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Potential of commercial hardwood forestry plantations in arid lands—an economic analyses of *Prosopis* lumber production in Argentina and the United States

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Abstract

Prosopis has one of the world's most dimensional stable lumbers. More than 100,000 t of *Prosopis alba* logs are being harvested annually in the Chaco Province, Argentina for the furniture industry. A growing luxury furniture industry has developed in southwestern USA with wholesale prices of US$ 1600 m^{-3}. As the production arises from unmanaged, non-certified native stands it will be important to initiate plantations to guarantee the sustainability of this resource. This economic analyses was developed to quantify the profitability of *Prosopis* plantations and was based on published values for basal diameter growth of unmanaged and managed native *Prosopis* stands, and plantations derived from seed and improved clones. The economic model assumed that the rotation lengths necessary to achieve 100 trees ha^{-1} with 40 cm diameters containing 15.4 m^{-3} of sawn lumber per hectare were: 100 years for unmanaged native forests at 707 mm rainfall, 24 year in plantations with improved seed at 707 mm rainfall, 15 year with clones at 734 mm rainfall, 17 year from seed at 1000 mm rainfall and 11 year using clones at 1000 mm rainfall. Using a lumber price of US$ 800 m^{-3} and after deducting a custom sawing rate of US$ 107 m^{-3}, and when the land value was not included in the economic analysis, the internal rate of returns (IRRs) were 5.3 and 3.1% for the unmanaged native stand and ranged from 11.8% (24 years, 707 mm rainfall) to 34.8% (11 years, clones, 1000 mm rainfall) and from 11.0% (24 years, 707 mm rainfall) to 32.5% (11 years, clones, 1000 mm rainfall) for the plantations in Argentina and the United States, respectively. The corresponding values when the land value was included were: 3.5 and 10.0–27.8% (Argentina), and 1.9 and 7.0–18.5% (USA). To simulate the scenario of selling logs and not custom sawing the timber, the price for logs in Argentina was used (US$ 33 t^{-1}). Under these conditions the IRR of the plantations was found to range from 1.3 to 10.0%, when land value was not included in the analysis. Thus, due to the lower productivity of semi-arid forests, it is necessary to convert logs into sawn lumber to achieve economically viable IRRs. Shortening the rotation from 24 to 15 years with clones (even with a 3-fold increase in planting stock cost) doubled the IRR while nearly a 4-fold increase in price was necessary to double the IRR. Clones cannot be commercially produced by rooted cuttings, but can be by grafting. High variability exists in *P. alba* clones for rooting ability and research is needed to develop systems for rooting cuttings. Inclusion of complimentary grazing, commercial wildlife, intercropping and pod production showed little increase in the IRR over plantations alone. *Prosopis* plantations had IRRs equivalent to many other commercial hardwood and softwood plantations

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suggesting that for the first time, commercial forestry may be possible in the world's arid zones that are in urgent need of reforestation and economic development.

Keywords: Agroforestry; Desertification; Arid zones; Economic development

1. Introduction

Nitrogen-fixing trees and shrubs of the genus *Prosopis* are distributed worldwide in arid zones where they have been problematic weeds. However, they are also useful for soil enrichment via nitrogen fixation, pods for human and livestock food, firewood and lumber for furniture (Pasiecznik et al., 2001). The radial and tangential shrinkage of *Prosopis glandulosa* (2.2 and 2.6%) (Weldon, 1986) a native of North America; *Prosopis alba* (1.8 and 2.9%) (Turc and Cutter, 1984) native to Argentina; *P. pallida* (2.5 and 3.61%, L. Alban, Univ. de Piura, pers. commun., 2000) native to tropical arid zones of Peru are lower than all the tropical species found in the worldwide compendium of Chudnoff (1984) including teak (*Tectona grandis*), mahogany (*Swietenia macrophylla*), and Indian rosewood (*Dalberghia latifolia*) and Brazilian rosewood (*Dalberghia nigra*). Because low shrinkage values and near equal radial and tangential shrinkages are probably the best measure of wood stability, and because wood stability is one of the most important characteristics in furniture manufacture, *Prosopis* technically ranks with the world's best furniture species. When this stability is combined with the reddish-brown wood color and above average specific gravity (ca. 0.75) and hardness (770 kg cm^{-2} *P. alba* and 1010 kg cm^{-2} *P. glandulosa* var. *glandulosa*), *Prosopis* lumber meets all the requisites to be included in the class of the world finest indoor furniture species. In the southwestern United States, despite the lack of availability of long clear logs on the 22 million hectares where *Prosopis* grows, it is being increasingly used for very high value custom furniture manufacture (Felker, 1998; Rogers, 2000). However, due to the spines and aggressive colonization of grazing lands, major US initiatives have attempted to eradicate *Prosopis*.

In contrast, in Argentina the Chaco Province yearly harvests 100,000 t of logs for furniture manufacture and in Santiago del Estero Province, the majority of doors, windows and home furniture are made from *P. alba*. Due to this demand, Santiago del Estero Province has greatly restricted log harvest and the Chaco Province obtained a US$ 600,000 loan from the Interamerican Development Bank to develop markets for its other subtropical woods to lessen the pressure on the *P. alba*. Government and private nurseries from both provinces are raising more than 1 million *P. alba* seedlings (albeit from wild trees) per year for new plantations. Multi-purpose clones with fast growth rates, high pod production and highly palatable pods have been selected from *P. alba* progeny trials (Felker et al., 2001) but the routine propagation of these clones by rooted cuttings has proven difficult (Felker, unpub. obs.). However, rapid mini-grafting techniques have been developed for 2 mm diameter, 35 day-old-seedlings (Ewens and Felker, in press) which will at least make grafted plantations possible.

Internationally recognized botanists such as the late Arturo Burkart (Burkart, 1976) have decried centuries of high-grading and overexploitation of *Prosopis* species in Argentina. We are concerned that the annual harvest of more than 100,000 t of *P. alba* logs per year from native Argentine forests for furniture and the ever-increasing importation of *Prosopis* logs and lumber from Mexico and Argentina into the USA for the flooring and furniture industry may not be sustainable. There is a need to stimulate investments into plantations to reduce pressure on the native forests.

