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Sustainable Use of Wastewater for Small Communities: A Model System for Short Rotation Woody Crop Production

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ABSTRACT

The U.S. Mexican border region has experienced rapid population growth in the last 30 years, resulting in natural resource degradation and increasing threats to public health. A primary concern is the threat posed by water pollution, especially through improper treatment and disposal of human wastes. Binational efforts are underway to find solutions, particularly through the development of alternatives to high-cost, conventional waste treatment systems. Alternative systems should reduce contaminants as well as innovatively recycle nutrients and carbon present in the waste materials. This pilot study, which is a full integration of applied research and technology transfer, demonstrates a wastewater land application system integrated with the production of fast growing trees for fiber and energy. In the first year of this study, trees reached an average height of 1.78 m and ground line diameter of 21.8 mm, with an average survival of 88%. The installation of a full-scale system of this type is economically justified based on cost-benefit analysis. This pilot study could serve as a model system for effective waste treatment in other communities in the border area.

INTRODUCTION

The Rio Grande, or Río Bravo, flows nearly 2,000 kilometers through the Texas-Mexico border region. Paradoxically, it is both the region's lifeblood and a source of environmental contamination. 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, the once-clean river 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).

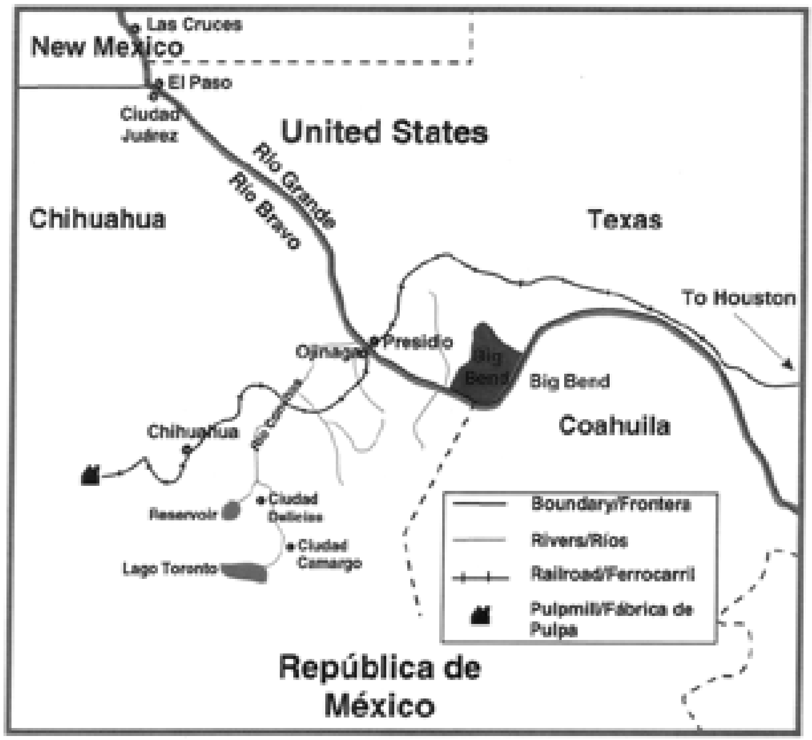
Binational efforts to address these environmental problems were initiated in 1983, with the establishment of the La Paz Agreement. The EPA followed in 1996 with the Border XXI Program an extensive plan designed to decentralize the management of environmental issues in order to increase public participation and to encourage better communication and collaboration among pertinent agencies (U.S. EPA 1996). The program's 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 region 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 as viable alternatives to the current lack of effective waste treatment in the border communities. These alternatives must not only be relatively inexpensive and capable of safely recycling sludge and wastewater, but they should also provide opportunities for economic development (Bastian et al. 1982). This chapter explores 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 Rio Grande and Río Conchos, about 500 kilometers southeast of El Paso Ciudad JuÆrez (Figure 1). Ojinaga, with a

