quiring such other important work as paving or multiplate arch pipes. Because our data were from a short timespan, we assumed constant factor prices for capital, material, and manpower. The joint explanation of the effect of these variables with those examined would require sampling a longer timespan, with both cross-section and time-series data. Finally, use of the equations should be limited to the events they represent: they may not work well for predicting costs of joint road-and-bridge construction projects.

An economic interpretation of regression coefficients is possible. Since the dependent variable is dollars, and all independent variables are physical units, the regression coefficients are implicit unit prices. The equations can be used directly for cost analysis. For example, the extra cost of adding another cubic yard of excavation per mile is $1.26. The equations can also be used to develop average and total project costs. Interestingly also, the coefficients in the models are numerically close to the average per unit costs used by engineers in contract cost appraisals.

CONCLUSIONS

In half of the sampled contracts the predicted value of the regression equations was closer to the winning bid than was the engineers' cost estimate. Thus the regression equations represent a reasonably accurate way of predicting costs based on preliminary and limited data. Since the data used in the study were essentially cross-section (as opposed to time series) in nature, certain dynamic phenomena were not reflected. For instance, bid prices may follow business cycles and the degree of competition in the public works sector. Also wage rates, capital costs, and the costs of material that underly the cost coefficients, can be expected to change in the future. Thus a more exhaustive study relying on a mixed time-series/cross-section sample would be useful in capturing these phenomenon.

However, considerable variation in forest transportation construction costs can be explained by carefully enumerating interproject differences in major physical characteristics. Using historical market data of construction contracts, we have developed accurate methods for predicting road-and-bridge construction project costs. Markets develop useful value information, and this study demonstrates how market information can be employed for transportation planning and development. □

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Ten-Year Results of a Ponderosa Pine Progeny Test in the Black Hills

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ABSTRACT. Ten-year survival and growth of seedlings from 77 parent trees from throughout the Black Hills were compared, using a cluster-analysis technique. Five clusters were identified that account for most of the variability in survival and growth of the open-pollinated families. One cluster, containing 6 families, exhibited exceptional survival and growth. Another, containing 12 families, exhibited poor survival and growth. The performance of families in these two groups appears to be related to location and elevation of parent trees.

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The Black Hills region of western South Dakota and northeastern Wyoming forms an ecologically unique forested island on the Great Plains. Formed by a domal uplift of the earth's surface millions of years ago, the Black Hills consist of Precambrian granite and schists surrounded by a series of inward-facing limestone and sandstone cuestas that are progressively younger away from the central dome (Hunt 1967). The Bear Lodge Mountains of northeastern Wyoming are geomorphologically and ecologically similar to the Black Hills, and in this paper the two areas are referred to collectively as the Black Hills. Ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.) predominates on all geologic landforms in the Black Hills, of which the central crystalline and limestone areas are the most productive (Boldt and Van Deusen 1974). Ponderosa pine occurs mainly as a climax species here and is usually found in pure stands that readily regenerate from seed. Even-aged management utilizing the shelterwood method is the silvicultural technique most commonly used in these forests (Shepperd et al. 1983); but, planting is necessary where fire or tornadoes result in inadequate regeneration (Boldt and Van Deusen 1974). Seed zones have been established that include the Black Hills (Cunningham 1975), but they encompass relatively large areas. Other than the testing by Read (1983) of several Black Hills provenances for adaptation on the Great Plains, there has been no comparative testing of Black Hills seed sources.

We report here the results of a study on and near the Black Hills National Forest begun in 1967 by James Van Deusen and Charles Boldt, formerly scientists at the Rocky Mountain Forest and Range Experiment Station. Their objectives were to determine the extent of genetic variation in silviculturally important traits of ponderosa pine growing on different parent materials; and to identify superior genotypes for use in local tree improvement programs. The study is limited to open-pollinated progenies of Black Hills parents, which were planted at a central location within the Hills.

METHODS

Cones were collected from 77 parent trees in 1967, 1968, and 1969. The seed trees grew on a variety of parent materials between 1052 and 2052-m elevation: granitic, metamorphic (schist), northern and southern limestone, northern and southern hogback (sandstone), and Bear Lodge metamorphic (schist) (Figure 1). Selected trees were larger than their immediate neighbors of the same age growing under similar stand conditions. They were of average or better form and vigor, with no evidence of insect or disease damage. The 77 selected parents averaged 18 9 m in height, 33.3 cm in diameter, and 86 years of age.

