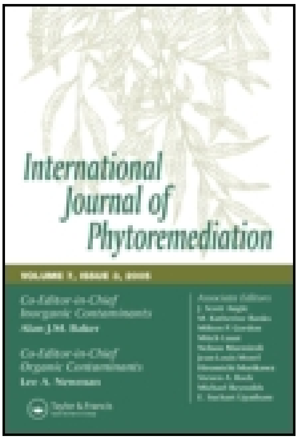

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Opportunities for Woody Crop Production Using Treated Wastewater in Egypt. I. Afforestation Strategies

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OPPORTUNITIES FOR WOODY CROP PRODUCTION USING TREATED WASTEWATER IN EGYPT. I. AFFORESTATION STRATEGIES

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The Nile River provides nearly 97% of Egypt's freshwater supply. Egypt's share of Nile waters is fixed at 55.5 billion cubic meters annually. As a result, Egypt will not be able to meet increasing water demand using freshwater from the Nile and has been developing non-conventional wastewater reuse strategies to meet future demands. The USAID Mission in Cairo began promoting strategies for water reuse in 2004, and guidelines for safe and direct reuse of treated wastewater for agricultural purposes were approved in 2005 (Egyptian Code 501/2005). Twenty-four man-made forests were established that have been useful for assessing the efficacy of using treated wastewater for afforestation. At present, approximately 4,340 hectares are under irrigation with treated wastewater, utilizing a total daily volume of 467,400 cubic meters. Wastewater has been applied to trees along roads, greenbelts in cities, and woody production systems. Currently, a joint USDA Forest Service—Agricultural Research Service technical assistance team has been evaluating the feasibility of scaling up such afforestation efforts throughout Egypt. We describe information about: 1) suitable tree species that have been identified based on local soil characteristics, water quality, and quantity of water supply; 2) the benefits and consequences of using these species; 3) strategies to maximize the potential of afforestation with regard to improving water quality, maximizing resource production, increasing biodiversity, and limiting commercial inputs; and 4) potential long-term impacts on the natural resource base from afforestation. A companion paper addresses irrigation recommendations based on species and local conditions (see Evett et al. 2000).

KEY WORDS: afforestation, forest products, phytoremediation, phytotechnologies, resource production, water quality

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INTRODUCTION

The Nile River provides nearly 97% of Egypt's freshwater supply, of which greater than 80% is utilized for agricultural purposes. The 3.5 million hectares of cultivated area within Egypt comprise approximately 3.5% of its total land area. This cultivated land is made up of that which has been traditionally irrigated (2.4 million hectares), reclaimed recently for irrigation (1.0), and rain-fed (0.1). Egypt also has 4 million hectares of rangelands located in the northwest coast (2.3 million hectares), Sinai Peninsula (1.1), and Halayeb-Shalateen Triangle (0.6). Although most of the country is desert, agriculture is the main economic sector of Egypt. Of the 22 million people in Egypt's labor force, 29% are engaged in agriculture, 22% in industry, and 49% in service (including the government) (MALR 2009).

The long-term sustainability of Egypt's agriculture depends on its ability to conserve and manage its water resources. Since 1959, Egypt's share of Nile waters is allocated according to international treaty obligations with the Sudan and is fixed at 55.5 billion cubic meters annually, most of which is already allocated (MWRI 2005). As a result, Egypt will not be able to meet increasing water demand using freshwater from the Nile and has been developing wastewater reuse strategies to increase water use efficiency to meet future demands. The daily volume of available treated wastewater (TWW) for agricultural purposes is expected to increase from 6.3 million cubic meters in 2000 to 8.3 million cubic meters by 2017 (MHPUNC 2005).

Primary contamination sources of the TWW include industrial wastes, pesticides, fertilizers, pharmaceuticals, field crop wastes, acid rain, and untreated sewage wastes. Historically, the latter have posed substantial environmental pollution and human health hazards. The common practice for both treated and untreated sewage water was to drain them into the Nile, pump them into sea or mine drains, or to dispose of them in the desert by allowing seepage into the ground. At present, through the National Program for the Safe Use of Treated Waste Water for Afforestation, substantial volumes of treated effluent generated from sewage treatment plants in cities and villages are used in forest plantations in the desert and bordering areas (MSEA 2006). The reuse of such TWW has become a popular potential water conservation strategy in Egypt, with other efforts including: (1) cooperating internationally with 10 other African countries of the Nile basin; (2) improving irrigation capacity; (3) reusing agricultural drainage water; (4) increasing the institutional and private capacity for water management; (5) maintaining the renewable ground water aquifer in the Nile basin and delta; (6) desalinating sea water; and (7) building the resource sustainability via integrated water resource management (MWRI 2005).

From 2004 to 2008, the United States Agency for International Development (USAID) Mission in Cairo promoted strategies for water reuse through its Livelihood and Income from the Environment–Integrated Water Resources Management (LIFE IWRM I) Project with Egypt's Ministry of Water Resources and Irrigation (MWRI). Guidelines for reuse of TWW for agricultural purposes were approved in 2005 (Egyptian Code 501/2005), which represented the legal foundation for farmers to begin cultivating crops (including wood trees) by irrigation with wastewater (MHPUNC 2005). The Ministry of Agriculture and Land Reclamation and Ministry of State for Environmental Affairs have established 24 manmade forests throughout the country, 21 of which have been useful for assessing the efficacy of using TWW for afforestation. The program targets an annual reuse of 2.4 billion cubic meters of treated wastewaters to irrigate 84,000 hectares (MSEA 2006).

The long-term plan consists of private investors operating future forests; they will lease the land, receive TWW, and grow crops (e.g., energy, fiber, oil, ornamental plants) according to the Egyptian code. Table 1 provides details according to the National Program for Safe Use of Treated Sewage Water for Afforestation (MSEA 2006). Nevertheless, at present, approximately 4,340 hectares are currently under irrigation with treated wastewater, utilizing a total daily volume of 467,400 cubic meters. The irrigation takes place across governorates in areas close to wastewater treatment plants that are adjacent to the desert. Wastewater has been applied to trees along roads, greenbelts in cities, and woody production systems. Furthermore, since 2008, the USAID Mission in Cairo has partnered with Egypt's MWRI on an extension of the LIFE IWRM I work. The primary objectives of the LIFE IWRM II project are to: (1) dispose of TWW and produce products with economic value, and (2) evaluate the feasibility of scaling up afforestation efforts throughout Egypt.

