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Original article

Stock quality and field performance of Douglas fir seedlings under varying degrees of water stress

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Abstract – An experiment was carried out on 12 Douglas fir seedling lots that were 3 years old and had all originated from the same seed lot. Treatments consisted in combining stock type with three different height to diameter ratios, storage duration and method (long at 2 °C or short in various conditions), and protection from desiccation (by bagging or not). Seedling lots were assessed at planting by root electrolyte leakage (REL), root moisture content (RMC) and predawn shoot water potential (ψ_{wp}). They were planted simultaneously in well-watered or water-stressed conditions. Performance level was based on survival and height growth at the end of the growing season. Slender seedlings not bagged had the lowest values of RMC, ψ_{wp} and field performance. The sturdier stock type was less sensitive to desiccation and had 100 % survival, in all stress conditions. In contrast to RMC and ψ_{wp}, REL was not influenced by stock type. RMC and ψ_{wp} values were highly correlated, on a seedling basis as on a batch basis. RMC was the best predictor of the field performance parameters (survival and growth for both water regimes) which were all well correlated. Moreover, lower stock quality resulted mainly in slower growth in the well-watered field trial, and in poor survival under drought conditions. (© Inra/Elsevier, Paris.)

planting stock / plant water status / *Pseudotsuga menziesii* / seedling morphology / transplanting shock

Résumé – Qualité et performance de plants de douglas soumis à différentes contraintes hydriques. L'expérience décrite comprenait 12 lots de plants de douglas âgés de 3 ans et issus du même lot de graines. Les traitements combinaient tous les niveaux des trois facteurs suivants: le type de plant, avec trois rapports hauteur / diamètre, le mode de stockage (long à 2 °C ou court en conditions variées), et la protection contre le dessèchement (mise en sac ou non). Les lots de plants ont été évalués à la plantation par la perte relative d'électrolytes des racines (REL), la teneur en eau des racines fines (RMC) et le potentiel hydrique de base des tiges (ψ_{wp}). Ils ont été plantés à une date unique et soumis à deux régimes hydriques, irrigué ou stressé. Le niveau de performance a été apprécié par la survie et la croissance en hauteur en fin de saison. Les plants les plus trapus ont été moins sensibles au dessèchement et ont survécu à 100 %, quels que soient les stress subis. Contrairement à RMC et ψ_{wp}, REL a été indépendant du type de plant. Les valeurs de RMC et ψ_{wp} étaient très corrélées, sur la base des plants individuels ou des lots de plants. RMC était le meilleur indicateur des critères de performance au champ (survie et croissance sous chaque régime hydrique), lesquels étaient bien corrélés entre eux. De plus, une moindre qualité d'un lot de plant s'est traduite par une faible croissance en régime irrigué et par une mauvaise survie en régime stressé. (© Inra/Elsevier, Paris.)

plant forestier / état hydrique des plants / *Pseudotsuga menziesii* / morphologie des plants / crise de transplantation

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1. Introduction

For more than 20 years, Douglas fir (*Pseudostuga menziesii* (Mirb.) Franco) has been one of the main species used for reforestation in France. Nowadays, 8–10 million seedlings a year (most of them bare-rooted) are still being planted in the country. In appropriate field conditions, the growth of Douglas fir is generally fast and final yield seems promising. Nevertheless, some difficulties are currently being observed during the establishment phase, and could partly be related to transplanting shock. Douglas fir is known to be highly sensitive to various stresses which can occur from lift date to the end of the first growing season after planting [10].

One of the main reasons seedlings could grow slowly or die after planting is that they suffer from water stress, as mentioned in various review articles [5, 19, 23]. Water stress is caused by the lack of soil water or the inability of plants to absorb or transport enough water to fully recover cell turgor. Water stress may result from desiccation before planting, lack of roots, poor root–soil contact and drought after planting. Such effects can be cumulative [23].

To help nurserymen and foresters to predict the field performance of variously produced and treated seedling lots in specific site conditions, different easy-to-use quality parameters can be proposed. Seedling quality can be defined as 'fitness for purpose', with the focus on identifying seedling lots that are not likely to survive or will grow poorly in the field [20]. When water stress is involved as a main causal factor, certain quality parameters such as root electrolyte leakage (REL) [22], root moisture content (RMC) and predawn shoot water potential (ψ_{wp}) are good candidates.