Seedlings were grown at the U.S.D.A. Forest Service Bessey Tree Nursery, Halsey, NE. They were planted as 2-0 stock on the Black Hills Experimental Forest, 1830-m elevation, in May 1971. The plantation is within the central metamorphic geologic type. Twenty-eight seedlings from each parent tree were planted in a randomized, complete block design, with 4-tree linear plots replicated 7 times. Spacing was 2.4 m × 2.4 m. A 2.4-m deer-proof fence surrounded the entire planting.

Growth characteristics of surviving seedlings were measured in 1980, 10 growing seasons after field planting. Total height, root-collar diameter, average crown width (average of widest crown diameter and diameter at 90° angle from widest), and percent live crown were measured on each tree.

Initially, a two-way analysis of variance separating seedlings by parent tree within geologic region was performed, but variation among parent seed sources (families) within regions was of the same order as that among regions, obscuring most patterns in the data. Linear regression analysis also failed to reveal any meaningful relationships between growth and parent location. Because these results are difficult to interpret in light of the overall performance and survival of specific families, they are not discussed here. Instead, a two-step procedure that considered all growth and survival characteristics was used to isolate families of seedlings into groups that performed similarly in the plantation.

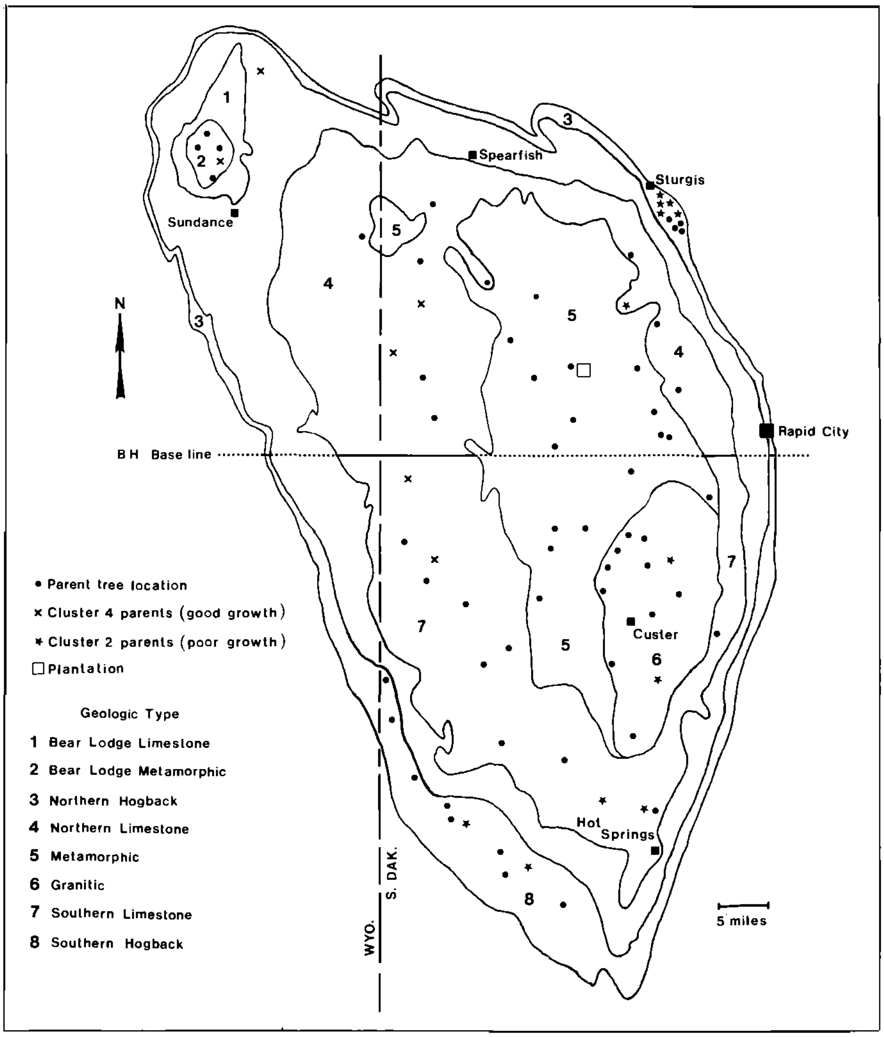

Fig. 1. Location of parent trees. Good sources (cluster 4) were all located at high elevations in the western side of the forest whereas poor sources (cluster 2) were located at low elevations in the south and east side of the forest.

