CHEMICALS FROM ARID/SEMIARID LAND PLANTS: WHOLE PLANT USE OF MILKWEEDS

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Abstract

The potential of arid/semiarid land plants **as sources** of commercial products is illustrated by the following examples: candelilla (wax); jojoba (oil, protein); ***Acacia*** spp. (gum); ***Astragalus*** spp. (tragacanth gum); guayule (rubber); rabbitbrush (rubber, chemicals); sunflowers (rubber, chemicals); yucca (soap); and cresote bush (antioxidants, phenolic resins). co-evolutionary selection is a cause of the accumulation of secondary compounds in arid and semiarid plants. Although extraction of a single chemical might prove economically feasible for a few species, analyses involving extraction of multiple components and use of the extracted residue show that significantly greater value can be obtained by fractionation to attain whole-plant utilization. Although efficient laboratory methods to screen plants have been developed, only a few chemicals can be screened in the field. Additional research and development in field screening techniques are needed. Milkweed is a potential new chemical crop. The present stage of development is at the research, demonstration plot, pilot-plant phase. Milkweed is expected to be grown as a dryland crop in the western Great Plains using conventional farming machinery now used in alfalfa 'hay production. Large-scale plantation farming would have an impact on imports of fuel and other commodities, By providing an alternative cash crop for the western Great Plains, milkweed farming could greatly strengthen the agricultural economy of the region.

Introduction

To illustrate the utility of obtaining chemicals from arid/semiarid land plants, it is useful to examine some species that currently or potentially could produce industrial raw materials. Candelilla (fig. 1), *Euphorbia antisyphilitica* Zucc. (Euphorbiaceae), is the source of candelilla wax imported from Mexico (13). The market is good, but imports have dropped from 871 metric tons (MT) (960 tons) in 1978 to 379 MT in 1981 due to internal problems of procurement from native stands in Mexico. Candelilla wax sells for $4.19/kg ($1.90/lb) (16).

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Figure 1

Candelilla *Euphorbia antisyphilltica,a,* In a natural **stand** in the Chihuahuan Desert of West Texas and northern Mexico la a current source of high-valued wax

Jojoba oil is obtained from the seeds of *Simmondsia chinensis* (Link) Schneider (Buxaceae) in approximately 50 percent yield. This species is native to deserts of northern Mexico and Southwestern United States. The oil, composed of long chain esters that are stable under high temperatures, is useful as a lubricant (24). At present essentially all jojoba beans come from natural stands. The first commercial harvest of 3-year old plants in the United States is expected to be this year (1982).

Gum arabic is obtained from *Acacia senegal* (L.) Wind. (Fabaceae) which is native to arid lands of Africa and the Middle East (31). Acacia gum is used in adhesives, bakery products, candies, ice cream, cosmetics, and many foods to suspend solids and emulsify ingredients (31). The United States imports approximately 5,080 MT annually (17). The gum sells for approximately $1.57/kg (16). Over 100 *Acacia* species are known to exude gum. *Acacia berlanderi,* native to southern Texas and northern Mexico, appears to be a good candidate for a domestic gum source (31).

Another important gum (tragacanth) comes from *Astragalus gummifer* Labill. (Fabaceae) and related species. These *Astragalus* species grow in the high, cold deserts of Iran and the surrounding area. Gum tragacanth is used in pharmaceuticals, cosmetics, and as thickening agents in foods (31). Due to the political instability of the area, imports are erratic. Approximately only 126 MT were imported last year at a price of $83/kg (16). No other gum has been found that is a substitute for tragacanth gum. The species seem to be well adapted to the high, cold deserts of the Western United States,

