**ENERGY EVALUATION OF THE HIGH VELOCITY ALGAE RACEWAY
INTEGRATED DESIGN (*ARID-HV*)**

by

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TABLE OF CONTENTS

LIST OF FIGURES	5
LIST OF TABLES	6
ABSTRACT	7
1- INTRODUCTION	8
2- LITERATURE REVIEW	11
3- PRESENT STUDY	13
4- REFERENCES	16
5- APPENDIX A: RESEARCH PAPER: ENERGY EVALUATION OF THE HIGH VELOCITY ALGAE RACEWAY INTEGRATED DESIGN (ARID-HV).....	17
Abstract.....	17
Introduction.....	18
Literature review.....	20
Materials and methods.....	22
Results and discussions.....	30
Channel length and geometry	30
Algae production.....	33
Power requirement and energy use.....	37
Conclusions and recommendations.....	42
Acknowledgements.....	43
References.....	43
APPENDIX A-1: ILLUSTRATIONS, TABLES, GRAPHS.....	47
Reynolds number for different depths and velocities.....	47
Channel length (L) vs. Required Slope for different velocities	47
Algae production, algae concentration, and temperature simulation using the temperature model	49

LIST OF FIGURES

Figure 1: Constructed ARID-HV system prototype layout: (a) ARID-HV dimensions (plan view), (b) cross-section of channels and canal	23
Figure 2: Installation of vinyl lay-flat tubing under liner.	25
Figure 3: ARID-HV system in operation.....	26
Figure 4. Electrical devices used in the ARID-HV prototype raceway.	28
Figure 5: Raceway overall slope vs. channel length and flow velocity (water depth in channels = 0.1m, head losses = elevation gain)	31
Figure 6: Possible channel lengths with raceway overall slope = 1%	33
Figure 7: Monthly average algae production simulation with different channel depths: ARID-HV vs. Conventional paddlewheel raceway	34
Figure 8: Algae average concentration (OD-750): (a) ARID-HV system and (b) Conventional paddlewheel raceway).....	36
Figure 9: Energy productivity of the optimized ARID-HV system vs. the conventional paddlewheel raceway	41

LIST OF TABLES

Table 1: Day and night algae culture volumes and depths in 0.6 m wide base and 450 side slope trapezoidal canal for different daytime channel flow depths	24
Table 2: Possible channel lengths (L), number of raceways per hectare (N), channel flow rate (Q), and power requirement per hectare (P).....	38
Table 3: Daily energy use for lifting algae culture from the canal to the channels (150 m channel length and 0.5 ha area).....	39
Table 4: Daily energy requirement (kWh ha ⁻¹ d ⁻¹) for the 0.1 m flow depth, 0.25 m s ⁻¹ , 150 m channel length, 3 m channel width, 10 channels, and 1% overall slope ARID-HV raceway	40

ABSTRACT

The Algae Raceway Integrated Design (*ARID*) system is an effective method to maintain temperature in the optimal growing range. However, the energy input is significant. Thus, the High Velocity Algae Raceway Integrated Design (*ARID-HV*) system was developed to reduce energy input requirements. This was accomplished by improving pumping efficiency, optimizing the operational hydraulic parameters, and using a serpentine flow pattern in which the water flows through channels instead of over barriers. A prototype *ARID-HV* system was installed in Tucson, Arizona, and the constructability, reliability of components, drainage of channels, and flow and energy requirements of the *ARID-HV* raceway were evaluated. Each of the energy inputs to the raceway (air sparger, air tube blower, canal lift pump, and channel recirculation pump) was quantified, some by direct measurement and others by simulation. An algae growth model was used to determine the optimal flow depths as a function of time of year. Then the energy requirement of the most effective flow depth was calculated. Channel hydraulics was evaluated with Manning's equation and the corner head loss equation. In this way, the maximum length of channels was calculated.

Keywords: *ARID-HV* system, algae-culture, energy, pumps, open channels.

1- INTRODUCTION

Open pond microalgae production systems have high light exposure and are less expensive than bioreactors. However, contamination, lack of temperature control, and lack of light exposure in lower water depths can decrease algae concentration and energy productivity. The Algae Raceway Integrated Design (ARID), which includes shallow basins and a deep canal, improves temperature control (*Ryan et al. 2010, Crowe et al. 2012, Waller et al. 2012*). Temperature is regulated by varying the water surface area between day and night. Removing the water from the shallow basins at night reduces long wave radiation to the night sky and convective heat loss. However, there were several weaknesses in the design and operation of the original ARID raceway, primarily inefficient pumps, low flow velocity, use of energy consuming barriers to control flow, and the management strategy of maintaining deep water in the canal during daytime operation. The High Velocity Algae Raceway Integrated Design, ARID-HV, was designed in order to minimize electrical energy input, while creating a turbulent high velocity flow regime with effective mixing and light exposure. This was accomplished by replacing the basins in the original ARID system with a serpentine flow path through channels.

The original ARID system continually recirculated water from the canal to the basins and used a sump pump to continually lift the water from the canal into the basins, an elevation difference of approximately 1 m (*Waller et al., 2012*).

The ARID-HV system reduces electrical energy input through recirculation of water in the channel area and only drops water into the canal when necessary for temperature management, cleaning, or harvesting.

