INTRODUCTION

The Río Grande, or Río Bravo, flows nearly 2,000 kilometers through the Texas-Mexico border region. Paradoxically, it is both the region’s “life-blood” and source of environmental and public health risk. Communities depend on the river for drinking water, farming, industry, and recreation. Yet, decades of rapid population growth, a lack of infrastructure, and poor environmental management have led to an escalating contamination risk. Thus, a river, once clean, is now polluted with industrial organic compounds, heavy metals, sewage waste, agricultural run-off and pesticides, and high levels of salts and sediments (Sharp 1998).

Binational efforts to address these environmental problems were initiated in 1983, via the La Paz Agreement. The United States Environmental Protection Agency (U.S. EPA) followed in 1996 with the Border XXI Program, which was an extensive plan designed to decentralize the management of environmental issues, to increase public participation, and to encourage better communication and collaboration among pertinent agencies (U.S. EPA 1996). The Border Framework Document identified several key areas of concern, but one of the principal areas was the alleviation of water pollution by “developing and rehabilitating infrastructure for drinking water, wastewater collection and wastewater treatment” (U.S. EPA 1996).

Many cities in the border area have wastewater treatment systems that provide only minimal treatment, or are inadequate to handle the large amounts of sludge and wastewater generated. Furthermore, some communities lack a treatment system altogether. Conventional wastewater treatment systems, while effective, are generally too expensive to install and maintain for many small communities. Instead, innovative, low cost systems are needed to offer a viable alternative to the current lack of effective waste treatment prevalent in the border communities. These alternatives must not only be low cost and capable of safely recycling sludge and wastewater, but they also should provide opportunities for economic development (Bastian et al. 1982). This report describes research on one alternative wastewater treatment
system being studied in Ojinaga, Mexico.

PROFILE OF OJINAGA, CHIHUAHUA

Ojinaga, located on the west Texas-Mexico border, is situated at the confluence of the Río Grande and Río Conchos, about 500 kilometers southeast of El Paso, Texas-Ciudad Juárez, Chihuahua. Ojinaga, with a population of approximately 25,000 inhabitants, is located across the river from its sister city, Presidio, Texas (population is 5,000). Unlike other border communities, the population of Ojinaga has dropped, from about 26,000 in 1980 to 23,600 people in 1995 (U.S. EPA 1996). This decline has been attributed to a lack of economic opportunities in the community, small landholding size, marginal farmland, flooding, and migration to the United States (Prieto Barrera 1995; Núñez 1997).

Ojinaga is hot (maximum temperature is 50°C; minimum temperature is -10°C) and dry (average annual rainfall is 235 millimeters), but the community has an irrigation infrastructure supporting approximately 12,000 hectares of agricultural land. Although Ojinaga produces an array of crops including alfalfa, cotton, corn, wheat, melons, onions, pecans, and forages, less than one-half the farmland is currently in production. This is due, in part, to small land holdings, averaging five hectares, making agricultural production uncompetitive (Núñez 1997). Furthermore, poor farm management has resulted in soil salinization, creating unsuitable conditions for the economical production of agronomic crops on some lands (CNA 1998).

Unlike other border communities, industry in Ojinaga does not play a major role in the town’s economy. There are few maquiladoras, which contribute less than agriculture in terms of income and employment opportunities in the community. More importantly, these maquiladoras are not a point source for contamination to either groundwater or river systems (Pando 1996).

In terms of infrastructure, Ojinaga currently lacks an efficient waste treatment system. For over 30 years, the municipal sewage had been piped into a 1.5 hectares (45,000 m³) unlined, anaerobic settling lagoon. The lagoon separated the solids from the waste stream and provided some reduction in waste strength. After filling with settled solids, a new two hectares (60,000 m³) anaerobic lagoon was constructed in 1995. Currently, about one-half of Ojinaga households are connected to the municipal wastewater system. The Junta Municipal de Agua y Saneamiento (JMAS) hopes to have 95 percent of the households connected to the system within a few years. Wastewater from Ojinaga is almost exclusively domestic in origin and current flow rates are expected to double from approximately 70 L/s to 150 L/s when the entire community is connected to the system (Flores 1994). With these projections, it is anticipated that the new lagoon will fill with collected solids within five years. These solids may have utility as a soil amendment if the organic content is high and the salt content is not deleterious.

At present, effluent from the sewage lagoon is used for irrigation of adjacent pasturage, with
the excess water discharged into the Río Grande. Measurements of Río Grande water quality near Ojinaga indicate that even this relatively small discharge of effluent into the river significantly increases fecal coliform levels. Water flow below Ojinaga averaged 7.9 m³/s from January 1996 through June 1998 (Waggoner 1998). Over this time period, the community effluent (0.07 m³/s) represented less than 1 percent of total flow (minimum is 0.3%; maximum is 4.0%). While the contribution from the effluent to river flow is negligible, fecal coliform contamination increased from an average of 110 colonies/100 milliliters (se is 28) above the Río Conchos to 579 colonies/100 milliliters (se is 101) below the Río Conchos (Waggoner 1998). Correcting for differences in flow over the course of the year indicates high contamination in the fall when flow is moderate, but irrigation demands are low (Figure 1). During this sampling period, the fecal coliform counts exceeded the TNRCC river quality standards (200 colonies/100 milliliters) over 50 percent of the time compared to less than 20 percent above the effluent outlet. This contamination represents a serious health hazard for downstream irrigation water users, children playing or fishing in the river, or anyone coming in contact with river water. More importantly, fecal coliform contamination indicates the likelihood that more serious biological hazards, such as hepatitis or cholera, may be present.

In order to address the wastewater situation in Ojinaga, a Search Conference and Participative Design (SCPD) workshop was held in Ojinaga in May 1995. Participative Design emphasizes specific organizational principles and community-based, participative democratic processes as the keys to sustainable human and natural resources development. This methodology asserts that projects imposed upon communities, or that simply assume community support of the project, are destined to fail because members of the community have played little or no part in the project’s design. This emphasis on self-determination is critical to the realization of technologically-appropriate, non-dependent and sustainable development of human and natural resources (Cabana et al. 1995). Thus, through a community referencing system, pertinent members of the Ojinaga community, along with other organizations concerned about Ojinaga’s future development, were invited to attend the SCPD workshop.

Within a historical, social, economic, and environmental context, the participants identified some key needs, challenges, and possible prescriptions for solving the wastewater problem. These were:

1. Given the economic conditions of the community, the future wastewater system must have low capital and operating costs, must help to revitalize the economy of the community, as well as be able to generate revenues to repay loans and investors.

2. The system must be technologically appropriate and easy to maintain by the community, rather than a costly, high-tech, conventional waste treatment facility that would be an economic and maintenance burden.