First, a cluster analysis ISODATA (Ball and Hall 1967) was used to group family means by overall performance based on an additive index of all variables measured. Height, basal diameter, average crown width, percent live crown, and survival were normalized by division, with the standard deviation of each variable to give all variables equal weight in this analysis. Next, a stepwise discriminant analysis was performed on the clusters assigned by ISODATA to analyze the relative importance of each variable for distinguishing among clusters and to determine whether a reweighting of variable importance by discriminant analysis affected the viability of cluster assignments. Posterior probability of correct classification, although not a validation of cluster assignment, provides information about how closely each family is aligned with the group to which it was assigned by ISODATA.

The above analysis only considered growth variables measured in the plantation. Differences in climate at seed source locations also could be expected to influence progeny performance. On-site climatic observations were not recorded at any of the locations where seed was collected, so limited climatic information available from other sources was utilized. Elevation of parent tree locations was obtained from USGS topographic maps. NOAA iso-temperature maps of average monthly temperatures for South Dakota and Wyoming were used to estimate maximum July and January temperatures, and Isohyetal maps (Orr 1959) were used to determine yearly precipitation at those locations. One-way analysis of variance and Scheffé's multiple-range comparisons were used to compare these climatic factors between clusters, geologic types, and other progeny groupings.

RESULTS

Growth and survival of all sources are summarized by cluster in Table 1. Plantation average survival, height,

Table 1. Cluster and overall means for 10-year growth of an open-pollinated progeny test of ponderosa pine in the Black Hills (ranges in parenthesis). Cluster averages with common subscripts are not statistically different at the 5% confidence level.

Cluster	Survival (%)	Height (m)	Basal diameter (cm)	Average crown width (m)	Live crown (%)	Parent tree elevation (m)
1 (n = 19)	53	1.28	4.5	0.65	88	$1573_{a,b}$
	(36–68)	(1.20–1.35)	(4.3–4.7)	(0.61–0.69)	(87–89)	(1201–2052)
2 (n = 12)	47	0.89	3.4	0.46	79	1284_{c}
	(25–71)	(0.71–0.97)	(3.0–3.7)	(0.33–0.51)	(74–82)	(1052–1540)
3 (n = 23)	47	1.14	4.0	0.57	85	$1482_{b,c}$
	(14–75)	(1.03–1.20)	(3.8–4.2)	(0.52–0.61)	(83–87)	(1098–1915)
4 (n = 6)	71	1.47_{a}	5.1_{a}	0.77_{a}	92_{a}	1855_{a}
	(68–86)	(1.33–1.62)	(4.6–5.4)	(0.69–0.85)	(89–94)	(1463–2024)
5 (n = 17)	39	1.41_{a}	4.9_{a}	0.72_{a}	90_{a}	1689_{a}
	(21–54)	(1.30–1.57)	(4.6–5.3)	(0.68–0.84)	(88–93)	(1120–1991)
Grand mean	49	1.22	4.3	0.62	87	1548
	(14–86)	(0.71–1.62)	(3.0–5.4)	(0.33–0.85)	(74–94)	(1052–2052)

and crown growth were somewhat less than those for some ponderosa pine plantations summarized by Read (1983), but within the range of data he reported.

Although some statistical differences were apparent, no geologic region was clearly superior in performance to others. However, progeny from the Northern Hogback Region were consistently inferior in height, basal diameter, and crown development (Table 2). These seed sources are not spread throughout the Northern Hogback, but are clustered near Sturgis, ND (Figure 1).

Average survival of all sources in the plantation was 49% after 9 years. This was not inconsistent with other progeny tests in the West (Read 1983, Shepperd et al. 1981). All geologic regions had similar survival curves with most of the mortality occurring within the first 2 years following planting (Figure 2). Only progeny from the Southern Hogback and Metamorphic regions survived in significantly different numbers (61% vs. 39%, p = .05).