There are several inputs to open pond algae raceways: energy, water, carbon dioxide, and fertilizers. This research focused on electrical energy, with the objective of maximizing the ratio of algae production to electrical energy input. The productivity factor can be used to evaluate the energy performance of algae raceways. Productivity factor methods include partial factor productivity, multifactor productivity, and total productivity (*Diewert et al., 2005*). In the present study, only partial productivity is considered (electrical energy input vs. algae production).

The overall objective of the present research was to design and construct an ARID-HV raceway and to evaluate the components, algae growth, and electrical energy input. There were four specific objectives:

- 1- Evaluate the reliability, constructability, slope, liner performance, and end of day drainage of the prototype ARID-HV system.
- 2- Evaluate the electrical energy inputs to the ARID-HV system: air sparger blowers, air tube blower, recirculation pumps, and canal lift pumps, through measurement and modeling.
- 3- Calculate the algae production in the ARID-HV raceway over the 12 months of the year using an algae growth model and operational limits.

- 4- Design the system in order to maximize the energy productivity within the practical constraints of the system. Compare the month-to-month energy productivity of the optimized ARID-HV raceway to the energy productivity of a conventional paddlewheel raceway.

2- LITERATURE REVIEW

Closed photo-bioreactors and open pond cultivation systems grow microalgae at small and large scales, respectively. Closed systems are much more expensive than open ponds (*Doucha et al.*, 2006), and due to practical limitations such as gas exchange, land area, and hydraulics, cannot be scaled-up for energy production. Open ponds, also, are subjected to the same limitations, but are much cheaper to build and operate. *Sheehan et al* (1998) concluded that there is little prospect for any alternatives to the open pond designs, given the low cost requirements associated with fuel production. However, open ponds suffer from biological invaders (other algae species, algae grazers, fungi and amoeba, etc...), and temperature limitations. Open pond microalgae production systems have high light exposure and are less expensive than bioreactors.

The cultivation of algae in open ponds is subject to complex interactions of various growth factors. The algae growth success is mostly related to the degree to which the environment is conditioned to meet the intrinsic requirements of each species (*Becker*, 1994).

Mixing is enhanced by a turbulent flow regime. In general, open channel flow is laminar if Reynolds number (**Re**) is less than 500, turbulent if **Re** is more than 12,500, and transitional otherwise (*Munson et al.*, 2002). A lower than normal flow velocity (0.06 m s^{-1}) results in fully turbulent flow and possibly

adequate light exposure; however, algae settling takes place at low flow velocities.

3- PRESENT STUDY

The methods, results, and conclusions of this study are presented in the paper appended to this thesis. The following is a summary of the most important findings in this document.

The propeller pumps, purchased for this project, were unreliable, and sewage lift pumps were substituted for the purpose of observing raceway performance during the experiment. Propeller pumps are not suitable for recirculation in the channels because they are inefficient at the low lift (0.3 m) required for recirculation. However, examination of pump curves indicates that propeller lift pumps may be suitable for the transfer of water from the canal to the channels in the morning. Evaluation of efficiencies of alternative pumps indicates that an Archimedes screw pump would be the most suitable alternative for recirculation. It is also likely that an Archimedes screw pump would be a better and more efficient pump for lifting water from the canal to the basins. In addition, an Archimedes screw pump would cause no disruption of algae cells.

The canal air sparger and the air tube blower were reliable and used relatively low energy, in comparison to the energy requirement of water pumps.

The liner, with air tubes underneath, was an effective method to create a serpentine channel path, and, by deflating the air bags, to drop water back into the canal at night. The 1% overall slope of the system was barely adequate for drainage; thus, it is likely that a lower slope would lead to puddles remaining in

the channel section after drainage. It was also found that it is important to construct an even grade for the slope; otherwise, puddles of water remain after drainage. With a 1% overall slope, the elevation difference from the upper side of channels to the lower is 0.03 m with a 3 m wide channel. A 3 m wide channel was selected as the maximum practical width of channels.

Five channel water depths were evaluated for biomass production ($\text{g m}^{-2} \text{d}^{-1}$). The evaluation was made with a model of algae growth (DOE species 1412) as a function of temperature and light model. The model evaluated 0.1, 0.15, 0.2, 0.25, and 0.3 m depths. The ARID raceway temperature model (Waller et al., 2012) was used to calculate water temperature. Weather station solar radiation and solar angle were used to calculate incident light. The model results indicated that 0.1 m flow depth had the same productivity ($\text{g m}^{-2} \text{d}^{-1}$) in winter as the deeper flow depths, and nearly the same productivity in summer. Because less overall energy is needed to maintain a shallower flow, along with other benefits of smaller components and volumes, we selected 0.1 m depth as the design flow depth. Less than 0.1 m depth was considered as impractical due to overall raceway slope and undulations in the liner surface; however, if areal growth ($\text{g m}^{-2} \text{d}^{-1}$) rate is not compromised, new raceway designs might be based on even shallower depths.