REL is a conductivity method used to compare levels of injury in fine roots. It is linked to the integrity of cell membranes, which is connected to desiccation tolerance [3]. REL was significantly related to survival and growth of variously desiccated Douglas fir on various sites with low spring rainfall [25] but not on other sites.

Provided the seedlings are not rewetted, RMC is a good predictor of poor survival after planting [33]. Similar, close relationships were also found between RMC and survival after one growing season, after cold storage [22, 24] or desiccation [23].

Water potential in Douglas fir and other conifer species was correlated with mortality [4, 33]. It provided good estimates of first- and second-year field survival and height increment in Douglas fir [21].

Nevertheless, the links between REL, RMC and ψ_{wp} were rarely studied, especially on a seedling basis. Moreover, the effects of a wide array of nursery treatments on field performance are still difficult to predict because of interacting factors and unpredictable weather conditions after planting in the field. Our study took place in that context. We were interested in finding relationships among the three physiological parameters defined above (REL, RMC and ψ_{wp}) and the field performance, in terms of survival and growth 1 year after planting, under two very different water regimes (well-watered and water-stressed). To provide the study with a sufficient array of plant water statuses and performance potentials at planting, we had previously managed 12 different treatments from the same seed lot. These treatments took into account stock type, transportation and storage conditions. Various stock types were chosen because they can play a role on field performance [17, 26] that quality parameters should detect.

The precise objectives of the study were 1) to induce very different levels of seedling quality across the 12 treatments, 2) to study the relations between REL, RMC and ψ_{wp}, 3) to analyse the effect of a severe drought after planting on the first-year field performance of seedlings produced by the various treatments, and 4) to identify the best predictors of field performance, irrespective of the water regime after planting.

2. Materials and methods

2.1. Planting material and induction of different quality grades

2.1.1. Seed source, nursery conditions and stock types

Seeds originated from seed zone no. 422 'National', Washington DC (USA). Seedlings were grown for 3 years in a State nursery at Peyrat-le-Château (Latitude: 45°47.1'N, Longitude 1°45.2'E, elevation 570 m).

Three stock types were produced:

– '2u1 *H*', sown at a relatively high (*H*) density (500 seeds per m^2) and undercut (u) four times;

– '2u1 *L*', sown at a lower (*L*) density (125 seeds per m^2) and undercut (u) four times;

– '2+1', sown at 500 seeds per m^2 and lined out (+) at 75 seedlings per m^2.

Seedbeds were fumigated with methyl bromide (80 g/m^2) in early May 1991. The seeds were sown on 29 May 1991. Non-transplanted seedlings were undercut at a 12- to 18-cm increasing depth, toward the end of second and third growing seasons (on 24 August and 13 October 1992, 20 July and 2 September 1993). Transplants were lined out mechanically on 28 April 1993. Fertilisation was based on seedling density [11] and all other cultivation practices were identical between treatments. Target macro-nutrient concentrations in needle tissue were 2, 0.24, 0.9, 0.4 and 0.12 % for N, P, K, Ca and Mg, respectively. Final seedling densities were 260 per m^2 for 2u1 *H* stock and 70 per m^2 for the two other stock types.

2.1.2. Treatments induced between lifting and planting

Two factors were considered: 1) storage combined with lifting date, and 2) seedling protection. First, planting stocks were lifted mechanically either on 21 December 1993, to be cold stored for more than 3 months, or on 16 March 1994 to be stored for several weeks; both are classic storage methods used in France. Second, at each lift date, half of the seedlings were sealed in plastic bags while the rest were tied in bundles of 50 seedlings and exposed to possible desiccation. Combinations of both factors resulted in four treatments for each stock type:

- long storage without protection;
- long storage in bags;
- short storage without protection;
- short storage in bags.

From lifting to delivery, all seedling lots were cold stored. For protected seedlings, black (inside) and white (outside) polyethylene bags, 120 μm thick, were used. On unprotected seedlings, water losses may have occurred during long cold storage at Peyrat-le-Château (2 °C ± 1 °C, 95 % ± 5 % RH, no light) and/or during transportation on 22 March 1994 from Peyrat-le-Château to Nogent-sur-Vernisson (290 km) in a covered van. From delivery to planting, all seedlings were stored for 2 weeks, to simulate a typical planting delay, either in a cold-store (at 2 °C) for bagged seedlings, or heeled in outdoors in sand for unprotected seedlings (air temperature: minimum –1.5 °C, mean 9.4 °C, maximum 22.7 °C).