Figure 1: West Texas Mexico Border Area along the Rio Grande



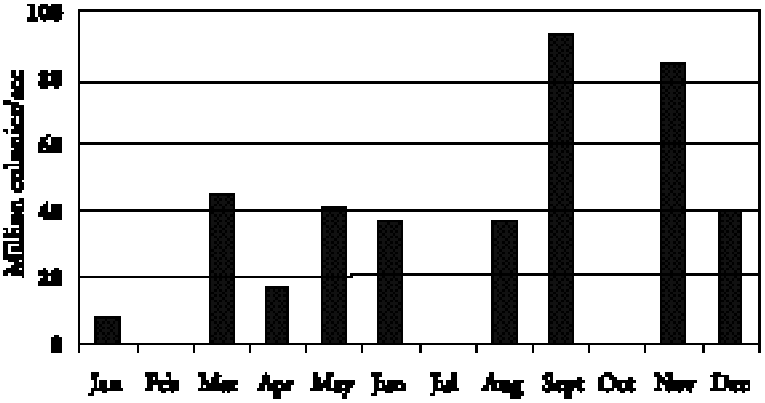
population of approximately 24,000, is located across the river from tis sister city, Presidio, Texas, (population 3,500). Unlike other border communities, the population of Ojinaga has decreased, dropping from about 26,000 in 1980 to 23,600 in 1995 (U.S. EPA 1996). This decline has been attributed to a lack of economic opportunities in the community, small landholding size, marginal farmland, flooding, and migration to the United States (Prieto Barrera 1995; Nuæz 1997).

Ojinaga s climate is hot (with a maximum temperature of 50° C, and a minimum temperature of 10°C) and dry (the average annual rainfall is 235 mm), yet the community has an irrigation infrastructure that supports approximately 12,000 ha of agricultural land. Although Ojinaga produces an array of crops, including alfalfa, cotton, corn, wheat, melons, onions, pecans, and forages, less than one-half of the farmland is currently in production. This is due, in part, to small landholdings, averaging 5 ha, making agricultural production uncompetitive (Nuæz 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 does not play a major role in Ojinaga'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 ha (45,000 m^3) unlined, anaerobic settling lagoon. The lagoon separated the solids from the waste stream and provided some reduction in waste strength. After the lagoon filled with settled solids, a new 2 ha (60,000 m^3) 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% 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 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.

Figure 2: Average Monthly E. coli Contamination of the Rio Grande below Ojinaga Effluent Discharge Point, Adjusted for River Flow (taken January 1996 through June 1998)



Source: Waggoner (1998).

Presently, effluent from the sewage lagoon is used for irrigation of adjacent pasturage, with the excess water discharged into the Rio Grande. Measurements of Rio 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 m^3/s from January 1996 through June 1998 (Waggoner 1998). Over this time period, the community effluent (0.07 m^3/s) represented less than 1% of total flow (min. = 0.3%; max. = 4.0%). While the contribution from the effluent to river flow is negligible, fecal coliform contamination increased from an average of 110 colonies/100 ml (se = 28) above the Río Conchos to 579 colonies/100 ml (se = 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 2). During this sampling period, the fecal coliform counts exceeded the Texas Natural Resources Conservation Commission (TNRCC) river quality standards (200 colonies/100 ml) over 50% of the time compared to less than 20% above the effluent outlet. This contamination represents a serious health hazard for downstream irrigation water users, or anyone coming in contact with river water, including children who play or fish in the river. 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 those 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, nondependent, and sustainable development of human and natural resources (Cabana et al. 1995). Thus, through a community referencing system, 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, and must 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 into the Rio 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 1996; Prieto Barrera 1995). With full community support, a pilot study was initiated in 1996 to integrate pulpwood production with wastewater remediation and economic development.

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 nonedible 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 multistepped 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 particulates and surface and ground water systems. As the wastewater infiltrates 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 semiarid 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 Engelbrecht 1973; Reddy et al. 1981). Similarly, antagonistic microorganisms, which occupy specific niches within the soil system, utilize a variety of mechanisms to effectively compete with introduced microbes. While there is the potential for harmful organisms to persist in the soil, the physical and biological processes are not conducive to the long-term survival of these pathogens. Generally, over 90% 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 minimal 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 semiarid climates, trees tolerant of high evaporative demands, yet capable of high nitrogen utilization, would be preferred.

ENVIRONMENTAL, ECONOMIC, AND SOCIAL BENEFITS OF LAND APPLICATION SYSTEMS

Land Restoration

Currently, there are over 2,000 ha 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 agronomic crops. This would restore the land to beneficial use, and after one or two rotations (about 14 years) with good management, the land would likely be suitable for agronomic crop production again, if desired.

Clean Water (70/70 20/20)

Currently, Mexico requires a 70 mg/L BOD and 70 mg/L total suspended solids (TSS) standard, while the United States requires a 20/20 standard for wastewater treatment. A system that returns no water to the Rio Grande, other than through groundwater infiltration, would not have to consider this guideline. The loss of flow to the Rio Grande with the land application system would be minor (less than 1 %), 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.

