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OPPORTUNITIES FOR WOODY CROP PRODUCTION USING TREATED WASTEWATER IN EGYPT. II. IRRIGATION STRATEGIES

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An Egyptian national program targets annual reuse of 2.4 billion m^3 of treated wastewater (TWW) to irrigate 84,000 ha of manmade forests in areas close to treatment plants and in the desert. To evaluate the feasibility of such afforestation efforts, we describe information about TWW irrigation strategies based on (1) water use of different tree species, (2) weather conditions in different climate zones of Egypt, (3) soil types and available irrigation systems, and (4) the requirement to avoid deep percolation losses that could lead to groundwater contamination. We conclude that drip irrigation systems are preferred, that they should in most cases use multiple emitters per tree in order to increase wetted area and decrease depth of water penetration, that deep rooting should be encouraged, and that in most situations irrigation system automation is desirable to achieve several small irrigations per day in order to avoid deep percolation losses. We describe directed research necessary to fill knowledge gaps about depth of rooting of different species in sandy Egyptian soils and environments, tree crop coefficients needed for rational irrigation scheduling, and depth of water penetration under different irrigation system designs. A companion paper addresses recommendations for afforestation strategies (see Zalesny et al. 2011, this issue).

KEY WORDS: irrigation management, phytoremediation, phytotechnologies, water quality, deep percolation, irrigation systems

INTRODUCTION

With population growth and infrastructure improvements in water delivery and wastewater treatment, the daily volume of available treated wastewater (TWW) in Egypt is expected to increase from 6.3 million m^3 in 2000 to 8.3 million m^3 by 2017. Guidelines for

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safe and direct reuse of TWW for agricultural purposes were approved in 2005 (Egyptian Code 501/2005), providing the legal basis for farmers to irrigate certain crops, particularly tree species, with TWW. The government of Egypt (Ministry of Agriculture and Land Reclamation and Ministry of State for Environmental Affairs) has established 24 manmade forests through the National Program for the Safe Use of Waste Water for Afforestation (MALR 2009). The National program targets an annual reuse of 2.4 billion m^3 of treated wastewaters to irrigate 84,000 hectares (MSEA 2006). At present, approximately 4,340 hectares are under irrigation with TWW, utilizing a total daily volume of 467,400 m^3, mostly in the desert areas bordering the Nile and Nile Delta (MSEA 2006). Some of these forests have been useful for assessing the efficacy of using TWW for afforestation. Since 2004, the United States Agency for International Development (USAID) Mission in Cairo has promoted strategies for water reuse through its Integrated Water Resources Management Project with Egypt's Ministry of Water Resources and Irrigation; and the Mission recently asked a joint USDA Forest Service – Agricultural Research Service technical assistance team to evaluate the feasibility of scaling up such afforestation efforts throughout Egypt.

A companion paper (Zalesny et al. 2011, this issue) describes the background against which this study was conducted. In short, Egypt's share of Nile waters is allocated according to international treaty obligations with Sudan and is fixed at 55.5 billion m^3 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 TWW reuse strategies to increase water availability to meet future demands. The long-term plan envisions private investors operating future forests, leasing the land, receiving TWW, and growing crops according to the Egyptian code, including fiber, energy and oil crops such as *Populus* sp. (poplar), *Jatrophacurcas* L. (jatropha) and *Simmondsiachinensis* L. Schneider (jojoba).However, the technical details of how this can be accomplished remain incompletely known. Therefore, since 2008 Egypt's Ministry of Water Resources and Irrigation (MWRI) has partnered with the USAID Mission in Cairo on the "Livelihood and Income from the Environment – Integrated Water Resources Management II" (LIFE IWRM II) project to: (1) use TWW and produce products with economic value, and (2) evaluate the feasibility of scaling up afforestation efforts throughout Egypt. The USDA technical assistance team traveled to three of the man-made forests in Egypt (at Ismailia and two forests at Luxor), as well as three tree nurseries (Ismailia, Luxor, and Cairo). In this paper we describe TWW irrigation strategies based on (1) water use of different tree species, (2) weather conditions in different climate zones of Egypt, (3) soil types and available irrigation systems, and (4) the requirement to avoid deep percolation losses that could lead to groundwater contamination. A companion paper addresses recommendations for suitable tree species and afforestation strategies based on local soils, water quality, and quantity (see Zalesny et al. 2011, this issue).

IRRIGATION RECOMMENDATIONS BASED ON TREE SPECIES AND LOCAL CONDITIONS

Background

The use of TWW for tree plantations is expected to take place in the desert areas outside of the Nile River delta and floodplain (see Table 1 in Zalesny et al. 2011, this issue). The soil textures are predominantly sandy, loamy sand and coarse sandy with some sandy loams and a few small areas of finer textures; and organic matter content is less than 1% (IRG 2005a). Depending on location, rock fragments may be common to rare, but do not present important challenges. Sandy soils with little organic matter are difficult to irrigate uniformly without deep percolation losses due to their large hydraulic conductivity and small water holding capacity. Providing plant water requirements in a timely fashion will be essential for maximizing productivity. Avoiding over irrigation will be essential to prevent environmental degradation and inefficient water use. Evapotranspiration (ET) rates vary widely from upper (southern) to lower (northern) Egypt, from west of the Nile (drier) to near the Suez Canal (larger relative humidities), and seasonally. Rates of ET also vary widely by species; for example, ET may be as small as the 6 mm d^{-1} observed by Tanaka et al. (2008) for natural teak forests in Thailand during the dry season, and as large as 14 mmd^{-1} for poplar (Shock et al. 2005).