3. The system should improve the quality of any water discharged to the Río Grande and meet the environmental standards of both Mexico and the United States. Given these criteria, a land application wastewater treatment system that reused the water for pulpwood
production was favorably received. Furthermore, the community committed to work toward bringing such a proposal to reality. Since the conclusion of the workshop, the community has collaborated with a binational, multidisciplinary team consisting of Ojinaga community leaders and experts from both Mexican and U.S. agencies (Lujan 1994; Prieto Barrera 1995). With full community support, this pilot study was initiated in 1996 to integrate pulpwood production with wastewater remediation and economic development.

**Research Objectives**

The objectives of this extended study were to continue with the determination of the effectiveness of wastewater treatment via land application to woody biomass plantations and to continue with the evaluation of the effect of wastewater application on the growth of woody biomass species. This continuation was to provide approximately two years of groundwater monitoring data and tree growth data, and to provide the framework for addressing three principal needs present throughout the U.S.-Mexican border area:

Need 1: Safe and effective municipal waste management for local communities.
Need 2: Improvement of environmental conditions along the U.S.-Mexican border.
Need 3: Opportunities for economic development.

Long-Term Objectives: Environmental, Economic, and Social Benefits of a Tree Plantation/Land Application System to the Ojinaga Area

**Land Restoration**

Currently, there are over 2,000 hectares of irrigable farmland in the Ojinaga region that have been removed from production because of high soil salinity. This land is unsuitable for economic production of most agronomic or horticultural crops. However, the land may be suitable for production of woody crops that are less sensitive to salt than most agronomic crops. This would restore the land to beneficial use, and after one or two rotations (about 14 years) with good management, the land could again be suitable for agronomic crop production if desired.

**Clean Water (70/70---->20/20)**

Currently, Mexico requires a 70 milligrams/liter BOD and 70 milligrams/liter total suspended solids (TSS) standard, while the U.S. requires a 20/20 standard for wastewater treatment. A system that returns no water to the Río Grande, other than through groundwater infiltration, would not have to consider this guideline. The loss of flow to the Río Grande with the land application system would be minor (less than one percent), and a greater benefit would be the tremendous reduction in biological contamination. Organisms, such as fecal coliforms, viruses, and parasites, would be confined to the land where they would pose little threat to surface water systems. Furthermore, system design would ensure worker protection standards equal to or exceeding federal guidelines.
REDUCE PRESSURE TO NATURAL FOREST SYSTEMS

There are over 7.6 million hectares of forest land in the state of Chihuahua, of which over 3.7 million hectares are classified as commercial forests. In 1998, the forest communities were permitted to cut 2.4 million m$^3$, or 70 percent of the mean annual increment of 0.9 m$^3$/hectares/year for the state (Iglesias 1997). It is projected that fiber plantations in Ojinaga could produce nearly 29 m$^3$/hectares/year or 200 m$^3$/hectares with a seven year rotation. Harvesting only 100 hectares/year of short rotation woody crops would meet 1 percent of the entire state’s fiber demand. In addition to providing a sustainable, economical approach to waste handling, the wastewater treatment project could serve as a catalyst to develop a tree farm cooperative in the Ojinaga community and surrounding areas. A successful cooperative could conceivably bring much of the abandoned agricultural land in Ojinaga back into production, and could replace a significant portion of the wood harvested in the Sierra Madre of Chihuahua. The production of wood fiber in Ojinaga could also provide valuable time for the ecological restoration of a region long exploited for its timber. Furthermore, this land could be used continuously on a sustainable basis, further reducing logging pressures to natural forest systems.

SUSTAINABLE RURAL DEVELOPMENT

Currently, between 20 to 40 percent of the land irrigated by the Ojinaga water district is no longer under cultivation due to salinization. By utilizing species of pulp trees with high salt tolerance (e.g., Eucalyptus spp.), it should be possible to reclaim much of this land. By bringing land into production not currently under cultivation, the development of a pulpwood plantation would create much needed jobs. Moreover, by adopting technology appropriate to the local economy, such development should be sustainable in the long run. The jobs created would be skilled to semiskilled, and would include field worker-type jobs (tree planting) as well as more skilled harvesting jobs (e.g., chain saw operators). Furthermore, many jobs would be outdoors, which is attractive to some people, and would pay wages competitive with other employment in the region.

MODEL SYSTEM FOR ARID REGIONS OF THE WORLD

Many small communities are pursuing alternative systems for wastewater treatment. The economics and safety are primary factors driving this movement. Several communities in New Mexico have constructed wetlands for wastewater treatment (Tessneer 1998). The advantage of constructed wetlands is ease and cost of operation. The disadvantage is it generates no future revenue stream. Thus, a tree plantation system with a market for the wood products would be favorable over a constructed wetland system. Currently, the City of Las Cruces, New Mexico, is designing a land application/tree system for its West Mesa Industrial Park, based upon the Ojinaga model (Watson 1998). As with Las Cruces, the Ojinaga system could serve as a model for other small communities throughout the arid and semi-arid world. In the case of Ojinaga, the target market is short fiber pulpwood, but in other communities the market could easily be fuelwood, specialty hardwoods, Christmas trees, pine for
pulpwood or saw timber, or even recreational or natural areas. Thus, the state of Chihuahua
could become a leader in system innovation.

**RESEARCH METHODOLOGY/APPROACHES**

**LAND APPLICATION OF WASTEWATER**

Land application of municipal wastewater and sludge for remediation, coupled with nutrient
and organic matter recycling by vegetation, is not a new concept, and has been practiced in
different countries including Australia, the United States, and Israel. Solids and wastewater
have been applied to forest plantations, disturbed lands such as mine spoil sites, edible and
non-edible crops, rangelands, and recreational areas including parks and golf courses (Sopper
and Kardos 1973; Sopper et al. 1982; Bastian and Ryan 1986; Cole et al. 1986; Luecke and
De la Parra 1994; Myers and Polglase 1996).

Land application systems include various designs, such as the application of wastes to the
soil-surface using Slow Rate, Rapid Infiltration, and Overland Flow treatment systems, and to
the subsurface, using leaching fields and absorption beds (WPCF 1990). Site characteristics
such as soil properties, ground topography (slope and relief), local hydrology, groundwater
depth and quality, land use, climatic factors (temperature, precipitation, evapotranspiration,
wind, and length of growing season), and expected waste loading rates, as well as
consideration of possible social and economic constraints, determine the suitability of a
particular system (Reed and Crites 1984; WPCF 1990). The land application concept should
be distinguished from water reuse, where wastewater is reused after complete multisteped
treatment. In land application systems, the application of wastewater to the land is an integral
part of the waste treatment system, occurring after minimal upstream pretreatment.

The underlying principle of land treatment systems is that the soil environment treats and
remediates applied wastes through dynamic physical, chemical, and biological processes
(Zasoski and Edmonds 1986). Physically, the soil acts as a buffer between wastewater/sludge
particles and surface- and groundwater systems. As the wastewater infiltrates and moves
through the soil profile, waste particles are trapped by the soil. Managing the quantity and
frequency of waste loading permits adequate drying, thereby avoiding pooling and soil
clogging, which result in anaerobic conditions (Thomas 1973). This system may be
particularly well-suited to arid and semi-arid lands where rainfall is less likely to interfere
with land application schemes.

