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Genetic evaluation of *Prosopis alba* (algarrobo) in Argentina for cloning elite trees

P. Felker[1,*], C. Lopez[2], C. Soulier[3], J. Ochoa[3], R. Abdala[3] & M. Ewens[4]
[1] *Secretaria de Producción y Medio Ambiente, Provincia de Santiago del Estero, Argentina;* [2] *Facultad de Ciencias Forestales, Universidad Nacional de Santiago del Estero, Santiago del Estero, Argentina;* [3] *Facultad de Agronomía y Agroindustrias, Universidad Nacional de Santiago del Estero, Santiago del Estero, Argentina;* [4] *Fernandez Experiment Station, Universidad Catolica Santiago del Estero, Argentina (*Author for correspondence: E-mail: peter_felker@hotmail.com)*

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Abstract

Algarrobo (*Prosopis alba*) is an important nitrogen-fixing tree adapted to the semiarid regions of northwestern Argentina. The tree provides fuelwood and dimensionally stable lumber for flooring and furniture; its pods that have a high sugar content are consumed by livestock and humans. *P. alba* has been one of the most heavily harvested species. This paper reports on the evaluation of a nine-year-old *Prosopis alba* progeny trial containing 57 half-sibling families of eight provenances in northwestern Argentina (of the 1,596 trees planted, 1,289 survived in 1999). Considering the multiple uses of *P. alba*, the selection criteria included: total biomass production (from basal diameter using regression equations), height, rate of pod production, and pod sensory characteristics. The family-narrow-sense-heritability was 0.487 for height. 0.548 for biomass production, and 0.244 for pod production. In 1998, 12 of the 1,289 trees were more than 4 m tall and had more than 1.75 kg pods per tree; and their pods had a sweet or very sweet non-astringent taste. Scions from these 12 trees were successfully grafted onto unselected *P. alba* rootstock. These are currently being used to produce rooted cuttings. The pod production, biomass, and height of the 12 clones ranged from 6.55 to 14.4, 1.57 to 13.5, and 1.29 to 1.70 times, the respective population means. The genetic gains of 13.5%, 77%, and 147% for height, biomass, and pod production respectively are greater than genetic gains for other tree species and are probably due to the great genetic variability in the local population and the lack of any prior genetic improvement program.

Introduction

The world center of biodiversity for arid-adapted, nitrogen fixing shrubs and trees of *Prosopis* is located in Argentina (Burkart, 1976) and the Province of Santiago del Estero is centrally located in the *Prosopis alba* distribution in Argentina. Before the arrival of Europeans, arboreal *Prosopis*, such as *P. alba*, *P. chilensis*, *P. flexuosa*, etc. were a major source of food, fuel and building materials for homes (D'Antoni and Solbrig, 1977). *Prosopis* was also a valuable resource for the early European settlers who consumed the high sugar content pods during droughts and who used the wood for charcoal and building materials (D'Antoni and Solbrig, 1977). *P. alba* also has considerable potential to stimulate economic development in contemporary

Argentina. *P. alba* has lower (and thus more dimensionally stable) lumber shrinkage coefficients (2.9% tangential, 1.8% radial and 4.8% volumetric-Turc and Cutter, 1984) than the hardwoods listed in the tropical timber compendium of Chudnoff (1984). In Argentina, *P. alba* is currently used to manufacture parquet flooring and rustic furniture. With 115,000 tons of logs used annually for these purposes, the Chaco Province has the greatest *P. alba* lumber production of all the Argentine Provinces (M. Bejarano, pers. comm., 2000).

Unfortunately until very recently 'natural forests of algarrobos were exploited without regard to reforestation. Wholesale destruction of these woodlands has led to the decimation of *Prosopis* forests throughout northern and western Argentina . . . especially during the two world wars when shortages of imported coal led to the use of *Prosopis* for steam locomotives and industrial furnaces (D'Antoni and Solbrig, 1977). The renowned Argentine botanist Arturo Burkart (1976) concurred' Trees (of *Prosopis alba*) with straight trunks 8 to 10 m occur, but these are becoming extremely rare, from being cut in preference to the shorter ones. Thus a negative artificial selection is taking place that should be counteracted by genetic improvement of the best lines in experimental plots.

Some of the first *P. alba* progeny trials (Felker et al., 1983a, b) were conducted in southern California using half-sib families collected by Simpson and Solbrig during the 1977 USIBP project between Argentina and the US. This work found high variation among trees from the same half-sib family for both biomass production (Felker et al., 1983b) and pod production (Felker et al., 1984). A study of the pod protein and sugar concentration of *Prosopis alba*, *P. glandulosa*, *P. velutina*, *P. nigra* and *P. articulata* over three years and two sites in young plantations in California (Oduol et al., 1986), found the heritability was higher for pod protein content than pod sugar content, and that pod protein content was more stable across sites than pod sugar content. The fastest growing individual *P. alba* trees from these trials (7 and 15 cm basal diameter at one and two years of age respectively) were cloned by rooting of cuttings (Klass et al., 1984). Several of these high biomass producing *P. alba* clones were later evaluated under non-irrigated Texas conditions on a 3 by 3 m spacing and found to have a high biomass productivity of 20 Mg ha^{-1} in the third growing season (Felker et al., 1989).