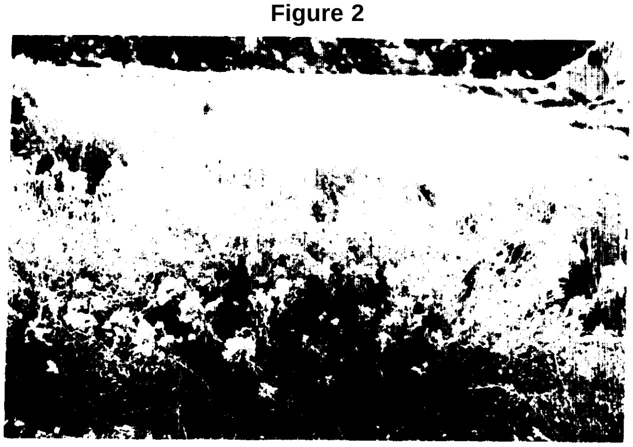
Natural rubber can be obtained from guayule *(Parthenium argentatum* A. gray (Asteraceae)), a desert shrub from the Chihuahua desert of northern Mexico and west Texas (13). Its molecular weight is comparable to that of *Hevea brasiliensis* Mull. (44). The United States imports approximately 770,000 MT/year of natural *Hevea* rubber, principally from Southeast Asia (39). Guayule rubber production in Mexico reached a peak from 1941 to 1945 with approximately 36,400 MT being exported from Mexico (13). Natural rubber prices are about $0.95/kg (47). Two other sources of natural rubber are rubber rabbitbrush *(Chrysothamnus nauseosus* (Pall,)) Britton (21) (fig. 2) and sunflowers *(Helianthus* species) (40,41), all in the Asteraceae family.

Soaps for shampoos are being extracted from various species of *Yucca* (Liliaceae) (13). Biologically active compounds are obtained from many plants, the most familiar of which are morphine (opium) from *Papaver somniferum* L. and digitalis from *Digitalis purpurea* L. **(46).** *Larrea tridentata* (DC.) Coville (Zygophyllaceae), the creosote bush, is a potential source of nordihydroguaiaretic acid (NDGA) which maybe used as an antioxidant (28) and in the production of phenolic resins (13).

Chemicals mentioned in the examples above generally are considered not involved in the primary metabolism of plants and are referred to as secondary compounds. It is now becoming apparent that secondary compounds may be of considerable importance to the survival of plants (37). Some secondary compounds repel deer (35), deter browsing by hares (8), and act as toxic and feeding deterrents in insects (42).

Herbivores can be divided into specialists and generalists. The specialist herbivores often prefer young leaves or rapidly growing tissue, whereas the generalists tend to prefer mature leaves and tissue (14). The generalists browse many different species, often over a considerable part of the year. Plants growing in arid lands can be subdivided into annuals, which take advantage of infrequent rains to grow to maturity and set seed quickly, and perennials, which have various adaptations enabling them to survive throughout the year. Major adaptations for drought survival are succulence (e.g., cactus), long roots to reach deep water tables (e.g., mesquite), and deciduous leaves during winter because many insects and animals may be inactive. Long-lived perennials need not reproduce every year, but they must survive drought, insects, diseases, and animal predation ultimately to reproduce, The evolution of environmental protection and more efficient metabolic processes is pitted against the relatively predictable selective forces of climate: natural variation in rainfall, wind, heat, and desiccation. In contrast, evolution of plant chemical defenses races constantly with the predator in a co-evolutionary battle,

Figure 2



Chrysothamnus **nauseosus,rubber rabbitbrush, from Nevada, is a future source of industrial chemicals and natural rubber**

After a plant evolves a new chemical or morphological defense, selection begins to operate on the predators that have mutations allowing them to overcome the plant defense. Perennial arid land plants tend to have morphological defenses (e.g., spines in cactus) and/or chemical defenses (e.g., bitter tasting phenolics in creosote). In more mesic regions, the species commonly can tolerate considerable browsing because adequate moisture is available for regrowth. As this is not the case in arid lands, it appears that accumulation of secondary products in arid land plants is necessary for survival. Since arid land plants have evolved and coevolved defenses for millions of years, these species are important for the discovery of fungicides, insecticides, and herbicides and as sources of accumulated secondary compounds.

Some major problems of growing plants in arid lands are that: biomass per area is low and harvesting costs may be expensive; wind and water soil erosion is already severe, so crops will have to be managed carefully; and a monoculture of an arid land crop, as with any crop, may allow the natural predators to increase,

Although initial emphasis may be on a single chemical or class of chemicals, few potential crops seem to be economically feasible if only a single product is obtained, Due to the costs of growing, harvesting, and extracting chemicals, each species should be examined for multiple uses (1,12). After the plant material has been collected at a central processing facility, the additional cost to process the material by several methods to extract additional products may not be large. For example, candelilla produces a fine wax, but this only accounts for 12 to 15 percent of the biomass. Cellulose from the remaining 85 to 88 percent can be used in fermentation or as an animal feed.

