compared to another similar study (Struve, 1995). In the case of P collected using the pour-through method, the general decreasing concentration in leachate over time (Fig. 1) could also be due to immobilization in the substrate by precipitation or fixation processes in the exchange complex (Ansorena, 1994; Eymar et al., 2000), especially when peat-vermiculite growing media is used (Huett, 1997). This is supported by the decrease in P concentration in the saturation extract at the end of nursery culture (Fig. 2). Potassium concentration in the pour-through leachates was always higher than in irrigation water, indicating greater rates of fertilizer release than plant uptake. The sharp increase for K concentration in September could be due to lower uptake or saturation of the exchange complex during the last months of culture (Broschat, 1995; Oliet et al., 1999). Minimum values for the three considered elements were found in June (Fig. 1), coinciding with the period of maximum plant demand as expressed by growth (Fig. 3).

The EC values measured in the saturation extract fell within the accepted range for conifer seedlings at both measurements (Landis, 1997), except for 17–10–10 at 5 and 7 g/l rates at the end of the cropping cycle. These EC levels were high for adequate development of many species in containers (Phillion and Bunting, 1983; Timmer and Aidelbaum, 1996). The EC

increase can be explained by the release of NO_3-N and K, with highest concentration values in November (Fig. 2), possibly associated with damage of the fertilizer prill at the end of its life span (Ansorena, 1994; Huett and Gogel, 2000).

With respect to plant growth, expressed as SVCI values (Fig. 3) the decrease observed around mid-summer could be due to water stress not balanced by irrigation, a function of high temperatures characteristic during that time of the year. Only the plants grown with 9–13–18 at 3 g/l did not show that decrease, possibly due to their smaller size which reduced both water interception and evapotranspiration losses. Excepting this temporary growth decrease, the increasing SVCI values over the experimental period indicated that conditions were favorable to growth and therefore, nutrient demand was high until the end of the cropping cycle.

Given the length of the experiment and environmental conditions, height, root collar diameter and biomass at the end of nursery culture were acceptable when compared to previous studies with the same species (Oliet, 1995; Villar-Salvador et al., 1999; Oliet et al., 1999; Royo et al., 1997, 2001; Puértolas et al., 2000). The effect of CRF rate on shoot development was always stronger than that of formulation and this response was always positive (Fig. 4), indicating no luxury uptake. Walker and Huntt (2000), testing three application rates of four types of CRF, also found that shoot growth response generally increased with application rate regardless of formulation.

Root dry weight was not affected by formulation or rate (Fig. 4), probably because the length of the growing period allowed maximum root development given the container volume used and the aeration capacity of the growing media. This has been confirmed in similar studies (Oliet et al., 1999), which stresses the need to use larger containers for these cropping conditions. Seedlings grown with Osmocote 17–10–20 were less well balanced according to standards for this species (Royo et al., 1997), with S/R values > 2.0, significantly higher than that of seedlings grown with Osmocote 9–13–18 (Fig. 4).

Regarding nutritional status at the end of nursery culture, N concentration values were slightly lower than those obtained in similar studies with *P. halepensis* in nurseries using CRF (Oliet et al., 1999; Royo et al., 2001) or fertigation (Puértolas et al., 2000); or even with those obtained with other *Pinus* species using CRF (Walker and Huntt, 1999, 2000). The optimum N value of 20 mg g^{-1} for post-transplant response of *P. halepensis* (Oliet et al., 1997; Puértolas et al., 2000) was not reached with any of the CRF treatments used in the present experiment. Phosphorus concentrations in tissues were also generally low (particularly in needles) in relation to the recommended levels for containerized conifer seedlings (Landis, 1989; Rook, 1991), and those obtained in studies with *P. halepensis* and other pines using CRF (Mexal et al., 1995; Oliet et al., 1999; Walker and Huntt, 2000; Royo et al., 2001). Cornelissen et al. (1997) found maximum seedling relative growth rates when P concentrations in *P. halepensis* needles reached 3 mg/g, but in our experiment maximum P concentrations hardly reached 2.3 mg/g. The low availability of this element in the growing media, as data from pour-through leachates and saturation extract showed (Figs. 1 and 2), helps to explain the lack of P uptake. K concentrations in all treatments fell within the recommended values for potted plants for reforestation purposes (Landis, 1989; Rook, 1991), but were lower than those obtained in other trials using CRF with *P. halepensis* (Oliet et al., 1999; Royo et al., 2001) or other *Pinus* species (Mexal et al., 1995; Walker and Huntt, 1999, 2000).

Both formulation and rate affected N content, which increased with amount applied. However, formulation did not significantly affect P or K content despite the fact that 9–13–18 was richer in these elements. Nutrient uptake efficiencies were generally higher than those found in fertigation, in which up to 90% of the applied fertilizer can be lost (Sanderson, 1987; Argillier and Raymond, 1993; Timmer and Aidelbaum, 1996). The efficiency values found for N, except for 17–10–10 at 7 g/l, were always above 40%, which is close to those reported using exponential fertigation combined with mycorrhizae (Gagnon et al., 1995; Quoreshi and Timmer, 1998). Nitrogen uptake efficiency of the 9–13–18 formulation did not decrease with an increase in rate. However, N recovery decreased with rate in 17–10–10, observations that are in agreement with previous research (Gagnon et al., 1995; McNabb and Heser, 1997; Oliet et al., 1999). The low absorption efficiency of P (lower than that of N and K for almost all treatments), would support the hypothesis of its immobilization by the growing media. Efficiency of K uptake was similar to that reported in a trial with CRF in *P. halepensis* (Oliet et al., 1999).

Nutrient losses in leachates are an important component of the total non-used nutrients in experiments with CRF (Huett, 1997) and these losses are greatly dependent on the leaching fraction (Catanzaro et al., 1998; Groves et al., 1998; Lamhamedi et al., 2001). In our work irrigation rates were very low (18 ml/seedling average daily water supply), so few losses were expected from this factor. Apart from leaching losses (and N volatilization or denitrification), residual content in the CRF prills may contain a significant percentage of the total element applied (Niemiera and Leda, 1993), particularly if the release period is longer than the production period (Prasad, 1996). Huett and Gogel (2000) found that the residual amount of nutrients in Osmocote were, in percentage of total applied, 11–20% for N, 0–38% for P, and 4–7% for K.

5. Conclusions

Both the 9–13–18 and 17–10–10 CRF formulations were relatively successful in controlling *P. halepensis* seedling quality in terms of growth and nutritional status. Regardless of formulation type, effects of application rates were detected on morphological properties of the shoot and nutritional status. The 17–10–10 formulation promoted higher N concentrations, close to optimum values, although P concentrations were quite low in relation to reference values, and significantly lower than that in 9–13–18. Thus, formulations with higher P contents should be utilized when producing seedlings of this species for reforestation purposes. Improvement of these fertilizers for production of quality seedling could be made by reducing the release rate at the beginning of the growing period to help provide a constant or increasing rate during the remainder of the culture.

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