During May 2009, a joint USDA Forest Service–Agricultural Research Service technical assistance team traveled to three of the man-made forests irrigated with TWW in Egypt (at Ismailia and two forests at Luxor), as well as three tree nurseries (Ismailia, Luxor, and Cairo) (Figure 1) to address the second objective of LIFE IWRM II. Despite interest and necessity of using wastewater to irrigate woody crops, there is a lack of scientific data about ongoing afforestation activities in Egypt's manmade forests. As promising work in these forests continues, rigorous experimentation and record keeping will help articulate the best management practices (BMPs) for continuing afforestation with TWW. Although it is too early to provide detailed instruction on how to move forward with specific afforestation activities, this paper is a summary of key information to help advance these technologies. Based on the recent technical assistance mission, we describe information about: (1) suitable tree species that have been identified based on local soil characteristics, water quality, and quantity of water supply; (2) the benefits and consequences of using these species; (3) strategies to maximize the potential of afforestation with regard to improving water quality, maximizing resource production, increasing biodiversity, and limiting commercial inputs; (4) potential long-term impacts on the natural resource base from afforestation and strategies to mitigate these impacts. This information is important because identifying strategies to utilize TWW for productive purposes will be instrumental to ensuring Egypt's water security. A companion paper addresses recommendations for irrigation based on species and local conditions (see Evett et al. 2011, this issue).

SUITABLE TREE SPECIES BASED ON LOCAL SOILS, WATER QUALITY, AND WATER QUANTITY

Site Description

There were 84,000 hectares made available for woody crop production systems from the Egyptian Ministry of Housing and Urban Affairs to their Holding Company for tree crops using TWW (LIFE IWRM II). The land allocated to the Holding Company is located on the desert fringes, mostly in Upper Egypt. The sites are close to the sources of TWW, with all parcels less than 3 km from any given source facility.

In general, soils are sandy, loamy sand and coarse sandy with some sandy loams and a few small areas of finer textures; organic matter content is less than 1% (IRG 2005a). Soils in Egypt are generally from slightly to moderately alkaline, with pH values from 7 to more than 8. Outside of the Nile valley and the Delta where alluvial soils predominate,

Table 1 The Egyptian National Program for Safe Use of Treated Sewage Water for Afforestation. Adapted from Ministry of State for Environmental Affairs (MSEA) (2006)

Governorate	Site	Area (hectare)	Discharge ($m^3\ d^{-1}$)	Irrigation Method[a]	Cultivated Plant
Alexandria	N9	25.2	10	D	*Khaya, Casuarina*
Aswan	Edfu	126.0	8,000	MS	*Khaya*
”	Blanna	518.7	8,000	D	*Khaya*
”	Nasr El-Noube	42.0	1,400	D	*Camphor, Khaya, Terminalia*
”	Allaky Valley	231.0	8,000	D	*Casuarina, Khaya senegalensis, Camphor*
Asyout	Asyout	16.8	28,000	D	*Khaya senegalensis, Jatropha curcas*
Bani-Swief	El-Wasta	210.0	10,000	D	*Khaya senegalensis, Jatropha curcas*
Dakahlia	Gamasa	63.0	1,500	D	*Cupressus, Pinus, Concarpus*
Giza	Al-Saf	210.0	65,000	D	*Khaya, Casuarina*
Ismailia	Sarabium	210.0	90,000	D	*Cupressus, Pinus, Khaya, Casuarina, Eucalyptus, Morus, Concarpus, Agava sisalana, Dendrocalamus strictus*
Luxor	Luxor	714.0	30,000	MS; D	*Khaya, Eucalyptus, Acacia saligna, Morus, Jatropha*
Menoufia	Sadat	210.0	18,000	D	*Cupressus, Pinus, Acacia saligna, Casuarina, Eucalyptus, Agava sisalana, Morus, Khaya,* Ornamental Trees and Plants
New Valley	Al-Kharga	168.0	13,000	MS	*Eucalyptus, Khaya, Casuarina, Terminalia*
”	Paris	84.0	18,000	D	*Cupressus, Pinus, Acacia saligna, Casuarina, Eucalyptus*
”	Moot	294.0	15,000	D	*Khaya, Terminalia*
North Sinai	Al Aresh	84.0	50,000	D	*Khaya senegalensis, Jatropha curcas*
Qena	Qena	210.0	23,000	MS	*Eucalyptus, Khaya*
Red Sea	Hurgada	84.0	4,000	D	*Casuarina, Khaya senegalensis*
Sohag	Gharb	420.0	28,000	MF; D	*Khaya senegalensis, Jatropha curcas*
”	Shark	420.0	94	MF; D	*Khaya senegalensis, Jatropha curcas*
South Sinai	Tour Sinai	84.0	3,500	MS; D	*Casuarina, Eucalyptus, Morus, Populus*
”	Sharm El-Sheikh	25.2	3,000	D	*Casuarina,* Ornamental Trees and Plants
”	Nouiba	84.0	na[b]	D	*Casuarina, Khaya senegalensis*
Suez	Attakah	168.0	30,000	D	*Jatropha curcas*

[a]Irrigation method deployed; D = drip irrigation, MS = modified surface irrigation, MF = modified flood irrigation.
[b]Not available.