In general, nonpolar solvents extract chemicals that might be useful as waxes, lubricants, and elastomers. Polar solvents extract compounds that may be more useful as chemical intermediates, since they may contain highly reactive oxygen groups. They may be used as adhesives, coatings, UV absorbers, antioxidants, dyes, etc. The polar fraction has the greatest concentration of biologically active compounds (3).

The water or acidic aqueous fraction may yield a gum, such as tragacanth, or other valuable poly - saccharides, such as pectin. Some water-soluble protein may be recovered at this step. The principal products left after extraction are cellulose, hemicellulose, lignin (if present), and protein. This residue can be nontoxic if biologically active compounds have been extracted previously. The residue may be used in several ways. Some of it may be burned to generate power at the processing plant. It may be burned in power generation stations in place of coal (12). Fiber may be removed during processing for use as paper, pulp, or fabric. The residue usually has an enriched concentration of protein and may be used as livestock feed. It could also be digested by fermentation to produce industrial chemicals (32).

Species with high yields of particular chemicals generally have been identified by solvent extraction in the laboratory (4,5,9,10,29). Field screening is extremely valuable once a selection program has begun. A rapid method to screen plants in the field would allow one to examine hundreds of plants per day and obtain seeds and cuttings immediately. Otherwise, each plant must be sampled and tagged. After the laboratory analysis, one must return to the field and find the desired individual. The plants may be from a remote site. The time lapse from the initial tagging through laboratory analysis to returning for germ plasm collection can span months or even a few years. In the meantime, the tags may be lost to wind or animals. Germ plasm could be collected at the time of initial sampling, but this necessitates collection and curing of a large volume of materials, 90 percent of which subsequently will be discarded. Collecting, preserving, and documenting field samples are time consuming activities and are major obstacles in massive screenings.

Two relatively new laboratory techniques have been developed for rapid screening: wide-line nuclear magnetic resonance (NMR) and near-infrared reflectance (NIR). Wide-line NMR is used in vegetable oil yield analysis because it specifically measures total hydrogen associated with only the liquids (oil and water) (36). Because NMR is nondestructive to oil seeds, plant breeders have used this technique extensively, Wide-line NMR is not portable enough for field screening and seems to be limited to liquid chemicals. NIR has a much broader potential range of applications. It has been used principally for seed oil and protein analyses (23,38). The plant material must be uniformly ground and its moisture content determined. NIR is, therefore, destructive of plant materials, although this is not a problem for whole plant chemicals. Field portable NIR units are available, but approximately 50 samples are needed for calibration on the large laboratory system to determine the optimum wave-length filters and regression equations. To my knowledge, Native Plants, Inc., is the only group that has tried to use NIR to predict the yield of a mixed group of chemicals—in particular, hexane and methanol extractable. Our results were not satisfactory. Further research is needed in this area.

Another method of field screening would be micropressure extraction coupled with a portable microwave oven and sensitive electronic field balance. Although this method probably is feasible, to my knowledge no one has developed such a system.

One major difficulty in developing a field screening technique is that chemicals of interest may not have unique spectral qualities or any reactive groups to which specific stains can be applied for color tests. The polar chemicals are more likely to have strong spectral properties and unique color reactions with reagents. For example, a color test for alkaloids is quite specific and relatively easy to do. However, a specific color test for only one alkaloid in a family may not be possible.

In summary, adequate field screening techniques for chemicals are not available. This is a serious obstacle to future development of chemical crops.

Milkweed

As part of a long-term study to discover new crops for production of phytochemicals, Native Plants, Inc., has been studying the showy milkweed *(Asclepias speciosa* Torr.) (fig. 3). The genus ***Asclepias*** includes approximately 140 species (48,49). All cytologically known species are diploids. Interspecific hybridization is reported to be extremely rare in spite of widespread self-sterility

Figure 3

A test plantation (5 ha) of showy milkweed, *Asclepias speciosa,* near Syracuse, Utah

(49). The North American species generally are erect, herbaceous perennials, although a few annuals are known (48).

No rhizomatous North American species are known except *A. syriaca* which "may produce gemmiferous roots giving rise to clones of limited extent" (48). However, rhizomatous growth has been observed in *A. latofolia* (R. Adams, observation). *Asclepias tuberosa* is reported to live over a century (48).