The chemical nature of the soil environment is critical for the reactions necessary for waste
remediation. Soil colloids and organic matter adsorb and exchange ions present in the soil
water solution. When waste is applied to soils higher in colloids and organic matter, the soil
acts as a chemical filter by removing ions from the soil water solution. This feature is
especially attractive in land treatment systems used in conjunction with cropping systems,
since nutrients are assimilated for plant production (Ellis 1973).
Biologically, the soil-plant system is a reservoir of diverse microorganisms that thrive and multiply under favorable environmental conditions (specific pH, temperature, moisture and oxygen levels, and adequate energy source). Applying organic matter at controlled rates, coupled with a favorable environment, results in increased microbial activity and subsequent decomposition of organic compounds in the waste.

Like other microbes, the survival of human pathogens is a function of the complete soil environment (Foster and Engelbrech 1973; Reddy et al. 1981). Similarly, antagonistic microorganisms, which occupy specific niches within the soil system, utilize a variety of mechanisms to effectively out-compete introduced microbes. While there is the potential for harmful organisms to persist in the soil, the physical and biological processes are not conducive to long-term survival of these pathogens. Generally, over 90 percent of the pathogen population die within 30 days of application to soil (Smith 1996). The overall effect of microbial activity in land application systems is that the indigenous microbes facilitate the recycling and transformation of wastewater constituents without extraordinary measures (Miller 1973). This means that wastewater can be applied to soil without prior disinfection with chlorine, and still be safe for humans with minimum precautions.

Trees play a useful role in a remediation program. Biologically, tree roots support a variety of organisms that decompose organic matter and absorb and metabolize nutrients. Furthermore, trees require less maintenance than other crops, thereby reducing the health risks to humans. Economically, the wood produced can be sold on the open market or used in the community to sustain the project. The selection of tree species should be based on the anticipated nitrogen loading rates as well as the water use requirements. For example, in semi-arid climates trees tolerant of high evaporative demands, yet capable of high nitrogen utilization, would be preferred.

Municipal sewage in Ojinaga is piped directly into an anaerobic lagoon, that provides primary treatment of the sewage. Sludge samples were obtained from both the old and new lagoons to determine quality and utility. A 1.2 hectare site, adjacent to an oxbow lake, was selected downstream from the lagoon. Soils were sampled to a depth of one meter to characterize texture and to model the effects of soil type on tree growth and water use. Routine sampling and analysis of the wastewater effluent and influent, along with water from an oxbow lake, the Río Grande, and the Río Conchos also were implemented. The depth to groundwater at the site is approximately three meters, and the slope is less than five percent. Wells were installed to monitor the groundwater (in particular, the levels of nitrate and chloride). Baseline samples from the monitoring wells were taken and analyzed prior to starting irrigation with full-strength wastewater.

One goal of the study has been to identify tree species and clones that exhibit the greatest biomass growth and ion uptake. Based on previous studies (Yadav 1980; Donaldson and Standiford 1983; Stewart et al. 1986; Mather 1993) and Eucalyptus field trials conducted by the INIFAP experiment station in Ojinaga (Núñez 1995a,b,c; Tena Vega 1998), Eucalyptus camaldulensis was selected for its cold tolerance and fast growth. Three Eucalyptus
camaldulensis clones from Simpson Timber Co., California, were chosen for inclusion in the study: SC5 ("505"), 4016, and 4019. Two other tree species also were selected: hybrid Populus (poplar) and Robinia pseudoacacia (black locust). Populus is native to the Rio Grande and is found in other river valleys in hot dry areas (Bongarten 1996). Three clones were purchased from Broadacres Nursery, Oregon: TD 15–029 (P. trichocarpa x P. deltoides), TD 50-197 (P. trichocarpa x P. deltoide), and OP 367 (P. deltoide x P. nigra). Robinia pseudoacacia known for its hardiness, has been used in stream bed stabilization and mine reclamation (Myatt 1997). Open-pollinated Robinia pseudoacacia plants were obtained from the Oklahoma Department of Agriculture.

In April 1997, the site was plowed, disked, and shaped into 54 separate test plots about seven meters x seven meters in size each. Containerized Eucalyptus camaldulensis, bareroot Robinia pseudoacacia seedlings, and Populus cuttings (20 centimeters in length) were transplanted at two meters x two meters spacing. At seven months, four representative trees of each of the seven tree sources (28 total trees) were selected based on mean tree diameter, excavated and fractionated into leaves, stems, trunks, and roots. Tissues were dried, weighed, and analyzed for chemical constituents. At eight and 20 months after planting, the survival, height, and diameter of the trees were measured.

During the first growing season, plots were manually flood irrigated with water from the oxbow lake to establish the trees before implementing irrigation regimes using full-strength wastewater effluent. The choice of flood irrigation versus other types of irrigation systems was based on the premise that flood irrigation technology was familiar to Ojinaga farmers, whereas other systems would be less familiar and more costly. Weeds were controlled mechanically and chemically with Fusilade. After the first growing season, the plots were irrigated at three regimes with wastewater effluent based on potential evapotranspiration (PET) data. The first irrigation regime was based on the PET plus 36 percent additional water for leaching. This resulted in the application of excess water throughout the year. This was done in consideration of the possibility that just enough trees will be planted to treat the wastewater, and that farmers using river-fed flood irrigation tend to use excess water. A second irrigation regime was based upon the PET plus approximately 20 percent additional water for leaching. This regime would tend to subject the trees to mild water stress as salts may accumulate in the upper soil profile. The third schedule was to examine deficit irrigation, supplying eight percent less water than PET. This irrigation regime would tend to maximize the accumulation of salts in the soil. Water application rates, plant growth, wastewater quality, weather data (rainfall, insolation, and temperatures), soil nutrient analysis to a depth of one meter, and the quality of the leachate below the root zone were analyzed.

In addition to the field research, the economic feasibility of a full-scale project was investigated. The standard method for evaluating the economic impact of a project extending over several years is to calculate the net present value (NPV) of the project. Evaluation of the economic return to short fiber production in Ojinaga is not a simple matter. Both the environmental benefits, as well as financial profitability, must be considered. Placing a value on environmental benefits is notoriously difficult, however, and this was not done directly in
this study. Rather, environmental benefits were evaluated indirectly by assuming that a specific environmental standard must be met, and that the preferred method for meeting this standard is the least costly method. In particular, it was assumed that the Ojinaga waste treatment system must meet the standards for effluent established by SEMARNAP (Secretaría de Medio Ambiente, Recursos Naturales y Pesca). Further, it was assumed that the alternative method for meeting these standards is a conventional sewage treatment facility similar to the facility proposed by the Comisión Nacional del Agua (1994). Thus, the return to fiber production includes both the tree plantation and the avoidance of costs incurred in constructing and operating a traditional sewage treatment plant. This approach ignores the environmental benefits arising from fiber production not associated with water quality, such as habitat creation and reduction in air pollution.