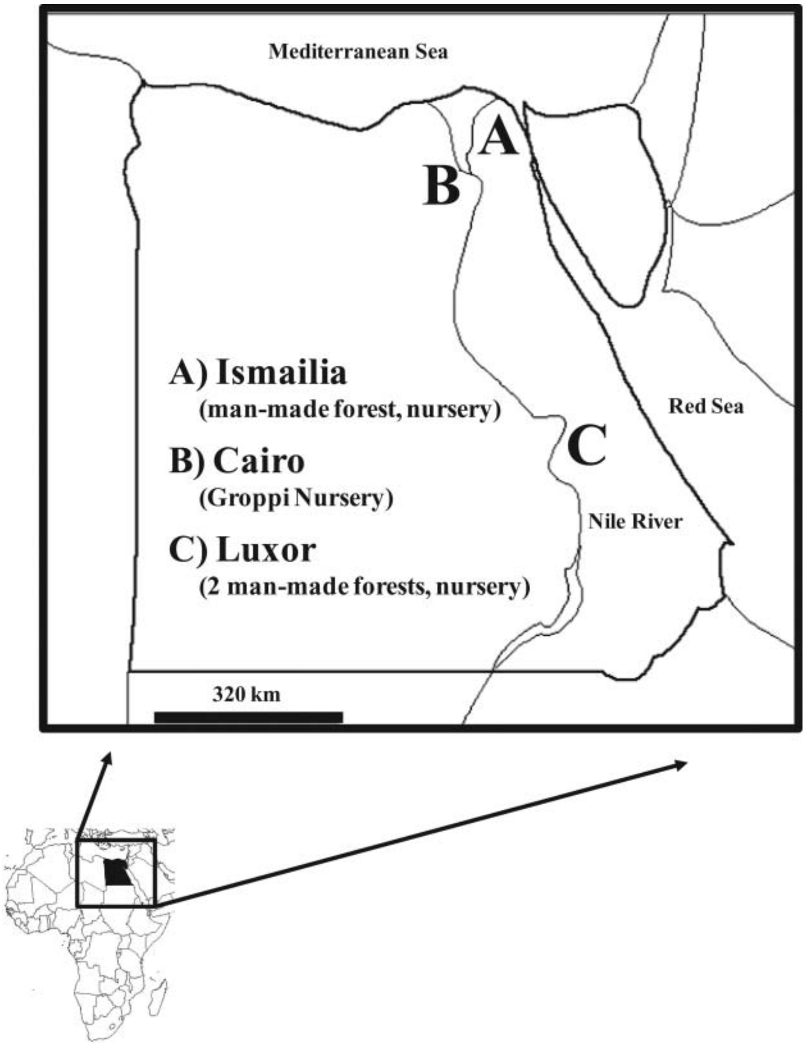

Figure 1 Egyptian man-made forests and tree nurseries evaluated during the technical assistance mission.

soils of the desert fringes have developed from Eocene or Miocene limestone or from Nubian sandstone. Soils developing from limestone generally will have higher pH than soils developed from sandstone, and may have free calcium carbonate ($CaCO_3$). The pH of the surface soil at the Luxor demonstration site was alkaline to strongly alkaline, 8.0 to 8.5. It is possible that other sites will have soils with somewhat lower pH. Soil reaction is important to species selection and is discussed below.

Climate is hot and dry. The mean maximum temperature for the hottest month ranges from 35.7°C in July at Ismailia (Lower Egypt) in the north; 41.4°C in June at Luxor (Upper Egypt); and 41.0°C in June and July at Aswan in the extreme south. Relative humidity (RH) is often increased by air masses moving in from the Mediterranean and Red Seas. This is most pronounced at Ismailia, where RH in June and July averages 50%. This effect is seen less at Luxor, where RH in June and July averages 30%. At Aswan, RH in June and July is

20%. In coastal areas of southern Sinai (Egypt in Asia), mean maximum temperature at Ras Nsrany near Sharm El Sheikh is 37.5°C in July and 37.4°C in August. Relative humidity in July and August averages 35% and 36% (data from http://www.climate-charts.com/; last accessed 7/1/10).

Irrigation Status

The demonstration projects visited by the technical assistance team (Figure 1) have shown that some tree crops can be grown under the prevailing site conditions in Egypt using TWW. The water requirements of the species in trials have not been established and because of the seemingly arbitrary irrigation regimes, we concluded that experience to date has not established which species can or cannot be grown, or even which ones are the most promising species selections. This situation is confounded because of uncertainty about the origin of the plant material. Our conclusion is also based on observations that irrigation regimes have not been adequate as shown by drought stress and tree death at Ismailia and the Groppi Nursery and lack of an engineering basis for irrigation scheduling at any of the sites visited.

We emphasize that successful irrigation of any tree species demands careful irrigation system design, irrigation scheduling based on the best scientific knowledge available, on-site measurement of weather data, and ongoing maintenance and repair of the irrigation system from pump intake to emitters and/or spaghetti tubing. With the higher water users such as poplar, success will also require a willingness to adapt manually run systems to automatic control in order to increase irrigation frequency to more than daily so as to prevent deep percolation losses and consequent aquifer contamination. See Evett et al. (2011, this issue) for a detailed description of irrigation strategies for increasing woody crop production using TWW in Egypt.

Favorable Traits

Species selection is dependent upon choosing trees species (and genotypes within species) that are able to be grown under Egyptian conditions, including potential contaminants in the TWW. It is also necessary for the trees to provide an economically desirable product. Given the local soils, water quality, and water quantity, the following is a list of the most important favorable traits that should be considered in species selection. The first four characteristics are essential, while the last two traits are desirable.

1. Fast-growth, although this is relative to the quality of the wood or other products produced. Generally, fast growth is suitable for pulpwood and materials for panel products but not for sawn wood products because of the often lower density of fast grown wood. Some species (e.g., *Populus* and *Eucalyptus*) that traditionally have been grown fast in plantations are now being managed for sawn wood by lengthening rotations, aggressive thinning, and early pruning (Stanton et al. 2002; Flynn 2008).
2. Tolerance of sandy soils of high reactivity (pH and/or salinity).
3. Tolerance of high temperatures and insolation.
4. Ease of propagation, including a reliable seed supply if seedlings are used.
5. Evergreeness is advantageous but not essential; this allows the plantation to utilize TWW year-round.

6. Some drought tolerance or adaptation in order to reduce the risk of failure if water supply is disrupted.

It should also be noted that nitrogen-fixing and shallow-rooted species should be avoided. The TWW contains enough nitrogen (N) for optimal growth, and adding N would increase the risk of nitrate leaching. Shallow-rooting would increase the risk of windthrow and reduce the contact time with TWW, thus increasing the risk of deep percolation losses and groundwater contamination. In circumstances where wastewater disposal is the primary motivation for creation of a forest irrigated with TWW, a high transpiration rate could be added to this list. However, a desirable outcome for the IWRM II project would be to have a successful afforestation effort that was economically and ecologically sustainable. High transpiration rate is not necessarily the means to this end. Since the cost of land is nil in this circumstance, it may be that larger irrigated areas and greater production are more favorable to economic and ecological sustainability.

Species Selection

The overarching strategy for species selection includes the establishment of species/provenance trials with 5 to 10 individual candidates at each site, stratified by climatic region (e.g., high, medium, low relative humidity in the hottest months). To select individuals for the trials, it is important to favor species for which there is much knowledge internationally, as well as some species with high potential market value. Egypt meets almost all its wood demand through imports, with limited local supplies coming from thinning and cutting of nut and fruit trees and urban plantings. The mostly desert climate with minimal rainfall produces few native tree species. In 2005, total lumber imports (softwood and hardwood) were estimated at 3.7 million cubic meters, mostly in the form of kiln-dried lumber (Giles and Ibrahim 2006). Given this, there is a potential demand for domestic wood production. Therefore, recommended species were grouped into three classes according to market groups: (1) pulpwood or sawnwood (versatile species)—pine (*Pinus* spp.), eucalyptus (*Eucalyptus* spp.), poplar (*Populus* spp.); (2) high value products—mahogany (*Khaya ivorensis* A. Chev.), teak (*Tectona grandis* L.); (3) pulpwood—beechwood (*Gmelina arborea* Roxb.). The species are characterized according to suitability and growth potential (Table 2). For species rated "Fast Growth" the expected rotation duration is 15 years or less. Suitability is evaluated in terms of adaptation to Egyptian conditions, including average maximum temperature of the warmest month (in its native range), evergreeness, economic uses, and ease of propagation. Adaptations to drought and high pH or saline soil are noted. Growth potential is in terms of reported volume growth (m^3 ha^{-1} yr^{-1}) and height (m), as well as form (poor, acceptable, exceptional). The column for "local experience" notes whether there is local experience in Egypt with the species as evidenced by urban plantings, nursery production, and use in manmade forests.