The ISODATA cluster routine was allowed to run in a stepwise fashion to produce up to 10 clusters. Families of progeny from a single parent were added or deleted from clusters at each step based on the amount of unaccounted variability among those variables in the analysis. Those families with the slowest overall height, basal diameter, and crown growth were isolated in a single cluster in the third step. These clusters remained unchanged as additional clusters were added throughout the analysis. Families with fastest overall growth were isolated into 2 of 5 clusters during the fifth step of the analysis. These clusters also remained unchanged throughout the additional steps of the analysis. About 77 percent of the overall variability in growth could be accounted for by grouping the sources in 5 clusters. Splitting the families into more than 5 clusters did not isolate additional sources exhibiting poor or good performance, and therefore was judged unnecessary.

Each of the five clusters isolated by the ISODATA routine was distinctly different from the other clusters (Figure 3). The mean normalized data values for cluster 2 were much lower than the other clusters. Survival of individual sources played a role in the clustering. Clusters 1, 4, and 5 had significant differences in average survival (Figure 3). Poor survival negated the otherwise good growth of cluster 5 sources in the plantation and appeared to be responsible for the separation of clusters 4 and 5.

Discriminant analysis using Wilk's method (Klecka 1975) indicated that basal diameter contributed the most to cluster assignment, followed by percent live crown, survival, average crown width and height. The small portion of variability accounted for by height is a result of the close correlation of height with basal diameter (r^2 = 0.98). Little variability is accounted for by height once basal diameter has been taken into consideration.

Discriminant analysis also showed probabilities (0.99+) of correct cluster assignment for all families in cluster 2 and for all but two families in cluster 4. Probability of correct cluster assignment for these families was only 0.53 and 0.58, respectively, with clusters 1 and 5 being the next most likely assignments. These families had slower growth rates than the other families in cluster 4, although both were considerably above the overall plantation mean. In both cases, the high survival rates of these families probably kept them from being assigned to the other clusters (Table 1).

Several relationships between growth of progeny in the plantation and climate at the seed source location were found, using the analysis of variance described earlier. First, differences in progeny growth were apparent when the average temperatures of parent locations were compared to those of the planting site. Progeny were assigned to two sets of groups in which maximum July and January temperatures at parent locations were (1) cooler than the plantation site, (2) the same as the plantation site, or (3) warmer than the plantation site. Height, diameter, and crown growth of progeny in group 3 was significantly different than that of progeny in groups 1 and 2 when either July or January parent site temperatures were used. Significant differences in elevation and yearly precipitation at parent sites also existed between progeny groups 1 and 3. Progeny from cooler more extreme temperature environments outgrew those from warmer, less extreme climates (Table 3).

Similar differences are apparent when maximum July and January temperatures are grouped according to cluster assignment of progeny in the plantation. Average July maximum temperatures at parent tree locations of the poor performing seedlings in cluster 2 were significantly higher than those at the parent tree locations of all other clusters. This 31.7°C average was also several degrees warmer than the 28.3° C average July maximum at the planting site. In contrast, the fast-growing seedlings in cluster 4 came from locations where the average July maximum temperatures were less than those of the planting site (27.2°C vs. 28.3°C).

Table 2. Mean progeny growth and climatic conditions when grouped by geologic region of seed source. Variable means with common subscripts are not statistically different at the 10% level of confidence.

	Geologic Region*						
	M	G	NL	SL	BLM	SH	NH
Height (m)	1.31_{b}	1.16_{ab}	1.26_{b}	1.28_{b}	1.36_{b}	1.17_{ab}	0.97_{a}
Basal Diameter (cm)	4.56_{b}	4.10_{ab}	4.43_{b}	4.53_{b}	4.75_{b}	4.18_{ab}	3.59_{a}
Crown Width (m)	0.67_{b}	0.58_{ab}	0.64_{b}	0.66_{b}	0.69_{b}	0.60_{ab}	0.49_{a}
Percent Live Crown	88_{b}	86_{ab}	88_{b}	88_{b}	90_{b}	86_{ab}	81_{a}
Percent Survival	41_{a}	44_{ab}	56_{ab}	49_{ab}	56_{ab}	61_{b}	47_{ab}
Elevation (m)	1625_{c}	1582_{bc}	1727_{c}	1634_{c}	1763_{c}	1333_{ab}	1106_{a}
Precipitation (cm)	54_{cd}	48_{b}	55_{d}	48_{b}	52_{bcd}	41_{a}	51_{bc}
Max. July Temp. (°C)	27.9_{a}	29.9_{ab}	28.4_{ab}	29.8_{ab}	28.8_{ab}	32.9_{b}	31.2_{ab}
Max. Jan. Temp. (°C)	0.8_{ab}	2.1_{c}	0.7_{ab}	1.1_{b}	0.0_{a}	0.8_{ab}	1.7_{bc}