Alternative ARID-HV raceway designs were evaluated for their energy productivity, length of channels and water depths. All designs assumed a typical

flow velocity of 0.25 m s^{-1} . Deeper flow has a proportionally smaller energy gradient and thus channels can be proportionally longer. However, additional energy and larger pumps are required to lift the algae culture from the canal in the morning, since the water volume would be larger. Channel lengths are also limited by CO_2 depletion, leading to the selection of shorter channels and shallower depths. Thus, the combination of the algae growth model, hydraulic analysis, and practical considerations led to the following recommended design for future ARID-HV raceways: 0.1 m channel depth, 0.25 m s^{-1} flow velocity, 150 m channel length, at least 1% overall slope, 3 m channel width and 10 channels per raceway.

For the winter algae growth model simulation for Tucson, Arizona, the algae production rate and energy productivity of the ARID-HV system were far higher than the algae production rate and energy productivity of the conventional raceway. Production ($140 \text{ kg ha}^{-1} \text{ d}^{-1}$) was approximately the same in summer in the ARID-HV and conventional raceways; however, the ARID-HV system had higher energy productivity in summer (6 kg kWh^{-1} vs. 3 kg kWh^{-1}).

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5- APPENDIX A: RESEARCH PAPER

ENERGY EVALUATION OF THE HIGH VELOCITY ALGAE RACEWAY INTEGRATED DESIGN (*ARID-HV*).

Paper is pending publication in ASABE journal

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Abstract: The original ARID (Algae Raceway Integrated Design) raceway was an effective method to increase temperature toward the optimal growth range. However, the energy input was high and flow mixing was poor. Thus, the *ARID-HV* (High Velocity Algae Raceway Integrated Design) raceway was developed to reduce energy input requirements and improve flow mixing. This was accomplished by improving pumping efficiency and using a serpentine flow pattern in which the water flows through channels instead of over barriers. A prototype *ARID-HV* system was installed in Tucson, Arizona, and the constructability, reliability of components, drainage of channels, and flow and energy requirements of the *ARID-HV* raceway were evaluated. Each of the electrical energy inputs to the raceway (air sparger, air tube blower, canal lift pump, and channel recirculation pump) was quantified, some by direct measurement and others by simulation. An algae growth model was used to determine the algae production rate vs. flow depth and time of year. Then the electrical energy requirement of the most effective flow depth was calculated. Channel hydraulics was evaluated with Manning's equation and the corner head loss equation. In this way, the maximum length of channels for several raceway slopes and mixing velocities were determined. Algae production in the *ARID-HV* raceway was simulated with a temperature and light growth model. An energy efficient design for the *ARID-HV* raceway was developed.

Keywords: *ARID*, *ARID-HV*, algae-culture, energy, pumps, open channels.

Introduction

Open pond microalgae production systems have high light exposure and are less expensive than bioreactors. However, lack of temperature control and low light decrease algae production rate. In order to improve temperature control, the Algae Raceway Integrated Design (ARID), which includes shallow basins and a deep canal, was invented (*Ryan et al. 2010, Crowe et al. 2012, Waller et al. 2012*).

Temperature is regulated by varying the water surface area between day and night. Removing the water from the shallow basins at night reduces long wave radiation to the night sky and convective heat loss. However, there were several weaknesses in the design and operation of the original ARID raceway: inefficient pumps, low flow velocity, use of energy consuming barriers to control flow, and the management strategy of maintaining deep water in the canal during daytime operation. The High Velocity Algae Raceway Integrated Design (ARID-HV) was developed in order to minimize energy input while creating a turbulent high velocity flow regime with effective mixing and light exposure. This was accomplished by replacing the basins in the original ARID system with a serpentine flow path through channels.

The original ARID system continually recirculated water from the canal to the basins with a sump pump, a lift of approximately 1 m (*Waller et al., 2012*). The ARID-HV system reduces energy input through recirculation of water in the

channel area and only drops water into the canal when necessary for temperature management, cleaning, or harvesting.

There are several inputs to open pond algae raceways: energy, water, carbon dioxide, and fertilizer. This research focused on energy, with the objective of maximizing the ratio of algae production to electrical energy input. The productivity factor can be used to evaluate the energy performance of algae raceways. Productivity factor methods include partial factor productivity, multifactor productivity, and total productivity (*Diewert et al., 2005*). In the present study, only partial productivity is considered (electrical energy input vs. algae production).

The overall objective of the present research was to design and construct an ARID-HV prototype raceway and to evaluate the components, algae growth, and energy input. There were four specific objectives:

- 1- Evaluate the reliability, constructability, slope, liner performance, and end of day drainage of the prototype ARID-HV system.
- 2- Evaluate the electrical energy inputs to ARID-HV systems: air sparger blower, air tube blower, recirculation pump, and canal lift pump, through measurement and modeling.
- 3- Calculate the algae production in the ARID raceway over the 12 months of the year with an algae growth model.

- 4- Design an optimized system and compare the month-to-month energy productivity of the optimized ARID-HV raceway to the energy productivity of a conventional paddlewheel raceway.

Literature review

The original ARID temperature model (*Waller et al.*, 2012) used the evapotranspiration calculated by a weather station to calculate latent heat of vaporization. *Khawam et al.* (2012) modified the standardized *Penman-Montieth* model and calculated evaporation from open ponds based on temperature, light, relative humidity, and wind speed. He also added an algorithm to calculate reflectance and light transmittance into the algae culture.

