The variables that best explained the hazard ratio of the Cox's proportional hazards model were the same variables selected for fitting the Weibull's accelerated failure time model, and although Tables 3 and 6 are similar, note that the value of the Akaike's information criterion was lower in Table 6 (AIC = 609.6) than that shown in Table 3 (AIC = 904.8). Therefore, the Cox's proportional hazards model performed better than Weibull's model for predicting the survival probability. The estimators calculated for fitting the Cox's model are shown in Table 7.

The hazard ratio values (Table 8) were calculated using equation (3). It was estimated that the lowest value of the hazard ratio of grafts death (0.18) would be obtained for the top cleft grafts with the scion buds at the end of the dormancy period, using rootstocks taller than 58.5 cm and scions with diameter smaller than 11.4 mm; this value implies that the risk of death would decrease by 82% [(HR_C-1) × 100 = (0.18-1) × 100 = -82%] when grafts are produced with this combination of variables, relative to the hazard ratio obtained for other combinations. On the other hand, the highest estimated hazard ratio corresponded to the side veneer grafts using scions with buds at the beginning of sprouting, for rootstocks shorter than 58.5 cm and scions with diameter greater than 11.4 mm, taking a value of 2.0, which indicates that the risk of death under this combination increases by 100% [(HR_C-1) × 100; (2-1) × 100 = 100%], relative to the other combinations.

Discussion

In this study, a higher survival of top cleft grafts was observed (56.7%) than in side veneer grafts (18.3%); the two types of grafts were maintained under climate-controlled conditions within the greenhouse. Temperature control during coniferous grafting is important to increase the survival probability, as observed by *Blada & Panea (2011)*, who found that callus formation in side veneer grafts of *Picea pungens* Engelm var. *glauca* Regel was favoured by temperatures between 20 and 25 °C.

In a recent study in Durango, Mexico, *Pérez Luna et al. (2019)* performed side veneer grafting with 5 to 7-year-old rootstocks of *Pinus engelmannii*, under greenhouse conditions without automatic climate control, and reported survival of only 22.5% six months after grafting, with no significant differences between grafting using scions with buds at the end of dormancy or at the beginning of sprouting. These low survival results were attributed by the authors to the high temperatures registered in the greenhouse during the months of March to May (maximum recorded, 42.6 ° C), and to the low relative humidity in the same months (on average, 38%). °C

However, in the present study, the survival obtained in the side veneer grafts, were similar to obtained for *Pérez-Luna et al. (2019)*, ~~and therefore the climate control applied in the present work does not seem to have influenced the survival in grafts this technique.~~ indicating that climate control appears to be ineffective in this regard.

On the other hand, the higher survival of the top cleft grafts than of the side achieved in the present study may be related to the more favourable (controlled) environment (maximum temperature of 26 °C and minimum relative humidity of 72%) inside the greenhouse. However, low temperatures also usually strong affect the survival of coniferous grafts, as observed by *Cuevas (2014)*, who reported 100% mortality in top cleft and side veneer grafts of *Pinus leiophylla* Schiede ex Schltdl. *et* Cham for a minimum temperature of -5.8 ° C. °C

In side veneer grafts of *Pinus greggii* Engelm var. *australis* Donahue & López in Veracruz, survival was greater than 60% after three months, which was partially attributed to the fact that both the seedlings with which the rootstocks were produced and the grafted scions were obtained from the same geographic location *(Alba-Landa et al., 2017)*. In the present study, the scions and rootstocks were of different origin, which may contribute to explaining the low percentage of successful grafts with this technique. In this respect, some studies did not observe any effect of the origin on the success of grafting; e.g. *Aparicio et al. (2009)* reported that the provenance of the scions did not influence the survival of terminal fissure grafts of *Austrocedrus chilensis* (D. Don) Pic Serm & Bizzarri; however, *Villaseñor & Carrera (1980)* reported that the provenance of the scions had a significant effect on the success of the top cleft and side veneer grafting of *Pinus patula* Schl. *et* Cham.

The genetic compatibility between the scion and the rootstock is also a determining factor in grafting success *(Lott et al., 2003; Hibbert-Frey et al., 2001)*; in this regard, it is important to consider the results of recent studies *(Wehenkel et al., 2020; Simental-Rodríguez et al., 2021)*, which indicate large genetic differences and even hybridizations between close populations of the genus *Pinus* in northern Mexico.

On the other hand, *Wendling, Stuepp & Zuffellato-Ribas (2016)* found that grafting of *Araucaria angustifolia* (Bertol.) Kuntze was effective with the chip budding technique (which is similar to the side veneer grafting regarding the cut made in the rootstock), reporting almost 40% survival at 130 days after grafting.

Mencuccini et al. (2007) recommend using rootstocks younger than two years for grafting *Pinus* species. *Dorman (1976)* pointed out that the sprouting of side veneer grafts in *Pinus* species was significantly lower when rootstocks older than three years were used. In the present study, the rootstocks were older than four years and the survival of side veneer grafts was low (18.3%) despite the fact that the rootstocks used in both grafting techniques were of the same age; however, the survival of top cleft grafts (56.7%) can be considered acceptable. In another study, *Zhang & Tang (2005)* reported 50% survival in top cleft grafting of *Pinus ponderosa* Douglas ex C. Lawson with two-year-old rootstocks. In the top cleft graft of *Pinus elliottii* Engelm., a survival rate of 30% was reported for grafting performed with two- to three-year-old rootstocks *(Mergen, 1955)*.