In analyses to find the major source of genetic variation in *P. flexuosa* Cony (1996a, b) examined 13 provenances containing 86 families of *P. flexuosa*. While he found that there were significant differences in the mean diameter growth of provenances, he also encountered very large family differences within the provinces. For example, the provenance with the highest ranking of height contained the family with the greatest height as well as the family that ranked 48 out of 86 in height. The major source of genetic variation was at the family level and not at the provenance or geographical level.

Prosopis is insect pollinated and self-incompatible (Hunziker et al., 1986) and thus seeds from the same mother tree can be expected to have high probability of multiple male parents, resulting in high variability among the progeny. Thus clonal propagation is an important tool for the genetic improvement of *P. alba*. Despite many years of research worldwide, a tissue culture technique for *Prosopis* has not been developed (Felker, 1992). Fortunately *P. alba* can be clonally propagated by grafting (Wojtusik and Felker, 1993), rooting of cuttings (Klass et al., 1984) and air layering. It is most effective to use grafting to capture the first clonal propagule of mature field trees and then to use rooting of cuttings to rapidly multiple greenhouse grown, rejuvenated stock plants.

Selection for superior *P. alba* genotypes is complicated by the need to select for multipurpose outputs that compete for photosynthate, i.e., fast trunk growth desirable for lumber production and high pod production. As there has been a resurgence of interest in the use of *Prosopis* pods as food for humans (Grados and Cruz, 1996) there is a need to select for pod quality. While most *P. alba* pods contain 30–40% sucrose (Oduol et al., 1986), and are highly desirable for human food applications, the pods from many trees have an astringent taste. This astringency was known as 'patalca' (H. Ochoa, pers.comm) by the original Quechua inhabitants indicating considerable antiquity to utilization of *Prosopis* pods for human food. Preliminary research (G. Fabiani., pers.comm., 2000) suggests saponins are responsible for this taste.

In 1998, the tree nurseries of the Provinces of the Chaco and Santiago del Estero produced 1 million and 200,000 *P. alba* seedlings respectively for plantations and use by small landowners. Unfortunately there is no source of genetically improved seed and thus all the current seed is obtained from good phenotypes in native forests and urban plantings. This work reports heritability analysis of height and pod production from *P. alba* progeny trials and the cloning of elite trees to produce genetically improved seeds and clones.

Materials and methods

A *P. alba* progeny trial was established in 1990, 10 km from the City of Santiago del Estero, Argentina (27°45′ S; 64°15′ W). The annual mean, absolute maximum and absolute minimum temperatures were 19.9 °C, 44 °C and –12 °C respectively (Universidad Nacional de Santiago del Estero, unpub. data). The mean annual precipitation was 605 mm and the potential evapotranspiration was 1633 mm (Instituto Nacional de Tecnologia Agropecuaria Argentina(INTA) local records.)

The origin of these trees is provided in Table 1. Seed was collected from 57 individual trees (half-sib families) in the eight northwestern Argentina provenances of Añatuya, Castelli, Gato Colorado, Ibarreta, Pinto, Quimili, Rio Dulce Irrigation district and Sumampa. The experimental design was a randomized complete block design with 57 families, seven replications and four trees per replication giving 1596 trees planted in 1990 (1289 trees survived in 1999) (Family 22 was not planted). The four trees were arranged in a square with a 4 m by 4 m spacing. The frequent abundance of *Atriplex* on this site is indicative of saline conditions. Little care was given to this progeny trial.

In December 1997 (summer in Argentina), seven years from establishment, a small percentage of the trees began to produce significant quantities of pods, thus providing an opportunity for early selection for pod production. The number of pods per tree was counted in 1997 and 1998 while the pods were still on the tree. The pods of the various families matured from late December to mid February and thus the counts were made over an eight week period. While there was variability among the pod weight per family, a mean pod weight of 7 g was used to estimate the biomass of the pod production from the number of pods tree^{-1}.

Height and basal diameter measurements (20 cm from the ground) were taken in July 1998. The basal diameter measurements were used to estimate biomass per tree with previously described regression equations (Felker et al., 1989) for 195 *P. alba* trees with a 7.7 cm mean diameter and a 2.1 to 16.4 cm diameter range. The equation was: Log fresh wt (kg) = 2.7027 log diameter (cm) – 1.1085 and had an r^2 of 0.9569, a stand error of 0.0360 and a P value of 0.0001.

In the present analyses it is not critical to know the absolute biomass with precision as would be the case if these results were used for economic analyses of $ per kg of biomass produced or harvested vs costs or production. However, as neither diameter or height are linearly related to biomass, we felt use of the biomass equations would provide a better comparison of the family means in relative terms. Whether the best family mean really has 57 kg biomass per tree biomass or 60 or 55 is not really important since all the families were treated equally. After initial selections were made based on height and pod production, the taste of the remaining trees (32 trees) was ranked as sweet, very sweet, astringent or very astringent and the 12 trees that were very sweet or sweet were cloned. This cloning was accomplished by grafting scions (Wojtusik and Felker, 1993) from the mature trees in the progeny trial onto common *P. alba* rootstock grown in the greenhouse. Shoots from these rejuvenated clones are being multiplied by rooting of cuttings.

The narrow sense heritability coefficients were estimated at the family, within family and individual using components of variance estimated by Restricted Maximum Likelihood variance components (Statistical Analysis Systems Institute, 1988). Genetic gains were estimated using an intensity of selection of 0.62 and 1.27 between and within families respectively as described by Falconer (1981).

Table 1. Ranked height and biomass of *Prosopis alba* ordered by biomass in a progeny trial in Santiago del Estero, Argentina.