The team concluded that irrigation scheduling based on engineering and plant sciences was not fully realized in the plantations visited. For example, trees at Luxor were irrigated every other day in the nursery and every third day in plantations, without a basis for frequency or volume of irrigation. At Ismailia, we are not certain of the irrigation regime but we were told that *Populus* was irrigated only until established; these trees subsequently died. Likewise, *Populus* trees and those of other species were severely drought stressed at Groppi Nursery in Cairo. At none of the sites was TWW applied in relation to actual crop water requirements, nor were data provided on how much water had actually been applied. In all cases, it seemed there was more than enough TWW available for the intended plantation development. Yet, drought-stressed trees were observed at all sites visited. Improved understanding of water requirements, monitoring of actual amounts of TWW applied, and appropriate silvicultural regimes are critical needs for each species if the pilot projects are to be scaled up to commercial production.

The Egyptian Experience in Reuse of TWW on Woody Trees

Much of the experimental work on use of TWW for irrigation of trees in Egypt appears in student theses, proceedings papers and in reports from various NGOs and consulting companies. There are few relevant peer-reviewed journal references. Poraas (2000) studied the environmental effect of irrigating woody tree species (i.e., Casuarina, Eucalyptus, Salix, Neem, and Populous) on sandy soil using primary TWW at Abu-Rawash farm. The concentrations of heavy metals in soil were increased, particularly in the 0–20 cm depth range. The transfer coefficient of metals from soil to plant showed that all trees were able to absorb Cd, Fe, Zn, Mn, Pb, and Cu, compared with a control irrigated with fresh water. Heavy metal contents in different polluted locations at Abu Rawash farm, after irrigation with primary treated waste water, were studied by Ahmed (2001). The availability of heavy metals in soil was increased by prolonged irrigation with sewage water. Also, the average values of the total content followed the order of Ni $>$ Pb $>$ Cr $>$ Co $>$ Cd, but the average values of the available content followed the order, Pb $>$ Ni $>$ Co $>$ Cr.

An experiment conducted at Orman Botanical Garden, Giza, in sandy and calcareous soils involved irrigation with both primary TWW and with a 1:1 blend with fresh water of a *Dodonaeaviscosa* L. plantation (Shahin and Poraas 2005). Concentrations of Cd and Pb were increased in leaves and roots of plants irrigated with primary TWW compared with the control, but did not cause toxicity for plant growth. The soil concentrations of both Cd and Pb were increased, particularly in the soil surface. It was found that $CaCO_3$ caused chelation of Cd and Pb.

To evaluate woody trees as hyper accumulators of Cd and Pb, Poraas (2005) irrigated three species (*Quercusrobur* L., *Acacia albida* Del., and *Macarium Tipu* L.) with sewage water on sandy soil. Soil concentrations of Cd and Pb were 0.176 and 28.4 mg/kg soil, initially. The initial concentrations were relatively high because the soil for this pot study was brought from Abu- Rawash farm, and had been irrigated with primary TWW from Abu-Rawash pump station for at least 25 years. After two years of cultivation, soil concentrations decreased to 0.094, 0.082, and 0.046 mg/kg soil of Cd and 8.88, 8.22, and 3.14 mg/kg soil of Pb for the three species, respectively, and *Macariumtipu* L. was considered the best accumulator of Cd and Pb. Abd El-Naim et al. (2002) studied the effect of irrigation with secondary TWW on landscaping at Orman Botanical Garden, Giza. The results indicated that reuse of TWW improved plant height, density, and fresh and dry weight of Bermuda grass in the first stage of growth. Total contents of Co, Cd, Cu, Fe, Mn, Pb, and Zn in leaves and roots were increased.

El-Sayed (2005) studied the impact of irrigation with secondary treated waste water from Alexandria on soil bio-physicochemical properties and on growth and heavy metals content of some fodder trees (*Acacia saligna* (Labill.) H. Wendl, *Acacia stenophylla* and *Ceratoniasiliqua* L.) grown on calcareous soil at Borg El-Arab. Conclusions were that secondary TWW was safe for irrigation purposes and had improved soil physical, chemical and biological properties, which enhanced fodder tree growth; the content of both macronutrients and heavy metals in tree species were within the permissible levels, which encouraged use of TWW for fodder tree irrigation; and *Acacia stenophylla* responded the most to irrigation, so it was recommended to be irrigated with TWW in calcareous soils in the western coastal region of Egypt, instead of wasting such water to the sea.

El-Arby and Elbordiny (2006) investigated the effect on taxodium (*Taxodiumdistichum*), Italian cypress (*Cupressussempervirens*), khaya (*Khayasenegalensis*), and jojoba (*Simmondsiacohinensis*) of irrigating with secondary TWW from El-Sadat city (industrial TWW) compared with irrigating with well water. Concentrations of Fe, Zn, Cu, Co, Ni, and Pb in the surface soil layer (0–5 cm) were 8.0, 3.4, 3.4, 10.3, 9.6, 7.4, and 3.3 times, respectively, the concentrations in soil irrigated with well water. Total heavy metals in the plough layer of this sandy soil did not exceed permissible levels set by the EU. Khaya was an accumulator of Co, Ni and Pb, while jojoba accumulated more Co and Pb than the other species. Taxodium and Italian cypress accumulated both Ni and Pb.

These studies indicate that irrigation with TWW in Egypt causes some accumulation of heavy metals in soils and plants, but that accumulations do not exceed permissible levels. This picture is clouded by the fact that many soils irrigated with TWW were sandy and had large hydraulic conductivities, while irrigations were often applied using surface flooding (particularly in the past), both of which contribute to a high potential for deep percolation losses. This could mean that heavy metals did not accumulate in the plough layer because they passed through it. We did not find reports of anoxic conditions in the root zone in Egypt, although this has been reported to result from irrigation with TWW in other countries. Again, this may be related to the large hydraulic conductivity and tendency of these soils to drain quickly, which would re-establish aerated conditions.