BENEFITS AND CONSEQUENCES OF THE TREE SPECIES IDENTIFIED

For all tree species, the need for intensive management at sites where weed control may be an issue could result in high costs during stand establishment and management. Loss of funding for such efforts could be very detrimental, especially before crown closure.

Table 2 Candidate tree species with potential for successful afforestation under the hot and dry conditions in Egypt using treated wastewater

Species	Local Experience	Fast Growth	Temperature Max (°C)	Evergreeness	Economic Uses	Saline/High pH Soil	Drought	Ease of Propagation	Volume (m^3 ha^{-1} yr^{-1})	Height (m)	Form	Native
Pulpwood or Sawnwood												
Pinus caribbea var. *hondurensis*		Yes	34	Yes	SRF			Stores 2+ yr	10 to 40	35 to 45	A	CAMER
Pinus caribbea var. *bahamensis*		Yes	32	Yes	SRF	Yes		Stores 2+ yr	10 to 28	15 to 20	E	BI
Pinus eliottii var. *densa*		Yes	32	Yes	SRF			Stores 2+ yr	10 to 20	20 to 30	E	US
Pinus merkusii		Yes	32	Yes	SF			Short viability	8 to 18	30 to 40	A	
Eucalyptus citriodora	Yes	Yes	34	Yes	SRO		Yes	Stores 2+ yr	10 to 21	30 to 40	E	AUS
Eucalyptus camaldulensis	Yes	Yes	36	Yes	SR	Yes	Yes	Stores 2+ yr	15 to 25	20 to 40	A	AUS
Eucalyptus grandis		Yes	35	Yes	SRV			Stores 2+ yr	24 to 70	40 to 55	E	AUS
Populus spp.	Yes	Yes	32		SRV	Yes		Vegetative	20 to 40	25 to 30	E	US, EUR
High Value Products												
Khaya ivorensis	Yes		40		SRV		Yes	Stores 3 mo	na	15 to 40	A	AFR
Tectona grandis			32		SRV			Stores 2+ yr	6 to 18	30 to 40	E	IN, SEAS
Pulpwood												
Gmelina arborea		Yes	35		SRF			Short viability	18 to 32	20 to 30	P/A	SEAS

Notes: Fast Growth – yes = rotation length less than 15 yrs; Temperature Max = mean maximum temperature of the hottest month in its native range (an indication of adaptation to Egyptian conditions); Economic Uses – S = sawnwood, R = roundwood (pulp and panel products), F = firewood (also bioenergy), O = oils, V = veneer; Saline/High ph Soil and Drought = adaptation to these conditions; Ease of Propagation refers to the ability to store seed or propagate vegetatively from cuttings; Volume and Height = growth averages at maturity (to be used to compare among species rather than as yield predictions); Form – E = exceptional, A = acceptable, P = poor; Native (areas where the species is native) – AFR = Africa (generally western), AUS = Australia, BI = Bahama Islands, CAMER = Central America, EUR = Europe, IN = India, SEAS = Southeast Asia, US = USA.

Pulpwood or Sawnwood (Versatile Species)

Pine (*Pinus* spp.). Both pulpwood and sawnwood systems have been instituted for pine species, including loblolly pine (*P. taeda* L.) and slash pine (*P. elliottii* Engelm.) in the Southern United States and radiata pine (*P. radiata* D. Don) in Australia and New Zealand. In the United States, pruning has not been shown to be economical (Alexander Clark, Research Wood Technologist (Retired), U.S. Forest Service, Athens, GA, personal communication 2008), but low labor costs in Egypt may favor pruning when sawnwood production is the goal. The pine species in Table 2 include two that are tolerant of high pH soils, Caribbean pine (*P. caribaea* var. *bahamensis*) and *P. elliottii* var. *densa*, but it may be that the *hondurensis* and *elliottii* varieties (not shown in Table 1) will do as well and should certainly be preferred for sites with lower pH (below 7.5). Certainly it will be easier to procure seed from commercial sources for the *hondurensis* and *elliottii* varieties.

Eucalyptus (*Eucalyptus* spp.). Eucalyptus trees are planted widely around the world, on small-holder plots as well as industrial plantations. With over 500 species to choose from, and several distinct provenances within most species, there are many possible choices. Nevertheless, only a relatively few species are grown in industrial plantations although some of these have been hybridized. The list in Table 2 includes only three species, two of which were observed growing in Egypt: river red gum (*E. camaldulensis* Dehnh.) and lemon eucalyptus (*E. citriodora* Hook.). Of the two, *E. camaldulensis* has demonstrated some tolerance of higher pH soils and some salinity tolerance. Another species that should be considered for lower pH sites is rose gum (*E. grandis* Hill ex. Maid.) or the hybrids of *E. grandis* with other species. One side-by-side comparison in India (Hunter, 2001) grew *E. grandis*, *E. camaldulensis* and Indian rosewood (*Dalbergia sissoo* Roxb.) on a lateritic soil with irrigation and fertilizer. The yields after 3 years were illustrative; the dry mass of the two Eucalypts averaged 45.3 Mg ha^{-1} and rosewood averaged only 7.6 Mg ha^{-1}. The stem volume growth rate of the two Eucalypts was 20 m^3 ha^{-1} yr^{-1}. Work in Australia confirms that *E. camaldulensis* and *E. grandis* can be grown using wastewater (Stewart and Flinn 1984), although there was some indication of iron (Fe) deficiency on calcareous soils. Irrigation requirement was 1550 mm yr^{-1} using border/strip flooding. In southern Brazil, Bernardo et al. (1998) reported similar yields as Hunter (2001), although Timor white gum (*E. urophylla* S.T. Blake) outgrew *E. camaldulensis* after 41 months. Also in Brazil, an *E. grandis* hybrid grown for pulpwood had a peak growth of 95 m^3 ha^{-1} yr^{-1} on a 6 to 7 year rotation (Almeida et al. 2007). Water use was 1092 mm yr^{-1}. Since economic viability of these afforestation efforts will depend on some early harvest, such short rotations are desirable for some fraction of each plantation.