Family	Origin		Biomass (kg tree^{-1})			Height(m)		
	Department	Province	Mean	Min/Max	95% CI	Mean	Min/Max	95% CI
5	Ibarreta	Formosa	57.4	3/329	32/85	3.6	1.9/5.4	3.3/4.0
12	Rio Dulce Irrigation Zone	Sgo del Estero	53.9	1/236	24/67	2.9	0.4/4.2	2.5/3.3
3	Ibarreta	Formosa	52.0	9/157	34/79	3.6	1.7/5.1	3.1/4.0
29	Sumampa	Sgo del Estero	47.9	1/117	27/57	2.9	0.3/4.0	2.5/3.3
23	Sumampa	Sgo del Estero	46.9	1/169	27/65	3.2	1.5/4.4	2.9/3.4
48	Anatuya	Sgo del Estero	45.4	1/134	10/70	3.2	1.5/4.2	2.5/3.8
8	Costelli	Chaco	44.5	1/206	20/63	3.3	1.4/4.6	2.9/3.7
17	Rio Dulce Irrigation Zone	Sgo del Estero	41.7	1/107	18/48	2.9	0.6/5.1	2.5/3.4
6	Costelli	Chaco	38.1	1/137	21/51	3.4	1.8/5.3	3.0/3.7
1	Ibarreta	Formosa	36.5	5/149	22/52	3.0	1.8/4.5	2.9/3.3
49	Anatuya	Sgo del Estero	34.9	1/88	11/49	2.9	1.8/4.4	2.4/3.4
13	Rio Dulce Irrigation Zone	Sgo del Estero	33.3	1/117	17/44	2.7	1.2/3.5	2.5/2.9
55	Pinto	Sgo del Estero	33.3	1/110	12/42	2.5	1.0/3.9	2.0/2.9
9	Costelli	Chaco	31.0	5/78	21/40	3.0	1.9/4.3	2.7/3.3
4	Ibarreta	Formosa	30.8	1/110	21/49	3.2	1.6/4.7	2.8/3.6
18	Rio Dulce Irrigation Zone	Sgo del Estero	30.1	1/130	10/37	2.6	1.3/4.8	2.3/2.9
32	Gato Colorado	Santa Fe	30.0	1/145	15/44	2.6	1.5/4.4	2.3/2.9
56	Pinto	Sgo del Estero	29.9	1/62	18/35	3.1	1.4/4.6	2.8/3.5
10	Rio Dulce Irrigation Zone	Sgo del Estero	28.3	1/110	15/36	3.0	0.6/4.4	2.6/3.3
21	Sumampa	Sgo del Estero	25.3	2/107	13/39	2.9	1.8/4.1	2.6/3.2
40	Quimili	Sgo del Estero	24.9	2/75	15/38	2.9	1.5/4.4	2.6/3.3
15	Rio Dulce Irrigation Zone	Sgo del Estero	24.9	1/57	18/31	3.0	2.2/4.2	2.8/3.3
7	Costelli	Chaco	23.8	1/130	12/34	2.9	1.6/4.8	2.6/3.2
26	Sumampa	Sgo del Estero	21.6	1/89	11/37	2.7	1.3/4.1	2.3/3.1
41	Quimili	Sgo del Estero	21.3	2/65	14/29	2.7	1.8/3.8	2.5/3.0
50	Anatuya	Sgo del Estero	20.6	1/80	14/31	2.7	1.5/3.8	2.4/3.0
54	Pinto	Sgo del Estero	20.3	1/49	14/27	2.8	0.7/4.5	2.4/3.1
34	Gato Colorado	Santa Fe	19.2	1/61	8/28	2.3	0.7/3.8	1.8/2.8
35	Gato Colorado	Santa Fe	19.0	1/61	11/27	2.7	1.6/3.9	2.5/3.0
38	Quimili	Sgo del Estero	18.8	1/97	8/30	2.5	0.9/4.3	2.0/2.8
52	Pinto	Sgo del Estero	18.7	2/91	9/31	2.8	1.2/4.4	2.4/3.1
16	Rio Dulce Irrigation Zone	Sgo del Estero	18.6	4/57	12/23	2.8	1.8/3.7	2.7/3.0
58	Pinto	Sgo del Estero	17.8	2/75	11/27	2.8	1.9/3.7	2.6/3.0
11	Rio Dulce Irrigation Zone	Sgo del Estero	17.7	1/70	11/25	2.8	1.7/4.0	2.6/3.1
28	Sumampa	Sgo del Estero	17.6	2/47	11/24	2.8	1.9/3.7	2.6/3.1
47	Anatuya	Sgo del Estero	17.3	1/92	9/32	2.7	1.7/3.6	2.4/3.0
51	Anatuya	Sgo del Estero	17.0	1/52	8/20	2.4	1.3/3.6	2.1/2.7
46	Anatuya	Sgo del Estero	16.9	1/78	6/22	2.7	1.6/3.5	2.4/2.9
36	Quimili	Sgo del Estero	16.8	1/86	10/23	2.7	1.3/3.8	2.4/2.9
53	Pinto	Sgo del Estero	16.6	1/52	6/21	2.5	1.2/3.7	2.1/2.9
9	Rio Dulce Irrigation Zone	Sgo del Estero	16.5	2/52	9/23	2.8	1.5/4.1	2.4/3.1
44	Anatuya	Sgo del Estero	16.5	1/52	9/21	2.5	1.5/4.2	2.2/2.8
14	Rio Dulce Irrigation Zone	Sgo del Estero	16.3	1/68	9/23	2.6	1.0/3.6	2.4/2.9
45	Anatuya	Sgo del Estero	15.5	1/49	9/22	2.8	1.8/4.2	2.5/3.0
42	Quimili	Sgo del Estero	15.5	1/57	9/22	2.9	0.9/4.3	2.5/3.3
24	Sumampa	Sgo del Estero	15.2	1/57	7/23	2.6	0.8/4.1	2.2/3.0
57	Pinto	Sgo del Estero	14.3	1/66	7/21	2.8	1.8/4.2	2.5/3.1
33	Gato Coloardo	Santa Fe	14.1	1/32	9/17	2.6	1.9/3.4	2.4/2.8
30	Gato Coloardo	Santa Fe	12.9	1/41	7/16	2.6	1.3/4.1	2.3/2.9
25	Sumampa	Sgo del Estero	12.1	1/49	7/17	2.6	1.8/3.5	2.4/2.8
37	Quimili	Sgo del Estero	11.9	1/38	6/15	2.6	1.5/3.6	2.3/2.8
20	Rio Dulce Irrigation Zone	Sgo del Estero	11.1	1/36	5/13	2.6	1.8/3.5	2.4/2.8
31	Gato Colorado	Santa Fe	10.7	1/61	4/15	2.2	1.1/3.5	1.9/2.5