2.1.3. Physiological assessment of seedling lots at planting

For each of the 12 seedling lots, a sample of 12 seedlings was taken at random at the time of planting. Each seedling lot sample was labelled, put in plastic bags and stored at +1 °C until measurements were completed. Plant quality was assessed in a local laboratory on 7–8 April for REL and 12–13 April for RMC and ψ_{wp}. On each occasion, seedlings were taken separately from the plastic bag, in order to avoid desiccation. Prior to REL measurement, the root systems were washed in tap water to remove excess soil.

For REL sampling, about 0.3 g of fine roots (< 2 mm in diameter) were cut from at least three places, mid-way down the root system of each plant. Each root sample was rinsed in three baths of deionised water, to remove surface ions, and transferred to a test tube filled with 16 mL deionised water. REL was determined by the McKay method [22]. Test tubes were capped, shaken and left at room temperature (19 °C) for 24 h. The conductivity of each bathing solution was first measured after 24 h (*Ci*) by using a probe with temperature compensation. All test tubes were then autoclaved at 110 °C for 10 min to lyse the root cells. When all bathing solutions had cooled to room temperature, a second conductivity measurement of each sample was made (*Ct*). The 24-h value (*Ci*) was expressed as a percentage of the autoclaved value (Ct) after subtraction of the conductivity of the deionised water (*Cw*):

$$REL = \frac{\mathrm{Ci} - Cw}{Ct - Cw} \times 100$$

For RMC sampling, about 0.5 g of very fine roots (< 1 mm in diameter) were quickly cut, after the roots had been washed and the surface water absorbed with gauze. The sampling method in the root system was similar to the one used for REL. All samples were weighed before (*FW*) and after (*DW*) drying at 105 °C for 24 h. RMC was expressed as a ratio of weight of water to dry weight of roots:

$$RMC = \frac{FW - DW}{DW} \times 100$$

Root diameters for sampling were specified by Mc Kay [22] for REL and Sharpe and Mason [31] for RMC.

The third measurement concerned ψ_{wp}. Leader shoots were cut at about 10 cm from the top and immediately inserted into a pressure chamber (model Skye 1400), as defined by Scholander et al. [30]. Air leakage was avoided by using a filler (Terostat VII) around the base of the sample. Pressure in the chamber was gradually increased until sap just started to appear at the cut ends of the xylem elements. ψ_{wp} value was the recorded pressure at that specific point.

2.2. Outplanting conditions and performance assessment

On 6 April 1994, seedlings were slit planted with a pick-axe in raised cold frames in the Cemagref nursery at Nogent-sur-Vernisson (Latitude 47°50.2' N, Longitude 2°45.1' E, elevation 150 m). Plant spacing was 25 × 25 cm. Two different regimes were applied on separate raised beds. A well-watered regime consisted in mist irrigation, twice a week in the absence of rainfall, to compensate for potential evapotranspiration. A water-stressed regime consisted in a total absence of rainfall and water supply from 8 April to 2 November 1994. This was obtained by stretching a thick, transparent polyethylene cover over a steel frame usually used for shading purposes, in a nearly flat plane 2 m above the beds. Nevertheless, soil humidity was able to spread from bottom to top in the raised beds. If water stress was the largest difference between the regimes, the plastic cover in the water-stressed regime also induced changes in light, temperature, air humidity and wind, which were not measured.

The soil used in the cold frames was a sand brought from the Loire river, spread 60 cm deep over a layer of gravel. Its texture consisted of 62 % coarse sand, 26 % fine sand, 7 % loam and 5 % clay. The 20-cm upper layer of soil had 3 % of organic matter, a pH of 5.8 and a cationic exchange capacity of 6.4 meq/100 g fine soil. The main nutrient contents are all above critical values.

The field trials were installed in a randomised block design with two and four blocks for water-stressed and well-watered regimes, respectively. Each block contained 120 seedlings, with ten randomised individuals per treatment.