Poplar (*Populus* spp.). Poplars are ideal for wastewater irrigation systems because of their fast growth and biomass accumulation, quick establishment and extensive root systems, ease of asexual propagation, elevated rates of transpiration, and exceptional growth on marginal lands (Isebrands and Karnosky 2001). These traits are favorable for wastewater afforestation projects because of the need for quick plot establishment, hydraulic control, and filtering capabilities to reduce subsurface contaminant movement (Ferro et al. 2001). Poplar productivity worldwide typically ranges from 10 to 20 Mg ha^{-1} yr^{-1}, with values exceeding 20 Mg ha^{-1} yr^{-1} being more common in recent years due to growing improved genetic stock at favorable sites (Stanturf et al. 2001). Poplars utilize a substantial amount of water, which is beneficial for afforestation systems in need of recycling wastewater (Zalesny et al. 2006), assuming allowable irrigation application rates are suitable for evapotranspiration demands of the plantations. For example, in sandy soils the required application rates may exceed the water holding capacity of the soil in the root zone, leading to the possibility of deep percolation losses and ground water contamination.

Despite the potential for improved environmental quality and secondary benefits such as carbon sequestration, a harvestable product, aesthetic improvements, improved landscape processes, and erosion control (Isebrands and Karnosky 2001), there are potential limitations to the successful use of poplar for wastewater afforestation projects in Egypt. First, while elevated water usage is an advantage of poplars for such wastewater projects, it can also be an important disadvantage during times when wastewater is not available. Given the broad amount of genetic variation, some clones can withstand periods of drought while others cannot. Second, as mentioned above, genotype × environment interactions are very important for poplars, with failure to match clones to sites of deployment often resulting in reduced growth or plantation failure.

High Value Products

Mahogany (*Khaya ivorensis* A. Chev.). Growth of mahogany (Figure 2) (based on modeling results from thinned natural forests) is around 31 m^2 ha^{-1} (basal area; Foli et al. 2003). From the modeled crown diameter-bole diameter work of Foli et al. (2003), a recommended spacing and silvicultural regime can be developed that appears to be very similar to the system for *Tectona grandis* used in Costa Rica (Pérez and Kanninen 2005). The biggest drawback to growing *K. ivorensis* in plantations is that in its native range in Africa it has been attacked by a shoot borer, *Hypsipyla robusta* (Ofori et al. 2007). Damage extends from mortality of young seedlings to forking of mature stems at 5 m. Newton

Figure 2 Two-year-old mahogany (*Khaya ivorensis* A. Chev.) growing in the desert approximately 10 km south of Luxor, Egypt. Notice irrigation furrows between trees within the plantation rows. Photo by Dr. Ron Zalesny Jr., U.S. Forest Service. (Color figure available online).

Table 3 Stand growth scenario for *Tectona grandis* on a medium site, 20-yr-rotation, with the objective of maximum volume production (adapted from Pérez and Kanninen 2005)

Age	Density (stems ha^{-1})	Thinning Intensity (%)	Diameter at Breast Height (cm)	Total Height (m)	Residual Basal Area (m^2 ha^{-1})	Basal Area Removed (m^2 ha^{-1})	Volume Removed (m^3 ha^{-1})
5	667	40	11.5	11.5	6.9	4.6	28.4
10	400	40	20.9	19.7	13.7	9.1	75.5
15	300	33	27.6	25.2	17.9	4.2	35.6
20	0	100	32.1	28.7	0	24.3	224.6

et al. (1994) suggested the solution would be a combination of resistant populations with an appropriate silvicultural system of mixed species. Mixing the mahogany with another species apparently lowers the detection of mahogany by the borer. Ofori et al. (2007) found some progeny to be resistant and it may be possible to develop borer-resistant material by vegetative propagation from superior individuals. Growth in shade also reduces the infestation by the borer but shade also severely reduces growth of mahogany (Opuni-Frimpong et al. 2008). Where mahogany has been planted outside its native range, it seems to be resistant to indigenous borers. The older mahogany we observed in Egypt, however, all seemed to fork between 2 and 3 m, possibly from borer damage.

Teak (*Tectona grandis* L.). Market demand for teak has outstripped the capacity of native forests to provide feedstock; and plantations have been established far outside its natural range. Costa Rica, for example, has 40,000 ha of teak plantations but these have not reached the expected productivity (Pérez and Kanninen 2005). Recently, Pérez and Kanninen (2005) developed management scenarios for teak plantations using density management approaches and competition indices to develop guidelines for thinning. Their guidelines appear to be applicable to Egypt, although they were not developed for plantations using TWW. They developed guidelines for plantations of 20 and 30 years rotation length, on low-, medium and high-quality sites. Their results for medium-quality sites would seem to be a conservative estimate for teak plantations using TWW in Egypt. An initial stand density of 1,111 trees ha^{-1} is assumed. This is a spacing of 3×3 m, which is quite common and reasonable to achieve full site-occupancy quickly. Thinning occurs every 5 years; only the results for 20-yr rotation with the objective of maximum volume are shown here (Table 3). The total volume removed under this scenario would be 364 m^3 ha^{-1}.

Pulpwood

Beechwood (*Gmelina arborea* Roxb.). Beechwood is among the leading plantation species in the world. Another native of Australia, beechwood grows well on deep, well-drained and fertile soils but generally develops poor form. Thus, most of the world's beechwood is used for pulp or bioenergy. Production rates in Nigeria are typical of beechwood growth; Onyekwelu (2004) reported on even-aged plantations 5 to 21 years old where aboveground biomass ranged from 83.2 Mg ha^{-1} (5 years) to 394.9 Mg ha^{-1} (21 years). Mean annual biomass increment varied from 16.2 to 20.9 Mg ha^{-1} yr^{-1}, with an average of 84% of biomass allocated to stems and 13% to branches. Stand densities ranged from 837 to 1,275 stems ha^{-1}.