Family 22 was not included in this trial. The Department is a political unit within the political unit Province. The eight provenances listed were those listed under the Department heading.

Results

While there was a 5-fold range in biomass per family and a 1.6 fold range in the height per family, there was also great variability within families (Table 1). For example, while the mean biomass and height of family 5 from Ibarreta, Formosa was 57 kg tree^{-1} and 3.6 m in height respectively, this family had a range from 3 to 329 kg tree^{-1} in biomass and from 1.9 to 5.4 m in height. This within-family variability offers great potential to clone outstanding individual trees.

While there was a general trend for the same families to have the same rank in height and biomass, some trees were more highly branched, leading to greater biomass for the same height. For example, family 12 from Rio Dulce had less height (2.9 m) than Family 3 from Ibarreta (3.6 m) but a greater mean biomass (53.9 vs. 52.0 kg tree^{-1}).

In considering the means of the eight provenances, there was a 20% difference in the mean height (2.7 to 3.7 m) and a 74% difference in biomass (19 kg to 33 kg) between the best (Ibarreta) and worst (Gato Colorado) provenance. There was a tendency for families from the Provinces of Formosa (families 1–5) and the Chaco (families 6–9) to have the greater height growth. As judged by pre-planned contrasts, provenance Ibarreta was significantly different (P = 0.0001) in height from the provenances of Sumampa, Gato Colorado, and the Rio Dulce Irrigation Zone but was not significantly different from the Castelli provenance (= 0.94). However the Castelli provenance was significantly different (P = 0.0001) in height from the Rio Dulce Irrigation Zone and the Sumampa provenances.

Of the 1289 trees in this progeny trial, 94 trees produced pods in the 1997 year and 678 trees produced pods in 1998. In 1998, the average number of pods per tree was 42 and the maximum number of pods tree^{-1} was 700. Also in 1998, 187, 93 and 56 trees produced more than 100, 200 and 250 prods tree^{-1} respectively.

As with the biomass production there was great variability in the mean and range of pod production per tree, among and within families (Table 2). For example in 1998, the mean pod production per family ranged from 874 g tree^{-1} (family 1) to 13 g tree^{-1} (family 53). Family 1, that had the greatest pod production also showed great variability; i.e. from 0 to 4,200 g tree^{-1}. It is also of interest to note that several families had individual trees equal in production to the maximum pod production/tree of the best family i.e. one and that family 34 had the individual tree with the greatest pod production of 4,900 g tree^{-1}. As occurred with height growth, the families with the greatest pod production tended to be from provenances of Ibarreta, Formosa (or from Castelli, Chaco. However, a few high pod production trees occurred in family 12 from the Santiago del Estero Irrigation Zone and in family 52 from Pinto, Santiago del Estero.

The variability from about 1 to 3% mean family pod production/tree biomass in the highest pod producing trees indicates considerable genetic

Table 2. Mean and range of *Prosopia alba* pod production per tree in a progeny trial in Santiago del Estero, Argentina.

Family	Number trees per family with pods		Pod production per tree (g yr^{-1})				
	1997	1998	1997[a]		1998[b]		
			Mean	Max	Mean	Min/Max	95% CI[c]
1	6	23	329	840	874	0/4200	421/1326
8	1	14	7	7	807	0/3500	146/1448
6	4	16	376	700	753	0/2800	360/1147
5	5	18	719	1750	721	0/4200	360/1147
9	7	19	303	1050	693	0/2100	361/1026
48	3	6	490	840	693	0/3500	–265/1651
32	6	21	500	1400	685	0/3500	310/1060
34	2	9	630	700	595	0/4900	–28/1220
3	6	14	607	1750	555	0/1750	302/809
12	2	16	1050	1050	549	0/3605	151/948

Table 2. (Continued).