While *Prosopis* has been considered a weed in some of the vast semi-arid areas of Latin America, Africa, the Middle East and the Indian subcontinent where it has become naturalized—these same areas are in urgent need of reforestation and economic development, which could be stimulated by the creation of value-added forest industries. World Bank officials have stated "there are no suitable technical forestry packages for the Sahel" (De Troyer, 1986) and, we might add, similar ecosystems throughout the tropics. There is no doubt that *Prosopis* is well-adapted to these areas (Pasiecznik et al., 2001).

Table 1
Basal diameter growth rates of *P. alba* and *P. glandulosa* grown in Texas and Argentina used in the economic model[a]

Species	Years of data	Mean annual rainfall (mm)	Comments	Growth conditions (basal diameter growth per year, cm)				Citation
				Native stands		Plantations		
				Unmanaged	Managed	Improved seedlots	Improved clones	
P. glandulosa	9	707	Young stand	0.54	1.20			Patch and Felker (1997a)
P. glandulosa	9	707	Overstocked mature stand	0.12	0.27			Patch and Felker (1997b)
P. glandulosa	75		Mature stand	0.12				Archer (1995)
P. alba	81		Various stands	0.41				Gimenez et al. (1998)
P. glandulosa	9	707				1.67		Duff et al. (1994)
P. alba	3	734					2.6	Felker et al. (1989)

[a] All of the sites were non-irrigated and without permanent groundwater.

If some combination of genetics, management, value-added products and marketing could be found to achieve market-driven reforestation of arid lands, this would be of tremendous social and ecological benefit worldwide. This paper examines scenarios that have sufficiently high internal rates of return to stimulate reforestation of arid lands in the private sector. As with all tree species, site indices vary greatly within a geographic area and, if *Prosopis* is deemed to be suitable, it would be necessary to identify the most appropriate sites for plantations.

The mean annual basal diameter growth rates for *P. alba* and *P. glandulosa* plantations and native stands under varying degrees of management are shown in Table 1. There is good agreement in the growth rates for mature *Prosopis* native stands without management in the independent reports of Archer (1995) and Patch and Felker (1997b). Both *P. glandulosa* mature Texas stands grew at 0.12 cm in diameter per year while the immature stand grew substantially faster. The *P. alba* native stands of varying ages in Argentina (Gimenez et al., 1998) only grew 0.41 cm per year, which for the targeted harvest diameter of 40 cm described below would require a 100-year rotation. With management (thinning and pruning), the growth rate of both immature and mature *Prosopis* native stands more than doubled over 9 years of measurement. The *P. glandulosa* plantation with improved seed sources grew faster than the managed native stand, obtaining 1.67 cm in diameter growth per year. The growth of *P. alba* in single tree plots without borders has been reported to be as high as 7.5 cm per year (Felker et al., 1983). Also while the 9-year mean annual growth rate of *P. alba* in a trial of *P. glandulosa* and *P. alba* was 2.85 cm per year (Duff et al., 1994), there was considerable mortality to the *P. alba* due to freezing weather and the remaining undamaged trees were able to grow faster due to less competition. Based on these previous studies, we have chosen to use diameter growth measurements for *P. alba* clones (Table 1) from a field design where each plot of 25 trees (5 × 5 array) was surrounded by two border rows of trees.

2. Materials and methods

The economic model assumed that the minimum-sized tree for commercial sawmill applications had a basal diameter of about 40 cm. By integrating lumber yield data from 105 short (0.76–2.0 m long), small-diameter (10–35 cm) *P. glandulosa* logs (Rogers, 1984) with detailed measurements on 10 trees ranging in basal diameter from 20 to 55 cm (El Fadl et al., 1989), regression equations were developed to predict sawn lumber volume of various size classes vs. *Prosopis* basal diameter. Using El Fadl et al.'s (1989) equations, the sawn lumber yield was predicted to be 0.164 m^3 per tree for the target basal diameter of 40 cm. The spacing required to achieve this 40 cm basal diameter (i.e. 10.3 m) was obtained from a regression of 24 plots on seven sites in the 650 mm rainfall region of Texas where the stand densities and stand biomass ranged from 6 to 19,000 stems ha^{-1} and

Table 2
Plantation costs and incomes in US dollars ha^{-1} for hypothetical *Prosopis* plantations in Argentina and the USA

Economic year	Plantation year	Item	Man (h)	Operation or labor costs		Material costs		Sum per operation		Sum per year	
				Arg	USA	Arg	USA	Arg	USA	Arg	USA
1	−1	Disk field two times		38	30			38	30		
		Subsoil		16	20			16	20		
		Apply diuron at 2 kg ha^{-1}		17	10	27.5	27.5	44.5	37.5		
		Total year before planting								98.5	87.5
2	0	Mark field 10.3 m × 10.3 m	2	1.2	12			1.2	12		
		Transplant 94 trees ha^{-1} with tractor and three man team in 0.5 h		3.75	7.5			3.75	7.5		
			1.5	0.9	9			0.9	9.0		
		Planting stock costs at 0.15 from seed or 0.45 from cuttings		14.1	14.1			14.1	14.1		
		Apply diuron at 3 kg ha^{-1} on 1.5 m on both sides of trees (0.3 ha)		5.1	3	12.4	12.4	17.48	15.38		
		Rabbit control by hunting at night with spotlight		3.5	3.5			3.5	3.5		
		Sweep cultivator for weed control three times per year with two passes per time		34.2	21.6			34.2	21.6		
		Stake and prune side branches to 2 m height three times	18	10.8	108			10.8	108		
		Insect control						30			
		Total first year of planting								115.9	191.1
3	1	Replant dead trees (10%)	2	1.2	12	1.35	1.35	2.55	13.35		
		Cultivate field three times per year with two passes per time (1.5 m each side of row)		34.2	21.6			34.2	21.6		
		Apply diuron and simazine at 1.5 kg ha^{-1} in 1.5 m wide strips both sides of row		5.1	3	9.49	9.49	14.59	12.49		
		Prune trees to 3 m height	9	5.4	54			5.4	54		
		Insect control						30			
		Total first year after planting								86.74	101.4