* M = Metamorphic; G = Granitic; NL = Northern Limestone; SL = Southern Limestone; BLM = Bearlodge Metamorphic; SH = Southern Hogback; NH = Northern Hogback).

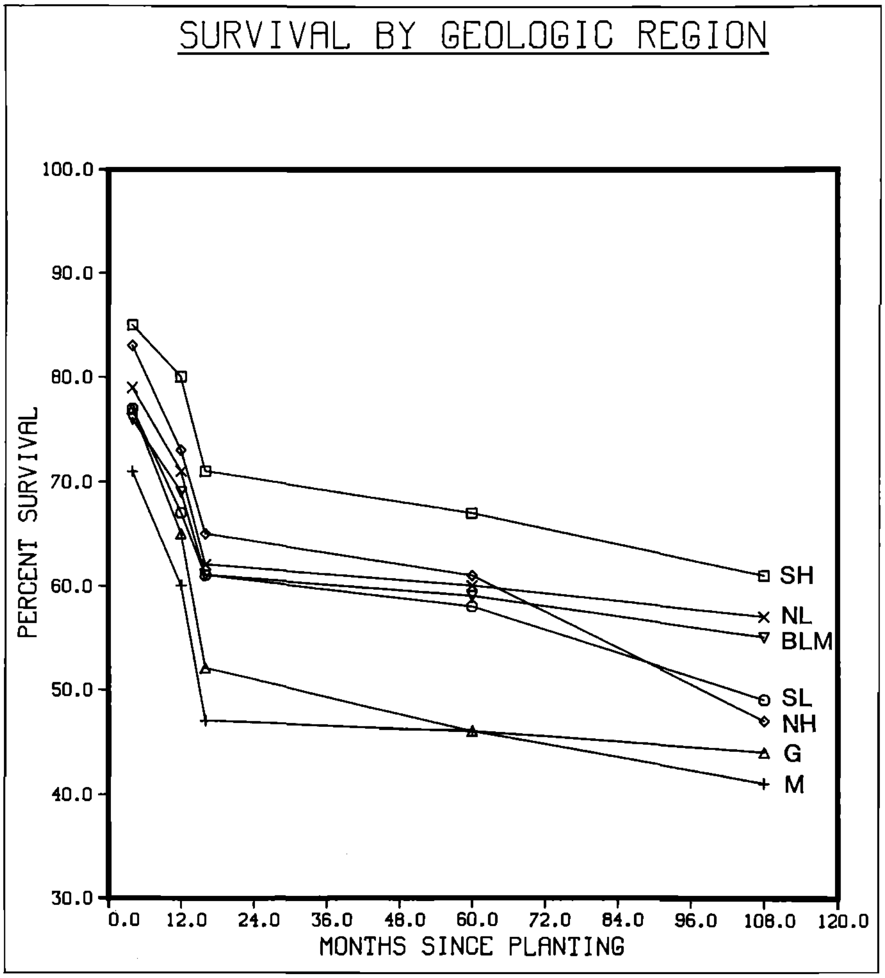

Fig. 2. Ten-year survival curves of progeny grouped by geologic region of seed source. SH = Southern Hogback; NL = Northern Limestone; BLM = Bearlodge Metamorphic; SL = Southern Limestone; NH = Northern Hogback; G = Granitic; M = Metamorphic.

The opposite seems to be true for January maximum temperatures. In this case, the fast-growing cluster 4 parent locations were significantly cooler than the slow-growing cluster 2 parent locations (0°C vs. 1.7°C). This range is split by the 0.6°C average January maximum at the planting site.