Reduction of Demand on Natural Forest Systems

There are over 7.6 million ha of forest land in the state of Chihuahua, of which over 3.7 million ha are classified as commercial forests. In 1998, the forest communities were permitted to cut 2.4 million m^3, or 70% of the mean annual increment of 0.9 m^3/ha/yr for the state (Iglesias 1997). It is projected that fiber plantations in Ojinaga could produce nearly 29 m^3/ha/yr or 200 m^3/ha with a seven-year rotation. Harvesting only 100 ha/yr of short rotation woody crops would meet 1% 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 for the development of 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 mountains 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.

Efficient Water Use and High Productivity

Wastewater can be utilized more efficiently in arid climates as a result of high evapotranspiration and solar energy rates available for plant growth. Additionally, the low rainfall reduces the uncontrolled water loss and drainage problems that are associated with humid regions. The combination of high evaporative demand and low rainfall leads to more efficient use of the nutrient-enriched wastewater for crop production.

Better Control in Nutrient Management

Because there is little rainfall in arid climates, the applied water is practically the only source of irrigation. This should minimize excessive loss of nutrients, due to uncontrolled runoff or deep percolation. Furthermore, crop water consumption can be estimated and water applications managed, such that the available water and its nutrients are efficiently used by the plant. However, even in a tree farm production system, it is imperative that soil salinity be managed to prevent further salinization or loss of production. This can be accomplished through proper irrigation scheduling and leaching of excess salts below the root zone of the trees.

Sustainable Rural Development

Currently, between 20 40% of the land irrigated by the Ojinaga water district is no longer under cultivation due to salinization. By using 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. Approximately the equivalent of one full-time job would be created for each 2 ha of land returned to production (Reiche et al. 1991). 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 semi-skilled, and would include field work jobs (such as 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 competitive wages.

Model System for Arid Regions of the World

Many small communities are pursuing alternative systems for wastewater treatment. Economics and safety are the primary factors driving this movement. Several communities in New Mexico have constructed wetlands for wastewater treatment (Tessneer 1998). The advantage of a constructed wetland is ease and cost of operation. The disadvantage is that 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 semiarid 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, or pine for pulpwood or saw timber. The tree plantations could even serve as recreational areas. Thus, the state of Chihuahua could become a leader in system innovation.

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 by 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% (T_{90}) of human parasites ranged from 2 10 d for protozoans, to 6 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 nonedible 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 organics 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 kg N/ha/d or 110 876 kg N/ha/yr (U.S. EPA 1992). Using this method, most of the NO_3 -N and ammonium-N (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 into the groundwater (Jewell 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 above concerns encountered in using land application systems throughout the world, there are some unique challenges with these systems in arid and semiarid 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 the 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 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.

OJINAGA PILOT STUDY

Materials and Methods

Municipal sewage in Ojinaga is piped directly into an anaerobic lagoon, which 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 ha site, adjacent to an oxbow lake, was selected downstream from the lagoon. Soils were sampled to a depth of 1 m 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 Rio Grande, and the Río Conchos also were implemented. The depth to groundwater at the site is approximately 3 m, and the slope is < 5%. 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 (Nuñez 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 were also 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 × P. deltoides), TD 50-197 (P. trichocarpa × P. deltoides), and OP 367 (P. deltoides x P. nigra). Robinia pseudoacacia, known for its hardiness, has been used in stream bed stabilization and mineland 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 7 m × 7 m in size each. Containerized Eucalyptus camaldulensis, bareroot Robinia pseudoacacia seedlings, and Populus cuttings (20 cm in length) were transplanted at 2 m × 2 m 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 months and at 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

Table 1: Selected Water Quality Indicators (min max range)
Ojinaga, Chihuahua, December 1996 March 1998

Test Parameter	Rio Conchos	Rio Grande	City Well Water (12/96)	Oxbow Lake at the Exp. Site	Wastewater Effluent
pH of water	7.3–8.4	7.8–8.4	7.73	7.6–9.6	7.3–7.7
Electrical Conductivity (dS/m)	1.3–2.5	1.4–3.3	2.51	2.9–3.4	2.7–3.1
Total Dissolved Solids (mg/L)	791–1460	1193–2160	1891	2167–2670	1948–2117
Sodium Absorption Ratio (SAR)	3.67–6.40	5.13–6.77	5.5	6.83–8.35	5.48–6.96
Fecal Coliform (MPN/100mL)	140	130–230	–	4–800	$(2.3–6.0)\times10^5$
BOD (mg/L)	–	5.0	–	13.2–14.6	28.6–43.5
COD (mg/L)	–	30	–	67–89	100–117
Nitrate/Nitrite as N (mg/L)	0.42–0.66	<0.05	1.8	<0.05–1.88	<0.05–0.16
Ammonium as N (mg/L)	0.47–0.88	0.88	–	0.06–4.1	7.6–12.3
Water Kjeldahl N (mg/L)	0.3–2.5	18.7	–	5.4–16.0	14.1–57
Sulfate (mg/L)	328–513	457–538	–	795–1079	728–1087
Chloride (mg/L)	98.6–264.3	440–680	191	240–284	201–283