Due to the wide distribution of *A. speciosa* and its apparent ecological success, this taxon was selected for intensive research on its domestication potential as a source of phytochemical products. *Asclepias speciosa*, the showy milkweed, is widely distributed from near the Mississippi River westward to the Pacific coast and from central Saskatchewan and Alberta south to central Oklahoma, West of the Rocky Mountains, it is chiefly found along banks of irrigation ditches. It produces a feathery plume on the seeds which are easily dispersed, In Minnesota, the northeastern part of its range, it competes with crops and can cause significant problems.

Milkweed Products

Hexane extracts of the aerial parts of *A. speciosa,* obtained by Soxhlet extraction for 20 hours, are dark green. The pigments are removed by decoloring (11), and natural rubber (cis-1,4-polyisoprene) can be removed by acetone precipitation followed by centrifugation. The decolonized, rubber-free hexane extracts have been subjected to analysis by thin layer chromatography (TLC) and glass capillary gas chromatography (GC) and gas chromatography mass spectroscopy (GC/MS) (in Tri-Sil 'Z'; Pierce Chemical Co.). Over 90 percent of the constituents of the hexane extracts could be identified and quantitated in this manner (2,3).

Pigments, mainly chlorophylls, account for approximately 11 percent of the hexane extract, and low molecular weight rubber accounts for approximately 2 percent of the extract (table 1). The nonpolar extracts contain small amounts of fatty acids, alcohols, hydrocarbons (alkales and squalene), monoglycerides, and phytosterols. Cardenolides were not detected in the hexane extract by TLC using the Kedde reagent for visilization (2). Approximately 85 percent of the nonpolar extract consists of derivatives of α- and ß-amyrin related triterpenes (2). Over 60 percent of the decolonized, rubber-free hexane extract consists of α - and ß-amyrin acetates, present in a ratio of about 5:1. Smaller amounts of the corresponding butyate, caproate (hexanoate), and palmitate esters of these triterpenes were found in roughly the same ratio of α- to ß-derivates.

The methanol extract of the aerial parts of *A. speciosa* following hexane extraction consists chiefly of inositol and sucrose (table 1). Other minor constituents identified by GC/MS in the methanol extract include malic acid, pyroglutamic acid, methyl pyroglutamate, citric acid, proline, methyl ferulate, and trace quantities of numerous carbohydrates. True phenolics account for only a minor part of the methanol extract, so *A. speciosa* does not seem to be a promising source for the economic extraction of "polyphenols" (table 1). Low polyphenol content has previously been reported for A. syriaca (20).

Also present in the methanol extract of *A. speciosa* are small quantities of cardenolides (demonstrated TLC using the Kedde reagent). Plants in the genus *Asclepias* biosynthesize varying amounts of toxic cardenolides (7). Aside from their digitalis-like toxic effects on the heart, cardenolides from *Asclepias* species affect the lungs, kidneys, gastrointestinal tract, and brain of experimental animals (6,7,22,34). They also possess general cytotoxic activity (26,27).

An additional acidic aqueous extraction of milkweed yielded approximately 4 percent pectin, a cell wall constituent present in all higher plants (3). Pectin is a valuable product ($3.91/kg) (16) but is difficult to extract and purify.

The milkweed residue, after *exhaustive* extraction with hexane and methanol, seems to be nontoxic and equivalent to alfalfa hay in digestibility by sheep **(18).** In research carried out by Native Plants, Inc., *Asclepias speciosa* was harvested in full flower (June 26, 1981) and extracted with hex-

Table 1.–Proximate Analyses and Product Values of Milkweed

Product	% Yield	Value $/kg ($/lb)	Product value from 1 MT (t)
Hexane extract	3.8		
Pigments	0.4	0.22(0.10)*	0.88(0.80)*
Natural rubber	0.1	0.95(0.43)+	0.95(0.86)+
Tri-terpenoids, esters and related compounds	3.3	0.24(0.11)*	7.92(7.19)*
		3.30(1.50)+	108.90(98.82)+
Methanol extract	17.5		
Sucrose	6.0	0.68(0.31)	40.92(37.13)
Inositol	0.9	24.00(10.90)	216.00(196.00)
Polyphenolics	1.1	0.13(0.06)*	1.43(1.30)*
		0.55(0.25)+	6.05(5.60)+
Residue			
Pectin	4.0	3.91(1.78)	156.40(141.92)
Fibers	5.0	0.47(0.21)	23.50(21.32)
Livestock feed	70.0	0.09(0.04) x	63.00(57.17) x
		0.13(0.06) y	91.00(82.58) y
Total gross value per MT (t)		Low	511.00(463.70)
		High	644.60(584.94)

*Price based on Btu Content.