Initial height (in cm) and stem diameter (in mm, at 5 mm above the ground level) were measured on 5 May 1994. At the end of the growing season, survival and final height were assessed on 27 October 1994.

Four performance parameters were analysed:

- survival on well-watered trial;
- height growth on well-watered trial;
- survival on water-stress trial;
- height growth on water-stressed trial.

2.3. Statistical analyses

Analyses of variance (Anova) were carried out mainly to compare the 12 treatments both in terms of quality parameters measured in the laboratory (one-way Anova) and on growth performance (two-way Anova, with block effect) for each water regime. The Duncan test was used to separate mean values at $P = 0.05$. For the effects of the three studied factors (stock type, storage, protection), additional three- or four-way (block effect) Anova were performed with the interaction model. The use of Anova was not appropriate on survival rates, because of non-normalcy of the distribution and low number of replicates. Thus, survival comparisons were based on Chi-square test with the 0.05 error level and validation on each block.

Regression analyses were performed, using the best prediction model, to determine the relations between quality parameters (at plant and batch levels) or between performance parameters (at batch level).

To compare quality parameters and field performance at batch level, some ordinary X-Y plots were made, including standard errors except on survival. Spearman rank correlations were calculated, because they fit both non-linear and linear models, for overall values. In addition, to refine prediction ability of quality parameters, threshold effects were sought. Threshold values should be closely related to a lower field performance (growth or survival, at $P = 0.05$), for each water regime.

3. Results

3.1. Seedling quality at planting

Morphological traits varied across stock types. Mean values of height, collar diameter, height to diameter ratio and shoot to root dry weight ratio, are given in *table I*. The 2+1 seedlings were relatively small, because they had been lined out in mid-spring. On sturdiness (low height/diameter ratio), stocks ranked in the order 2+1 (sturdy) > 2u1 *L* (intermediate) > 2u1 *H* (slender). Shoot/root ratio decreased slightly as sturdiness increased.

The different treatments resulted in a wide range of values of the different physiological parameters (*table II*). This outcome was linked to various factor effects and interactions (*table III*). The effect of protection with bags and the interaction of stock type by storage were significant on the three parameters. When seedlings were not put in bags, low RMC and ψ_{wp} values were associated with high REL values. Across stock types, ψ_{wp} rose slightly with sturdiness but only for long storage, whereas RMC rose in a more pronounced way for both long

Table I. Morphological parameters of the different stock types.

Stock type	2u1 *H*	2u1 *L*	2+1
Mean height (cm)	65 a	64 a	37 b
Collar diameter (mm)	6.9 b	9.2 a	6.5 b
Height / diameter	98 a	73 b	58 c
Shoot / root dry weight *	2.7 a	2.3 ab	2.1 b

On each line, mean values followed by all different letters differ significantly at $P = 0.05$ (Anova followed by Duncan's range test).
* Measurements on 30 seedlings per stock type.

Table II. Effect of treatments on physiological parameters used at planting.

Stock type	2u1 *H* (slender)				2u1 *L* (intermediate)				2+1 (sturdy)			
Storage	Long		Short		Long		Short		Long		Short	
Protection	No bags	With bags	No bags	With bags	No bags	With bags	No bags	With Bags	No bags	With bags	No bags	With Bags
REL (%)	26.3	18	27	18.1	26.9	18.3	34	21.9	32.8	15.9	25.1	19.6
	c	ab	c	ab	c	ab	d	bc	d	a	c	ab
RMC (%)	76	96	121	186	112	189	151	190	204	263	145	291
	g	fg	f	c	f	c	d	c	c	b	de	a
ψ_{wp} (MPa)	–2.16	–1.82	–1.33	–0.77	–1.41	–0.73	–1.44	–0.60	–0.85	–0.53	–1.24	–0.56
	d	c	b	a	b	a	b	a	a	a	b	a

On each line, mean values not sharing a common letter are significantly different at $P = 0.05$ (Anova followed by Duncan's range test).

Table III. Significance levels of the effects of three factors (stock type, storage and protection) and interactions between two or the three of them, on quality parameters and first-year height growth after planting (multifactor Anova with interaction model).