The hydraulics of open ponds and the effect of flow velocity mixing on algae growth have not been sufficiently quantified to develop functions of algae growth vs. flow rate; more research on this topic is needed (*Benemann, 2008*). Most outdoor open raceways have 0.15 to 0.30 m algae depth in channels and 0.15 to 0.30 m s⁻¹ flow velocity (*Sing et al.* 2011).

Depth of water in channels, flow velocity, channel length, channel width, and over all raceway slope, are the design parameters for the ARID-HV system. The hydraulic design has a direct impact on algae growth, dispersion of algae in the water column, frequency of exposure to light, homogeneous distribution of nutrients and dissolved gases, utilization of CO₂, prevention of outgassing from channels, prevention of CO₂ depletion, and thermal stratification. It is believed

that intensive mixing increases the efficiency of light utilization and raises algal productivity (*Grobbelaar, 1994; Ogbonna et al., 1995*). Reported productivities in open raceways have ranged from 14 to 50 g m⁻² d⁻¹ (*Laws et al., 1986; 1988; Sheehan et al., 1998*).

Pump energy use is a function of efficiency, flow rate, and lift. Thus, the overall ARID-HV raceway slope, flow velocity, flow depth, and pump selection all contribute to the pump energy requirement. Archimedes screw pumps are efficient at the low lift required for recirculation, providing high flow rates at low lift (*Hof, 2000*). In general, Archimedes screw pumps are assumed to have greater than 70% efficiency. In addition, Archimedes screw pumps do not disrupt algae cells. Small axial-flow propeller pumps that are suitable for the ARID raceway operate between 25% and 50% efficiency. In addition to low efficiency, they can disrupt algae cells.

Huesemann et al. (2012a) developed an algae growth model for DOE1412 species that is a function of heat and light exposure. The model divides the water column into 100 layers and calculates the light exposure and growth rate for each layer. *Huesemann et al. (2012b)* adapted this model for open pond cultivation systems. Huesemann's algae growth model was integrated into the ARID raceway temperature model.

Materials and methods

The ARID-HV experimental site is located at the Campbell Avenue Agricultural Center of the University of Arizona. The geographic coordinates are Latitude = 32° 16' 49" N, Longitude = 110° 56' 45" W. The raceway elevation is 655 m above sea level.

The ARID-HV system included a serpentine channel path for the upper section and a canal (fig. 1). The serpentine path in the prototype system includes 10 channels, each 13 m long, 0.15 m deep, and 3 m wide. Water can spill over the last barrier into a deep canal that is 2 m deep, 5 m wide and 16 m long. The channel area was lined with two 7.6 mm thickness linear low density polypropylene sheets (*LLDP Aquafarm E-300, Colorado Lining International, Parker, CO.*) that were laid lengthwise in the N-S direction and welded in the middle with a heat gun. An extra 2.2 m (in addition to 13 m) was used to cover berms on the sides. A single 7.6 m wide liner section was laid in the E-W direction in the canal, with a narrow section welded on the south side in order to complete the covering of the canal, as shown in figure 1. A smaller canal, as would be needed for a 0.1 m depth in channels, could be covered with one 6 m wide liner section. With a 1% overall slope, the elevation difference between the top and bottom of each channel is 1% of the width of channels. Three meter wide channels were selected, resulting in a depth difference between the upper and lower sides of 0.03 m. With 0.1 m average flow depth, the average depth at the lower side of the channels was 0.115 m and the depth on the upper side was

0.085 m. A greater channel width would have resulted in a larger difference in depth. With 10 channels and 3 m width per channel, the total elevation difference was 0.3 m.

Figure 1. Constructed ARID-HV system prototype layout (pipes not to scale): (a) ARID-HV dimensions (plan view), (b) cross-section of channels and canal.

The required canal dimensions for different daytime channel flow depths are shown in table 1.

Table 1. Day and night algae culture volumes and depths in 0.6 m wide base and 45° side slope trapezoidal canal for different daytime channel flow depths.

Daytime channel flow depth (m)	Canal normal day depth (m)	Canal Day volume (m ³ /m)	Canal normal night depth (m)	Canal night volume (m ³ /m)
0.10	0.10	0.05	1.54	3.08
0.15	0.15	0.07	1.95	4.66
0.20	0.20	0.1	2.30	6.25
0.25	0.25	0.12	2.62	7.84
0.30	0.30	0.14	2.90	9.5

Blue vinyl Layflat irrigation tubes of 0.2 m diameter were laid under the liner in order to make the serpentine channel path (fig. 2). One PVC pipe manifold supplied air to the short tubes and another supplied air to the long tubes. A 0.2 m diameter pipe delivered return flow from the lower channel and canal to the upper channel. However, in order to decrease recirculation energy, the plan for future raceways, and the design in the energy analysis in this paper, is a return channel rather than a return pipe. The grade of the return channel would be nearly level rather than sloped. Water would be lifted from the lower channel to the return channel with an Archimedes screw pump.

Figure 2: Installation of vinyl lay-flat tubing under liner.