+Price based on substitution for an appropriate chemical feedstock

[x]Price based on low hay value.

[y]Price based on high hay value.

SOURCE: Adams, et al., 1983; Adams, Balandrin, and Martineau, 1983. Prices: *Chem. Mkt. Rptr.*, Nov. 8, 1982, and *Wall Street Journal*, Nov. 1, 1982.

ane/methanol. The residue contained 16.3 percent crude protein (N X 6.25), which is similar to alfalfa hay (16 percent) and greater than corn grain (9.7 to 10 percent) (1). Amino acid analysis of the sample revealed that the amino acid content is comparable to alfalfa and generally superior to corn grain (l). The protein has high amounts of lysine (280 percent of the corn value) and a greater concentration of the essential amino acids than corn (1).

All toxic constituents in showy milkweed could be removed by exhaustive methanol extraction. The feasibility of using showy milkweed as an animal feed, therefore, depends on detoxification of the residue, either by high extraction efficiencies, heat, or acid treatment. The detoxification of the residue must be established by feeding trials.

The total gross value of products that could be obtained from nonselected (wild) *A. speciosa* ranges from $511/MT to $645/MT. Unfortunately, several technological problems need to be solved before its commercial potential can be realized. Commercially viable extraction and purification of the two highest value products, inositol and pectin, have not been demonstrated. Both products are expensive because they are difficult to extract and purify. In addition, inositol and pectin have limited markets: inositol, 0.45-0.9 million kg (R.W. Greef & Co., pers. comm.); pectin, 1.6-1.8 million kg (15). If the technology is developed, demand for these products could support a small 6,000-ha plantation, but could not sustain unlimited sized plantations as would be the case for some petrochemicals.

All current extraction processes for milkweed use hexane followed by methanol in a conventional extractor, such as the Crown extractor. To date, two proto-commercial extractions have been made, one at the POS (Protein-Oil-Starch) pilot plant at the University of Saskatchewan and the other at the Northern Regional Research Center, ARS, USDA, in Peoria, Ill. Extraction efficiencies at the POS Pilot Plant were only 67.5 percent for the hexane-soluble material and 55.7 percent for the methanol-soluble material (18), Problems were encountered with fine particles plugging the system and in pumping the viscous hexane extract after partial solvent removal. Additional research is needed on grinding, particle sizing, extract handling, and extraction residence times. Research also is needed on decolonizing the hexane extract and separating rubber from triterpenoids. As previously mentioned, considerable technological! development is needed before the production of inositol and pectin is commerically feasible. More efficient methods are needed for detoxification of the livestock feed.

Agronomics

Plant Establishment

The optimum planting methods for milkweed are not well known. Native Plants, Inc., has successfully established a 4-ha plot in Utah and small test plots in New Mexico, Texas, and Kansas. We have experienced establishment failures in Texas, Utah, and Saskatchewan, Canada, Additional research is needed on depth and time of planting. Density trials have indicated that a closed canopy yields higher biomass.

Wood Control

Weed control is a major problem with milkweed, especially during stand establishment. During the seedling stage, milkweed seems to direct most of its energy into root development. This contributes to drought tolerance, but the above-ground portion grows slowly and is not competitive with fast growing weeds during the first year after establishment. A selective, pre-emergent herbicide must be developed for use during the first year. In the absence of such an herbicide, Roundup® was used prior to emergence to control hard-to-kill perennials such as salt grass *(Distichlis stricta)* and common mallow *(Malva neglecta).* A wick applicator has been used to apply Roundup® to control the taller weeds during the season. Weed control is perhaps the most critical research need for the economical production of milkweed.

Harvesting and Yields

All of the equipment used in growing milkweed is standard farm equipment readily available to

Figure 4

Harvesting of milkweeds uses conventional farm equipment for cutting, crimping, and baling western farmers. Harvesting has been performed with equipment used in alfalfa haying operations. Harvesting techniques are essentially the same for milkweeds as for alfalfa hay.