4	2	Cultivate field three times per year with two passes per time (1.5 m each side of row)		34.2	21.6			34.2	21.6		
		Apply diuron and simazine at 1.5 kg ha^{-1} in 1.5 m wide strips both sides of row		5.1	3	9.49	9.49	14.59	12.49		
		Prune trees to 3 m height	9	5.4	54			5.4	54		
		Insect control						30			
		Total second year after planting								84.19	88.09
5	3	Cultivate field three times per year with two passes per time (1.5 m each side of row)		34.2	21.6			34.2	21.6		
		Apply diuron and simazine at 1.5 kg ha^{-1} in 1.5 m wide strips both sides of row		5.1	3	9.49	9.49	14.59	12.49		
		Prune trees to 3 m height	9	5.4	54			5.4	54		
		Total third year after planting								54.19	88.09
		Fourth year after planting till harvest (year 24)									
		Disk field two times		38	30			38	30		
		In addition to years 10 and 15 prune trees	9	10.8	108						
		Income total sawn lumber of 15.4 m^3 at US$ 800 m^{-3}								12320	12320
		Sawing cost of US$ 107 m^{-3}								1648	1648
		Net sales of lumber								10672	10672

0.65 to 1300 kg $stem^{-1}$, respectively (Felker et al., 1990). Thus, 1 ha with 94, 40 cm diameter trees were predicted to have a sawn lumber volume of 15.4 m^3.

The economic analyses examined the profitability of achieving this production of 15.4 m^3 ha^{-1} as a function of time using the various management and genetic improvement strategies are listed in Table 1. All monetary values are in US dollars.

We used two scenarios with regard to the value of the land. One scenario assumed that potential investors already own the land, and thus this sunken cost was not included when the IRR was calculated. This assumption is reasonable since, as noted in the discussion, returns from arid lands suitable for *Prosopis* are very low and rarely provide an adequate IRR to purchase the land. In the United States, desires for land ownership for recreational uses such as hunting and wildlife, often outweigh the income generating potential of the land. However, to aid institutional forestry investors who wish to purchase land, we have conducted an alternative scenario that includes land purchases. The land prices of US$ 300 ha^{-1} in Argentina (M. Ewens, Director Fernandez Forestry Exp. Station, pers. commun., 2003) assumed either (1) non-irrigated land suitable for cultivation of soybeans and cotton in the Province of Santiago del Estero or (2) irrigated land with underground water within 5 m of the surface that was too salinized for vegetable crops but below the 12 dS m^{-1} salinity at which *Prosopis* growth is impaired (Velarde et al., in press). USA land prices assumed a value of US$ 1250 ha^{-1} which is the price for rangeland purchased in large tracts.

The base case, shown in Table 2, used the mean annual growth rate of 1.67 cm in diameter per year measured for plantations of *P. glandulosa* in Texas, but with the subsoiling and herbicide packages that resulted in the rapid growth of the *P. alba* clones in Texas (Felker et al., 1989). Although research has shown the value of growth retardants to prevent resprouts from pruned surfaces of *P. glandulosa* (Patch et al., 1998) these chemicals were not used in these analyses. Thus the base case achieved a 40 cm diameter tree in 24 years and the scenario with clones achieved this diameter in 15 years. There are extensive areas in Argentina with more favorable growth conditions but where data does not exist from long-term trials. Such areas include: irrigated land with shallow groundwater that has been abandoned as too saline for vegetable crop production (4–10 dS m^{-1}) but whose salinity is below the threshold that affects the growth of *P. alba* (Velarde et al., in press) and the higher rainfall areas (800–1000 mm) of the Chaco Province where the *P. alba* furniture industry is concentrated. In the absence of any other functions relating growth to precipitation, we assumed that growth was linearly related to annual rainfall and that the growth with permanent groundwater would be identical to the growth in the higher rainfall regions of the Chaco. Since the mean rainfall in the base case with *P. glandulosa* and the *P. alba* clones was 707 and 734 mm, respectively (Table 1), we assumed that growth would be 41 and 36% faster in the Chaco with 1000 mm rainfall per year for 17 and 11 year cycles for the seed-generated and clonal-generated plantations, respectively.

Options for inclusion of additional income from intercropping, pod production, wildlife or grazing were included where appropriate. Revenue from pod production was not included for the USA due to the lack of mechanical harvesting techniques and high labor costs but was included for Argentina. Pod production is extremely variable from year to year and has been estimated to be as high as 4 t ha^{-1} per year. We assume a 1 t ha^{-1} per year average production after 30% of the tree life cycle and a return to the landowner of US$ 30 t^{-1} independent of collection costs (Felker et al., 2003). In spite of the nutrient removals in the pods, we believe this loss of N and P will not be a serious drain on the ecosystem, since correlations between trunk diameter and soil nutrient increase were highly significant and positive for both of these nutrients (Geesing et al., 2000). (The increased N of up to 3000 kg ha^{-1} was attributable to N fixation while the 15 kg ha^{-1} increase in P was attributable to P solubilization.) While the commercial use of wildlife is highly developed in the USA with typical leasing of about US$ 7 ha^{-1} (Teague et al., 2001), no revenue for wildlife was included for Argentina due to lack of such an industry. Income from intercropping assumed an equivalent value for land rental at 80% of the surface area not occupied by the trees and assumed that intercropping would only be possible for the first 30% of the tree growth cycle due to canopy closure, which would then preclude efficient movement of agricultural machinery and light availability. After the trees achieved trunk diameters of

10 cm, large domestic animals would no longer damage the trees and livestock grazing would be an option. While the growth of young trees at the time of establishment is diminished about 300% by herbaceous competition (Felker et al., 1986), the growth and protein concentrations of the highly productive Guinea grass (*Panicum maximum*) is greatly stimulated by *Prosopis* (East and Felker, 1993) evidently due to a combination of nitrogen fixation/soil improvement and shade. Intensive grazing in the later stages of the plantation might substitute for some of the weed control measures. USA revenues for cattle grazing have been estimated to be about US$ 7 ha^{-1} (Teague et al., 2001) for typical leasing rates of US$ 90 animal per unit per year and a stocking rate of 13.4 ha animal per unit. Argentina revenues for cattle grazing was estimated to be about US$ 3 ha^{-1} (A. Fumagalli, INTA, pers. commun., 2002).