Irrigation Application Systems

The large hydraulic conductivity means that irrigation by surface flooding in basins or furrows will lead to deep percolation losses of water near the inlet to a tree plot if enough water is applied to adequately irrigate the plot areas furthest from the inlet. We observed two responses to this problem in the plantations that we visited: (1) adoption of what is termed a modified surface irrigation system, and (2) adoption of drip irrigation. The modified surface irrigation system consists of keeping tree plot sizes small (dimensions were variable, but were within several tens of meters, not hundreds) and conveying water to plot inlets using piping, which prevents conveyance losses between the reservoir and plot. We saw various plot sizes, the larger of which were too large for efficient water distribution. Plot leveling was generally adequate to provide for reasonably uniform depth of standing water at full flooding, though this will not eliminate the deep percolation problem nearer to the inlet, which can lead to increased nitrate in the ground water, even in finer textured soils (Eade 2004).

The drip irrigation systems routinely used 18-mm diameter polyethylene tubing of Egyptian manufacture for lateral lines and polyethylene spaghetti tubing of 4-mm diameter for emitters at each tree, one per tree. Compared with even the modified surface irrigation systems, the drip systems are much more water efficient and likely to provide more uniform distribution of water. The fact that spaghetti tubing is used, rather than tortuous path emitters or drippers, should eliminate most plugging problems. Plugging was not observed, but is still possible, which means that routine maintenance of the drip systems will be required. Moreover, the spaghetti tubing has a large flow rate compared to drip emitters and requires a larger pump flow rate and larger lateral line diameter to provide for uniform distribution than would be the case with lower flow rate drip emitters. The irrigation application efficiency of the drip systems we saw was probably on the order of 75%, much smaller than can be obtained with pressure compensated drip emitters. The maintenance required will be both for inspection and cleaning/flushing of the filtering system at the drip system head works, and inspection of spaghetti tubing placement and flow during irrigation. In the older plantations, we observed missing spaghetti tubing and spaghetti tubing that was misplaced, terminating in the interrow between trees, rather than at the base of the tree; both are signs of lack of maintenance.

Biofilm formation was observed in furrows and in basins around drip-irrigated trees (e.g., Figure 1). This is due to the large amount of organic matter in the TWW. Biofilms can have the effect of reducing infiltration rates; but this effect is not predictable or controllable. The drip irrigation systems that we observed were all adequately filtered with two-stage systems and back flushing. We also saw flush-out lines at the ends of drip laterals, another essential system component since lateral lines should be flushed at the beginning and end of each season (or twice a year for continuous irrigation). We saw a limited amount of drip tape with non-pressure compensating integral emitters used in tree plantations. This type of drip tape is common in Egypt and may be a useful alternative to spaghetti tubing if water quality and filtration are good enough to prevent plugging. Another alternative is bubbler irrigation, which requires careful design and siting on flat landscapes (not much elevation difference) but may avoid plugging problems common to in-line drip emitters (Lamm et al. 2006). Hassanli et al. (2007) used bubblers in a drip irrigation system for 14 tree species in Iran and had no plugging problems. If the chosen silvicultural system includes thinning, removal of drip irrigation lines will be required in the thinned row. Because thinning most likely will be by removing entire rows, this will influence the kind of irrigation system used but does not preclude a drip system.

There is typically a large capital cost difference between drip and surface irrigation systems, which makes surface irrigation appear to be more economical. However, two factors tend to balance out the relative cost of these systems for irrigation of tree plots in Egypt. One factor is that the modified surface irrigation systems must have costly large

Figure 1 Jatropha plantation at Luxor Egypt irrigated with one spaghetti tube per plant feeding into a basin. Biofilm formation was observed in the basins, but the amount of water in each basin varied widely, from full as in the near field of this photograph to empty. Since plant size in this plantation seemed fairly uniform, it is likely that infiltration rate reduction was non-uniform rather than irrigation amount being non-uniform. Photo by Dr. Ron Zalesny, U.S. Forest Service.

diameter piping and valves for each tree plot inlet in order to deliver the large flow rates necessary to quickly flood the plots. This considerably reduces the cost differential. The other factor is the expected improved performance of tree growth under drip irrigation due to the better uniformity of water distribution. However, these factors will be rendered of little consequence if irrigation scheduling does not provide water as needed for good tree growth, and if tree cultural practices are not carried out in a timely fashion so that tree boles are free from knots and unproductive growth. Both of these were problematic in one or more of the plantations visited.

Irrigation Scheduling

In the sandy soils to be irrigated with TWW in Egypt, it is essential to irrigate only enough to meet consumptive use in order to minimize deep percolation losses and potential ground water pollution risks. There appeared to be little rationale for irrigation scheduling in the plantations that the team visited beyond general guidelines that irrigation should take

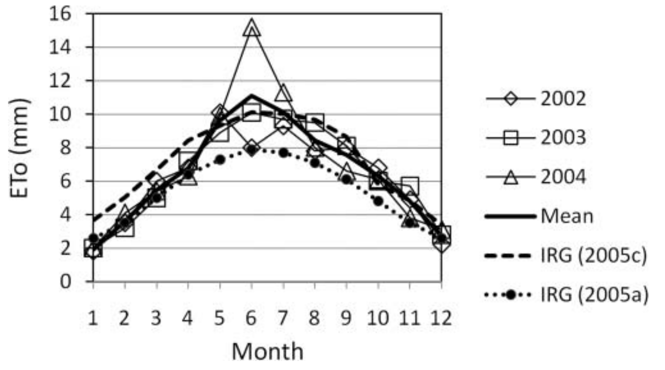

Figure 2 Mean monthly reference evapotranspiration (ETo) for 2002, 2003, and 2004 at Luxor, Egypt, and the monthly mean values over the three years. The extreme value of 15 mm d^{-1} in 2004 is likely the result of an incorrect weather datum, particularly since other data from the same source do not show this outlier (IRG 2005c). Another report gives monthly mean values of ETo that are much smaller in mid year, but match the 2002 to 2004 data in the winter (IRG 2005a). Data from Central Laboratory for Agricultural Climate (CLAC) (www.clac.edu.eg).

place every two to three days in summer and every week in winter. One misunderstanding that was repeated at more than one plantation is that irrigation could be reduced after the trees had become established. This is not true unless the desired outcome is to establish a minimal tree cover and small growth rate. If the desired outcome is near-maximal growth rates (high production), then irrigation rate must increase as the trees grow until full ground cover is achieved or full crown extension is achieved, after which irrigation rate may become essentially stable, but not decline.