STRATEGIES TO MAXIMIZE THE POTENTIAL OF AFFORESTATION

Improving Water Quality

Water quality improvements associated with the use of TWW for irrigation of tree plantations in the desert areas outside of the Nile Delta derive mainly from: (1) the avoidance of return flow of TWW as surface water to the Nile and its tributaries, and (2) avoidance of the return of these waters to the alluvial aquifer as could happen through deep percolation losses associated with irrigation of delta soils. Even where deep percolation occurs, there should be substantial improvements in the quality of TWW through uptake of nitrogen and phosphorus by the tree crops and the filtering out of organic matter by the soil. Still, there are substantial possibilities for movement of pollutants to ground water, perhaps most importantly in the form of nitrates. For example, nitrate was found to range from 12.4 to 35.0 mg L^{-1} in the TWW at Luxor (IRG 2005b). Deep percolation of water under surface irrigation can be expected, but is possible even under drip or sprinkler irrigation if systems are not well designed to ensure adequate wetted soil percentage and if they are not managed to avoid exceeding the permissible application rate given the rooting zone depth and wetted soil percentage. For example, Evett et al. (2000) found deep percolation of water to at least the 3-m depth in deep sand at Ismailia under sprinkler irrigation of maize.

Also, the movement of salts that are initially present in desert soils and in TWW cannot be ignored. Ground water monitoring should continue for nitrate and total dissolved salts (TDS) at a minimum. For example, analysis of the soil at Luxor showed it to be sandy with high pH (8.05 to 8.45) and EC (3.5 to 7.4 dS m^{-1}), which would indicate the presence of considerable salt (IRG 2005b). The sandy texture would enhance deep percolation losses of irrigation water to the ground water, which is at 18- to 20-m depth. Initial nitrate tests at the site can serve as a baseline against which future ground water samples are compared. The water testing protocol included tests for turbidity, pH, biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), residual chloride, oil and grease, heavy metals, nematode cells/eggs, *E. coli*, and/or fecal coliform. The ground water monitoring protocol specified tests for depth to water table, pH, electrical conductivity (EC), nitrates, and fecal coliform. It cannot be over emphasized how important it is to establish monitoring wells (at least 3) at each tree plantation, to make initial measurements of ground water quality to establish a baseline for comparison, and to repeat tests yearly to monitor for rising ground water, nitrates, salts and bacteria.

Uniformly, responses to our questions about quality of TWW emphasized the lack of any problem with heavy metals, which are all below limits established by the government. Still, soils should be initially tested for heavy metal content, and then periodically re-tested to confirm that a buildup of heavy metals is not occurring. One concern is that when tree harvest occurs, perhaps after 20 years of growth and gradual build up of organic matter in the soil, which may sequester heavy metals and other pollutants, there may be a flush of pollutants to ground water as root systems perish after harvest. The likelihood of this occurring can be assessed by the periodic re-testing of soils to the depth of the root zone, which increases with time.

Maximizing Resource Production

Maximizing the potential of afforestation efforts requires judicious choice of species, development of quality planting stock, and appropriate methods for plantation establishment and management, including initial spacing, thinning regimes, and very importantly, appropriate irrigation regimes for the site and species.

Choice of species. While suggestions have already been made for species selection (Table 2), it is important to reiterate that the best choice of species cannot be made at this time as too little is known about performance of key species in Egyptian growing conditions. Information about markets is also generally lacking. Nevertheless, a prudent strategy is to increase system success with early genotypic screening and selection trials prior to deployment in field-based production systems. Such testing is referred to as "phyto-recurrent selection" and involves the evaluation, identification, and selection of favorable species and genotypes using multiple testing cycles (Zalesny and Bauer 2007; Zalesny et al. 2007). Developed specifically for phytoremediation projects, phyto-recurrent selection is directly applicable to wastewater afforestation efforts in Egypt. Information about each species (genotype) increases with subsequent cycles, while the number of species (genotypes) tested decreases. Successful establishment is the first biological requirement for long-term ecological sustainability. Thus, genotypes that are successful in greenhouse, growth chamber, and/or nursery cycles are more likely than those that are erratic to produce adequate biomass for end products; they are also effective biological filters for uptake, storage, utilization, or volatilization of potential wastewater contaminants (Hasselgren 1998; Erdman and Christenson 2000; Moffat et al. 2001).

Given the short timeframe over which afforestation efforts are needed in Egypt, as well as the limited amount of resources for detailed testing strategies, we propose a modification to the program described above. We recommend multiple selection cycles within a short time period that can be conducted with limited resources. Rather than conducting initial phyto-recurrent selection cycles *ex situ*, genotypes should be selected based on current growth and favorable productivity in similar climates and should represent a broad range of parental species and genotypes. Trees should be planted at available field sites in cycle 1. Separate tests should be made under the different climatic conditions, particularly the range of relative humidity. Within even a provenance, there may be land races with variation in stomatal control such that one land race would do better than another under high heat loading and evapotranspirative demand. After two years of field establishment (cycle 2), sites should be inventoried, tree height, diameter, or equivalent surrogate for tree health recorded, and final genotypes selected. The elimination of unsuccessful genotypes at the earliest selection cycle is imperative to the final goal of field deployment of well-suited genotypes (Zalesny et al. 2007). Thus, those genotypes that are not suitable for wastewater afforestation efforts in Egypt should be thinned out of the plantings, followed by replanting with the favorable clones during year 4 or 5, with cycle 3 lasting until final harvest. Unsuitable genotypes can be replaced at any time during development, and additional cycles can be added, if resources are available.

Planting Stock. A factor in species selection is having readily available material (seeds or cuttings) to develop planting stock when needed. For seeds, this means that seeds are readily available for purchase or collection, or that seed can be stored for extended periods. Because mast development in seed trees may be infrequent or irregular, seed that can be stored for a year or more without substantial loss of viability is important. Most of the species identified in Table 2 are readily available because seed can be stored for more than a year.

There is a need for nursery research to identify what constitutes acceptable quality of seedlings. While some general guidelines exist, particularly for widely planted species such as Eucalyptus and pine, the definition of a quality seedling must be based on performance after outplanting under the local climate conditions, water quality, and irrigation regimes. Recent research with hardwood seedling quality in the Southern United States suggests that the biggest seedling is seldom the best performer (Jacobs et al. 2005). Two key parameters with any species are getting the correct balance between roots and leaves (the root/shoot ratio) and having sufficient development of lateral roots on the seedling. In many nurseries, this involves periodic root pruning (Mbora et al. 2008) to encourage development of lateral roots, retard rooting into the underlying soil when open pots are used, or to avoid J-rooting in closed pots (as was observed at Luxor). One thing to keep in mind is that planting with immediate and effective irrigation reduces the need to develop seedlings with large taproots.