US herbicide prices (diuron active ingredient = US$ 13.75 kg^{-1}, simazine = US$ 7.33 kg^{-1}) of year 2002 were taken from University of Florida survey (http://www.edis.ifas.ufl.edu/BODY_WG056) while Argentine prices (diuron active ingredient = US$ 13.76 kg^{-1}) were taken from a local wholesaler. No costs were included for control of insects in the United States since in no case were insecticides used or deemed necessary in the USA. In contrast, evidently due to the coevolution of insects and *P. alba* in Argentina, Argentine plantations suffer from a variety of unidentified, leaf chewing and gall forming insects. These insects negatively impact growth and form, particularly in the earlier growth stages, when the ratio of foliage along the central main leader to horizontal branches is the greatest (M. Ewens, Director Fernandez Forestry Exp. Station, pers. commun., 2002). Since a definitive chemical treatment has not been developed, we used an insect control cost of US$ 30 ha^{-1} for two average insecticide applications on soybeans in Argentina of US$ 15 ha^{-1} application as provided by a local agrochemical dealer. Insect control was not used after the third year, since at this time the main leader would be above the 3 m height for the main commercial stem and since it was deemed that sufficient foliage on the lateral branches would be available to provide photosynthate for the main trunk.

Costs for cultural applications were taken from 2000 South Dakota statewide average custom farming rates were US$ 20 ha^{-1} for subsoiling, US$ 15 ha^{-1} for light disking, US$ 12 ha^{-1} for row crop cultivation, US$ 10 ha^{-1} for herbicide application and US$ 15 h^{-1} for 70 kW tractor used for tree planting. Argentine costs for the same operations (H. Emili, Universidad Nacional de Cuyo, pers. commun., 2002) were US$ 16 ha^{-1} for subsoiling, US$ 19 ha^{-1} for light disking and row crop cultivation, US$ 17 ha^{-1} for herbicide application and US$ 7.5 h^{-1} for tree planting. The costs for the planting stock were assumed to be US$ 0.15 per each tree when derived from seed and US$ 0.45 each when derived from rooted cuttings. The overhead costs for overall management were assumed to be 19.1% of total direct costs and for the IRR calculations, all values in Table 2 were increased to 19.1%.

The sensitivity analyses of the effect of sawn lumber price on profitability used ITTO (http://www.itto.or.jp/market/recent/mns060102.html) and Hardwood Market Report (www.hmr.com) prices and assumed that the minimum price for *Prosopis* lumber would be similar to railroad carload quantities of white oak (*Quercus alba*) (US$ 400 m^{-3}) and the maximum price would be that of Honduran mahogany (*S. macrophylla*) (US$ 2000 m^{-3}). Due to the lower absolute biomass productivity in semi-arid regions, it is important to obtain the highest value from the plantations and we have therefore assumed that the owner of the plantation would contract to have the logs sawn into lumber at a contract sawing price of US$ 107 m^{-3}. However to test the hypothesis of the economic viability of selling the lumber from plantations in log form, we have used the commonly accepted Argentine log price of US$ 33 m^{-3} which is assumed to yield about 0.28 m^3 of lumber for a price to the landowner of US$ 117 m^{-3}.

3. Results

The sensitivity of the IRR and management/genetic improvement scenarios to the final selling price of *Prosopis* lumber in Argentina and the United States are shown in Figs. 1 and 2. Even at the highest selling price of US$ 2000 m^{-3}, none of the scenarios without management or genetic improvement achieved an IRR greater than 6.4%, when the land value was not included in the analysis (Fig. 1) and 4.5% if land value was included (Fig. 2). These options therefore

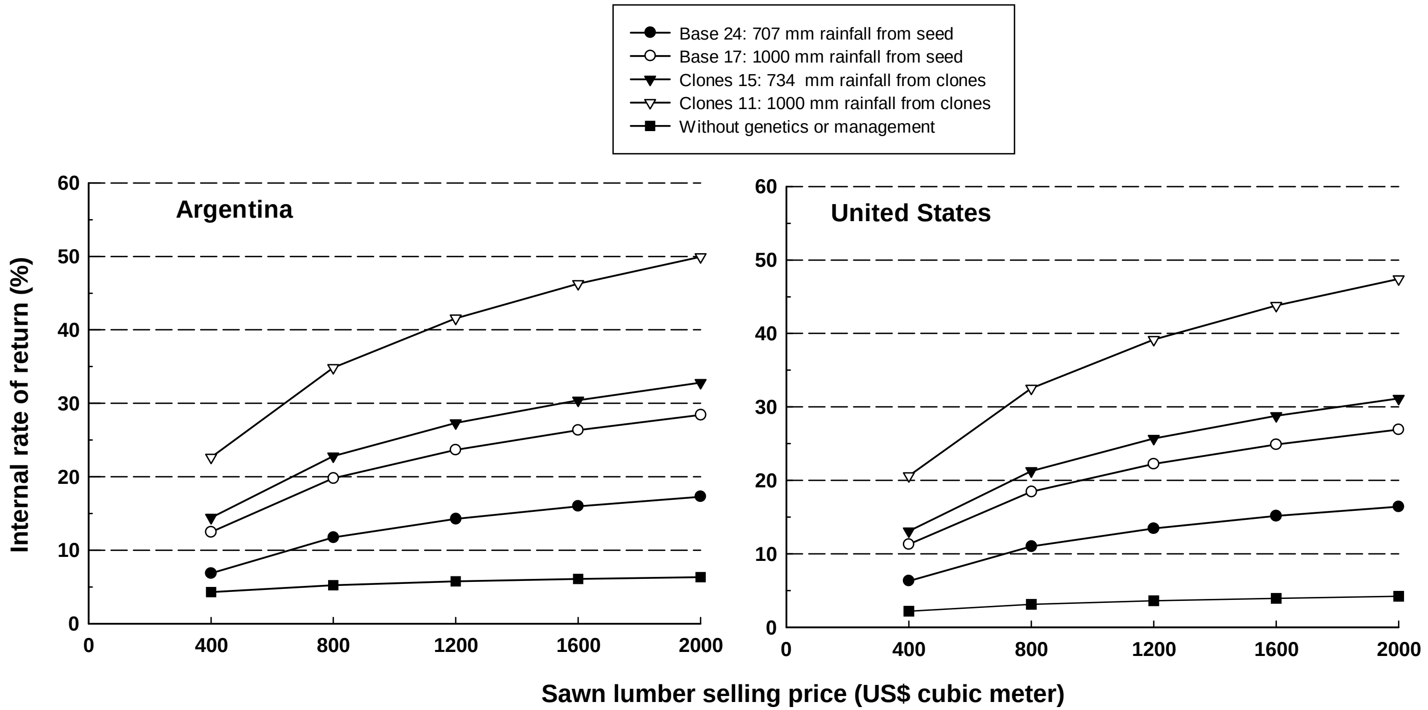

Fig. 1. Sensitivity of the IRR of *Prosopis* plantations in Argentina and the United States to the selling price of sawn lumber, after discounting the price for contract sawing, without additional incomes and land value.