In the more populous regions of Egypt, irrigation water demand should not be unduly large since wind speeds are not generally large, relative humidities are often increased by air masses moving in from the Mediterranean and Red Seas, and elevations are low (e.g., 88 m above mean sea level at Luxor). The latter two result in considerable reduction in solar radiation due to atmospheric transmission losses, despite clear skies. These mitigating factors combine to produce reference evapotranspiration (ETo) rates as small as $\sim$2 mm d^{-1} in January to as large as 11 mm d^{-1} in June through July at Luxor (Figure 2), which is more southerly and warmer than most locations considered for afforestation with TWW. Experiments with well-watered crops at Ismailia indicated that peak ETc (crop water use or evapotranspiration) for high water users such as maize and alfalfa ranged up to 10 mm d^{-1} (Evett et al. 2000). It is likely that an upper bound on ETo is 10 mm d^{-1} for most regions being considered for afforestation in Egypt. The evaporative demand in the more populous regions of Egypt is generally less than in some other cultivated regions, for example, the Southern Great Plains of the USA (Figure 3) (Evett et al. 1999). Unfortunately, existing weather data do not appear to be very reliable. One example is given in Figure 2, in which one set of data gave an outlying value of 15 mm d^{-1} for ETo, which was 43% larger than the mean of data from four other data sets for the same location. Other weather data encountered included monthly mean values of ETo $>$ 20 mm for Beni Swaef governorate, which is much too great (250% of peak ETo for nearby Assiout and Menya governorates), and a suspiciously small peak value of 7.9 mm for Luxor in upper Egypt.

Crop water use depends on the weather, tree height, leaf area index, ground cover fraction and the surface resistance of the canopy. The latter is species specific, being larger

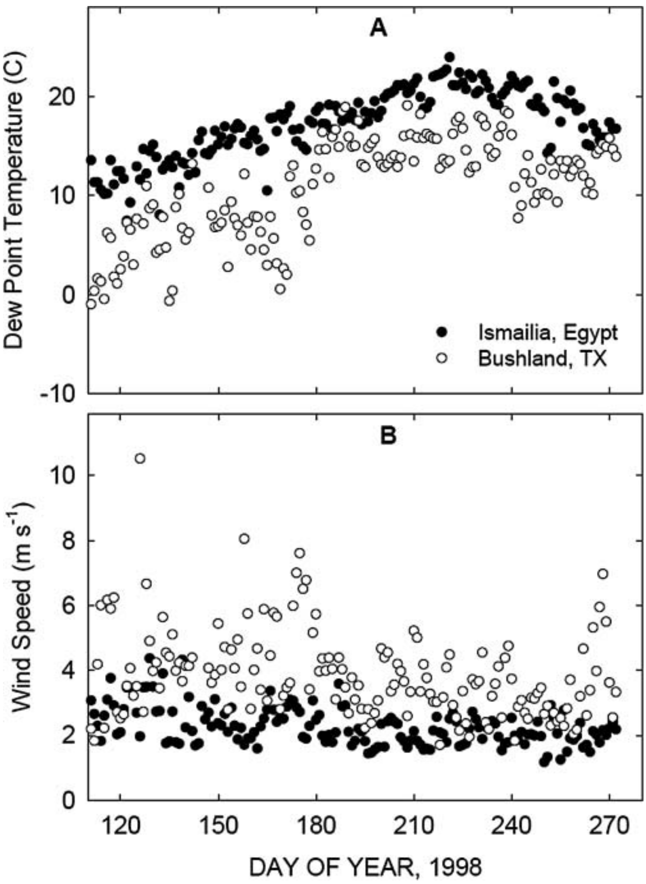

Figure 3 Dew point temperatures and wind speeds for the maize growing season at Ismailia, Egypt and at Bushland, Texas in 1998 (Evett et al. 1999). Larger dew point temperatures indicate more moist air, which when combined with smaller wind speeds leads to less evaporative demand.

for waxy leaved and needle leaved species (e.g., *Pinus*) and smaller for broad leaved species such as *Populus*. Smaller surface resistances lead to larger water use rates. Irrigations are applied to keep up with estimated crop water use (evapotranspiration, ETc) plus any water needed for leaching of salts and any extra water needed to account for inefficiency in irrigation. The ETc is normally evaluated on a daily basis as:

$$\mathrm{ETc} = K\mathrm{c} \cdot \mathrm{ETo}$$

where ETo is a reference ET calculated from weather data (solar radiation, wind speed, air temperature, and relative humidity) using one of the several methods of calculation that are based on the Penman-Monteith formulation, and *K*c is a crop-specific coefficient that is a function of plant growth and is sometimes estimated from the fractional canopy cover or from growing degree days. Recent standardized methods of estimating ETo are from Allen et al. (1998, 2005). The design for the afforestation demonstration site at Luxor contains an example ETo calculation for that location (IRG 2005c), which indicates that ETo varies from 3.4 mm d^{-1} in December to 10.1 mm d^{-1} in June. That report acknowledges that *K*c values are not available in Allen et al. (1998) for the tree crops grown for wood or fuel using TWW in Egypt. And, no *K*c values are available in Allen et al. (2005). Nor can *K*c values be based on the nearest crop category (e.g., fruit trees). Following that recommendation would lead to the same *K*c values being used for jatropha and jojoba, two very different plants, both grown for oil, with different water requirements. In a review of irrigation of tree plantations with TWW in Australia, Boardman (1991) called for "continuous monitoring, adaptive and applied research" to refine irrigation schedules, which were not well known, including both frequency and amount of irrigation as they differ by genotype and cultured environment. The same recommendation applies to the present state of the art in Egypt.