Low lift pumps were needed to recirculate algae culture from the lower channel to the upper channel and from the canal to the upper channel. Propeller pumps were initially selected for this purpose. However, the propeller pumps were unreliable. Thus, four sewage pumps were installed to recirculate water from the lower to the upper channel, and two sewage pumps were used to lift water from the canal to the upper channel. These temporary pumps are not suitable for the application, and efficiency was low. They were used to evaluate the raceway flow and drainage and are not included in the energy analysis.

The blue vinyl tubes were inflated by a small recreational equipment blower (*Overtons 110V High-Pressure Inflator/Deflator 14209*) that generated approximately 30 kPa pressure and inflated the air tubes in 3 min. The blower was connected to the long and short air tube manifolds by check valves. This allowed each air tube system to be deflated independently by valves on each manifold. The short length tube manifold was connected to the four short tubes (3 m length) that are represented by dashed lines in Figure 1(a). The short tubes

were inflated to varying pressures in order to increase flow depth within the channels. They could be fully inflated to store water in channels. All of the air tubes were deflated at night, if necessary, in order to drain the algae culture into the canal. Rapid air tube deflation resulted in a large downslope drainage flow into the canal, which helped to clean the liner in the upper area.

Water flowing in the ARID-HV raceway is shown in figure 3. Water was returned from the lower channel to the upper channel through the white pipe at the left of the raceway. The tanks in the foreground contained fertilizer and were not part of the return system.

Figure 3. ARID-HV system in operation.

The algae culture in the raceway (fig. 3) was DOE1412, a new *Chlorella* strain discovered by *Juergen Polle* of SUNY and the National Association for Advanced Biofuels and Bio-products (NAABB). This strain is robust, fast-growing, and heat tolerant. Maximum algae culture temperature during the summer experiments was 42 °C, and the algae did not die at this temperature. The algae

growth model used in this research (*Huesemann et al*, 2012b) was parameterized for the same DOE1412 species.

Two air spargers in the canal provided air (oxygen) to the algae culture when it was stored at night in the canal. This was necessary in order to prevent the algae culture from becoming anoxic at night in the deep canal water. A ceramic stone sparger added carbon dioxide to the system during the day, either in the canal or at the channel recirculation pumps, depending on whether flow was allowed to cycle through the canal during daytime operation. The carbon dioxide injection was controlled with a pH sensor: carbon dioxide was injected when the pH rose above 6.5, from sunrise to sunset. The channel air tubes were 0.2 m diameter; however, due to side to side variations in grade across the raceway, the effective depth of flow was approximately 0.1 m.

The electrical devices used in the raceway are shown in figure 4. Energy input was measured with a watt meter during normal operation.

Water pumps(canal, recirculation)

Air-tube blower

Air-pump for air sparger

Air sparger in canal

Campbell Scientific data logger

Wattmeter

Figure 4. Electrical devices used in the ARID-HV prototype raceway.

A theoretical simulation of algae growth in the ARID-HV raceway was also performed. A computer model was developed in order to calculate ARID raceway temperature and algae growth as a function of weather parameters and operation strategy (Waller et al., 2012). This model was used to simulate algae production during the 12 months of the year in Tucson, Arizona. Weather data for the model was acquired from the Arizona Meteorological Network (AZMET) weather station

in Tucson, which is located 100 m from the ARID experimental site. Data required for the model includes air temperature ($^{\circ}\text{C}$), relative humidity (%), solar radiation (J h^{-1}), rainfall (m), wind speed (m s^{-1}), and evapotranspiration (m h^{-1}).

Channel hydraulics was evaluated in order to determine the optimal raceway design and energy requirements. The linear head losses in channels were calculated using Manning's equation:

$$h_l = L * V^2 * n^2 / R_h^{1.33} \quad (1)$$

where:

h_L = head loss, m;
 L = channel length, m;
 V = velocity, m s^{-1} ;
 n = Manning's roughness coefficient;
 R_h = hydraulic radius, m.

The ARID-HV raceway is lined so the Manning's n coefficient was assumed to be 0.01. Undulations in the liner could increase the Manning's n , but the liner is generally flat under water.

The head losses at the 180 degree turns between channels were calculated with the corner head loss equation for channels (*Green, 1995*):

$$H_K = K * V^2 / 2 * g \quad (2)$$

where:

H_K = kinetic head loss, m;
 V = mean surface velocity, m s^{-1} ;
 g = acceleration of gravity, 9.81 m s^{-2} ;
 K = kinetic loss coefficient (assumed to be 2.4).

Results and discussions

In this section, the energy input $\text{kWh ha}^{-1} \text{d}^{-1}$ was calculated for several ARID-HV operational scenarios. Algae production and energy use were divided by water surface area (kWh ha^{-1}) to calculate areal production rate and energy use. The water surface area in shallow channels during operation was 390 m^2 , and the canal surface area during operation was 40 m^2 , resulting in a total water surface area of 430 m^2 during daytime operation.

Channel length and geometry

Channel lengths were calculated for a range of flow depths, velocities, and raceway slopes. Head loss was calculated with Manning's equation and the corner head loss equation; channel lengths were set so that head losses equaled elevation difference (fig. 5). For example, the combination of 0.25 m s^{-1} flow velocity, 0.1 m channel depth, and 150 m channel length, had a 0.02 m linear head loss, and 0.01 m corner head loss, which was equal to the 0.03 m elevation difference between channels with 1% overall slope.