A. speciosa **test** fields, 2 ha (5 ac) planted in rows 91 cm (36 in) apart, were first harvested on June 26, 1981. The plants were cut and crimped with a hay conditioner and swathed into windrows. Stems were dehydrated to a dry crack stage and baled within 3 days. The leaves dried considerably faster and became brittle. Some losses due to leaf shatter occurred during baling. Hay that fell into the furrows between rows could not be picked up by the baling machine, resulting in additional crop loss.

In 1982, our two fields of 2 ha each averaged 4.35 MT/ha and 4.26 MT/ha, respectively. Annual precipitation in the area is approximately 50.4 cm. Denser stands are expected to yield between 6.7 MT/ha and 9.0 MT/ha.

Crop Storage

There would be a considerable economic savings in plant capacity if an energy/chemical crop could be stored and processed throughout the year. Two apparent methods for storage are fresh-cut as silage (70+ percent water) and dried as hay (15 to 20 percent water, fig, 5). Because both procedures use existing farm equipment, they would not require extensive new equipment or costly acquisitions by farmers.

Native Plants, Inc., carried out some tests on the effects of storing milkweed. Five bales were stored uncovered under ambient conditions. This storage test presented the worst possible conditions. The bales were subjected to several feet of snow in the fall and winter and a number of freezing and thawing cycles. The nonpolar extractable were found to be quite stable over time. For example, the nonpolar extracts of the March sample after 8 months of storage (3.75 percent ± 2 (0.116)) were not significantly different from the first month's sample taken in August (4.07 percent ± (0.072)). The methanol extractable, however, showed a sharp decline after 2 months of storage and a gradual decline thereafter. This decline probably is due to the catabolism of carbohydrates by microorganisms during the rotting.

Figure 5

Milkweed Is stored in conventional bales until processed for the removal of chemicals

Three additional storage conditions have been studied: bales stacked in a barn; bales stacked in the open and covered with clear plastic; and bales stacked in the open and covered with black plastic. The nonpolar extractable yields show no significant differences. The methanol extractable yields decreased only slightly.

In general, it seems that moisture and subsequent rotting are the major potential problems associated with storage of baled milkweeds. This generally is not a problem in semiarid lands. In moister areas, the bales could be covered with either clear or black plastic.

Agricultural Scale

A survey of vegetable oil processing facilities revealed that processing plants range in capacity from 91 MT/day to 1,090 MT/day. An extraction plant with a capacity of 91 MT/day would process 27,300 MT/year, given the current yields from wild milkweed (4.3 MT/ha) and assuming a processing season of 300 days/year. This would require a 6,349-ha plantation. If 100 percent of this area were planted, it would represent a block approximately 8 km x 8 km. If only 25 percent of the area were planted to milkweed, the plantation would be equivalent to a 16 km x 16 km block, with a maximum haul distance to a centrally located plant of 11.31 km. This compares favorably to current maximum haul distances on the western Great Plains for grain and ensilage (24 to 32 km.).

Milkweed ***(A. speciosa)*** is distributed widely over a range of climate and soils. It appears that milkweed can be grown easily in the western Great Plains of the United States. This area is mining water from the Ogallala aquifer, and water shortages are resulting in a steady reversion from irrigated to dryland farming (43). The introduction of a new dryland crop will compete for land with dryland wheat, grain, sorghum, and sunflowers. However, this land is not very productive and the dryland crops contribute only a small portion to total

U.S. production of these crops. The cost of farming milkweeds eventually may be comparable to farming dryland alfalfa. The first year of growing milkweeds has been difficult due to the lack of an effective method of weed control and problems in stand establishment and obtaining a uniform stand. In order to displace dryland wheat or grain sorghum, the new crop must be more profitable for the farmer. An examination of yields and prices (45) of Hansford County, one of the most productive counties in the northern plains of Texas, shows the precarious position of present farming units. The average dryland yield of wheat for Hansford County for 1976 through 1980 was only 30.4 bu/ha (824.5 kg/ha) and the gross income was only $104.89/ha (table 2). The economics of grain sorghum is similar; the average yield was 1,508.8 kg/ha, which returned an average of $135.44/ha. If one could introduce a new crop that costs approximately the same as dryland wheat or grain sorghum to grow, the gross revenue needed to displace one of these crops probably would be about 20 percent greater than the present gross income of $135, or $162/ha.