A search for irrigation scheduling guidance from other parts of the world produced little useful information. Guidelines for timber tree irrigation tend to stop at recommendations like "irrigate adequately for normal growth." Irrigation of trees with TWW has been ongoing in Australia for some 20 years, but with the emphasis on maximum use of TWW so that irrigation scheduling is often done on the basis of ETo, with no consideration of any *K*c value to manage irrigation to meet actual tree consumptive water use (Boardman 1991; Eade 2004). In the sandy soils to be irrigated with TWW in Egypt, however, it is essential to irrigate only enough to meet consumptive use if deep percolation losses and potential ground water pollution risks are to be minimized.

Due to the dearth of *K*c values for timber and pulpwood tree species, it is reasonable to use initially the fractional cover approach given in Allen et al. (1998), taking into account the adjustments for partial soil surface wetting that occurs in drip irrigation, climate, and effective ground cover. Any dormancy periods, and the timing of leaf drop and new leaf initiation, are important knowledge needed to apply these equations. The cover fraction is important since young trees cover less ground, receive less solar radiation, have less leaf area and so use less water than larger, older trees. For example, the *K*c of 0.7 recommended for jatropha and jojoba by IRG (2005c) is erroneous for young plants, and may be erroneous for fully grown plants if spacing is large enough to prevent full ground cover. Since aisles are left between these oil crops for harvesting purposes, the *K*c value may never reach unity. Once *K*c is estimated, calculation of actual water requirements can be computed as described in IRG (2005c), taking into account irrigation application efficiency. Often, the daily water requirement cannot be met by a single irrigation because an irrigation of the depth needed would cause deep percolation losses, which could lead to TWW reaching any existing water table. Instead, the water requirement should be met by multiple irrigations, each of which does not exceed an irrigation application depth (IA) that is calculated so that deep percolation losses do not occur.

DRIP IRRIGATION APPLICATION DEPTH AND FREQUENCY DESIGN

The examples of irrigation system design given here illustrate how deep percolation losses, which could cause environmental degradation, can be avoided through design that integrates knowledge of crop coefficient, soil texture, available water holding capacity, allowable depletion level for the desired plant productivity and quality, root zone depth, and the percentage wetted soil surface area provided by a particular arrangement of drip lines and emitters or spaghetti tubing.

Allowable Application Depths and Effect on Required Irrigation Frequency

The allowable irrigation application depth (IA, m) to avoid deep percolation loss is

$$IA = (FC - PWP) \cdot (d_m/100) \cdot Z \cdot (P/100)$$

where FC is water content ($m^3\ m^{-3}$) at field capacity, PWP is soil water content ($m^3\ m^{-3}$) at permanent wilting point, d_m is allowable moisture depletion (percent), P is the wetted soil area (percent), Z is the root zone depth and the units of Z and IA are the same. For a loamy sand soil, the water content at saturation is typically 0.33 $m^3\ m^{-3}$, FC is typically 0.101 $m^3\ m^{-3}$ and PWP is typically 0.066 $m^3\ m^{-3}$ (Evett 2007). Using the allowable moisture depletion of 50% and the wetted area percent of 75 given in IRG (2005c), the IA depth is:

$$IA = (0.101 - 0.066) \cdot (50/100) \cdot 0.5 \cdot (75/100) = 0.0065 \text{ m for a 0.5 - m root zone}$$
$$IA = (0.101 - 0.066) \cdot (50/100) \cdot 1.0 \cdot (75/100) = 0.0131 \text{ m for a 1.0 - m root zone}$$

Thus, irrigation application depths that would largely avoid deep percolation losses in a loamy sand should not exceed 13 mm for a 1-m root zone depth. The value of IA for sandy soils will be slightly less. The wetted area was much less than 75% for the jatropha trees that we saw planted in pits that were irrigated with spaghetti tubing (Figure 1); in fact the basin area was measured to be ~11%. Appropriate irrigation application depths are correspondingly smaller:

$$IA = (0.101 - 0.066) \cdot (50/100) \cdot 0.5 \cdot (11/100) = 0.0010 \text{ m for a 0.5 - m root zone}$$
$$IA = (0.101 - 0.066) \cdot (50/100) \cdot 1.0 \cdot (11/100) = 0.0019 \text{ m for a 1.0 - m root zone}$$

These allowable irrigation depths of 1 and 2 mm will require multiple irrigations in a day to meet jatropha water requirements.

Wetted area percentage, P, is affected by lateral spreading of water as it infiltrates (minor for sandy soils), number of drippers per tree (P increases with number of emitters assuming they are properly spaced apart), and the presence of any basins or soil dikes to control surface flow (such as the basins seen with jatropha at Luxor). The wetted area was likely smaller than 75% for poplar trees that we saw irrigated with spaghetti tubing laying on a flat surface with no depression around the trees, due to the large hydraulic conductivity of sandy soils (on the order of 12.5 cm h^{-1}; AbouKheira and Atta 2008) and the consequent lack of lateral spreading. Formation of biofilms on the soil surface due to the large organic matter content of the TWW may reduce infiltration rate and enhance lateral spreading unless the latter is prevented by basins (Figure 1). But biofilm formation is not predictable or reproducible. Also, there is an important difference between wetted area percentage and tree canopy cover percentage under these conditions. Since tree rooting lateral extent typically reflects canopy cover extent, additional spaghetti tubing should be added for each tree as canopy cover expands.