Climatic differences between parent locations are also evident when they are grouped by geologic region. Seed source locations in the Southern Hogback region have significantly higher maximum July temperatures than those in the Granitic, Metamorphic, and Northern Limestone regions. January maximum temperatures at parent sites in the Bearlodge Mountains are cooler than those at parent sites in the Granitic and Southern Limestone regions. Bearlodge Mountain sites were also cooler in the winter than the plantation site.

In addition to the indirect relationship of elevation and temperature mentioned above, elevation of seed source was directly related to progeny performance in the plantation. Height, diameter, and crown growth of progeny from parent locations higher than the plantation were significantly greater than that of progeny from locations lower than the plantation. Again, this trend was reflected in the cluster assignment. The average elevation of seed sources in clusters 2 and 3, which grew poorly, was significantly lower than that of the fast growing sources in cluster 4. Only one of the sources in cluster 4 was from an elevation below that of the plantation.

Precipitation received at parent locations may affect growth or survival of progeny in the plantation only indirectly through the relationship to temperature mentioned above. No growth or survival differences were apparent when progeny were assigned to groups where parent locations received more or less precipitation than the planting site.

DISCUSSION

These 10-year results indicate that several of the 77 families tested exhibit superior growth and survival in the central Black Hills and could be utilized in a ponderosa pine tree-improvement program for the Black Hills. All of the families in cluster 4 should be good candidates. Controlled crosses of parents of cluster 4 seedlings now can be made, and controlled crosses among the best individuals in the plantation will be possible in a few years as flowering increases.

In contrast, cluster 2 families should be ruled out as sources of seed for planting in the central Black Hills. Progeny from trees growing on the Northern Hogback soil type near Sturgis performed poorly in all measured growth variables. Their parents' origin is a small, isolated population not actually within the Black Hills, and their performance may be related to inbreeding depression.

Geology appears to indirectly affect survival of Southern Hogback families. This region of the Black Hills receives less precipitation and, because it is somewhat lower in elevation, may have a warmer climate than the other soil types. Families of Southern Hogback parents ranked first out of the seven parent materials in survival, but fifth in each of the measured growth characteristics. This suggests that under droughty conditions, natural selection favors characters related to tree survival rather than rapidity of growth.

Based on the climatic comparisons discussed above, it would appear that temperature regime differences between seed source and planting site can be critical to progeny growth, while elevation and precipitation differences are less directly related. Moving ponderosa pine progeny in the Black Hills to a temperature regime even slightly cooler than that of the parent location is clearly not beneficial to overall growth. The indirect relationship between elevation and temperature of seed source groups in this study supports the well-established adage that seedlings will not grow well if moved to a higher elevation than their origin. The Black Hills do not have extreme variations in elevation, but it appears that a planting site should be no higher than the location where seed was collected.

An interesting pattern is apparent when the location of parent trees of the worst and best clusters (2 and 4) are plotted on a map of the Black Hills region (Figure 1). The best families are from parent trees on the western side of the Black Hills and in the Bearlodge Mountains immediately to the northwest; poor families are in a separate group to the east. Sources in the Bearlodge Mountains occur on sites with cooler January maximum temperatures than those of the planting site, which may explain the better performance of those progeny in the central Black Hills planting site. July maximum temperatures at the planting site and at parent tree locations in the Bearlodge Mountains are similar,