Sustainable economic development includes the creation of local financing. Information was obtained from the Banco Nacional de Credito Rural (BANRURAL) officials in Ojinaga concerning yields and the cost of production of various crops. In addition, investigators also discussed terms under which credit might be made available for long-term financing of wood production beyond the pilot project. Interest rates in Mexico are moderately high by international standards, but favorable rates are available for small farmers and also for financing of exports. The Chihuahua y Pacifico railroad has experience in shipping timber, and has railcars suitable for shipping logs, chips, or pulp to U.S. or interior Mexican markets. To determine the extent of the domestic (Mexican) market for short fiber pulpwood, the COPAMEX facility in Anáhuac, Chihuahua, was visited.

PROBLEMS/ISSUES ENCOUNTERED

CHALLENGES OF LAND APPLICATION SYSTEMS

Although land application systems provide many benefits, there are also some constraints. The four frequently voiced objections are: (1) human pathogens; (2) organic compounds; (3) nitrogen contamination; and (4) metals and trace elements (Bastian et al. 1982; Kowal 1986). Pathogens can pose a health threat to both humans and animals, through contamination of surface water and groundwater and subsequent crop contamination. However, the survival of most pathogens, including bacteria, viruses, and protozoans, is greatly reduced through exposure to sunlight, high temperatures, and drying (Kowal 1986). Helminths (worms) have more adaptive resistance and can persist in the soil for longer periods, from a few days to several years, depending on the species (Burge and Marsh 1978; Feacham et al. 1980). However, adults, eggs, and cysts are not likely to be problematic where primary treatment of the wastes precedes land application (Kowal 1986; Zasoski and Edmonds 1986). Treatment as minimal as a settling pond, like that used in Ojinaga, in which the sludge and organic matter separate from the effluent, removes most protozoans and helminths. Smith (1996) reported the time to kill 90 percent \( (T_{90}) \) of human parasites ranged from two to ten d for protozoans, to six d for viruses, to 17 d for Ascaris, to less than 30 d for E. coli. Thus, the major risk to humans would be all but eliminated after 30 days. Nevertheless, caution should be exercised during land application processes to limit public access and to allow periods of
drying out to facilitate pathogen die-off (Foster and Engelbrecht 1973). Generally, pathogens pose little health risk when applied to non-edible crops. Chlorination would be effective in reducing pathogen numbers, but the treated wastewater would have to be dechlorinated prior to land application to minimize subsequent damage to the trees. Both chlorination and dechlorination are expensive and unnecessary if simple precautions are taken.

Groundwater contamination by toxic organic compounds from industrial wastes and household wastewater is another potential threat. Although most organic compounds are eventually biodegradable, many are resistant to decomposition because of their chemical complexity. Subsequently, they could eventually leach into the groundwater (Kowal 1986). The best management strategy for these materials is to enforce laws requiring industry to remove these materials from their waste streams before they enter the municipal system. Likewise, implementing toxic waste minimization programs by providing alternative depositories for household chemical wastes such as pesticides and automotive lubricants, and educating people about the proper use of the municipal sewage system are important strategies. Beyond this, wastewater streams containing toxic organic compounds at low levels should be applied at low rates, thus providing optimal conditions for degradation.

High levels of nitrogen, which are typical of domestic wastewater, can pose a threat of nitrate (NO$_3^-$) contamination to the groundwater, since NO$_3^-$ is mobile within the soil system and susceptible to leaching. However, nitrogen loading can be managed to avoid leaching. Waste application can be based upon the amount of mineralized nitrogen (plant-available forms of nitrogen) that the tree crop needs at a particular growth stage. Typical loading rates for land application systems supply 0.3–2.4 kilograms N/hectares/d or 110–876 kilograms N/hectares/year (U.S. EPA 1992). Using this method, most of the NO$_3^-$-N and ammonium (NH$_4^+$)-N should be available for plant assimilation (some NH$_4^+$-N may volatilize from the system) (Brockway et al. 1986; Sommers and Barbarick 1986). In addition, microbially-mediated pathways of nitrification/denitrification can affect further nitrogen removal.

Heavy metals and trace elements are of concern in terms of drinking water and groundwater quality and possible assimilation into edible plant parts. Of the heavy metals, only cadmium is significantly absorbed by plant roots (U.S. EPA 1984; Sommers and Barbarick 1986). Lead and mercury can be problematic, although they are insoluble and immobile in plant root systems. Furthermore, most metals become less soluble as pH increases, with the exception of anionic metals (Logan and Chaney 1983). Generally, soils with a neutral to alkaline pH immobilize toxic metals as precipitates, which are not available to plants and not susceptible to leaching to the groundwater (Jewel 1982; Zasoski and Edmonds 1986). Under moderate waste loading rates, it would take decades to accumulate lead and mercury in soils to dangerous levels (Kowal 1986). To avoid potential risks, applications can be controlled and limited by determining the maximum cumulative amounts acceptable for each element applied over a period of years, and then, managing the loads accordingly (Sommers and Barbarick 1986).

These concerns are valid and can pose a possible health threat, through the contamination of
surface water, groundwater, and subsequent crops. Yet, overall, the potential health threats posed by land application systems are no greater than conventional waste treatment systems, if land application systems are properly managed (Kowal 1986). Sustainable, safe management practices must be based on a thorough understanding of land application design, the soil-plant system, the surrounding environment, and the risks associated with handling wastes.

In addition to the aforementioned concerns encountered with using land application systems throughout the world, there are some unique challenges with these systems in semi-arid and arid regions. Any land application system using water high in salts must be managed to minimize salt buildup in the plant rooting zone. Excess salts can decrease crop productivity and, in severe cases, destroy productive farmland. The salt concentration in the soil is a function of salt concentration in the applied irrigation water and the leaching fraction (the ratio of drainage water to irrigation water). Agricultural systems use a leaching fraction to flush salts below the rooting zone but not into the groundwater. In reusing wastewater for crop production, where the soil and the plants are used as a treatment unit, the success and the level of treatment can be measured in the groundwater. The level of salt and nitrogen accumulation in the groundwater will show the effectiveness of the management of the land treatment system. Therefore, the groundwater should be monitored throughout the life of the project. Increased nitrogen levels in the groundwater can present a health hazard in places where shallow wells are used to obtain potable water.

Another challenge is organic matter-induced soil deterioration. High organic matter in untreated wastewater can plug soil pores and create a reducing environment, rendering the soil unfit for agricultural uses. Properly designed primary wastewater treatment results in the separation of a significant part of the organic material from the wastewater before it is applied to the land.