Jatropha Irrigation Design Example. The irrigation frequency required to avoid deep percolation is the daily crop water requirement (e.g., mm d^{-1}) divided by IA in the same units. Irrigations are then separated during the daylight hours by enough time for the trees to uptake the water applied in each irrigation. As an example, given the ETo, Kc, and irrigation efficiency (Ei) values in IRG (2005c), the water requirements for jatropha vary from 2.8 to 8.9 mm d^{-1} over the year (Table 1). Given the IA values calculated above, the

Table 1 Water requirements (WR) for jatropha at Luxor given ETo and *K*c values from IRG (2005c) and an irrigation efficiency (*E*i) of 0.8, with no extra water added for leaching. Also irrigation application depths (IA) and numbers of irrigation per day needed for 0.5- and 1.0-m rooting depths, and for 75% and 25% wetted areas and 50% allowable depletion. The ETo values were calculated using FAO 56 (Allen et al. 1998)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ETo (mm d^{-1})	3.68	5.03	6.67	8.43	9.33	10.12	10.01	9.66	8.66	5.79	4.85	3.39
*K*c (jatropha)	0.65	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.65
ETa (mm d^{-1})	2.39	3.52	4.67	5.90	6.53	7.08	7.01	6.76	6.06	4.05	3.40	2.20
*E*i (%/100)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
WR (mm d^{-1})	2.99	4.40	5.84	7.38	8.16	8.86	8.76	8.45	7.58	5.07	4.24	2.75
For 0.5-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Irrigations/day	0.5	0.7	0.9	1.1	1.3	1.4	1.3	1.3	1.2	0.8	0.7	0.4
For 1.0-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
Irrigations/day	0.2	0.3	0.4	0.6	0.6	0.7	0.7	0.6	0.6	0.4	0.3	0.2
For 0.5-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Irrigations/day	3.3	4.9	6.5	8.2	9.1	9.8	9.7	9.4	8.4	5.6	4.7	3.1
For 1.0-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Irrigations/day	1.7	2.4	3.2	4.1	4.5	4.9	4.9	4.7	4.2	2.8	2.4	1.5

irrigations per day needed to meet the water requirements vary from less than once per day (all values <1 in Table 1) to 10 times per day. This highlights a major problem with irrigating using a single spaghetti tube per tree, which we saw was standard practice in the plantations we visited, regardless of tree species or whether or not a basin was dug around each tree. Irrigation frequencies more than once a day are high frequency, often referred to as "spoon feeding" the irrigation water. The idea is to apply water in concert with its uptake by the plant. This can only be done effectively using an electronic irrigation controller. Since all of the systems that we saw were controlled manually by opening and closing valves, addition of irrigation controllers would entail important changes in the irrigation system hardware and operational philosophy (less dependence on manual labor). Solenoid valves would have to replace manual values, and power and control wires would have to be run to each solenoid valve. This is standard practice in many countries and is certainly feasible in Egypt. But avenues for reducing irrigation frequency can be approached as well.

The main way to reduce irrigation frequency on sandy soils is to increase wetted area by using multiple drippers per tree. Any basins used should be large enough in diameter to accommodate the spread of drippers. The answer is not to eliminate the basins, which serve a useful purpose in improving irrigation uniformity by preventing runoff in areas where biofilms inhibit infiltration. Using multiple spaghetti tubes alone will be problematic due to the high flow rate of spaghetti tubing, which compromises the pressure distribution in the system as more tubing is attached to the lateral line. But, spaghetti tubing may be used to connect from the lateral line to drippers that regulate flow rate. Dripper flow rate should be chosen so as to maintain system pressure throughout each irrigation block (area irrigated by one valve) in order to ensure acceptable uniformity of application. Maintenance needs will increase since the drippers will be more prone to plugging than the spaghetti tubing alone. However, replacing drippers at the ends of spaghetti tubing is simple. If trees are thinned in the future, spaghetti tubing or its attachment point in the lateral line may be plugged accordingly.

The analysis above and in IRG (2005c) is based on a Kc value of 0.7, which is larger than the Kc for seedlings. As trees grow, the cover factor will increase and the Kc and IA values along with it. Also, the irrigation system may require modification to increase the spread of water as the root zone spreads (additional drippers, probably on the ends of spaghetti tubing). Often, the root zone horizontal area is considered to be equivalent to the crown area. When Kc is not well known, ETc can be calculated from the full-growth Kc value, modified by a factor, Kr, that depends on the plant cover factor as a fraction of total area, G_c, such that $K\mathrm{r} = G_c/0.85$. The divisor of 0.85 indicates that Kc is not completely dependent on cover factor alone, but must be increased in order to account for sensible heat energy from bare soil between plants, which increases ETc.

$$\mathrm{ETc} = \mathrm{ETo} \cdot K\mathrm{c} \cdot K\mathrm{r}, \;\; K\mathrm{r} \leq 1$$

Application of this method requires routine measurement of cover factor, which may be done with a tape measure to measure crown diameter, d, which is then converted to area and then divided by the total area of land per tree obtained by multiplying the tree spacing, S_t, along the row by the spacing between rows, S_r: $G_c = (3.14159 \cdot d^2 \cdot 0.25)/(S_t \cdot S_r)$.

Jojoba Irrigation Design Example. Much more irrigation scheduling work has been done with jojoba than with jatropha since jojoba has been cultivated in plantations in Australia, Israel, USA and other countries since the 1960s. Denham and Rowe (1985) state that rainfall plus irrigation for optimum commercial jojoba production is 500 mm to 600 mm per year in Western Australia. In Argentina, irrigation trials at 0, 300, 600, and 900 mm of water per year showed that yield increased steadily with irrigation amount (Ayerza 1993). No upper limit of irrigation was established. In the United States, annual irrigation amounts vary from 500 to 900 mm for commercial jojoba (NRC 1985). It is likely that irrigation for maximum production in Egypt would approach 900 mm per year. Assuming that Kc remains constant over the year, the daily ETc would range from 1.17 mm in December to 3.49 mm in June, and $K\mathrm{c} \cdot K\mathrm{r}$ would be 0.35 for fully grown jojoba (Table 2). This is reasonable since rows of jojoba are typically widely spaced so that equipment can be driven between the rows for harvest. If narrower spacings are used, then Kc will increase. An analysis of irrigation frequency analogous to that shown in Table 1 shows that irrigation frequency ranges from less than once a day to 5 times per day (Table 2).