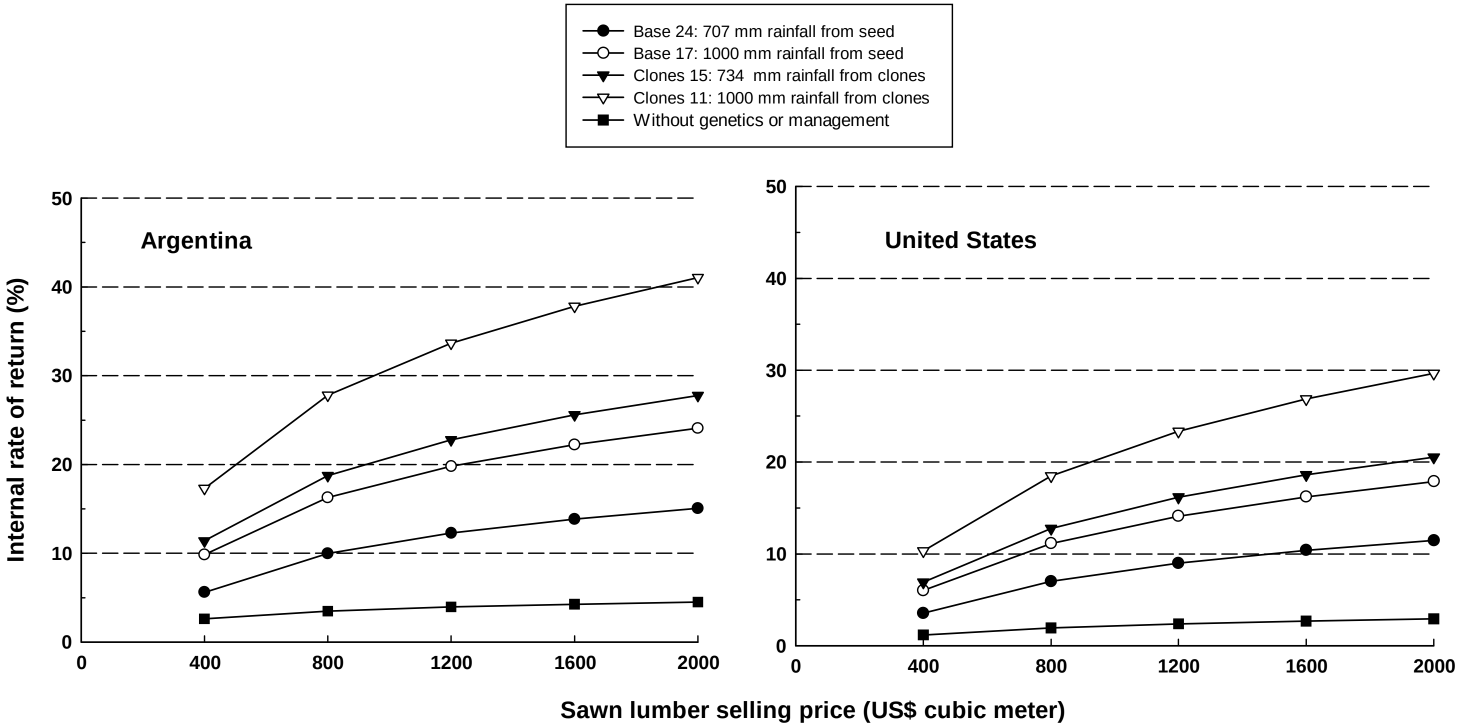

Fig. 2. Sensitivity of the IRR of *Prosopis* plantations in Argentina and the United States to the selling price of sawn lumber after discounting the price for contract sawing, without additional incomes and including land value.

Table 3
Influence of revenues from grazing, wildlife, pod production and intercropping on the IRR of *Prosopis* plantations in Argentina and the USA assuming a selling price of US$ 800 m^{-3} of sawn lumber for investors that owned the land and those that have to buy it

Case	Rainfall (mm per year)	Rotation years	Land value	IRR (%)									
				Argentina					USA				
				No additional revenue	Pods	Grazing	Intercropping	All additional	No additional revenue	Wildlife	Intercropping	Grazing	All additional
Base case plantation from seed	707	24	Without	11.8	12.6	11.9	12.0	13.1	11.0	11.3	11.3	11.3	11.8
			With	10.0	10.6	10.1	10.2	10.9	7.0	7.1	7.1	7.1	7.3
Plantation with clones	734	15	Without	22.8	23.9	22.9	23.3	24.5	21.3	21.6	21.7	21.6	22.2
			With	18.7	19.5	18.8	19.0	19.8	12.8	12.9	12.9	12.9	13.1
Plantation from seed	1000	17	Without	19.8	20.7	19.9	20.2	21.3	18.4	18.7	18.8	18.7	19.4
			With	16.3	17.0	16.4	16.5	17.3	11.1	11.3	11.2	11.3	11.5
Plantation from clones	1000	11	Without	34.8	36.0	35.0	35.4	36.8	32.5	32.9	33.0	32.9	33.7
			With	27.8	28.6	27.9	28.1	29.0	18.5	18.6	18.6	18.6	18.8
Without genetics or management	707/734	100	Without	5.3	7.3	–	–	7.3	3.1	–	–	–	3.1
			With	3.5	4.3	–	–	4.3	1.9	–	–	–	1.9

are not considered to be economically viable. In the base case for managed plantations (707 mm annual rainfall, 24 years rotation, no clones, land value not included), the minimum IRR was similar to the maximum level for unmanaged native stands and ranged from 6.3 to 17.3% (Fig. 1). For the same base case, the IRR ranged from 3.5 to 15.1% when the land value was incorporated into the economic analysis (Fig. 2).