Variable	Factors combined in the experiment			Type of interaction between factors			
	Stock type	Storage	Protection storage	Stock type × protection	Stock type × protection	Storage × crossed	All factors
Quality parameters:							
REL	ns	ns	***	*	ns	ns	*
RMC	***	***	***	***	***	***	***
ψ_{wp}	***	***	***	***	ns	ns	ns
Height growth on:							
Well-watered trial	***	ns	***	ns	ns	*	ns
Water-stressed trial	**	ns	*	ns	ns	ns	ns

*** Significant at $P \leq 0.001$; ** significant at $P \leq 0.01$; * significant at $P \leq 0.05$; ns, not significant ($P > 0.05$).

and short storage duration. REL was independent of stock type and storage, but there was a slight interaction between both factors.

All regression analyses performed between two quality parameters on a plant basis (144 seedlings in total) were significant ($P < 0.05$). The best relation was between RMC and ψ_{wp} (*figure 1*). The parameters of the relation were not altered by storage duration, but the correlation coefficient was slightly better with long storage ($r = 0.91$) than with short storage ($r = 0.78$). Looser relations were obtained between REL and the two water parameters ($r = -0.35$ for RMC, $r = -0.33$ for ψ_{wp}).

On a batch basis, regression analyses were slightly improved. The relationships were very strong between ψ_{wp} and RMC ($r = 0.96$) but remained rather loose between REL and the two water parameters ($r = -0.43$ for RMC, $r = -0.57$ for ψ_{wp}).

3.2. Field performance

For each treatment, survival and height growth under both regimes are presented in *table IV*. Sturdy seedlings lifted in December and with cold storage in bags until spring performed very well, with a 100 % survival and the highest growth, irrespective of water regime. On the contrary, slender seedlings not protected in bags and intermediate seedlings given long cold storage in unprotected bundles, had a lower performance for all parameters, especially if water stressed. Stock type and bag protection played a major role in height growth under the two regimes (*table III*).

On a batch basis, all performance parameters were highly correlated ($P < 0.01$; $r \geq 0.76$). The best model to compare both water regimes on height growth ($r = 0.89$) or on survival ($r = 0.86$) was linear. For height growth versus survival, whatever the water regime of each vari-

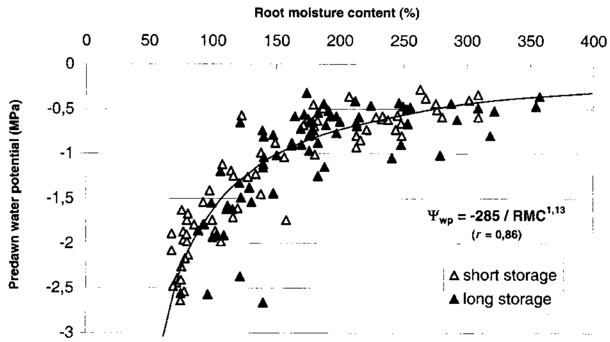

Figure 1. Relationship between root moisture content (RMC) and predawn shoot water potential (ψ_{wp}), on a plant basis, by using 12 seedlings for each of the 12 treatments.

able, the best fitting was made with the Y-reciprocal model: when survival is high, differences in height growth are more pronounced. Height growth and survival were strongly correlated ($r = 0.87$) for each water regime (*figure 2*). Nevertheless, height growth was more variable in the well-watered trial, whereas survival range was wider in the water-stressed trial. Mean performance was also lower under drought conditions.

3.3. Relations between stock quality and field performance

Regarding rank correlations (*table V*), REL was systematically independent of performance parameters, whereas RMC was significantly correlated to all of them. Correlations between ψ_{wp} and field data were generally meaningful, except for survival in the water-stressed trial, but coefficients were lower than those of RMC.

In addition, to identify the treatments that led to a lower field performance in both regimes, threshold effects were disclosed on REL, RMC and ψ_{wp} (*figure 3*). Thus, when REL > 25 %, RMC < 130 % and $\psi_{wp} < -1.3$ MPa, subsequent survival was generally affected. Nevertheless, some well-performing batches were also encountered: three times for REL, twice for ψ_{wp} and once for RMC, on water-stressed regime. When using performance parameters other than survival in dry conditions, results are corroborated, in terms of threshold value and prediction ability applied to each physiological parameter. When REL < 25 %, RMC > 130 % and $\psi_{wp} > -1.3$ MPa, subsequent survival was relatively high in each water regime (> 95 % with irrigation; > 80 % in dry conditions); in most cases, especially for RMC, height growth was also improved (> 20 cm with irrigation; > 9 cm in dry conditions).