Poplar Irrigation Design Examples. Poplar is increasingly grown for sawnwood in the United States and elsewhere due to its straight grain, fast growth, and good wood quality. However, poplar is a freely transpiring plant with very large water use. Here we give examples for both a constant Kc for full-cover poplar assuming no senescence and a probably more realistic scenario in which Kc depends on growing degree days.

Shock et al. (2005) stated that poplar water use can be as large as 14 mm d^{-1}, with seasonal water use equal to 1140 mm in the high desert of eastern Oregon where leaf drop occurs around September 20 and the trees are bare over the winter until approximately April 15. In the first three years of poplar cultivation, they saw a positive response to water applied (irrigation plus precipitation) up to the largest water application of 686 mm in the 1st year, 1143 mm in the 2nd year, and 1448 mm in the 3rd year. They recommended that *at minimum* poplar should be irrigated when soil water potential reaches –50 kPa and with application rates that guarantee 584, 813, and 1041 mm of applied irrigation and precipitation in the 1st, 2nd, and 3rd years (Shock et al. 1999). In the 11th year, seasonal water applications

Table 2 Water requirements (WR) for jojoba at Luxor given ETo values from IRG (2005c), a *K*c value of 0.35, and an irrigation efficiency (*E*i) of 0.8, with no extra water added for leaching. Also irrigation application depths (IA) and numbers of irrigation per day needed for 0.5- and 1.0-m rooting depths, and for 75% and 25% wetted areas and 50% allowable depletion. The ETo values were calculated using FAO 56 (Allen et al. 1998)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ETo (mm d^{-1})	3.68	5.03	6.67	8.43	9.33	10.12	10.01	9.66	8.66	5.79	4.85	3.39
*K*c (jojoba)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
ETa (mm d^{-1})	1.29	1.76	2.33	2.95	3.27	3.54	3.50	3.38	3.03	2.03	1.70	1.19
*E*i (%/100)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
WR (mm d^{-1})	1.61	2.20	2.92	3.69	4.08	4.43	4.38	4.23	3.79	2.53	2.12	1.48
For 0.5-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Irrigations/day	0.2	0.3	0.4	0.6	0.6	0.7	0.7	0.7	0.6	0.4	0.3	0.2
For 1.0-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
Irrigations/day	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.1
For 0.5-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Irrigations/day	1.8	2.4	3.2	4.1	4.5	4.9	4.9	4.7	4.2	2.8	2.4	1.6
For 1.0-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Irrigations/day	0.9	1.2	1.6	2.0	2.3	2.5	2.4	2.3	2.1	1.4	1.2	0.8

(irrigation plus precipitation) of 1476 and 2126 mm resulted in water use efficiencies of 0.00254 and 0.00331 m^3 of wood per m^3 of water (Shock et al. 2008). The reason that so much water was required in eastern Oregon may be due to the "clothes line" effect on small tree plantings in a diversified irrigated farming region. Similar island effects would occur for plantings in the Egyptian desert. Given the amount of water use in a 5-month growing season in the Oregon desert, one can project nearly double that amount of water use for maximum production under a year-long growing season in Egypt. We calculate that *K*c for full-cover, maximum production poplar is approximately 1.5 on average (assuming no dormancy), which translates to an annual water use of 3,910 mm. Frequency of irrigation could be greater than 20 per day for certain situations, particularly if multiple drip tapes or drippers for each tree were not used to increase the wetted area (Table 3).

Gochis and Cuenca (2000) published *K*c values for years 1–3 of hybrid poplar grown at Boardman, Oregon, and found that maximum *K*c increased from 0.44 in year 1 to 0.82 in year 3. Their *K*c values were based on alfalfa reference ET values, which are approximately 1.15 times greater than grass ETo values. Equivalent *K*c values for the grass reference ETo used herein are 0.51 and 0.94 for years 1 and 3, respectively. O'Neill developed relationships between accumulative growing degree days (AGDD) and *K*c for the first three years of cultivation using the Boardman, Oregon data (personal communication 2009).

Lombard et al. (2005), using O'Neill's *K*c(AGDD) relationship, suggested that *K*c values calculated from the Boardman data for one- and two-year old poplar may have underestimated poplar water use in Farmington, New Mexico, where the growing season is longer, precipitation is less, and total pan evaporation is more ($>$1900 mm per season) than in Oregon (Note: ETo is approximately 0.7 times pan evaporation). Mean AGDD

Table 3 Water requirements (WR) for poplar at Luxor given ETo values from IRG (2005c), a *K*c value of 1.5, and an irrigation efficiency (*E*i) of 0.8, with no extra water added for leaching. Also irrigation application depths (IA) and numbers of irrigation per day needed for 0.5- and 1.0-m rooting depths, and for 75% and 25% wetted areas and 50% allowable depletion. The ETo values were calculated using FAO 56 (Allen et al. 1998)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ETo (mm d^{-1})	3.68	5.03	6.67	8.43	9.33	10.12	10.01	9.66	8.66	5.79	4.85	3.39
*K*c (poplar)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
ETa (mm d^{-1})	5.52	7.55	10.01	12.65	14.00	15.18	15.02	14.49	12.99	8.69	7.28	5.09
*E*i (%/100)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
WR (mm d^{-1})	6.90	9.43	12.51	15.81	17.49	18.98	18.77	18.11	16.24	10.86	9.09	6.36
For 0.5-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Irrigations/day	1.1	1.5	1.9	2.4	2.7	2.9	2.9	2.8	2.5	1.7	1.4	1.0
For 1.0-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
Irrigations/day	0.5	0.7	1.0	1.2	1.3	1.4	1.4	1.4	1.2	0.8	0.7	0.5
For 0.5-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Irrigations/day	7.7	10.5	13.9	17.6	19.4	21.1	20.9	20.1	18.0	12.1	10.1	7.1
For 1.0-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Irrigations/day	3.8	5.2	6.9	8.8	9.7	10.5	10.4	10.1	9.0	6.0	5.1	3.5

exceeded 1,600°C at Farmington. Since annual AGDD can exceed 5,000°C at Luxor, it can be expected that water use at Luxor will exceed that in New Mexico.