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 30% 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% 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 8% 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 1 m, 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

Table 2: Analysis of Sludge Samples Obtained in Ojinaga, Chihuahua, December 1996

Parameter	New Lagoon Sludge	Old Lagoon Sludge
pH	7.29	7.73
EC (dS/m)	2.35	6.54
TDS* (mg/L)	1947	–
SAR*	1.2	–
Magnesium (meq/L)	1.6	–
Calcium (meq/L)	22.5	–
Sodium (meq/L)	4.3	–
Nitrate-N (mg/L)	0.0	246 mg/kg
Ammonia-N (mg/L)	–	0.3%
Kjeldahl-N(mg/L)	72.0	–
Chloride (mg/L)	277	355
Phosphorus (mg/kg)	29.0	–
Potassium (mg/kg)	78.0	–
Sulfate (mg/L)	27.0	–
Coliforms[1] (col/100ml)	–	<2FC* count/g

*TDS (total dissolved solids); SAR (sodium absorption ratio); FC (fecal col-

[1] Coliform data from analysis taken June 1997.

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 the 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 envi-

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 the U.S. EPA Part 503 Sewage Sludge Annual Pollutant Loading Rate Regulations

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

*Source: U.S. EPA 1994.

ronmental 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 Banco Nacional de Crédito 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 Ferrocarril Nacionales de México railroad has experience in shipping timber, and has railcars suitable for shipping logs, chips, or pulp to U.S. or Mexican markets. To determine the extent of the domestic (Mexican) market for short fiber pulpwood, the Copamex facility (one of the largest manufacturer of paper products in Mexico) in Anáhuac, Chihuahua, was visited.

Results

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 val-

Table 4: Tree Survival, Height, and Diameter Growth, Measured 8 and 20 Months After Planting (First and Second Growing Seasons)

Genus/clone	Survival (%) Yr 1	Survival (%) Yr 2	Height (m) Yr 1	Height (m) Yr 2	Diameter Yr 1		Diam. Yr 2
					Ground-line (mm)	% Achieve Breast Height	Breast Height (mm)
Eucalyptus 4876	99	97	2.19	5.36	36.5	97	67.49
Eucalyptus 4979	98	94	1.59	5.26	31.8	99	43.66
Eucalyptus SC3	99	98	2.09	5.16	36.1	98	44.96
Populus 029	71	67	1.71	4.75	30.6	49	55.57
Populus 197	59	34	1.36	3.90	16.5	51	20.86
Populus 567	95	89	2.17	6.01	37.8	97	54.69
[illegible]	95	74	1.35	5.36	17.2	41	19.87

Note: Both survival measurements are based on initial stocking levels at the time of planting.

ues 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 (NH_4^+-N and organic-N) of 14 37 mg N/L of wastewater. Most of the nitrogen was in the NH_4^+ form, with low NO_3 levels, suggesting that leaching of nitrates would not be a problem. At an application rate of 2.0 m^3/m^2, the loading rate of N as NH_4^+ would be approximately 250 kg N/ha/yr.

There were 2.3 6.4 ¥ 10_5 colonies of fecal coliform bacteria/100 ml of effluent. International guidelines suggest a maximum geometric mean concentration of 1,000 fecal coliforms/100 ml for wastewater applied for edible crops (Kowal 1986). For crops raised intensively with a short rotation, such as vegetable crops, these levels are clearly 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 5 8% organic matter with 0.25 kg NO_3 -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

Figure 3: Biomass (in grams) at Seven Months of Eucalyptus camaldulensis, Hybrid Populus, and Robinia pseudoacacia