Family	Number trees per family with pods		Pod production per tree (g yr^{-1})				
	1997	1998	1997[a]		1998[b]		
			Mean	Max	Mean	Min/Max	95% CT[c]
43	8	14	482	980	515	0/1820	248/782
41	2	11	332	350	495	0/2800	145/845
42	2	13	542	910	491	0/1680	192/790
2	0	12	0	0	484	0/2100	190/778
10	1	19	280	280	477	0/1890	239/714
4	1	12	420	420	431	0/2100	147/714
47	0	9	0	0	379	0/2100	29/729
11	1	15	35	35	365	0/2100	139/595
40	1	13	560	560	358	0/1960	80/635
58	1	8	70	70	336	0/2030	43/630
45	1	8	350	350	311	0/4200	–132/754
55	0	7	0	0	298	0/1470	35/161
52	1	6	700	700	290	0/3500	–124/706
36	3	17	107	217	286	0/1540	92/480
23	4	12	218	420	265	0/2100	35/495
17	3	15	490	700	247	0/2100	48/447
49	1	5	105	105	238	0/2100	–230/706
39	1	9	154	154	235	0/3500	–114/584
35	1	7	280	280	228	0/1400	40/417
38	1	8	210	210	217	0/1540	10/424
44	0	9	0	0	209	0/1400	42/375
19	3	9	583	1260	207	0/1260	24/390
27	0	11	0	0	205	0/1820	34/387
7	1	7	315	315	199	0/1960	0/398
29	1	11	350	350	198	0/1050	29/367
14	0	7	0	0	136	0/1120	14/259
15	0	12	0	0	134	0/735	41/227
18	0	6	0	0	113	0/980	–4/229
56	0	11	0	0	112	0/1330	–14/239
46	1	3	1400	1400	111	0/2100	–96/320
31	2	5	175	280	109	0/1400	–36/259
21	0	11	0	0	108	0/770	19/196
37	0	6	0	0	93	0/910	–8/194
13	1	11	91	91	91	0/630	22/160
50	0	7	0	0	89	0/910	–4/183
33	0	8	0	0	84	0/1050	–27/197
26	0	6	0	0	82	0/420	8/156
54	2	7	280	420	64	0/560	2/127
28	0	5	0	0	58	0/420	–1/117
16	1	7	1400	1400	57	0/525	0/115
30	0	7	0	0	56	0/581	–3/116
20	1	5	1750	1750	52	0/840	–21/125
51	0	9	0	0	46	0/420	2/90
57	3	3	560	700	39	0/630	–25/103
25	0	4	0	0	28	0/385	–12/69
24	0	3	0	0	17	0/310	–9/45
53	0	2	0	0	13	0/154	–7/33

Family 22 was not included in this trial.
[a] Means are only for trees with pods.
[b] Means are for all trees in family (with and without pods).
[c] 95% Confidence interval.

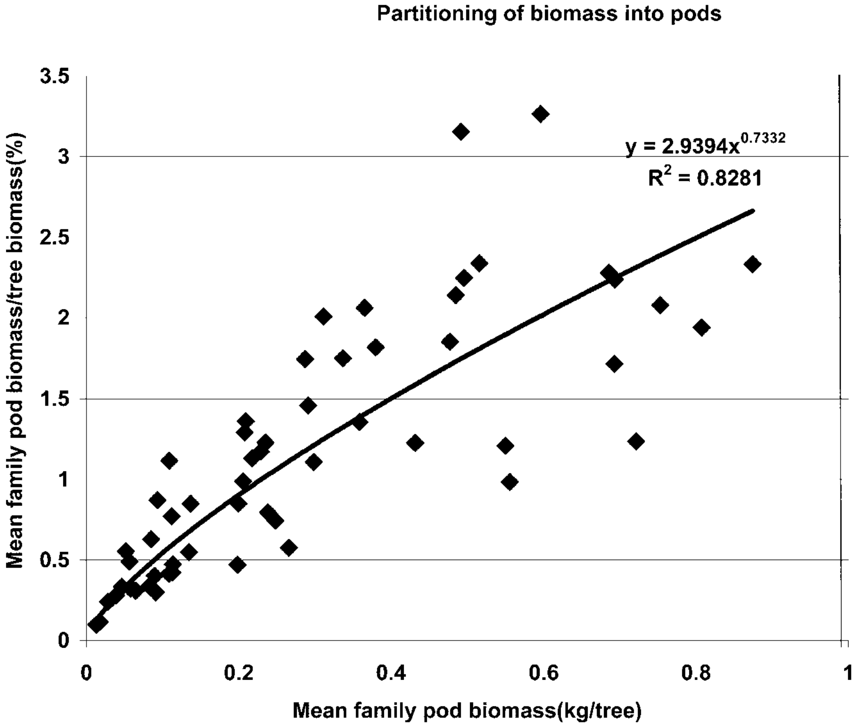

Figure 1. Partitioning of *Prosopis alba* growth in biomass or pods. The data points represent the family means of pod production biomass^{-1} × 100.

diversity in vegetative/reproductive partitioning in *Prosopis alba* (Figure 1). As opposed to annual crops, for the same pod production per tree, a low partitioning of pod biomass/total biomass is desirable since this implies both high timber production and high pod production. Some very healthy and large trees in this progeny trial produced no pods. It is also to be noted that values in Figure 1 are based on family means and that as noted in Table 2 the maximum pod production per tree was 4.9 kg tree^{-1}.

The pod production per hectare on this 4 m by 4 m spacing would range from 0 to 546 kg ha^{-1} based on the family means. However using the production of the clones, the production per hectare would range from 1,187 to 2,625 kg/ha. As this is only the second year of production the yield at maturity could be expected to be significantly greater.