We calculated GDD based on monthly T_{max} and T_{min} for Luxor and computed *K*c values for poplar ranging from 0.59 to 1.27 based on O'Neill's equation for third-year poplar and after converting from alfalfa to a Grass ETo (Table 4). Irrigations per day calculated with these Kc values were about 75% of those calculated using a *K*c of 1.5. Considering that Lombard et al. (2005) found that the *K*c values based on GDD underestimated poplar ET, a maximum *K*c value of 1.5 is probably a good assumption for closed cover poplar plantations in the fifth and later years in southern Egypt.

SUMMARY

The examples given here for jatropha, jojoba and poplar may serve as a guide to further analysis for other tree species. Where *K*c values are lacking for timber and oil trees, the cover factor adjustment approach is recommended for the immediate future, along with increases in the frequency of irrigation or changes in the position and number of drippers to increase the wetted area when needed to prevent deep percolation. A lack of data on tree rooting depth in the desert sands of Egypt is an impediment to analysis of irrigation application depths. The need for deep rooting to mitigate deep percolation losses means that pruning of tap roots during seedling development may not be a good practice.

Directed research to discover irrigation scheduling parameters for tree crops in Egypt is clearly needed and should pay off in better tree growth and timber and oil yield, while preventing deep percolation losses and the resulting inefficiency in water use and possible pollution of ground water. Irrigation scheduling research should use a combination of approaches: the cover factor approach to adjust for tree growth over the tree lifetime and

Table 4 Water requirements (WR) for poplar at Luxor given ETo values from IRG (2005c), *K*c values based on accumulative growing degree days (GDD, °C), and an irrigation efficiency (*E*i) of 0.8, with no extra water added for leaching. Also irrigation application depths (IA) and numbers of irrigation per day needed for 0.5- and 1.0-m rooting depths, and for 75% and 25% wetted areas and 50% allowable depletion. The ETo values were calculated using FAO 56 (Allen et al. 1998)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum Air Temperature (°C)	23	25.5	29.5	34.8	38.7	41.1	40.6	40.7	38.6	35.3	29.6	24.6
Minimum Air Temperature (°C)	5.4	7	10.6	15.7	20	23	23.6	23.4	21.5	17.5	12.1	7.2
GDD/day	6.5	7.75	10.05	15.25	19.35	22.05	22.1	22.05	20.05	16.4	10.85	7.3
Days/month	31	28	31	30	31	30	31	31	30	31	30	31
GDD/month	202	217	312	458	600	662	685	684	602	508	326	226
Accumulative GDD	202	419	730	1188	1787	2449	3134	3818	4419	4927	5253	5479
Kc_{grass} (O'Neill)	0.61	0.64	0.70	0.80	0.97	1.14	1.25	1.26	1.12	0.88	0.65	0.45
ETo FAO (mm d^{-1})	3.68	5.03	6.67	8.43	9.33	10.12	10.01	9.66	8.66	5.79	4.85	3.39
ETa (mm d^{-1})	2.25	3.22	4.64	6.79	9.04	11.53	12.56	12.13	9.69	5.07	3.14	1.53
Irrigation efficiency (%/100)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Water requirement (mm d^{-1})	2.81	4.02	5.81	8.48	11.30	14.42	15.70	15.16	12.11	6.34	3.92	1.92
For 0.5-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Irrigation/day	0.4	0.6	0.9	1.3	1.7	2.2	2.4	2.3	1.9	1.0	0.6	0.3
For 1.0-m deep root zone, 75% wetted area, and 50% allowable depletion:												
IA (mm)	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
Irrigation/day	0.2	0.3	0.4	0.6	0.9	1.1	1.2	1.2	0.9	0.5	0.3	0.1
For 0.5-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Irrigation/day	3.1	4.5	6.5	9.4	12.6	16.0	17.4	16.8	13.5	7.0	4.4	2.1
For 1.0-m deep root zone, 25% wetted area, and 50% allowable depletion:												
IA (mm)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Irrigation/day	1.6	2.2	3.2	4.7	6.3	8.0	8.7	8.4	6.7	3.5	2.2	1.1

for different planting densities, a growing degree day basis for describing the change in *K*c values over the season, and calculation of the reference ET, ETo, from weather data for use with *K*c to estimate daily water use. Suitable percentages for research planned to determine optimal water use include 50, 75, 100, and 125% of ETo. Some effort should be made to measure rooting depth and lateral spread under different irrigation conditions and wetted areas for each species. This will require measurement of root water uptake as it changes with depth using suitable equipment such as the neutron probe or time domain reflectometry (Evett 2007). A weather station should be included as standard equipment in each research effort since available weather data appears to be inconsistent in quality and availability. Given the number of tree species and varieties being grown, it may be that a modeling approach would be useful. For example, Al-Jamal et al. (2002) developed a tree growth and irrigation scheduling model for *Eucalyptus camaldulensis* and applied it with good success to a plantation in Chihuahua, Mexico. They found that *K*c could vary from 0.4 to 1.2 depending on the time of year. One fact to keep in mind when looking at tree water use is that *K*c values for high production tree plantations can easily exceed 1.0.

Given the dearth of peer-reviewed journal literature, research should continue to determine the effects of irrigation with TWW on soil and aquifer qualities, including accumulations of heavy metals and organic matter, pathogens, salinity, infiltration rate and ground water quality. 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-operated irrigation 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.

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