Wastewater application in arid areas is coupled with consumption of the wastewater by vegetation based on the evapotranspiration. Thus, the most effective way to utilize the wastewater is to use species that have the longest possible growing season, including native plants that may initiate growth earlier than non-native types, and to incorporate perennial or winter-type forage crops that can be intercropped between the trees, thereby utilizing the wastewater during periods of tree dormancy. Land application treatment systems in humid areas, where the water is almost inconsequential, are well studied. However, arid regions have received less attention, with the bulk of the research centering in Australia and Israel (Myers et al. 1995; Myers and Polglase 1996; Myers et al.1997). Thus, there is a need to determine site-specific factors and management approaches, which are most effective in waste remediation and utilization in arid regions.

**SPECIFIC DIFFICULTIES/CHALLENGES ENCOUNTERED WITH THE OJINAGA STUDY**

The logistics of working in Mexico, across an international boundary, added to the complexity and time required to start this study. This project has been a collaborative effort
between the Ojinaga community (represented by JMAS), INIFAP, PROFORE, and NMSU. Because of the proximity of INIFAP to the experimental site and the availability of an INIFAP agronomist to supervise day-to-day work at the site, NMSU and INIFAP entered into a working agreement to cover INIFAP’s expenses for this project. There were many delays in finalizing the contract between NMSU and INIFAP because of the extensive, time-consuming bureaucratic protocol deemed necessary to ratify such an agreement. Because of this delay, PROFORE agreed to provide interim on-site services at the start of the project, even though this is not something they would normally do. Ultimately, patience and persistence carried the project through the bureaucratic delays. Another major problem encountered while working across the U.S.-Mexican border was transporting equipment and seedlings into Mexico. This problem was resolved with the help and intervention of people in Ojinaga and Presidio who were familiar with the procedures necessary to successfully move these items into Mexico.

Delays were encountered in attempting to obtain the approval of budget reallocations among the various budget categories in this research contract. Working within the confines of a tight budget made it necessary to reallocate funds as monies were depleted in the various budget categories. The bureaucratic protocol needed to make budget changes and the resulting delays made it difficult to continue this research in the most effective manner possible.

There appear to be many political forces at work in the decision as to what type of waste treatment system will be considered for Ojinaga. Apparently, the desires of the community and the scientific viability of the system under consideration are not the only factors that will determine what type of system the community will be able to use. For this reason, the Ojinaga community requested help from the NMSU team, and the group has provided technical support to the community in an attempt to ensure that the tree plantation treatment alternative is given due consideration.

RESEARCH FINDINGS/CONCLUSIONS

WATER ANALYSIS

All of the water sources have high pH (pH > 7.3), electrical conductivities (EC) between 1.3 and 3.4 dS/m, and sodium absorption ratios (SAR) between 3.7 and 8.8 (Table 1). These high EC and SAR values indicate that the water is marginal for traditional agriculture (Miller and Donahue 1990); however, short rotation woody crop production is feasible with this water. The wastewater had a total Kjeldahl nitrogen (NH₄⁺-N and organic-N) of 14 to 37 milligrams N/liter of wastewater. Most of the nitrogen was in the NH₄⁺ form, with low NO₃⁻ levels, suggesting that leaching of nitrates would not be a problem. At an application rate of 2.0 m³/m², the loading rate of N as NH₄⁺ would be approximately 250 kg N/ha.

There were 2.3–6.4 x 10⁵ colonies of fecal coliform bacteria/100 milliliters of effluent. International guidelines suggest a maximum geometric mean concentration of 1,000 fecal coliforms per100 milliliters for wastewater applied for edible crops (Kowal 1986). For crops
raised intensively with a short rotation, such as vegetable crops, these levels clearly are unacceptable. In contrast, woody crop production is extensive, and in comparison to vegetables, the rotation is long. Most importantly, these trees are not being raised for food and represent no secondary health hazard.

**BIOSOLIDS (SLUDGE) ANALYSIS**

Dried sludge from the original lagoon had high pH and EC (Table 2), but it had only five to eight percent organic matter with 0.25 kg NO₃⁻-N/Mg dry matter. The sludge consists primarily of soil particles carried by wind or water, precipitated calcium carbonate, and “caliche”, which is calcium carbonate typically found in the desert soils of the area. Thus, this sludge is worthless as a crop nutrient source. The sludge contained small amounts of lead and mercury in insufficient amounts to pose problems for land application. The EPA limit for annual loading rate for both Pb and Hg is 15,000 g/ha/yr (U.S. EPA 1994). The sludge from the old lagoon contained 75.0 g Pb/Mg and 1.7 g Hg/Mg, and the new lagoon contained 81 g Pb/Mg and 10.3 g Hg/Mg sludge, on a dry weight basis. Using the EPA Annual Loading Rate criteria, the concentration of every metal analyzed was well below the limit specified (Table 3). The sludge poses little environmental threat. Unfortunately, the sludge from the lagoon also has no economic value.

**SOIL ANALYSIS**

The soils at the experimental site are non-uniform. The site is situated in the flood plain of the Río Grande, immediately next to an old river channel, and soils (fluvents) of varying texture have been deposited over time as a result of flood events. The experimental site measures 290 meters (roughly east-west) by 45 meters, and straddles a variety of soil deposits. At one end of the site, the soils are predominately silty clays and silty clay loams, with plant available water (AW) contents ranging from 12 to 15 centimeters water in the top meter of soil. In the central area of the site, there are layers of loam, sandy loam, and sand, with lower AW in the top meter. Moreover, some of these layers are extremely gravelly (>60% gravel by volume), very gravelly (35 to 60% gravel by volume), and gravelly (15 to 35% gravel by volume), which further lowers the AW. In this part of the site, AW ranges from a low of four cm water/m soil with more typical values running from six to 12 centimeters water/meter soil. At the other end of the site, the gravelly layers disappear, and a mixture of clay, clay loam, silty loam, loam and sandy loam layers are found. The AW here ranges from 10 to 15 centimeters water/meter soil.

These variations in texture and the resulting AW, can affect tree growth. On loamy soils, the Populus 367 clone had an average height of 2.8 meters at the end of the first growing season, while on soils containing layers of gravelly to extremely gravelly sand, these clones were only 1.9 meters in height. In contrast, Robinia pseudoacacia plants had a height of only 1.1 meters on loamy soils, but a height of 1.7 meters on gravelly soils. Thus, the Populus 367 clone grew taller in soils with higher AW than in soils with lower AW, whereas the Robinia pseudoacacia grew taller in soils with lower AW than in soils with higher AW. This response
agrees with the preference of Robinia pseudoacacia for lighter, well-aerated soils (Bongarten 1996), in contrast to Populus, which is native to riparian areas (Little 1950). In addition, there were no significant changes in the growth of the Eucalyptus clones observed for the various soil textures present at the site.