Under the higher moisture availability regimes of either shallow, permanent groundwater or 1000 mm annual rainfall, but without genetically improved clones, the IRRs rose above the 10% (Fig. 1) or 6% (Fig. 2) levels for all selling price scenarios. With clones, managed plantations and the higher soil moisture scenario, the minimum IRR was 20.6% (Fig. 1) or 10.3% (Fig. 2) at the lowest selling price of 400 m^{-3} in the USA and reached maximum IRRs of 47.4 and 49.9% in the USA and Argentina, respectively, at the highest selling price of US$ 2000 m^{-3}. These maximum IRRs were 29.6 and 41.0% in the USA and Argentina, respectively, when the land value was included in the analysis.

In spite of the nearly 10-fold lower labor rates in Argentina compared with the USA, the IRRs were only very slightly lower in the USA than Argentina for the scenario that excluded the land value. This is evidently due to the fact that the plantations were mechanized with minimal labor and that the higher labor cost in USA was compensated by higher machinery costs in Argentina, as well as the insect control included in Argentina. In contrast, when the land value was included in the analysis, the ratio between the IRRs for USA and Argentina ranged from 0.46 for the scenario without management or genetic improvement at the selling price of US$ 400 m^{-3} to 0.76 for the base case at 707 mm annual rainfall with managed plantations of 24 years rotation at the selling price of US$ 2000 m^{-3}.

If the Argentine custom of paying US$ 33 t^{-1} for logs to the landowner is used (US$ 117 m^{-3} of sawn lumber), the IRR for the 24-year rotation using planting stock from seed was 1.3% (vs. 11.8% at US$ 800 m^{-3} for sawn timber) and 10.0% (vs. 34.8% at US$ 800 m^{-3}) with the highest rainfall scenario, with use of clones, and when the land value was not included in the analysis. Since only the main trunks of the logs are purchased by sawmill owners, leaving a considerable percentage of useable lumber in the forest, use of this US$ 117 m^{-3} figure for logs represents an overestimate of the revenue that traditional Argentine landowners would derive from plantations and an underestimate of the value of the forest.

Since arid lands are invariably multiple-use lands with predominant activities such as grazing, wildlife, and pod uses, it is important to compare the economic returns with and without these other activities (Table 3). To simplify a comparison of these activities, we chose a common lumber selling price of US$ 800 m^{-3}. Surprisingly, even in combination, these activities contributed not more than a 3.7% (clones 11 in USA) to 11.0% (base 24 in Argentina) increase in the IRR of the plantations designated for lumber with genetic or management improvements for the scenario in which the land value was not included. For the same management/genetic scenarios, these activities contributed not more than 1.6% (USA) or 9.0% (Argentina) when the land value was incorporated into the analysis. In plantations without genetics or management improvements in Argentina, pod production contributed a 38% increase in the IRR (land value not included) or a 23% (land value included). In decreasing order of importance, pod production, intercropping, and grazing contributed to the economic viability of the ecosystem in Argentina. Intercropping was the most important contributor to the ecosystem in the USA for the scenario that did not include the land value while contributions of all activities were almost equivalent when the land value was incorporated into the analysis. In spite of the small monetary contributions to the economic viability, the value of strong cultural associations with ranching and wildlife must be considered. In addition, ranching and wildlife activities should benefit the plantations (at the latter stages) through reduced herbaceous competition and animal herbivory.

4. Discussion

There are three quite different bodies of literature that need to be considered in the financial analyses of these *Prosopis* plantations. The first is the weed science literature that computes the economic value of eradicating *Prosopis* as a weed. The second is the ‘‘semi-arid alternative agriculture’’ literature that is primarily based on profitability from pod production for human and livestock food. The third is traditional forestry literature that bases its analyses on log prices as opposed to sawn lumber as we have done.

Virtually all the US literature related to economic analyses of *Prosopis* has focused on the benefits of increased forage production from eliminating *Prosopis*. We believe the differences between this analysis and the range analyses are attributable to differences in *Prosopis* size class/stand density relationships. Teague et al. (2001) alluded to these differences with the statement that ‘‘an increase in herbage with clearing was only obtained if pretreatment mesquite cover was 30% or more’’. We observed practically zero forage production in young, unthinned high density control plots (1739 trees ha^{-1}) (Patch and Felker, 1997a) or in the highest density plots (18,000 stems ha^{-1}) in a self-thinning study (Felker et al., 1990). However, we observed significantly greater biomass of the tropical forage grass *P. maximum* under the *Prosopis* canopies (5120 kg ha^{-1}) vs. outside the canopies (3370 kg ha^{-1}) (East and Felker, 1993) when the mean stand density and stem diameter were 196 trees ha^{-1} and 17 cm, respectively. Furthermore, Geesing et al. (2000) found that the soil C and soil N under the canopies of *Prosopis* was linearly related to tree size, reaching a maximum increase in soil C and soil N above background of 17.7 and 4.4 Mg ha^{-1} for a 70 cm diameter tree.

With regard to *Prosopis* silviculture, ‘‘range ecosystems’’ fall in the category of unmanaged native stands with no spacing, pruning or genetic improvement and only yield economic returns in the 3–6% IRR range for a lumber selling price of US\$ 800 m^{-3} when land value was not included. The low percentage increase in the IRR when grazing is incorporated into *Prosopis* lumber plantations is apparently due to the fact that while 13 ha (one animal unit) are required to produce about 500 kg of beef per year, this 38 kg ha^{-1} increase in beef at a price of approximately US\$ 1.2 kg^{-1} is a much lower revenue (US\$ 46) than an annual production of 0.64 m^3 (480 kg) ha^{-1} of sawn lumber at a price of US\$ 800 m^{-3} for a value of US\$ 513 ha^{-1}. Additionally, one might speculate that after more than a half century of mechanical and chemical weed control to eliminate *Prosopis* from rangelands, the availability of erect, fast growing *Prosopis* germplasm useful for sawn timber has been greatly reduced.

In a recent review of US efforts to control *Prosopis* where it was a weed (Bovey, 2001), none of five mechanical and weed control options achieved the desired IRR of 8% for cattle grazing. However, none of these options included production of a significant hardwood lumber component.