Table 3 shows the variable production costs in 1982 for a 2-ha field in Syracuse, Utah. Based on 4.5 MT/ha using "wild" milkweed seed, the production costs were $418.45/ha or $92.99/MT. Of the $418.45,$233.13 was spent on weed control. More economical weed control is a priority for reducing milkweed farming costs. The other large expenditure was harvesting. Because relatively small farm equipment and small bales (30 kg) were used, conversion to larger swathing equipment and to stack loader bales or round bales (450 kg) could represent a considerable cost reduction. In any case, dryland milkweed cannot be grown as cheaply as dryland wheat or grain sorghum. On the other hand, the products obtained from milkweed promise to be of much greater value than those from wheat or grain sorghum after efficient processing technology is developed, One should also note that the cost drops from $92.99/MT to $53.85/MT if yields can be increased from 4.5 to 9.0 MT/ha (table 3). Research in breeding, selection, and agronomic development, resulting in increased yields, will have a positive impact on the profitability of milkweed.

Impacts

The development of a new crop which does not compete directly for a market share with the traditional food/fiber crops (e.g., wheat, corn, grain sorghum, soybeans, sunflowers, cotton, etc.) could free the U.S. farmer from his dependence on pro-

Table 2.–Yields and Gross Income From Dryland Wheat and Grain Sorghum in Hansford County, Tex., for 1976-80

	Wheat			Grain Sorghum		
Year	Yield bu/ha	Price/ bu	Gross Income/ ha	Yield lb/ha	Price/ lb	Gross Income ha
1976	21.0	3.17	$66.57	3326.0	.0355	$118.07
1977	19.8	2.14	42.37	3019.6	.0315	95.12
1978	3.9	2.92	8.76	2236.3	.0392	87.66
1979	61.0	3.82	233.02	5779.7	.0438	253.15
1980	46.7	3.72	173.72	2273.3	.0542	123.21
Avg. Yield	30.3 (= 824.5 kg/ha)			3327.0 (= 1508.8 kg/ha)		
Avg. Gross Income/ha			$104.89			$135.44

SOURCE: Texas Department of Agriculture, 1981

Table 3.—Variable Production Costs for Milkweed in the Second Year of Production at Syracuse, Utah, 1982, 1 Harvest (4.5 MT/ha, or 2 t/ac) and Prorated Costs @ 9 MT/ha (4 t/ac)

Variable Cost	Basis: Rates and Materials	costs @ 4.5 MT/ha	Prorated Costs @ 9 MT/ha
Herbicide	2.5 gal/ha Roundup @ $72.00/gal.	180.00	180.00
Spray	Machine and labor, $6. 18/ha	6.18	6.18
Swath	Machine and labor, $22.41/ha	22.41	22.41
Bale	$12. 10/MT, 4.5 MT/ha	54.45	108.90
Pickup and Haul Bales	&23/bale x 150/ha	34.50	69.00
Fertilizer	80.4 kg/ha (160.8 kg/ha) 34-O-O @ 0.28/kg	22.51	45.02
Spread Fertilizer	Machine and labor, $6. 18/ha	6.18	6.18
Herbicide	0.93 gal/ha Paraquat @ $44/gal	40.77	40.77
Spray	Machine and labor, $6. 18/ha	6.18	6.18
Total Variable Costs/ha		418.45	484.64
Cost/MT		92.99	53.85

SOURCE: DOE Final Report, 1982.

ducing surplus commodities. The major milkweed products would have an impact on the following markets:

- triterpenoid: could substitute for oil imports if converted to fuel or used for a lubricant, or for foreign wax imports if converted to fuel or used as a wax.
- sucrose: could substitute for foreign, and possibly some domestic, sugar markets, although only a small impact would be anticipated in this high-volume market.
- inositol: could substitute completely for imported inositol; all inositol currently is imported, mostly from Japan, with lesser amounts from China.
- pectin: could substitute completely for domestic and imported pectin, apparently now all produced from citrus peels.
- fiber: could compete with Douglas fir, tamarisk, and other woods for the paper-pulp market; impact probably would be insignificant.
- livestock feed: could compete with corn ensi-

lage, alfalfa, hay, possibly small grains. Impact could be considerable, particularly since the western Great Plains is a center of cattle feeding operations. The local cattle feed (grain corn, corn ensilage, grain sorghum) has been produced with water from the Ogallala aquifer which is being depleted (43). A replacement source of cattle feed will be important for survival of western Great Plains feedlots.