**TREE GROWTH**

During the first and second growing season, the three Eucalyptus clones had high survival (Table 4). In contrast, survival of Populus was clone dependent, with the 367 clone having the highest survival (95% for year one and 88 percent for year two) and clone 197 having the lowest survival (53% for year one and 24% for year two). Robinia had a high survival the first year (93%), declining to 73 percent in the second year. Eucalyptus clones had good height and diameter growth both years. However, during the first winter, temperatures dropped to -10°C, resulting in damage to all of the Eucalyptus clones. Clones 4016 and 4019 died back to ground level, whereas the SC5 clone had damage only to the leaves. Nevertheless, during the second growing season, the 4016 and 4019 clones outgrew the SC5 variety in height, although the SC5 maintained a slightly greater breast height diameter. In the second winter, freeze damage was minimal for all three Eucalyptus clones, with only slight foliar dieback on scattered trees.

Growth of the Populus clones was clone dependent, with clone 367 growing best. During year two, clone 367 outperformed all other clones and species for both height and diameter, growing over four meters in the second year to an average height of 6.4 meters. This average height was over one meter taller than the other species (Eucalyptus camaldulensis) and nearly two meters taller than the second best Populus clone (029). Robinia growth was highly variable both years, because it was an open-pollinated seed source and was sensitive to heavy soils. However, a number of trees grew well and show promise for the development of Robinia clones adapted to conditions in Ojinaga.

**BIOMASS/ION UPTAKE DATA**

Eucalyptus camaldulensis (4019) and Populus clone (367) produced the most biomass the first growing season (Figure 2). However, Eucalyptus camaldulensis had the greatest proportion of biomass in woody tissue. All three Eucalyptus clones had the lowest percentage of biomass in root tissue (19%), while Robinia had the highest percentage (40%). There appeared to be no relation between root biomass and survival among and within species. However, the greater survival and growth of Robinia in xeric plots might be explained by the greater root production relative to shoot biomass.

There were also differences in the ability of the species to accumulate salts (Table 5). Robinia had higher nitrogen contents in both roots and stem tissues, but foliage nitrogen levels were comparable to the other species. However, Robinia had higher accumulation of calcium in the foliage, almost to the total exclusion of sodium. This trend was followed for woody tissue as well. There were no differences in magnesium accumulation. Populus had higher chloride
accumulation in the foliage, but generally lower levels in woody tissue. Long-term accumulation could impact soil restoration or species performance if excessive levels develop.

**ECONOMIC ANALYSIS**

The COPAMEX mill has the capacity to process 160,000 tons of wood fiber per year but currently only processes 140,000 tons per year. Of that quantity, 50 percent is short fiber from hardwood species and 50 percent is softwood fiber from pine. The rail lines connecting Ojinaga to Chihuahua allow direct transhipment into the sorting yard of the Anáhuac facility. Currently, the short fiber is imported from the United States. COPAMEX officials are interested in developing domestic sources of short fiber, and COPAMEX is willing to purchase all output from Ojinaga. Indeed, COPAMEX has investigated the possibility of developing large-scale production of Eucalyptus and other species near Ojinaga.

Table 6 presents the differences in estimated net present value returns for forest production and traditional waste treatment facility for various interest rates and over different time periods. The calculations in the table assume that 424 hectares are planted in Eucalyptus and Populus in the initial year, and then harvested in seven-year cycles. It is assumed that production at harvest is 160 tons/hectare and that a price of $20/ton is received. Regardless of interest rate or time period considered, waste treatment could be achieved at lower cost with fiber production than with a traditional sewage treatment facility. Fiber production requires less initial capital expenditure and has a lower operating cost than a traditional waste treatment plant. Of particular interest is the last line of Table 6, which is the actual budgetary savings to Ojinaga from fiber production. In the initial year, lower capital costs of fiber production saves Ojinaga $2 million. Cumulative savings over 28 years are more than $7.4 million compared to constructing and operating a conventional wastewater treatment system.

An important goal of sustainable development is the creation of employment opportunities. This is an especially important issue for Ojinaga given the job losses and accompanying decline in population experienced by the city in recent years. Potential employment arising from biomass production is broken down into three categories: fiber farm establishment, which occurs during the initial year and includes site preparation, planting, and irrigation; growth and maintenance, which occurs during years two through six and involves primarily irrigation; and harvest, which occurs in year seven and includes harvesting activity (Table 7). For each set of activities, 2,000 labor-hours per year were included for administration including management, organization, and secretarial support.

**RECOMMENDATIONS FOR FURTHER RESEARCH**

The foundation has been laid for continued research on the application of tree plantations to the treatment of municipal wastewater by way of land application in arid climates. Many small communities in the border region lack suitable wastewater treatment facilities. Furthermore, these communities lack incentives to implement waste management programs.
An approach that creates financial benefits for these communities has the best chance of effecting change. The experience gained in Ojinaga provides the basis for a sustainable model of waste treatment. Moreover, with appropriate infrastructure development, Ojinaga could serve as a valuable training center for other border communities. The Ojinaga model has short fiber pulpwood as the target outcome, based on the need in Chihuahua and the availability of rail transport. However, other communities could produce fuel wood (for cooking or co-firing), pines for different products (including Christmas trees), specialty hardwoods, or even amenity plantings for recreation and wildlife habitats.

A key to success is identification of tree species suitable for the target outcome. The three species used in this model are suitable for pulpwood production. However, differences in growth rate, cold-hardiness, drought tolerance, and salt tolerance indicate a need for continued development of suitable plant material. From this study, only one clone each of Eucalyptus and Populus are suitable for long-term use. There are selections of Robinia that could be valuable on droughty soils. However, propagation techniques must be developed. There are other species (Liquidambar or Platanus) and cultivars of native cottonwood that may be better suited to the Ojinaga situation of calcareous soils, high evaporative demand, and long growing season. Moreover, an evergreen softwood species such as Pinus Eldarica may prove superior for winter water use, when deciduous species are dormant.

A successful land application system includes not only an economically viable system, but also an environmentally safe system. Both are required for sustainability. Continued monitoring of effluent can prevent endangering the treatment process through contamination with heavy metals or toxic organic compounds, while monitoring the groundwater can minimize the risk of compromising groundwater quality through overloading the system. Both will require continued community involvement to prevent inappropriate dumping of toxic chemicals.

**Benefits of Research Project**

Two graduate students were employed by the project. An article describing this project was written jointly by NMSU and INIFAP investigators and published in the November 1997 volume of the New Mexico Journal of Science. A joint presentation on the project was made by Rolando Núñez Saldaña (INIFAP), Holda Leyva (JMAS), and John Mexal (NMSU) at the SCERP Technical Conference in September 1997 in El Paso, Texas. Another joint presentation describing the project was made before the XVI Biennial Reunion of the Asociacion Mexicana de Profesionales Forestales/Southwestern Society of American Foresters by Leonel Iglesias (INIFAP) and John Mexal (NMSU) in September 1997 in Flagstaff, Arizona. The results of the cost benefit analysis were presented by Christopher Erickson (NMSU) at the Association for Borderlands Studies meetings in February 1998 in Nogales, Arizona-Nogales, Sonora A joint presentation on the project was made by Rolando Núñez Saldaña (INIFAP), Martín Sánchez Vallez (JMAS), and John Mexal (NMSU) at the SCERP Technical Conference in November 1998 in El Paso, Texas. A thesis for a master of science degree in horticulture, titled Survival, Growth, and Ion Uptake in Eucalyptus
Camaldulensis, Hybrid Populus, and Robinia Pseudoacacia Irrigated with Saline Municipal Wastewater, by Brenda Lee Jessen, was completed in August 1999.