Figure 5: Raceway overall slope vs. channel length and flow velocity (water depth in channels = 0.1m, head losses = elevation gain).

Figure 5 shows that the prototype ARID raceway could carry a flow velocity equal to 0.46 m s^{-1} , which is at the upper end of flow rates in algae raceways. Deeper flow results in longer channels because the hydraulic radius increases, and friction loss gradient decreases. In theory, extremely long channel lengths could be used at low flow velocities; however, practical limitations, such as; total raceway water volume, raceway area, and CO_2 depletion time in channels place a practical limit of 100 to 200 m on channels lengths.

The prototype ARID-HV system was installed with two ridges and four side slopes perpendicular to the direction of drainage in order to facilitate flow to the canal. The ridges and slopes can be seen in Figure 2. This design was complicated to install, did not improve drainage, and made it impossible to maintain uniform depth of flow in channels. Thus, the liner was pulled back and the ground surface was leveled with a uniform side slope, which was easier to install, resulted in better flow characteristics during daytime operation, and had

better drainage. In addition, stretching the liner was a key to preventing puddling after drainage. Another hindrance to drainage was ridges that remained over the air tubes after deflating air tubes. The ridges would be more pronounced if larger diameter air tubes were used for deeper flow depths in channels. Thus, shallower channels and smaller air tubes are preferable for better drainage.

Carbon dioxide is consumed by algae and also diffuses out into the atmosphere. A typical maximum residence time in algae raceways between sparging pits is 1.5 h. Maximum residence time in the channels could be 1.5 h if sparging pits were placed at the end of each channel, but it would be preferable to have just one CO₂ sparging at the recirculation pump and a total raceway residence time of 1.5 h.

Because 0.25 m s⁻¹ is a typical raceway flow rate, this velocity was selected as the design flow rate. With a 0.1 m flow depth, and 1% overall raceway slope, the channel length would be 150 m, which would have a 10 min residence time per channel. This would result in slightly more than 1.5 h residence time in the entire raceway (fig. 6), an acceptable length of time between CO₂ sparging stations. In contrast, the combination of 0.25 m s⁻¹ flow velocity and 0.15 m channel depth resulted in 250 m channel length. This length results in a residence time of 17 min per channel and 2.8 h for 10 channels, which is as twice as long as the typical length of time between sparging stations. Thus, there is little advantage in exceeding the 0.1 m depth with the 0.25 m s⁻¹ design flow velocity. Other channel lengths for deeper flows and higher velocities

that would fit within the 1.5 h residence time per channel criterion are shown in Figure 6.

Figure 6 : Possible channel lengths with raceway overall slope = 1%

Algae production:

Monthly average production was calculated for both ARID-HV and conventional paddlewheel raceways. Production was measured as the product of daily harvested water volume and algae concentration. The harvested volumes were 20% from October through February, and 35% from March through September. Simulations indicate that higher harvesting percentages would result in 10% higher production rate, but this would come at the expense of increasing harvesting cost.

Figure 7 shows the average monthly areal production rate. There was essentially no production in the conventional raceway in winter while there was

approximately $60 \text{ kg ha}^{-1} \text{ d}^{-1}$ ($6 \text{ g m}^{-2} \text{ d}^{-1}$) production in the ARID-HV raceway in winter. The ARID-HV raceway had significantly greater production in spring and fall than the conventional raceway. Production rates were similar in summer. The highest production in the ARID-HV raceway was in June, $160 \text{ kg ha}^{-1} \text{ d}^{-1}$ ($16 \text{ g m}^{-2} \text{ d}^{-1}$), and the highest production in the conventional raceway was $140 \text{ kg ha}^{-1} \text{ d}^{-1}$ ($14 \text{ g m}^{-2} \text{ d}^{-1}$), both with 0.3 m channel depth. The ARID-HV system, which uses the deep canal to store algae culture at night, has a beneficial effect on algae growth rate. It keeps algae culture at a higher temperature, especially with an insulation cover during cold months (Crowe et al., 2012).

Figure 7. Monthly average algae production simulation with different channel depths: ARID-HV vs. Conventional paddlewheel raceway.

The areal production rate was not sensitive to channel depths. In the ARID-HV raceway, the difference between 0.1 and 0.3 m depth areal production

rate was generally in the range of 5%. The greatest increase in production vs. depth was observed in the summer months, but the difference was not large. In winter, the lower depth even has a higher production rate during some months.

The reason that low flow depth had nearly the same production rate as high flow depth is that the concentration was proportionally higher in the low flow depth. Algae concentration in channels is shown in figure 8 (a, b) as optical density (OD-750). For reference, optical density is five times higher than g L^{-1} ash free dry weight.

Figure 8. Algae average concentration (OD-750): (a) ARID-HV system and (b) Conventional paddlewheel raceway.

The optical density was almost inversely proportional to depth; for example, the OD-750 in the ARID-HV system in June was 2.0 at 0.1 m depth and 0.74 at 0.3 m depth. In the conventional raceway, the OD-750 was 1.71 at 0.1 m depth and 0.62 at 0.3 m depth. Note that the daily dilution rate (harvest)

increased at the beginning of March from 20% to 35%, decreasing average concentration.