With threshold values, the most reliable quality parameter was RMC again. Nevertheless, for one treatment (slender seedlings cold-stored for months in bags), desiccation occurred (RMC < 130 %) but REL was under 25 %, which indicates a high tolerance of cold storage, and field performance was good. Thus, we can speculate that, for this specific seedling lot, unexpected additional drying could have occurred in the laboratory between the REL measurement and the RMC measurement (made 4 days later). This assumption seems to be corroborated by the ψ_{wp} values (third measurement) which were also very low and which varied in conjunction with RMC

Table IV. Effect of treatments on field performance for each regime.

Stock type	2u1 *H* (slender)				2u1 *L* (intermediate)				2+1 (sturdy)			
Storage	Long		Short		Long		Short		Long		Short	
Protection	No bags	With bags	No bags	With bags	No bags	With bags	No bags	With Bags	No bags	With bags	No bags	With Bags
Well-watered trial:	85	97	82	97	90	100	97	97	100	100	100	100
Survival (%)	c	ab	c	ab	bc	a	ab	ab	a	a	a	a
Height growth	13.9	19.7	14	16.1	15.8	23.7	21.7	24.6	24	31.4	25.4	24
(cm)	d	bcd	d	cd	cd	b	bc	b	b	a	b	b
Water-stressed trial:	35	90	55	100	30	85	85	85	100	100	100	100
Survival (%)	b	a	b	a	b	a	a	a	a	a	a	a
Height growth	7.6	8.8	6.6	9.7	6.7	11.1	10	12.9	11.9	14.5	10.5	12
(cm)	bc	abc	c	abc	c	abc	abc	ab	abc	a	abc	abc

On each line, mean values not sharing a common letter are significantly different at $P = 0.05$ (Anova followed by Duncan's range test on growth, Chi-square test on survival).

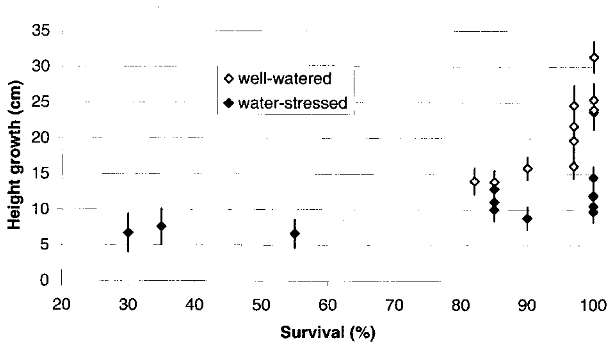

Figure 2. Relations between survival and height growth at the end of the first growing season after planting, for both regimes.

Table V. Coefficients and significance levels of Spearman rank correlations between quality and performance parameters.

Quality parameters	REL	RMC	ψ_{wp}
Well-watered trial:			
Survival	–0.32 ns	0.74 *	0.65 *
Height growth	–0.30 ns	0.74 *	0.71 *
Water-stressed trial:			
Survival	–0.37 ns	0.63 *	0.54 ns
Height growth	–0.38 ns	0.91 **	0.88 **

** Significant at $P \leq 0.01$; * significant at $P \leq 0.05$; ns, not significant ($P > 0.05$).

values. We checked that this possible error on one treatment did not affect the conclusions of the experiment.

For the two other physiological parameters (ψ_{wp} and REL), threshold values were less reliable for various causes. For ψ_{wp}, apart from the possible bias mentioned above, the precision on mean values was rather low compared to that of RMC, for there were fewer statistical differences between treatments than on RMC (*table II*). For REL, the main problem is that, contrary to field performance, this criterion was independent of stock type.

4. Discussion

Our experiment confirms that Douglas fir seedlings are very sensitive to desiccation [14] and must be handled with great care, avoiding at all times exposure of roots to drying during transportation or cold storage [33]. Root desiccation may result in slower growth [28] and/or lower survival rates [33]. When seedlings are bagged, desiccation is avoided, as revealed by all the quality parameters in our experiment.