One of the most recent economic evaluations of eradicating young dense *Prosopis* stands with fire or herbicides, assumed a US\$ 7.4 ha^{-1} wildlife income, a discount rate of 5% and found that the most favorable treatment (a controlled burn) had a US\$ 18.5 ha^{-1} net present value (NPV) (Teague et al., 2001). For the scenario in which land prices were not included, a 5% discount rate, and without genetics or management, the NPVs of Teague et al. (2001) were higher than we calculated for Argentina, i.e. US\$ −29.5 and 17.4 ha^{-1} at the lowest selling prices US\$ 400 and 800 m^{-3}, respectively, and in the USA at all selling prices, i.e. a NPV range from US\$ −412 to −225 ha^{-1}. However the Teague et al. (2001) returns were smaller than we calculated for all other scenarios when the land value was not included. On the other hand, when the land value was included, the NPV found by Teague et al. (2001) was higher than those we calculated for the scenario without genetics or management in Argentina and the United States at all selling prices.

For arid lands, it is clear that the analyses without land values is legitimate since given the combined range plus wildlife income of US\$ 14 ha^{-1} and a USA land price of US\$ 1250 ha^{-1} (income equal to ca. 1% of the land investment), none of the current competing scenarios can justify the land purchase.

The second area of *Prosopis* economic analyses is the semi-arid alternative cropping systems using *Prosopis* plantations (Stanton et al., 2001). Stanton et al. (2001) considered *P. alba* and *P. velutina* plantations for lumber and/or pod production in northern Mexico on salinized land on the fringes of the irrigated agricultural areas where groundwater was within 2 m of the surface. The authors justified the short rotation length of 15 years for production of 15.9 m^{-3} of sawn lumber with *P. alba* by noting that, across the border in the Imperial Valley, nearly six times the annual diameter growth was measured for *P. alba* (Felker et al., 1983). Depending on the factorial scenarios of price and yield, these authors calculated that the IRR for lumber production ranged from 15.4 to 22.7%. Economic returns from pod production (from *P. velutina* since it is a more prolific pod producer) assumed manual pod collection at rate currently paid by Mexican dairies, rather high values (US\$ 1–3.5 kg^{-1}) for ground mesquite pod products and scenarios of 4, 6 and 10 t ha^{-1} pod production. The internal rates of return for the various pod production scenarios ranged from 27.9 to 275%. Also considered was intercropping *P. velutina* for pod production and *P. alba* for lumber production and these scenarios had IRRs ranging from 28.3 to 284.7%. While these very high IRRs are probably unique to special conditions of low labor rates, a shallow permanent underground water source and very high value-added prices for pod products, this work nevertheless confirms the substantial profitability of *Prosopis* plantations.

The third comparison of our data is to the traditional forest industry (mostly pine plantations) that calculates IRRs on the basis of log prices as opposed to sawn lumber derived from the plantation. In southern United States, Coleman et al. (1998) examined two scenarios and found that the IRR for an unthinned 20 year pulpwood rotation ranged from 9.1 to 12.4% for *P. elliotti* depending on the site index and from 11.3 to 13.8% for *P. taeda* depending on the site index. For a 33-year multiple product rotation, they found that the IRR ranged from 9.8 to 12.3% for *P. elliotti* and from 12.7 to 14.7% for *P. taeda*, depending on the site index. In temperate New Zealand, Mannothra (2000) reported that the IRR ranged from 7 to 13% for *P. radiata* for a 25–30-year rotation that produced 20–25 m^{-3} of logs per hectare per year. In subtropical Uruguay, with longer growing seasons, McKinnie (2002) reported that the southern pines *P. elliotti* and *P. taeda* had IRRs of 14–21% and that *Eucalyptus* had IRRs ranging from 16.5 to 27%. In Sri Lanka, Pitigala and Gunatilake (2002) found that the IRR ranged from 10.3% for *Pinus caribaea* to 16.5% for *T. grandis*.

As Evans (2001) pointed out in his review of tropical hardwood plantations, ‘‘slow growing’’ teak plantations produce from 3 to 16 m^3 of sawlogs per year while *Acacia mangium* and *Gmelina arborea* produce 15–40 m^3 ha^{-1} per year and *Albizzia falcataria* may produce in excess of 60 m^3 ha^{-1} per year. This contrasts markedly to our sawn lumber production ranging from 0.64 to 1.4 m^3 of sawn lumber per hectare per year. Thus, given the lower absolute productivity, it is essential to obtain the greatest value from the product possible and thus our analyses assumes the value of the sawn timber after paying a contract fee to have the lumber sawn.

In spite of an Argentine furniture industry that consumes 100,000 t of *P. alba* logs per year from existing stands, only a few scattered *P. alba* plantations of 20–30 ha exist. Our analyses of potential Argentine plantations that pay the current log prices of US\$ 33 t^{-1} have IRRs ranged from 1.3 to 10.0% (when the scenario involving land purchase was included) and 1.0 to 7.1% (when land value was included), depending on the rainfall and genetics, and explain the lack of Argentine *Prosopis* plantations given the large existing demand.

Apparently the IRR is more sensitive to use of clones and shorter rotations that the lumber selling price, since nearly a 4-fold increase in selling price was necessary to double the IRR while the use of clones that decreased rotation length by about 35% respect to the base 24 case, achieved the same doubling of the IRR. It is also prudent to point out that although the planting stock cost for the clones was triple that of stock produced from seed, the near doubling in IRR more than compensated for the increased price of the planting stock. Multiple-purpose *P. alba* trees from Argentine progeny trials have been cloned with characteristics of high pod production, sweet pods, and fast growth (Felker et al., 2001) and can be efficiently produced by grafting (Ewens and Felker, in press), but rooting of these clones has proven difficult. Some progress has been made in rooting of cuttings by taking into account natural clonal variation in ease of rooting and with new growth promoting bacteria (*Azospirillum*, *Agrobacterium rhizogenes*, and *Pseudomonas* to control *Fusarium*), but much research remains before commercial rooting of *Prosopis* will be possible (Felker, unpub. obs). However, a seed orchard of these clones has been established. These clones are adaptable to northern Argentina and would be adaptable to southern Arizona, California and Baja California, Mexico, but not Texas due to lack of frost hardiness. Clones have also been made of the truly tropical *P. pallida* for improved form, fast growth, high pod production and palatable pods (Alban et al., 2002). This species is adaptable to tropical deserts such as in Haiti, Sahelian Africa, Pakistan and India (Alban et al., 2002), but is rapidly damaged by short durations of only several degrees below zero. This species can be asexually propagated commercially by rooted cuttings and a seed orchard has been established (Alban, pers. commun., 2000). For the coldest *Prosopis* regions that exist in Texas, a seed orchard of tall erect growing *P. glandulosa* var. *glandulosa* has been established (Felker and Ohm, 2000). An erect, spineless *P. glandulosa* var. *glandulosa* that can be propagated by grafting has been patented for ornamental use (Felker and Korus, 1995) but could also be used for commercial lumber production in Texas.