The heritability for height, biomass production and pod production in Table 3, shows that biomass production and height had higher heritabilities than pod production. Nevertheless pod production was highly heritable. The selection intensity of 60% between families (k1 = 0.63) and 25% within families (k2 = 1.27 resulted in a genetic gain in relation to the population mean of 13.5% for height versus much higher values of 77% and 147% for biomass and pod production. These values are quite high as might be expected from

Table 3. Heritability for height, biomass and pod production of *Prosopis alba* in a progeny trial in Santiago del Estro, Argentina.

	Individual narrow sense heritability	Family narrow sense heritability	Genetic Gain (%)
Height	0.37	0.48	13
Biomass production	0.37	0.55	77
Pod production	0.17	0.24	147

the large variability in diameter and pod production. Obviously a higher genetic gain could be obtained if a smaller selection intensity were used that included fewer families.

A combination of height, pod production and pod flavor was used to select the trees to clone as shown in Figure 2. Of the total of 1289 trees in this trial, after nine years, only 98 trees were more than 4 m in height and only 56 had produced more than 1.75 kg of pods yr^{-1}. Of this group only 32 trees had more than 4 m in height and more than 1.75 kg pods yr^{-1}. Only 12 of these 32 trees had sweet or very sweet non-astringent taste. The height, biomass, pod production, pod flavor and partitioning of biomass into pods of the 12 elite clones is presented in Table 4. These clones exhibited a striking variability in biomass for trees of similar height. For example, within family 5, block 1 tree 4 had 329 kg biomass (22 cm in diameter) while block 6 tree 2 had only 38 kg biomass (diameter of 9.9 cm). In contrast, the smaller tree in family 5 had the greatest pod production of all 12 clones and this resulted in a higher ratio of pods/biomass i.e. 11% vs. 0.64% than the other tree (Block 1 tree 4) in this family. Perhaps a high pod productivity in previous years contributed to the lower biomass per unit of height.

Scions were taken from these 12 trees and successfully grafted onto unselected *P. alba* rootstock and are currently being used to produce rooted cuttings. It is to be noted that the 12 clones ranged from 6.55 to 14.4, 1.57 to 13.6 and 1.29 to 1.70 times the population mean of pod production (0.29 kg $tree^{-1}$), biomass (24.2 kg $tree^{-1}$) and height (3.1 m). Similarly the pod production, height and biomass of the clones ranged from 2.1 to 4.8, 1.11 to 1.47 and 0.66 to 5.77 times the best family means respectively.

Discussion

Previous work has reported *Prosopis* clones for high biomass production for use in bioenergy farms in southwestern United States (Felker et al., 1983b), *Prosopis juliflora* clones for erect form and fast growth in Haiti (Wojtusik et al., 1993) and *Prosopis juliflora* clones for biomass production and form in India (Harsh et al., 1996). However this is the first report of clones that have been selected on the basis of both pod production, pod flavor and height growth.

In spite of the high value of the lumber, it is our opinion that landowners in Argentina are unlikely to plant *Prosopis alba* in plantations at spacings

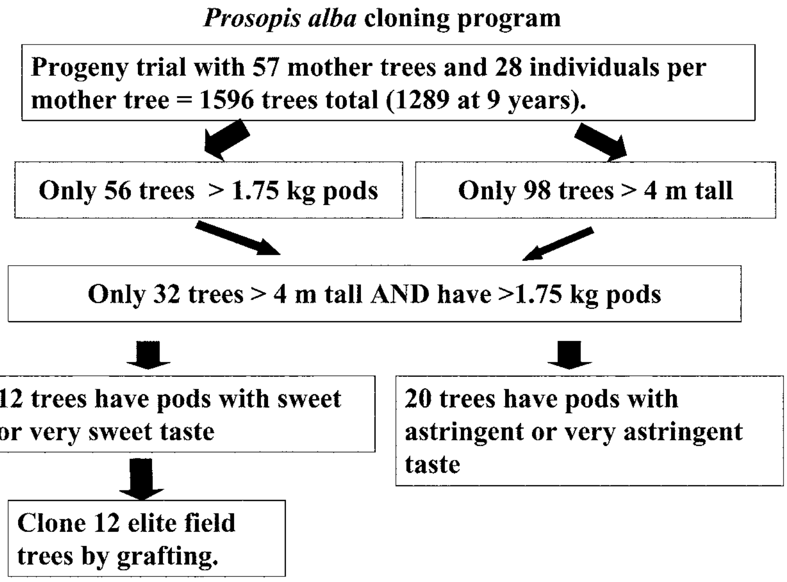

Figure 2. Selection criteria for *Prosopis alba* cloning program.