Taking into account the hydraulic operational parameters, raceway constructability, drainage, and algae production, the most favorable design for the ARID-HV system is 0.1 m channel depth, 0.25 m s⁻¹ flow velocity, 150 m channel length, 3 m channel width, 10 channels, and 1% overall raceway slope.

Power requirement and Energy use:

The daily energy use per hectare is the sum of the electrical input to the canal pumps, recirculation pumps, and air pumps (air tube blowers and night air spargers). The daily required power (kW) for algae recirculation per hectare is calculated for a range of channel lengths and their associated flow velocities and channel depths, assuming 50% recirculation pumping efficiency at 0.3 m lift, in table 2. The recommended design (0.25 m s⁻¹ flow velocity, 0.1 m channel depth, 150 m channel length, 3 m channel width, at least 1% overall slope, and 10 channels combination) requires 0.9 kW ha⁻¹ at a 50% pumping efficiency for recirculation.

Table 2. Possible channel lengths (L), number of raceways per hectare (N), channel flow rate (Q), and power requirement per hectare (P).

		Depth (m)					
Velocity (m s ⁻¹)	Calculated parameters	0.10	0.15	0.20	0.25	0.30	
0.25	L (m)	150	Combinations not feasible: Excessive channel length and residence time.				
	N	2					
	Q (m ³ s ⁻¹)	0.075					
	P(kW ha ⁻¹)	0.9					
0.30	L (m)	90					148
	N	3					2
	Q (m ³ s ⁻¹)	0.09					0.13
	P (kW ha ⁻¹)	1.62					1.62
0.35	L (m)	52	86	121	157	192	
	N	5.4	3.3	2.4	1.8	1.5	
	Q (m ³ s ⁻¹)	0.10	0.15	0.21	0.26	0.31	
	P (kW ha ⁻¹)	3.4	3.1	3	2.82	2.82	
0.40	L (m)	28	46	64	83	102	
	N	10	6	4.4	3.4	2.8	
	Q (m ³ s ⁻¹)	0.12	0.18	0.24	0.30	0.36	
	P (kW ha ⁻¹)	7.15	6.45	6.31	6.08	6.02	
0.46	L (m)	8	13	19	25	30	
	N	33.6	21	14.7	11.4	9.4	
	Q (m ³ s ⁻¹)	0.13	0.20	0.27	0.34	0.41	
	P (kW ha ⁻¹)	27.72	25.93	24.25	23.48	23.21	

The energy use required to lift the water from the canal to the channels in the morning is shown in Table 3. The required canal volume for the 0.1 m channel depth is 1/3 that of the 0.3 m channel depth. The canal depth for the 0.1 m channel depth is 1/2 that of the 0.3 m channel depth. Thus, the energy requirement to lift water from the canal to the channels in the morning for the 0.1 m daytime depth would be approximately 1/5 (table 3) that of the 0.3 m daytime flow depth.

Table 3. Daily energy use for lifting algae culture from the canal to the channels (150 m channel length, 0.5 ha area/raceway, and 2 pumps per canal).

Channel depth (m)	Canal day depth (m)	Canal day volume (m ³)	Canal night depth (m)	Canal night volume (m ³)	Average lift (m)	Average volume lifted (m ³)	Energy use per raceway (kWh d ⁻¹)
0.10	0.10	10.3	1.48	460	1.98	450	4.85
0.15	0.15	16.4	1.87	692	2.32	676	8.53
0.20	0.20	23.3	2.20	925	2.60	901	12.7
0.25	0.25	30.8	2.50	1160	2.85	1130	17.4
0.30	0.30	39.0	2.77	1390	3.07	1350	22.6

It is assumed that the daily air sparger energy requirements would increase proportionally with ARID-HV size. Thus, the air sparger energy for two raceways covering one hectare would be 10 times greater than the blower energy used for the prototype system. The air tube blower, which requires a power of 0.6 kW, would operate for 35 min d⁻¹ (0.58 h d⁻¹) in the 150 m channel length with 10 channels raceway. Consequently, for two raceways per hectare, the air tube blower would require 0.7 kWh ha⁻¹ d⁻¹.

The operating time for the recirculation pump and night air sparger varied. From November through February, the recirculation pump was turned on at 9:00 h and off at 17:00 h. Thus, the night air sparger was turned on at 17:00 h and off at 9:00 h. From March through October, the recirculation pump was turned on at 6:00 h and off at 19:00 h and the night air sparger was turned on at 19:00 h and off at 6:00 h. The night air sparger power requirement would be 0.24 kW ha⁻¹. Table 4 summarizes the daily unit energy use for all the electrical devices used in the optimized ARID-HV system for winter and summer.

Table 4. Daily energy requirement ($\text{kWh ha}^{-1} \text{d}^{-1}$) for the 0.1 m flow depth, 0.25 m s^{-1} , 150 m channel length, 3 m channel width, 10 channels, and 1% overall slope ARID-HV raceway.