Once the target "optimal" seedling ideotype is developed, nursery management can be optimized to produce quality seedlings. All nurseries will need to develop proper spacing in nursery beds to develop quality seedlings with few culls. Although labor to cull seedlings is not a problem, quality control could be. Spacing varies by species and desired product, with a typical spacing for fast-growing species being 1,111 stems ha^{-1}. For a 100-ha plantation stand to be planted in a year, this requires 111,100 quality seedlings. If cull rates are 40–50%, a nursery would have to produce around 250,000 seedlings annually to meet the need, which is on the order of the capacity of the Groppi Nursery (Figure 1). Moreover, for vegetatively-propagated material such as poplars (and possibly other species), a local source can be developed from material that is initially purchased. A cutting orchard can be established but must be maintained and renewed as needed.

Plantation Establishment

Plantations can be developed for fast-growing pulpwood species with rotations of less than 10 years, for versatile pulpwood/sawnwood species with 15- to 20-year rotations, or for high-quality species grown for 20 to 30 years. It may also be desirable to grow mixed species plantations, combining fast-growing and high-quality species although this presents difficulty with irrigation management as plant water needs will be quite different if tree growth rates differ greatly. Harvest would also be problematic. A compromise would be block mixtures, rather than intimate mixtures, where a single species is planted for several rows, then another species for several rows. Obviously, this places greater demand on the irrigation system design and on the manager to control irrigation timing and amounts. Mixed species plantations will provide insurance that there will not be a total failure from pest, disease, or moisture stress (if irrigation supply is disrupted). Inter-planting fast-growing species with slower growing ones could provide needed protection for some species as well as the potential for early returns. Another possibility is to choose species that coppice readily. A caution, however, is that coppicing may not be advisable when using TWW. Experience in Australia (D. Lamb, personal communication) is that Eucalyptus species grew well with treated tannery wastewater but coppice was a failure, possibly from pathogens entering through logging wounds. All these possibilities affect the spacing between seedlings and between rows.

Choice of spacing must balance the need to capture site resources as quickly as possible (generally taken as achieving crown closure) with the avoidance of mortality due to self-thinning (mortality caused by inter-tree competition for resources). If spacing is too wide, branches may develop on the lower bole and reduce log quality. If spacing is too narrow, growth of individual trees is slowed and the potential for self-thinning (mortality) increases. Intentional thinning can be undertaken to remove material before it dies and trees can be pruned to remove branches before they get so large that they reduce bole quality.

Either intervention is a cost that must be carried until the end of the rotation. If spacing is wide enough, however, the thinnings may remove material large enough to be sold and pay for the costs of the thinning (thus a commercial thinning, as opposed to a pre-commercial thinning where costs must be absorbed). The rate of tree growth on a particular site, labor costs, and the existence of local markets for small diameter material must all be considered in deciding on an initial spacing, often before there is any information on growth rates (Evans 1992). In Egypt, local need for wood probably means that all thinnings and prunings will have ready markets. That plus low labor costs mean experience in other countries may not be totally applicable. Thus, narrower pulpwood spacing, with early thinning and possibly pruning, may be more profitable than wider spacing.

Spacing trials will be needed to identify optimum spacing. Initially, we recommend spacing of 3×3 m for high-value species and 3 by 1.5, 2, or 3 m for versatile and pulpwood species. The 3-m-wide space between rows allows for access to maintain irrigation lines and growing space for the trees, even under intensive pulpwood management. Research may determine that narrower spacing is feasible under TWW irrigation.

Development of plantations with irrigation rows or drip lines oriented parallel to the expected strongest wind will reduce drag and windthrow potential. Experience with poplars in the western United States was that roots seemed to follow irrigation lines and trees were more windfirm if rows were oriented in the same direction as the wind. It may be desirable to develop permanent windbreaks around the plantations to reduce turbulence at the forest edge, which may also reduce transpiration, and which will reduce blown sand damage to young seedlings and windthrow of mature trees.

Planting time should be when temperatures are the lowest in order to reduce moisture stress on the seedlings until they develop a better root system. At Luxor this was in the Spring (February to April or May) and the Fall (November and December). Skips and dead plants should be replaced within one year of planting to maximize returns.

Increasing Biodiversity

The vast majority of wastewater treatment sites, and consequently afforestation sites, are located along the periphery of the Nile valley and Red Sea coast. Both the Nile valley and the Red Sea coast represent important corridors for migratory bird species. Egypt lies along the Great Rift Valley flyway, which more than 500 million birds traverse on a biannual basis as they head south to wintering grounds in Africa and then return north for the summer breeding season in Europe and Asia. The Nile valley is a key piece of this flyway and bird habitat within the riparian corridor is under constant and increasing pressures from shrinking habitat, urban development, and industrial and agricultural pollution. Wetlands have been drained, rangelands have been overgrazed and each year migrating birds encounter less and less stopover habitat suitable for resting and foraging.

With over 84,000 ha dedicated to afforestation activities, the Government of Egypt will create important habitat for these migratory birds. During the team's visit, birds were present and easily observed at the manmade forests that already provide suitable habitat for rest and foraging on the outskirts of urban centers. Black storks were observed near the Luxor manmade forest as they climbed a thermal to continue their migration north. Newly forested areas created by afforestation activities in the Nile valley will augment the decreasing habitat of these migratory birds and contribute to biodiversity conservation along a globally important migratory bird corridor.

That being said, afforestation efforts will likely attract birds, mammals, and other fauna that were not at the site previously. The potential long-term impact is that some of these species may attempt to utilize the contaminated wastewater, or may be directly affected by its application (i.e., belowground arthropods, etc.). The likely strategy to mitigate potential impacts on these populations is to continuously monitor what species are using the forests, assess whether they show negative impact, consider supplying alternative drinking water sources where drip systems are used, and utilize adaptive management to alter practices according to potential impacts.

Afforestation by definition will change local conditions. Exotic tree species will be introduced into a hot desert ecosystem and change microclimate. Because the afforestation will be located on desert land, no native vegetation will be displaced. Although noticeable within the stands, the changes in microclimate caused by the irrigation and afforestation will be localized. The scale of the afforestation blocks are too small to have regional effects such as has been suggested for very large-scale afforestation in China (Liu et al. 2008).

Limiting Commercial Inputs

Commercial inputs of nearly all afforestation efforts include site preparation, stand establishment, stand management, irrigation and timber harvest. Overall, commercial inputs for afforestation in Egypt may be less compared with other regions of the world, except for the irrigation component (see Evett et al. 2011, this issue). Because the land allocated to the project is desert, there are no land costs and site preparation costs for the first rotation will be minimal. Site preparation for plantation-grown trees typically consists of mechanical treatment, chemical treatment, or both to remove most of the competing vegetation. Specifically, leveling or disking a site is common, followed by application of a pre-emergent herbicide. Furrowing or trenching may be needed but depends on the specific species used. Intensive site preparation should be minimal in Egypt because the desert soils lack competing vegetation during the site preparation stage. The wastewater should provide most or all of the macronutrient fertilization needs, although micronutrients may need to be supplemented using commercial fertilizers.