Table 4. Elite trees cloned by grafting onto common *P. alba* rootstock in the *Prosopis alba* progey trial in Santiago del Estero, Argentina that were greater than 4.0 m tall, had more than 1.75 kg pods tree^{-1} a sweet or very sweet taste.[a]

	Pods kg tree^{-1}	Height (m)	Biomass (kg tree^{-1})	kg pods kg biomass (%)	Flavor
Family 4 Block 2 Tree 3	2.1	4.5	100	2.1	Sweet
Family 5 Block 1 Tree 4	2.1	5.15	329	0.64	Sweet
Family 5 Block 6 Tree 2	4.2	4.3	38	11.0	Very sweet
Family 6 Block 1 Tree 3	2.8	4.6	138	2.0	Sweet
Family 6 Block 7 Tree 4	2.3	5.3	110	2.0	Very sweet
Family 8 Block 1 Tree 4	3.5	4.25	100	3.5	Very sweet
Family 9 Block 5 Tree 2	1.9	4.2	54	3.5	Sweet
Family 11 Block 6 Tree 4	2.1	4.0	70	3.0	Very sweet
Family 12 Block 6 Tree 1	3.6	4.0	130	2.7	Sweet
Family 12 Block 6 Tree 4	3.5	4.0	236	1.5	Very sweet
Family 17 Block 2 Tree 2	2.1	4.1	107	2.0	Very sweet
Family 52 Block 1 Tree 3	2.1	4.35	92	2.2	Sweet
Population mean (n = 1289)	0.29	3.1	24.2		

[a] Pod flavor was ranked as very astringent, astringent, sweet or very sweet. Only pods in categories sweet and very sweet were cloned.

similar to that of other commercial forest species (3 × 4 m) due to the multipurpose needs of the communities. Pods that could be used for livestock feed or new products for human food (Grados and Cruz, 1996; Bravo et al., 1994) are highly valued by these communities. Therefore it is critical that *Prosopis* clones and seed sources for use in arid lands must be selected for both pod characters and growth.

In addition, we have shown that in the 650 mm annual rainfall zone, trees of sufficient size to be sawn into lumber (38 cm basal diameter) cannot be obtained at spacings less than 9.5 by 9.5 m (Felker et al., 1990). These wide spacings lend themselves to agroforestry systems with cultivation of other crops and the production of pods. As pod production frequently begins at five years of age in intensively managed plantations (Felker, unpub. obs.), these pods would help greatly to reduce the long-term debt incurred from the initial planting costs.

The growth of the *P. alba* in this progeny trial was much lower than that obtained for *P. alba* in progeny trials in the United States. For example, *P. alba* clones were obtained from a progeny trial in the California Imperial Valley that had basal diameters of 6.5 to 7.9 cm at the end of the first growing season (nine months) and 9.9 to 17.2 cm in diameter at the end of the second growing season (Felker et al., 1983). A trial with some of these clones under rainfed conditions with 700 mm annual rainfall in Texas achieved 39 Mg ha^{-1} dry weight in three years on a 3 m by 3 m spacing (Felker et al., 1989) in which the trees were about 7 cm in diameter and 5 m tall. We believe the differences in the growth rates of *P. alba* between Texas and Argentina are due to the presence of competing 1–1.5 m tall vegetation in Argentina and the intensive use of both preemergence herbicides and mechanical cultivation for weed control in the US trials.

Due to the difficulty in producing massive quantities of clones from either grafting or rooted cuttings (Felker, 1992), it has been suggested that clones will probably only be used in high value applications such as seed orchards or ornamental applications in urban settings. However preliminary results in rapidly grafting (200/day), 30-day old, 2-mm diameter *Prosopis alba* seedlings (Ewens, M., pers. comm.2000) may bring clonal commercial plantations into reality in developing countries where low labor costs are available. Should this not be possible, *Prosopis* clonal seed orchards should provide much improved genetic material. In a review of genetic improvement with exotics, Zobel et al. (1987) reported that genetic gains of 26% could be achieved from *Eucalyptus grandis* seed orchards from seed and 51% from clonal seed orchards. Installation of a seed orchard with the clones in Table 4 is scheduled for 2001.

The unusually large genetic gains we have measured for biomass and pod production are a result of the great variability in *Prosopis* that results from its obligately outcrossed breeding mechanism. We suggest that due to this outcrossed breeding mechanism, in many ways *Prosopis* progeny are similar to an F2 population with great individual variability. It is these highly variable progeny with possible highly productive segregants that offer exceptional possibilities to clone unique highly productive individual trees. In this trial we have cloned less than 1% of the population leading to a selection intensity of 99%.

As edaphic, light and wind factors have considerable variability in practically all field trials, field position may cause two genetically identical trees to have very different growth. Thus there is a significant possibility that any one of the 12 clones may not be as good as the overall population mean. However we feel is highly unlikely that the 12 clones taken together would not be significantly better than the population mean and the best family mean.

The narrow sense individual heritability in height we observed of 0.37 is considerably lower than the value of 0.68 observed by Cony (1996) for *P. flexuosa*. Cony (1996) also observed that heritabilities were higher at the family level than at the individual level and that height had a lower heritability than thorniness but was higher than straightness, basal diameter and number of branches. While there is a tendency for high production in certain regions and families, the greatest source of variability is at the individual tree level. Given the lack of uniform production for any given geographical location or family, it is critical to use clones to capture both the additive and non-additive variance.

In conifers, where it is not possible to rejuvenate and thus asexually propagate mature trees, large numbers of clones are made from seedlings and tested in replicated trials where the heritabilities and variances are measured (Russell and Libby, 1986; Park and Fowler, 1987). These conifer clones are preserved in juvenile form by hedging and other techniques until their performance in field trials is known (Park and Fowler, 1987). Fortunately with *Prosopis*, due to the ability to clone mature trees, it is possible to plant many families and progenies that are exposed to various edaphic or environmental factors and then only clone the superior trees of interest. This obviously greatly simplifies the breeding work by avoiding the necessity to maintain a considerable number of clones of unknown performance for many years.