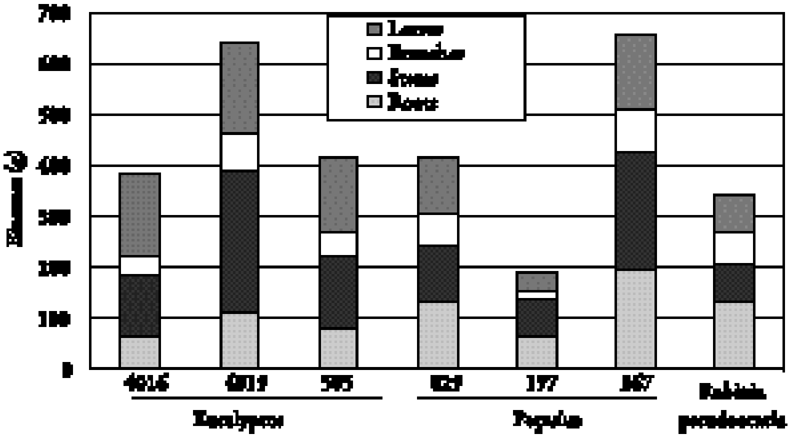


Table 5: Nutrient Analysis of Eucalyptus camaldulensis, Hybrid Populus, and Robinia pseudoacacia at Seven Months

Plant Tissue		**N (%)**	**Ca (%)**	**Mg (%)**	**Cl (%)**	**Na (%)**
Leaves	*Eucalyptus*	2.79	1.17	0.21	0.79	0.36
	Populus	2.57	2.55	0.40	1.47	0.28
	Robinia	2.48	3.57	0.40	0.69	0.02
Woody	*Eucalyptus*	0.63	0.69	0.10	0.45	0.09
	Populus	0.70	0.61	0.10	0.13	0.40
	Robinia	1.52	0.86	0.09	0.18	0.04
Roots	*Eucalyptus*	0.73	0.31	0.10	0.55	0.11
	Populus	0.50	0.63	0.09	0.22	0.07
	Robinia	1.53	0.57	0.08	0.33	0.04

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 81.0 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 this lagoon also has no economic value.

Soil Analysis

The soils at the experimental site are nonuniform. The site is situated in the floodplain of the Rio Grande, immediately next to the 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 m (roughly east-west) by 45 m, 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 15 cm 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 60% gravel by volume), and gravelly (15 35% gravel by volume), which further lowers the AW . In this part of the site, AW ranges from a low of 4 cm water/m soil with more typical values running from 6 12 cm water/m 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 15 cm water/m 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 m, while on soils containing layers of gravelly to extremely gravelly sand, these clones were only 1.9 m in height. In contrast, Robinia pseudoacacia plants had a height of only 1.1 m on loamy soils, but a height of 1.7 m 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).

Table 6: Cumulative Difference (in U.S. dollars) between Net Present Values from Fiber Production and Conventional Waste Treatment Plant at Different Loan Rates*

Interest Rate	Year 1	Year 7	Year 14	Year 21	Year 28
25.0%	1,660,071	1,675,881	1,667,653	1,708,408	1,708,055
10.0%	1,886,445	2,086,229	2,160,658	2,710,808	2,750,552
0.0%	2,075,050	2,617,151	3,110,588	6,545,209	7,448,606

*Note: Assuming 424 hectares under cultivation, a price of $20 per ton, and a yield of 160 tons per hectare at harvest.

Table 7: Employment from Fiber Production

Activity	**Employment per ha/yr**	**Employment for 424 ha farm/yr**
Establishment (Year 1)	**150 labor-hours**	**63,600 labor-hours**
Growth & Maintenance (Years 2–6)	**50 labor-hours**	**21,200 labor-hours**
Harvest (Year 7)	**250 labor-hours**	**106,000 labor-hours**

Tree Growth

During the first and second growing season, the three Eucalyptus clones had high survival rates (Table 4). In contrast, survival of Populus was clone-dependent, with the 367 clone having the highest survival rate (95% for year one and 88% for year two) and clone 197 having the lowest survival rate (53% for year 1 and 24% for year 2). Robinia had high survival rates the first year (93%), declining to 73% 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 4 m in the second year to an average height of 6.4 m. This average height was over 1 m taller than the other species and nearly 2 m 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 3). 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 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 146,000 metric tons of wood fiber per year but currently only processes 128,000 metric tons per year. Of that quantity, 50% is short fiber from hardwood species and 50% 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 are 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 a traditional waste treatment facility for various interest rates and over different time periods. The calculations in the table assume that 424 ha 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/ha 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. The cumulative savings over 28 years is 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

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.

A key to success is the 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 Ojinaga, with its 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 by contamination with heavy metals or toxic organic compounds, while monitoring the groundwater can minimize the risk of compromising groundwater quality by overloading the system. Both will require continued community involvement to prevent inappropriate dumping of toxic chemicals.

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