As our self-thinning line for *Prosopis* in the 650 mm rainfall region in Texas indicates that a minimum spacing of about 10 m is required to obtain 40 cm diameter trees, we would expect that under the lower rainfall and higher evapotranspiration demands of the Sahel, this spacing would have to increase. Thus for the locations in the Sahel where there is no groundwater within 8 m of the surface, the plantations would take the form of the natural savannah. In the United States, the highly productive *P. alba* plantations would only be possible in southern California and Arizona where this species is widely grown as an ornamental. Apart from the Rio Grande Valley, it is not adapted to the more severe frosts that occur in Texas (Felker and Korus, 1995). As pointed out by Stanton et al. (2001) in the Arizona–California region, substantial areas of partially salinized land with shallow groundwater that are adjacent to irrigated fields, but without rights to irrigation water are available for *Prosopis* plantations (both *P. alba* and *P. velutina*) at low costs.

Due to the longer investment time required for tree plantations than annual crops, small landowners that are unaccustomed to forestry investments are not likely candidates for *Prosopis* plantations. Timber Investment Management Organizations (TIMOs) that manage investments from major banks and pension funds (primarily into USA pine plantations) are conservative, wish to invest in plantations with a maximum rotation length of 15 years and are not likely to invest in new species without detailed financial analyses (R. Jolley, CANAL Wood, pers. commun., 1999). Having achieved IRRs comparable to traditional forestry projects with rotation lengths of approximately 15 years, the majority of the requisites have been fulfilled to meet the investment needs of TIMOs.

For various reasons, we believe that a sawn lumber price of US\$ 800 m^{-3} will be the most common baseline price in the immediate future. First, this was the price in Argentina before the devaluation and as the majority of import/export commodities are quoted in US dollars; the price in pesos is rising to this equivalent. Second, despite the fact that *Prosopis* lumber prices at the point of sale of small sawmills in Texas frequently are in the US\$ 1600 m^{-3} range, we doubt that this price can be sustained with competition from lower priced oak, cherry, and walnut if the volume from plantation-grown *Prosopis* becomes substantial. Third, although some excellent quality international hardwoods are selling at or below US\$ 400 m^{-3} (http://www.itto.or.jp/market) the demand for *Prosopis* lumber is increasing in Latin American for custom doors and furniture to export to the US west coast at delivered prices of not less than US\$ 811 m^{-3} (confidential industry sources). These US importers are having difficulty in finding quality, kiln dried, *Prosopis* in container quantities. Finally, given the much superior dimensional stability of *Prosopis* than oak, cherry and walnut, it would seem reasonable that production of large quantities of *Prosopis* lumber from plantations should settle at about the same US domestic prices for cherry or walnut of about US\$ 800 m^{-3} (http:www.itto.or.jp/market).

To our knowledge, none of the *Prosopis* used in the world is derived from plantations or ecologically certified native forests. A central pillar in consideration for ecological certification is sustainability. Economic sustainability can only occur when the IRR is sufficiently high to attract investments into new plantations or sustainably managed native forests. If we assume that an IRR of 10% is the minimal level needed to attract investments, then none of the unmanaged native stands are sustainable. The conditions in which an IRR greater than 10% would be achieved (with cost of land included) are: (1) the base case for a 24-year rotation in Argentina at prices of US\$ 800 and in the USA at US\$ 1600; (2) base 17 (seed at 1000 mm rainfall) at prices of US\$ 800 m^{-3} in Argentina and the USA; (3) clones at 734 mm rainfall in Argentina for all prices and in the USA for prices greater than US\$ 800; (4) clones at 1000 mm rainfall in Argentina and the USA at all prices.

This implies that lumber arriving at US ports with prices less than US\$ 600 m^{-3} is derived from unsustainably managed forests, where the selling price only represents the cost of extraction, sawing and delivery.

Support for the Ecological Certification process and consumer willingness to pay more for certified products is the only foreseeable way out of this dilemma.

As one anonymous reviewer pointed out, the IRR on plantations with the inclusion of value-added infrastructure is not the only factor governing success in arid lands and that access to capital, business organization and long-term discounting issues are critical to the success of such projects. We could hardly agree more. Local investors in arid lands neither have the cultural tradition for forestry investments that are of considerably longer term required for annual crops, nor access to the infrastructure necessary to manage commercial scale forestry projects. For this reason we believe it will be important to attract traditional forestry companies to arid land projects in order to provide reliable transportation, telecommunications and business management skills at the local level. Forestry is more than a science or business—it is a culture, and to our mind this culture does not exist in arid lands. It is unlikely that dryland farmers or livestock producers will ever grow trees no matter what the profitability. Thus for forestry to be successful in arid lands, we believe it will be necessary for forestry enterprises to bring the science, business expertise and culture from the outside.

Despite the excellent technical quality of *Prosopis* lumber, the fact that extensive *Prosopis* stands exist in Latin America, Sahelian Africa and the Indian subcontinent, and the urgent need for economic development in these impoverished regions, plantations for *Prosopis* lumber do not exist. We suggest that the existing forestry paradigm of growing hardwood plantations in which the ultimate product is sawlogs is not appropriate for these ecosystems since the returns are not sufficiently attractive to stimulate plantations from the private sector. However, the incorporation of one additional step to custom saw the logs to lumber provides sufficient value-added to generate very attractive IRRs in the 10–30% range and makes commercially viable *Prosopis* plantations in arid regions attractive. *Prosopis* is not a panacea for arid lands, but by the same token, it is an important tool that should not be ignored and when judiciously used in appropriate ecosystems and on appropriate sites, can provide much needed economic development.

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