The evolution of commercial forestry species solely used for timber is heavily dependent on environmental gradients and thus the concept of provenances containing genotypes with similar characteristics is most useful (Zobel et al., 1987). In contrast, the current *Prosopis* distribution is highly dependent on man and his animals that preferentially consumed pods from trees with exceptionally high sugar contents and defecated the scarified seeds with high germination several days later in different locations. Over the coarse of centuries of domestication, this process has blurred environmental trends in *Prosopis* and generally lead to the lack of significant differences between vs. within geographical sources. For example, no differences in biomass production were observed among various geographic regions of the California native *Prosopis glandulosa* var. *glandulosa* (Felker et al., 1983b) or among native Haitian *P. juliflora* (Lee et al., 1992). However, Lee et al., (1992) observed significant differences in height growth for two provenances of the *Prosopis juliflora/pallida* complex from Peru and Felker et al. (1984) observed that one provenance of *P. velutina* from Arizona had significantly higher pod production than other provenances. However these dwarf, shrubby types of high pod producing *P. velutina* have been reported to be serious weeds after introduction into South Africa (H. Zimmerman, pers. comm. 1999) and care should be taken in distributing the Arizona provenance outside its native range.

In a comparison of pod production of *P. alba*, *P. chilensis*, *P. glandulosa*, *P. nigra* and *P. ruscifolia* in irrigated plantations, Felker et al. (1984) found that *P. velutina* produced 20 to 30 times more pods per tree (3.1 to 7.1 kg/tree) at five years of age than *P. alba*, *P. chilensis*, *P. nigra* etc. The maximum pod production estimated from densely planted trees (1.22 × 1.22 m) intended for bioenergy production was estimated to b 3100 kg/ha for *P. velutina* accession 0020 at age 5. This value is greater than the production we observed based on family means of 0 to 546 kg/ha or the maximum based on the production of the clones, i.e. from 1,187 to 2,625 kg/ha. As the trials containing *P. velutina* were intensively managed on the University of California Riverside Experiment Station and as this *P. alba* progeny trial was essentially abandoned for the first six years after planting, a direct comparison is not possible. Furthermore as *P. alba* produces pods later than *P. velutina*, and as this was only the second year of production for *P. alba*, these species may have comparable yields at maturity. *P. alba* trees are generally much larger at maturity than *P. velutina* trees (Burkart, 1976) and thus will also serve for other purposes such as fine lumber production.

In annual crops the reproductive biomass divided by the total biomass is known as the harvest index. Wheat plant breeders in particular made great strides in increasing grain yields by increasing ratio of reproductive biomass to total biomass in short statured wheat varieties (Donald and Hamblin, 1976). However in tree crops where both the vegetative biomass (i.e. timber) and the reproductive biomass are valuable, it is of interest to know the relative trade offs between timber growth and pod production. To assess the partitioning of photosynthate into pod production vs. total biomass, we have presented the family means of the ratio of pod production per tree to standing biomass as a function of pod production. The maximum partitioning of pod production vs. total biomass is about 3%. This is much lower than the 40–50% partitioning of total biomass into reproductive growth observed for annual crops. However the biomass presented here has been accumulated over nine years and is not directly analogous to annual crops. Short prostrate, thorny *Prosopis glandulosa* from New Mexico were estimated to have a much higher partitioning of biomass into pod production (50%) in their third growing season (Felker et al., 1984). However it is to be noted that these shrubby thorny types have been found to be very weedy when introduced into South Africa (P. Felker, unpub. obs).

Various techniques could be used to estimate the maximum pod production per hectare on the 10 m by 10 m spacing designed to produce 40 cm diameter lumber trees in 30 years. The regression equations of El Fadl et al. (1989) predict the biomass of a 40 cm diameter tree to be 814 kg. At a 3% pod production per kg of biomass this would be 2,400 kg pods per ha. If, as the trees mature, the partitioning ratio of pods/annual biomass increases and becomes similar to that observed for New Mexico *P. glandulosa* (i.e., 50%), and if annual biomass increases of 13 Mg ha^{-1} yr^{-1} observed for high biomass producing *P. alba* clones are achieved (Felker et al., 1989), then pod yields in the 5,000 kg ha^{-1} yr^{-1} range should be possible. This would imply individual tree yields of 40–50 kg each, which are not unreasonable, as many extension agents have frequently reported individual tree pod yields in excess of 100 kg.

In summary, for the first time we report heritability data for height, biomass and pod production in *Prosopis alba*. We employed a composite selection index composed of growth, early pod production and pod palatability characteristics to clone 1% of best individual trees in a nine year old progeny trial. These clones will be used in seed orchards to produce seed for new government subsidized plantings of *Prosopis alba* in Argentina. These clones are a first step to counteract centuries of overexploitation and genetic erosion of this species. These new genetic materials will result in increased economic viability of *P. alba* plantations in non-traditional forestry areas of Argentina due to increased production of both pods and lumber. Due to the excellent technical characteristics of *Prosopis* for fine furniture and flooring and the resultant high value of fine hardwoods ($850/cubic meter = $1,000 Mg^{-1}) it has been suggested that *Prosopis alba* plantations destined for hardwoods could provide a profit driven incentive to reforestation of arid lands (Felker, 2000). These plantations would also benefit the environment through soil organic N and carbon build up, increase the livelihood of Argentina's poorest communities and reverse the loss of biodiversity in one of Argentina's most important native species.

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