Cold storage may increase [14, 16] or decrease [27] resistance to dehydration stress but this could not be studied in our trial. Nevertheless, we verified that plant water status and subsequent forest performance can be affected when seedlings are not stored in bags [31].

Stock type and seedling morphology played a major role in field performance. Some authors observed that sturdy Douglas fir stocks performed the best after planting [7, 15]. Seedbed density can influence seedling size and field performance [32]: low densities generally lead to better sturdiness and sometimes better survival [26, 34] and growth [32]. Our results revealed similar trends. Sturdy seedlings performed very well, even when different stresses were applied; in contrast, slender seedlings did not support cumulative stresses. Regarding quality parameters, RMC and ψ_{wp} were influenced by stock type, but not REL. In particular, plant water status of seedlings given long cold storage, bagged or not, decreased less with sturdier seedlings. Apparently, the integrity of fine root cell membranes, which underlies REL values, did not account for such results. Nevertheless, root diameters were higher for REL (< 2 mm) than for RMC (< 1 mm), and this could result in slower desiccation and a less detrimental effect on membrane integrity.

Coutts [8] observed a transport of water from bagged shoots to roots exposed to desiccation. On a batch basis, when fine roots dry, ψ_{wp} decreases [8, 33]. We found a high correlation between RMC and ψ_{wp}, even on a seedling basis. Thus, in seedlings stored in the dark, there is a real balance between fine root and shoot water status, the first being expressed by water content (because of a lack of desiccation-avoiding strategy on fine roots), and the second by water potential (because of an efficient stomatal closure on needles). In contrast, the relationships between water parameters and REL were not reliable, because they varied widely with seedlings and treatments.

The performance of seedlings can be altered by soil moisture stress after planting. Under drought conditions, Douglas fir seedlings and trees grow more slowly [1, 2, 13] but survival remains generally high because this species is drought-tolerant [2, 6, 9, 18]. This strategy of dehydration tolerance results from a considerable osmotic adjustment that enables undamaged plants to maintain turgor throughout the growing season [18]; the turnover of fine roots is also faster on dry sites than on moderate or wet sites [29]. Our results complied with the references mentioned above, although water supply was not the only difference between both regimes. Low stock