Limiting commercial inputs during stand establishment depends on the species planted, which determines the type of planting stock needed, as well as the necessary equipment for planting. Given Egypt's capacity for rearing their own planting stock at nurseries (such as those visited by the team in Luxor, Ismailia, and Cairo—Figure 1) there should be minimal need for commercial inputs, except in the beginning of the program when genetic material from sources outside Egypt will be most needed (e.g., poplar clones). The majority of commercial inputs during stand establishment and stand management will be related to the irrigation system.

Commercial inputs for plantations often include application of fertilizer that is based on nitrogen requirements of the trees. Depending on the macro- and micro-nutrient concentrations of the wastewaters, these expenditures will likely not be necessary. Wastewater used as a fertigation source may supply water and elemental nutrients at a lower cost than traditional sources (Erdman and Christenson 2000; Duggan 2005). Other inputs include herbicides and insecticides, the needs for which are difficult to predict before plantation establishment. Depending on the desired end product, some pruning may also be necessary.

The most substantial commercial input during timber harvest will be fuel for harvesting equipment, as well as haul trucks and/or ships. This can be especially high in Egypt if processing facilities are limited. Economic analyses are needed to assess the potential for siting facilities near locations where wood can be harvested and delivered efficiently and in a manner that minimizes the amount of transportation fuels needed. But highly efficient processing depends on an abundance of one or several similar wood species at a given location, conditions that may not be met by diversified afforestation projects.

POTENTIAL LONG-TERM IMPACTS ON THE NATURAL RESOURCE BASE FROM AFFORESTATION AND ASSOCIATED MITIGATION STRATEGIES

The primary objective of the wastewater afforestation projects is to maximize tree biomass accumulation while minimizing impacts of wastewater chemistry on tree health, as well as negative impacts on water and soil quality, and on populations of fauna that are utilizing the newly developed forest ecosystems (Zalesny and Bauer 2007). Potential long-term detrimental impacts on the natural resource base from afforestation are related to the wastewater rather than the trees.

The primary concern is direct leaching into the soil and ground water aquifers as a result of irrigating with volumes of water that exceed allowable application rates as determined by percentage wetted surface area, rooting depth and ET levels. Transpiration capacity will range across the tree species and should be monitored to reduce impacts from excessive leaching. Strategies to mitigate these impacts are included with the recommendations for irrigation described in Evett et al. (2011, this issue) but an important sub-objective of the afforestation, regardless of tree species used, should be to utilize the trees for removal and sequestration of excess nutrients and chemicals found in the wastewater to prevent such leaching. In addition, it is important to test tree leaves for concentrations of specific wastewater constituents in order to assess the potential impact of releasing these contaminants into the soil from abscised leaves. These concerns have been articulated for heavy metals in Europe (Laureysens et al. 2004) and are likely to need attention in Egypt.

One advantageous strategy to mitigate these potential impacts is to select tree species and/or specific genotypes that may sequester less of the contaminant in the leaves and more in their wood. The most efficient strategy, however, is to routinely test the concentration of potential contaminants in the wastewater and tree leaves to assess whether some type of leaf collection or reduction of irrigation volume is necessary.

As Evans (1992) points out, a large-scale plantation project requires an on-going commitment to refining species and cultivar choices, identifying or creating new material that will perform better for subsequent rotations. Species and provenance selection and irrigation regime choices cannot be made exclusively from literature study and site data. One of the reasons that an introduced species does well in new locations is that it may be free of native pests and pathogens in the new location. This is one of the reasons that Eucalypts do better in other countries than in their native Australia. Nevertheless over time, it is probable that pests or pathogens will spread or develop. This may be from local species that adapt to the new material or from native pests being imported into Egypt. In today's world of global trade, problems almost certainly will develop over time. This requires an active monitoring program to detect problems before they lead to total failure.

Because these plantations will be developed using TWW, macronutrient deficiencies are unlikely. However, over time it is possible for micronutrient deficiencies to develop, or for nutrient imbalances to occur. A monitoring program should be in place to detect nutrient problems. If conifers are planted, it will be wise to watch for iron (Fe) deficiency. Most planted conifers are adapted to acidic, low-fertility soils and will develop chlorotic needles symptomatic of Fe-deficiency. Iron deficiency was also observed on *Eucalyptus grandis* treated with winery wastes (Stewart and Flinn 1984). This can be corrected by application of micronutrients (foliar sprays or liquids in the irrigation water). Weed problems may develop, especially after the first rotation. We observed ample herbaceous weed development on sites where drip lines were delivering water away from the trees. Although it is unlikely that competition from weeds will be a problem to established trees over the first-rotation, a weed cover could hinder survival of planted seedlings in subsequent rotations. Mechanical control by disking and chemical control using herbicides may be required in preparing sites for re-planting.

Another factor to watch will be fire hazards. Most of the species suggested are susceptible to fire at some stage of their development. While wildfire should not be a problem, human-caused fire (accidental or intentional) cannot be discounted. Sustainability should be a guiding concern for plantation establishment. This includes economic sustainability; not only should the project be designed to generate revenue, but the financial commitment should be firm to establish and maintain the irrigation system, ensure the commitment of sufficient wastewater of suitable quality and quantity delivered in a timely fashion, and provide needed management inputs (such as thinning or pruning, if needed). Ecological sustainability is also needed, which may take the form of certification. This may require development of a new certification standard for exotic species grown in plantations using TWW. Such a certification scheme will no doubt require testing and monitoring of soils to ensure that groundwater is not contaminated. It may also require testing of metals in wood produced, and monitoring of birds, mammals, and invertebrates in the plantations for TWW toxicity.

Identifying and developing markets will be a necessary step once species selections are made. Some markets may require development of processing facilities. Furniture manufacturers, for example both domestic and export, expect to purchase dried and rough sawn wood, although some markets will accept log imports. As noted previously, Eucalyptus species are now grown for saw timber products but this requires careful handling and processing to avoid splitting and other quality problems (Flynn 2008). An emerging market globally is pellet wood for biofuels, especially in Europe to meet national commitments to renewable energy sources. Egypt would seem to be in an advantageous position to serve these markets given the Suez Canal and associated railways. Green certification may be a consideration, however, especially the testing and monitoring of heavy metals in the wood. These points are raised not to directly influence the choice of species, but to highlight the importance of determining as soon as possible the target markets for the wood produced in the TWW plantations.

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