With this first and second year of funding by SCERP, the foundation has been laid for continued research on the application of tree plantations to the treatment of municipal wastewater by way of land application in arid climates. Similar research to date has been conducted primarily in humid areas or in semi-arid areas, where the management challenges of salty water and soil are less severe or are non-existent. The establishment of the experimental site in Ojinaga gives this community a tangible demonstration site to point to, something that adds credibility to the idea of a sustainable approach to waste treatment as an authentic alternative to the more expensive conventional systems. The establishment of this site also benefits other communities in the border region and beyond with a particular research site and scientific data to support this approach to waste treatment. The challenge today for those who would improve environmental conditions in the border region is to recognize that this approach is truly the leading edge technology, that the days of expensive, unwieldy, conventional systems must give way to sustainable methods such as the one being researched in Ojinaga.

REFERENCES


Cole, D.W., C.L. Henry, and W.L. Nutter, eds. 1986. The forest alternative for treatment and


Table 1. Selected Water Quality Indicators (Minimum-Maximum Range), Ojinaga, Chihuahua, 12/96-3/98

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>Río Conchos</th>
<th>Río Grande</th>
<th>City Well Water (12/96)</th>
<th>Oxbow Lake at the Exp. Site</th>
<th>Wastewater Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH of water</td>
<td>7.9–8.4</td>
<td>7.8–8.4</td>
<td>7.73</td>
<td>7.6–9.6</td>
<td>7.3–7.7</td>
</tr>
<tr>
<td>Electrical Conductivity (dS/m)</td>
<td>1.3–2.3</td>
<td>1.4–3.3</td>
<td>2.51</td>
<td>2.9–3.4</td>
<td>2.7–3.1</td>
</tr>
<tr>
<td>Total Dissolved Solids (mg/L)</td>
<td>791–1460</td>
<td>1192–2160</td>
<td>1892</td>
<td>2167–2670</td>
<td>1948–2217</td>
</tr>
<tr>
<td>Sodium Absorption Ratio (SAR)</td>
<td>3.67–6.40</td>
<td>5.17–8.77</td>
<td>5.5</td>
<td>6.89–8.85</td>
<td>5.49–6.96</td>
</tr>
<tr>
<td>Fecal Coliform (MPN/100mL)</td>
<td>140</td>
<td>130–230</td>
<td>–</td>
<td>4–800</td>
<td>(2.3–6.4)x10^5</td>
</tr>
<tr>
<td>BOD (mg/L)</td>
<td>–</td>
<td>3.0</td>
<td>–</td>
<td>13.2–14.6</td>
<td>28.6–42.5</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>–</td>
<td>30</td>
<td>–</td>
<td>67–99</td>
<td>100–117</td>
</tr>
<tr>
<td>Nitrate/Nitrite as N (mg/L)</td>
<td>0.42–0.66</td>
<td>&lt;0.05</td>
<td>1.8</td>
<td>&lt;0.05–1.03</td>
<td>&lt;0.05–0.16</td>
</tr>
<tr>
<td>Ammonium as N (mg/L)</td>
<td>0.07–0.08</td>
<td>0.08</td>
<td>–</td>
<td>0.06–8.1</td>
<td>7.6–12.3</td>
</tr>
<tr>
<td>Water Kjeldahl N (mg/L)</td>
<td>0.3–2.5</td>
<td>10.7</td>
<td>–</td>
<td>5.4–16.0</td>
<td>14.1–37</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>90.8–244.3</td>
<td>440–680</td>
<td>191</td>
<td>240–284</td>
<td>201–233</td>
</tr>
</tbody>
</table>
Table 2. Analysis of Sludge Samples Obtained in Ojinaga, Chihuahua, December 1996

<table>
<thead>
<tr>
<th>Parameter</th>
<th>New Lagoon Sludge</th>
<th>Old Lagoon Sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.29</td>
<td>7.73</td>
</tr>
<tr>
<td>EC (dS/m)</td>
<td>2.35</td>
<td>6.54</td>
</tr>
<tr>
<td>TDS* (mg/L)</td>
<td>1947</td>
<td>–</td>
</tr>
<tr>
<td>SAR*</td>
<td>1.2</td>
<td>–</td>
</tr>
<tr>
<td>Magnesium (meq/L)</td>
<td>1.6</td>
<td>–</td>
</tr>
<tr>
<td>Calcium (meq/L)</td>
<td>22.5</td>
<td>–</td>
</tr>
<tr>
<td>Sodium (meq/L)</td>
<td>4.3</td>
<td>–</td>
</tr>
<tr>
<td>Nitrate-N (mg/L)</td>
<td>0.0</td>
<td>246 mg/kg</td>
</tr>
<tr>
<td>Ammonia-N (mg/L)</td>
<td>–</td>
<td>0.3%</td>
</tr>
<tr>
<td>Kjeldahl-N(mg/L)</td>
<td>72.0</td>
<td>–</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>277</td>
<td>355</td>
</tr>
<tr>
<td>Phosphorus (mg/L)</td>
<td>29.0 mg/kg</td>
<td>–</td>
</tr>
<tr>
<td>Potassium (mg/L)</td>
<td>78.0 mg/kg</td>
<td>–</td>
</tr>
<tr>
<td>Sulfate (mg/L)</td>
<td>27.0</td>
<td>–</td>
</tr>
<tr>
<td>Coliforms¹ (col/100ml)</td>
<td>–</td>
<td>&lt;2FC* count/g</td>
</tr>
</tbody>
</table>

*TDS (Total Dissolved Solids); SAR (Sodium Absorption Ratio); FC (Fecal Coliform)

¹Coliform data from analysis taken June 1997
Table 3. Comparison of the Concentration of Metals in Sludge Samples taken from the Former and Present Sewage Lagoons near the Ojinaga Pilot Study Site and U.S. EPA Part 503 Sewage Sludge Annual Pollutant Loading Rate Regulations. (U.S. EPA 1994)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Old Lagoon Sludge (g/Mg)</th>
<th>New Lagoon Sludge (g/Mg)</th>
<th>U.S. EPA Annual Pollutant Loading Rate (g/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>0.0</td>
<td>7.6</td>
<td>1,900</td>
</tr>
<tr>
<td>Cr</td>
<td>14.5</td>
<td>8.9</td>
<td>150,000</td>
</tr>
<tr>
<td>Cu</td>
<td>0.0</td>
<td>192.0</td>
<td>75,000</td>
</tr>
<tr>
<td>Hg</td>
<td>1.7</td>
<td>10.3</td>
<td>15,000</td>
</tr>
<tr>
<td>Ni</td>
<td>10.0</td>
<td>0.0</td>
<td>29,000</td>
</tr>
<tr>
<td>Pb</td>
<td>75.0</td>
<td>81.0</td>
<td>15,000</td>
</tr>
<tr>
<td>Zn</td>
<td>0.0</td>
<td>573.0</td>
<td>140,000</td>
</tr>
</tbody>
</table>