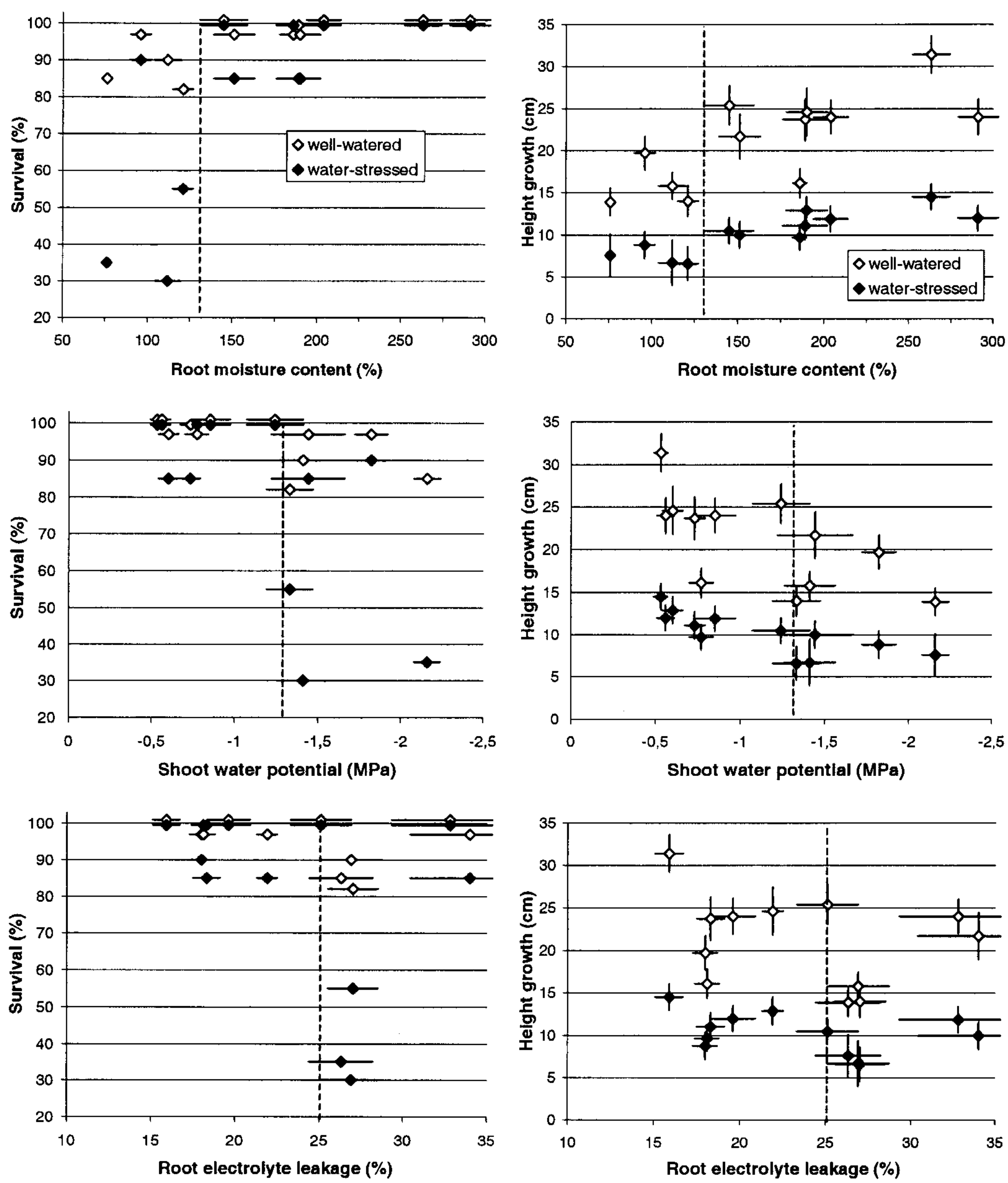

Figure 3. Relations between RMC, REL or ψ_{wp} at planting (x), and survival or height growth at the end of the first growing season after planting (y), for both regimes.

quality resulted mostly in slower growth under well-watered conditions and in poor survival under drought conditions (*figure 2*). Moreover, the treatments ranked nearly in the same order in both regimes and for both performance criteria (survival and height growth). In contrast, the value range varied widely between the four performance parameters.

By rank correlation and threshold methods, the prediction abilities of the tested quality parameters increased in the order REL < ψ_{wp} < RMC. Threshold values can help to identify low-quality stocks that would bring about a lower field performance. For Douglas fir, 50 % mortality was associated with 30 and 50 % REL in two different experiments [22, 33]. Tabbush [33] could not define a unique minimum threshold value for RMC. On desiccated Corsican pine, Girard et al. [12] found a precise threshold value of –1.3 MPa for predawn needle water potential at planting: under that value, 90 % of the plants died, whereas above that value 90 % of the plants survived. In our experiment, threshold values were 25 % for REL, 130 % for RMC and –1.3 MPa for ψ_{wp} (*figure 3*). However, when stock type was not slender, a 25–35 % REL value can be misleading because half of those seedling lots survived and grew well in the field. As sturdier stocks performed well, even when previously exposed to air-desiccation, REL was not fully reliable as a predictor of field performance within this experiment. Moreover, the thresholds selected should not be used to discard stocks of lower quality, because such batches could perform rather well on sites of low stress.

5. Conclusions

The field results of our experiment revealed a cumulative effect of water stresses: desiccation during transportation or storage and drought after planting. The tolerance to water stress depended on stock type and morphology: the use of sturdy and relatively small seedlings (with also a low shoot / root ratio) was very safe, whereas tall, slender stocks were highly susceptible to water stresses. All stocks were preserved from desiccation when sealed in bags after lifting in the nursery: in such conditions, survival and initial growth were relatively high for all stock types in each field trial.

Therefore, plant water status was of prime importance to alleviate severe transplanting shocks. Contrary to REL, RMC and ψ_{wp} parameters were shown to be in close relation within a seedling, irrespective of the combination of factors (stock type, storage and bag protection). RMC and ψ_{wp} were also good predictors of the four performance parameters which were well-correlated. Strong, steady links between growth and survival data were observed under both water regimes, and similarities in treatment ranking were obvious for both water regimes.

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