Development of milkweed as a crop will have a positive economic impact on agriculture of the western Great Plains. With essentially stable grain prices and increasing operating costs, the farming economy of that region is severely depressed and many farmsteads may fail soon.

The current strategy for the establishment of a commercial milkweed plantation is to encourage a large company with sufficient financial resources to contract the required amount of land (6,400 ha) to be planted and harvested. The company would begin construction of the processing plant with the appropriate lead time, Each farmer probably would be offered a guaranteed profit or gross price per hectare, depending on the company's confidence in the projected growing costs and yields of milkweed. The first year's contract would be a total expense for the company and would have to be prorated over several years' income. After a few years, the company would probably begin to pay the farmer on a per-ton basis to encourage farming efficiency. Since it is likely that milkweed will produce several products, the market's risk would be buffered. Ultimately, if products are obtained that feed into fossil fuel related markets, it is conceivable that many millions of hectares will be farmed with milkweed or similar crops. This would have some impact on U.S. wheat and grain sorghum production, but considerable idle land is available for growing these traditional crops if the price increases sufficiently. Since 80 to 90 percent of our grain production is used for livestock feed, the loss of the dryland wheat and grain production in this area would have to be compensated by production of livestock feed as a byproduct of the operation. For example, suppose a farmer who produces an average of 1.35 MT/ha of wheat begins to grow 4.5 MT/ha of milkweed. The wheat has approximately 11 to 14 percent protein. After extraction, the yield of milkweed residue would be 3.15 MT/ha (70 percent of 4.5 MT/ha) (table 1) of 12 to 16 percent protein livestock feed, Even if the extractable yield were increased to 50 percent, the residue would equal 2.25 MT/ha of 12 to 16 percent protein livestock feed. Thus, the battle between food and fuel (or chemicals) can be muted effectively if crops are developed that contribute significantly to livestock feed. Only a small portion of grain produced is used for human consumption, so the vast grain producing area from central Kansas eastward through Iowa, Illinois, Indiana, and Ohio still could produce all our necessary food grain.

Constraints

The principal constraints to developing such a system are scientific and economic factors. Selection and breeding are needed. Extraction and processing technology must be developed. There is a need to continue research on product development and industrial use. Establishing a plantation and extraction facility will be expensive. Native Plants, Inc., is working with a major oil company that has the resources to initiate such a venture. Few corporations will have both the resources and the desire to enter into this technology.

Many environmental constraints were considered when selecting milkweed as a potential crop. These include drought, wind, heat, cold tolerance, and soil constraints. A major concern in the western Great Plains is soil erosion, particularly by wind. This could be a severe constraint unless adequate stubble is left in the field to prevent wind and water erosion. Strip harvesting could assist with erosion control. Leaving stubble in the field would also help compensate for the loss of soil humus by continued cropping. The problem of a general decline in critical soil minerals may be alleviated partially by recycling manure from the cattle feedlots.

Sustainability of the Resource Base

The rapid loss of irrigation water from the Ogallala aquifer in the western Great Plains (43) signals a potential change in the agricultural output of this region. The proposed new crop will be grown dryland in that region, so will not have a significant impact on ground water resources. Growing milkweed may affect the local farmer. For example, because bees obtain nectar from milkweed flowers, the potential exists for development of a honey bee industry. Monarch butterfly larvae feed on milkweed. It is anticipated that these populations will increase. Aphids are a serious pest on milkweed and probably will be controlled by both natural predators and insecticides. As already mentioned, soil fertility will decline, approximately in proportion to the amount of biomass removed. Nitrogen is one of the principal elements that will have to be replaced.

In general, our goal is to promote an ecologically sound approach to land and crop management. Growing milkweed and other plants that are adapted to arid and semiarid conditions offers an unusual opportunity to apply a biorational approach to new crop development on lands with a limited water supply. The constant process of coevolution of plants with other plants, insects, and animals provides a great untapped source of phytochemicals for industrial chemical feedstocks.

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