Table 4. Tree Survival, Height, and Diameter Growth, Measured Eight and 20 Months after Planting (First and Second Growing Seasons)

<table>
<thead>
<tr>
<th>Genus/clone</th>
<th>Survival (%) Yr 1</th>
<th>Survival (%) Yr 2</th>
<th>Height (m) Yr 1</th>
<th>Height (m) Yr 2</th>
<th>Diameter Yr 1 Ground-line (mm)</th>
<th>Diameter Yr 2 % Achiev. Breast Height</th>
<th>Diameter Yr 2 Breast Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eucalyptus</em> 4016</td>
<td>99</td>
<td>97</td>
<td>2.19</td>
<td>5.24</td>
<td>24.5</td>
<td>97</td>
<td>37.49</td>
</tr>
<tr>
<td><em>Eucalyptus</em> 4019</td>
<td>98</td>
<td>94</td>
<td>2.58</td>
<td>5.24</td>
<td>31.8</td>
<td>99</td>
<td>43.66</td>
</tr>
<tr>
<td><em>Eucalyptus</em> SC5</td>
<td>98</td>
<td>98</td>
<td>2.00</td>
<td>5.18</td>
<td>24.1</td>
<td>90</td>
<td>44.96</td>
</tr>
<tr>
<td><em>Populus</em> 029</td>
<td>71</td>
<td>67</td>
<td>1.71</td>
<td>4.75</td>
<td>20.6</td>
<td>69</td>
<td>35.97</td>
</tr>
<tr>
<td><em>Populus</em> 197</td>
<td>53</td>
<td>24</td>
<td>1.36</td>
<td>3.90</td>
<td>16.5</td>
<td>51</td>
<td>29.36</td>
</tr>
<tr>
<td><em>Populus</em> 367</td>
<td>95</td>
<td>88</td>
<td>2.17</td>
<td>6.41</td>
<td>27.4</td>
<td>87</td>
<td>54.49</td>
</tr>
<tr>
<td><em>Robinia</em></td>
<td>93</td>
<td>74</td>
<td>1.35</td>
<td>3.23</td>
<td>17.2</td>
<td>41</td>
<td>19.67</td>
</tr>
</tbody>
</table>

Both survival measurements are based on initial stocking levels at time of planting.
Table 5. Nutrient Analysis of Leaves, Woody Tissue (Branches and Stems), and Roots of *Eucalyptus Camaldulensis*, Hybrid *Populus*, and *Robinia Pseudoacacia* at Seven Months

<table>
<thead>
<tr>
<th>Plant Tissue</th>
<th>N (%)</th>
<th>Ca (%)</th>
<th>Mg (%)</th>
<th>Cl (%)</th>
<th>Na (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaves</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus</em></td>
<td>2.79</td>
<td>1.17</td>
<td>0.21</td>
<td>0.79</td>
<td>0.36</td>
</tr>
<tr>
<td><em>Populus</em></td>
<td>2.57</td>
<td>2.55</td>
<td>0.40</td>
<td>1.47</td>
<td>0.28</td>
</tr>
<tr>
<td><em>Robinia</em></td>
<td>2.48</td>
<td>3.57</td>
<td>0.40</td>
<td>0.69</td>
<td>0.02</td>
</tr>
<tr>
<td>Woody</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus</em></td>
<td>0.63</td>
<td>0.69</td>
<td>0.10</td>
<td>0.45</td>
<td>0.09</td>
</tr>
<tr>
<td><em>Populus</em></td>
<td>0.70</td>
<td>0.61</td>
<td>0.10</td>
<td>0.13</td>
<td>0.40</td>
</tr>
<tr>
<td><em>Robinia</em></td>
<td>1.52</td>
<td>0.86</td>
<td>0.09</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>Roots</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus</em></td>
<td>0.73</td>
<td>0.31</td>
<td>0.10</td>
<td>0.55</td>
<td>0.11</td>
</tr>
<tr>
<td><em>Populus</em></td>
<td>0.90</td>
<td>0.63</td>
<td>0.09</td>
<td>0.22</td>
<td>0.07</td>
</tr>
<tr>
<td><em>Robinia</em></td>
<td>1.53</td>
<td>0.57</td>
<td>0.08</td>
<td>0.33</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 6. Cumulative Difference (in U.S. $) between Net Present Values from Fiber Production and Conventional Waste Treatment Plants at Different Loan Rates, Assuming 424 Hectares under Cultivation, a Price per Ton is $20 and a Yield is 160 Tons per Hectare at Harvest

<table>
<thead>
<tr>
<th>Interest Rate</th>
<th>Year 1</th>
<th>Year 7</th>
<th>Year 14</th>
<th>Year 21</th>
<th>Year 28</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0%</td>
<td>1,660,071</td>
<td>1,675,881</td>
<td>1,667,633</td>
<td>1,708,408</td>
<td>1,708,055</td>
</tr>
<tr>
<td>10.0%</td>
<td>1,886,445</td>
<td>2,086,229</td>
<td>2,160,698</td>
<td>2,710,808</td>
<td>2,730,992</td>
</tr>
<tr>
<td>0.0%</td>
<td>2,075,090</td>
<td>2,617,191</td>
<td>3,110,588</td>
<td>6,945,209</td>
<td>7,448,606</td>
</tr>
</tbody>
</table>

Table 7. Employment from Fiber Production

<table>
<thead>
<tr>
<th>Activity</th>
<th>Employment per ha/yr</th>
<th>Employment for 424 ha farm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishment (Year 1)</td>
<td>150 labor hours</td>
<td>63,600 labor hours</td>
</tr>
<tr>
<td>Growth and Maintenance (Years 2–6)</td>
<td>50 labor hours</td>
<td>21,200 labor hours</td>
</tr>
<tr>
<td>Harvest (Year 7)</td>
<td>250 labor hours</td>
<td>106,000 labor hours</td>
</tr>
</tbody>
</table>
Figure 1. *E.coli* contamination (colonies, million/sec) of the Rio Grande below effluent discharge site, adjusted for river flow from January 1996 through June 1998 (IBWC 1998).

Figure 2. Biomass (in grams) at seven months, of *Eucalyptus Camaldulensis*, Hybrid *Populus*, and *Robinia Pseudoacacia*