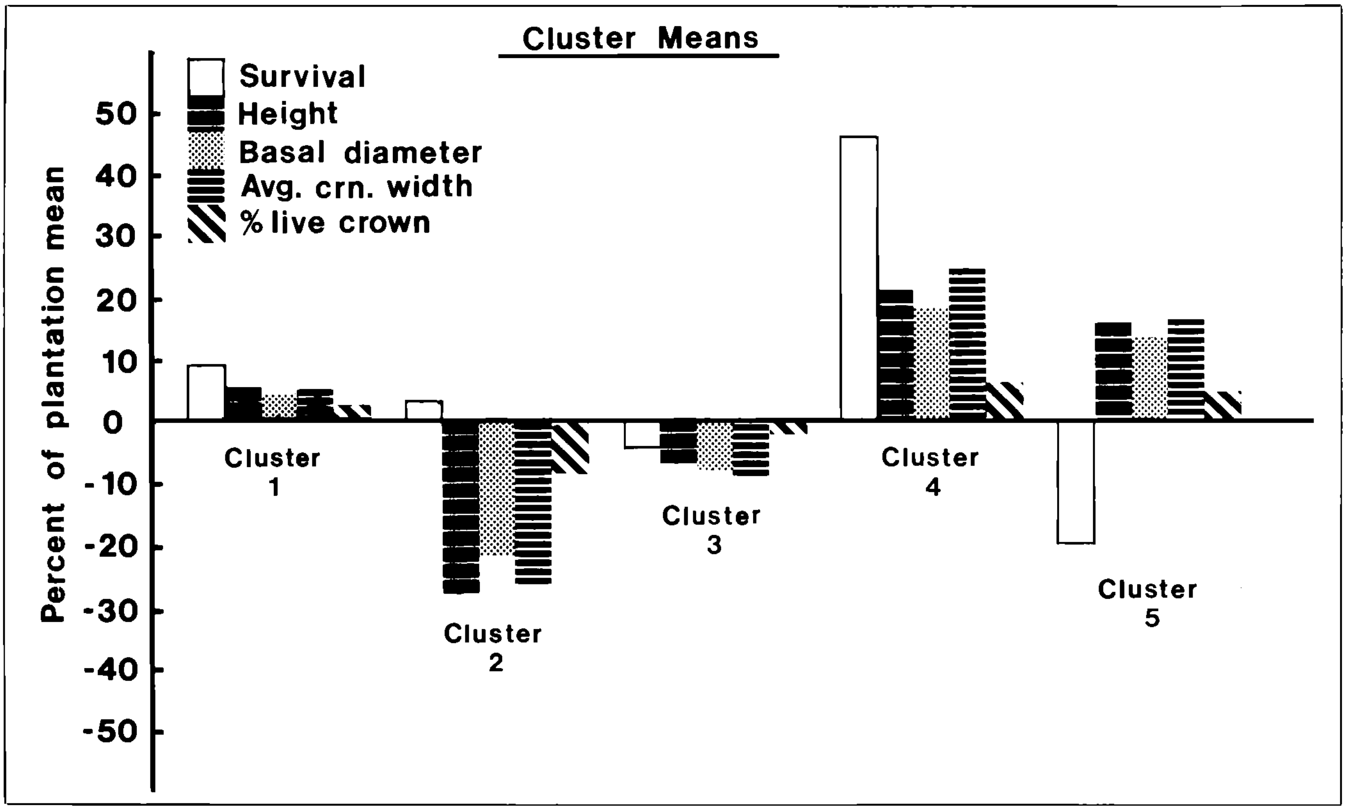

Fig. 3. Ten-year survival and growth means for each cluster expressed as a percent deviation from the overall plantation mean.

Table 3. Mean progeny growth and climatic condition data grouped by average maximum July and January temperatures at seed source. Progeny were assigned to groups in which maximum July and January temperatures at parent locations were (1) cooler than the plantation site, (2) the same as the plantation site, or (3) warmer than the plantation site. Variable means with common subscripts are not statistically different at the 10% level of confidence.

	Max July Temp.			Max Jan. Temp.		
Temperature Group	1	2	3	1	2	3
Height (m)	1.35_b	1.32_{ab}	1.15_a	1.35_b	1.30_b	1.15_a
Basal Diameter (cm)	4.72_b	4.67_b	4.12_a	4.72_b	4.52_b	4.10_a
Crown Width (m)	0.70_b	0.67_b	0.59_a	0.69_b	0.66_b	0.58_a
Percent Live Crown	89_b	88_{ab}	85_a	89_b	88_b	85_a
Percent Survival	47_a	51_a	49_a	56_a	45_a	46_a
Elevation (m)	1837_b	1710_b	1421_a	1822_b	1536_a	1446_a

however. The average elevation of parent trees in the western group (cluster 4) is significantly higher than that of the eastern group (cluster 2) (Table 2), and nearly the same as that of the 1830-m plantation site. The parents of cluster 2 seedlings are located from 305 m to 760 m lower than the plantation. Planting progeny of these trees at this higher elevation appears to have hurt their performance in this case.

In conclusion, we found considerable genetic variation among progeny of ponderosa pines selected from throughout the Black Hills, and we identified potential superior seed sources for planting in the central Black Hills of South Dakota. The relationship between the genetic variation of ponderosa pine in the Black Hills and geologic region or other environmental parameters remains unclear. □

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