Other authors have also achieved good survival when grafting conifers with the top cleft technique. For example, *Almqvist (2013a; 2013b)* reported survival rates of 75.0 and 84.7% in two *Pinus sylvestris* L top cleft grafting experiments. In *Abies fraseri* (Pursh) Poir grafts, *Hibbert-Frey et al. (2011)* reported 86% survival with the same technique. Similarly, *Singh (1992)* reported good success when grafting *Pinus gerardiana* Wall, using the top cleft technique, with 70% survival.

Villaseñor & Carrera (1980) reported survival of 63.0% in top cleft grafts of *Pinus patula* in Mexico, using scions with dormant buds. Likewise, *Świerczyński et al. (2020)* achieved survival greater than 80% for side veneer grafts on *Pinus mugo* Turra, established in winter (using scions with dormant buds). Survival greater than 60.0% was reported for top cleft grafts of *Araucaria* *angustifolia*, in Brazil, using scions with dormant buds *(Gaspar et al., 2017)*. On the other hand, when grafting *A. angustifolia*, *Zanette, Oliveira & Biasi (2011)* reported only 20% and 0% survival in grafts with buds at the beginning of sprouting (spring) and during full sprouting (summer), respectively. These results are consistent with those obtained in the present study and, although different species of the order Pinales were used, they must share certain characteristics in terms of their phenological functioning *(Bodnar et al., 2015)*.

To analyze graft survival, *Pérez-Luna et al. (2020b)* fitted the Weibull's accelerated failure time model to data on side veneer grafts of *Pinus engelmannii*, estimating an average survival time of 154 days after the end of the six-month evaluation period. The higher values of potential survival time (up to 457 days) observed in the present study can be attributed to the automated temperature and environmental humidity controls in the greenhouse where the grafting was conducted in the present study. By contrast, only two shading meshes (providing 70 and 50% light retention) were placed above the greenhouse in the previous study, to reduce the temperature inside.

The negative values of the estimators of the coefficients of the explanatory variables in Table 7 appeared in the same variables that had already been detected when calculating the Weibull's risk function (for "grafting technique" and "height of rootstock") (Table 5). Interpretation of the algebraic signs of the estimators is similar in both tables and is based on the interpretation of Table 5, which refers to the risk of death of the grafts (*Cox, 1972)*. Therefore, the negative values of the estimators shown in Table 7 also indicate that the risk of death of the grafts decreases when the value of these variables increases, i.e. when $x_i > 1$; i.e. when using the top cleft grafting technique and when the height of the rootstock is greater than the mean value observed (58.5 cm), the risk of death decreases and therefore, the probability of survival increases. On the other hand, the positive values of the variables "phenological stage of buds" and diameter of scion" indicate that the risk of death increases when $xi > 1$ (grafts with buds at the beginning of sprouting and scions with diameters greater than the observed mean value, i.e. 11.4 mm).

"phenological stage of buds" and "diameter of scion"

The effects of the other seven grafting variables considered in the present study (Table 1) were also evaluated in the aforementioned study *(Pérez-Luna et al., 2020b)*, and it was found that these variables did not significantly affect the risk of graft death. The significant effects observed in the present study contrast with these previous findings, which can be attributed to the fact that on this occasion the climatic conditions inside the greenhouse were controlled, thus reducing the variation caused by factors not evaluated. The survival of the grafts can therefore be more directly attributed to their response to the treatments and to the grafting variables evaluated. In a grafting experiment with *Araucaria angustifolia*, *Wendling, Stuepp & Zuffellato-Ribas (2016)* obtained survival greater than 20% after 130 days of evaluation for rootstocks between 80 and 100 cm in height; our findings indicate that the survival of *P. engelmannii* grafts is improved by using rootstocks taller than 55.8 cm.

Using scions with diameter larger than the rootstock diameter can cause localized graft incompatibility. This effect was visualized by *Sweet & Thulin (1973)*, who reported this type of incompatibility in grafts of *Pinus radiata* D. Don, as the cambium did not coincide between the grafted organs. On the other hand, *Pérez-Luna et al. (2020)* observed that when using short rootstocks of *P. engelmannii* (less than 30 cm), the graft was also short (less than 15 cm height in average), hampering establishment of a protective microenvironment and subsequent management of the grafts.

Pérez-Luna et al. (2019) also used the Cox's proportional hazards model and the associated hazard ratio to evaluate the effect of the phenological stage of the scion buds (end of latency and beginning of sprouting), observing that this factor did not have a significant influence on the risk of graft mortality. The difference in the hazard ratio due to the effect of the phenological stage of the scion buds in the present study relative to the aforementioned research can mainly be attributed to the differences in management of the greenhouse conditions, as in the previous study the climate control was not used.

Conclusions

Two survival models used in medical studies proved useful tools for evaluating the success of *P. engelmannii* grafts. Thus, the Weibull's accelerated failure time model and the Cox's proportional hazards model and their respective hazard ratios were validated for use in predicting the survival rate (risk of death) as a function of the factors considered, such as the grafting technique, the phenological stage of scion buds and some other grafting variables ~~(Table 1)~~ inherent to the scions and rootstocks. Although the Cox's proportional hazards model provided better fit to the data, the use of the Weibull's accelerated failure time model is also recommended, as it enabled reliable prediction of the estimated graft survival time after the end of the evaluation period. The best grafting technique for asexual propagation of *P. engelmannii* proved to be the top cleft method, and the best phenological condition for the scion buds was at the end of the latency period. Grafting was more successful with scions of diameter smaller than 11.4 mm. In addition, in order to reduce the risk of death of top cleft and side veneer grafts of *P. engelmannii*, the use of rootstocks taller than 58.5 cm is recommended. The results of the present study can serve as a guide for decision-making for grafting in the studied species.

✓ It is not appropriate to refer to the tables in the conclusion of the manuscript.

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