Period of the year	Recirculation pump		Night air sparger		Canal pump ^[b]	Air tube blower	Total energy use
	DOT ^[a] (h)	E ($\text{kWh ha}^{-1} \text{d}^{-1}$)	DOT (h)	E ($\text{kWh ha}^{-1} \text{d}^{-1}$)	E ($\text{kWh ha}^{-1} \text{d}^{-1}$)	E ($\text{kWh ha}^{-1} \text{d}^{-1}$)	E ($\text{kWh ha}^{-1} \text{d}^{-1}$)
Nov. Feb.	8	7.2	16	3.84	9.7	0.7	21.4
Mar. Oct.	13	11.7	11	2.64			25.0

^[a] Daily Operating Time. ^[b] From table 3, canal pump energy use = 4.85 kWh d^{-1} per raceway.

The typical conventional paddlewheel raceway energy requirement is 2.4 kW ha^{-1} (Lundquist et al., 2010), and it operates 24 hours per day. Thus, the paddlewheel system requires $57 \text{ kWh ha}^{-1} \text{d}^{-1}$. The optimal ARID-HV system uses only $21.4 \text{ kWh ha}^{-1} \text{d}^{-1}$, during winter, and $25.0 \text{ kWh ha}^{-1} \text{d}^{-1}$, during summer (Table 4). Even if the conventional paddlewheel operated only during the day (12 h), which would reduce its energy use to $28 \text{ kWh ha}^{-1} \text{d}^{-1}$, the energy use would be lower in the ARID-HV system. One reason that the ARID-HV system is more efficient is that Archimedes screw pumps are more efficient than paddlewheels, and there is little difference in channel hydraulics between the ARID-HV and paddlewheel systems. The second reason is that using an air sparger at night in the canal is less expensive than running a paddlewheel.

Using the algae growth simulations and hydraulic evaluation, figure 9 compares energy productivities for both systems with 0.25 m s^{-1} flow velocity. Note that the depth of 0.3 m is not recommended for the ARID-HV system because of the excessive length of channels, excessive residence time, and the difficulty of lifting the large volume from the canal in the morning. Thus, the 0.1 m

depth in the ARID-HV system is compared to the 0.3 m channel depth for the conventional paddlewheel raceway (Lundquist et al., 2010). Moreover, the depth of the conventional paddlewheel raceway should not change the energy use significantly since deeper depths can have longer channels.

Figure 9. Energy productivity of the optimized ARID-HV system vs. the conventional paddlewheel raceway.

The energy productivity represents the ratio of the production rate over the energy input into the system. Since the algae production rate in the case of optimized ARID-HV system (fig. 7) was always higher than the algae production rate of the conventional paddlewheel raceway, and the energy input into the optimized ARID-HV system was less than the energy input into the conventional paddlewheel raceway (table 4), the energy productivity was much higher in the optimized ARID-HV raceway. The energy productivity variation followed the production rate variation. Production and energy productivity increased during

the warmer period of the year (March through November). The energy productivity peak for both raceways was reached during June with 6 kg kWh^{-1} for the optimized ARID-HV and 3 kg kWh^{-1} for the conventional paddlewheel raceway. The lowest values were in December, with 1.58 kg kWh^{-1} for the ARID-HV raceway and $0.054 \text{ Kg kWh}^{-1}$ for the conventional paddlewheel raceway. The energy productivity fluctuation in the case of the design ARID-HV raceway was caused mainly by the production rate variation: the energy input into the system only varied slightly during the year; however, the production varied significantly. The energy productivity fluctuation in the case of the conventional paddlewheel raceway was solely due to the production rate variation since the energy input does not change during the year.

Conclusions and recommendations

An *ARID-HV* prototype raceway was constructed and operated. The 1% overall raceway slope was appropriate. Placing air tubes under the liner to form channels and allow drainage at night was successful. The practice of constructing intermittent changes in side slope across the channels was unsuccessful. The prototype system demonstrated that air pumps for sparging and air tube inflation were effective and had a low energy input

Based on the ARID temperature and algae growth model, hydraulic analysis, and practical considerations, the selected design flow depth was 0.1 m. Algae production was nearly the same as 0.3 m depth, and overall energy use

was less. Based on algae growth and channel hydraulics, the following design is recommended: 0.1 m channel depth, 0.25 m s⁻¹ flow velocity, 150 m channel length, at least 1% overall slope, 3 m channel width and 10 channels per raceway.

Assuming that an Archimedes pump has 50% efficiency (a conservative assumption), the energy productivity of the optimal ARID-HV system was far higher than the algae production rate and energy productivity of the conventional raceway in Tucson, Arizona.

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APPENDIX A-1:

ILLUSTRATIONS, TABLES, GRAPHS

Reynolds number for different depths and velocities (water density=1000Kg/m³, dynamic viscosity at 24°C = 0.000911 Kg/ms).

water depth in channels (m)	0.10	0.15	0.20	0.25	0.30
hydraulic radius (m)	0.094	0.136	0.176	0.214	0.250
Reynolds for V= 0.06 m/s	6175	8981	11623	14113	16465
Reynolds for V= 0.18 m/s	18524	26943	34868	42340	49396
Reynolds for V= 0.2 m/s	20582	29937	38742	47044	54885
Reynolds for V= 0.25 m/s	25727	37421	48428	58805	68606
Reynolds for V= 0.3 m/s	30873	44906	58113	70566	82327
Reynolds for V= 0.35 m/s	36018	52390	67799	82327	96048
Reynolds for V= 0.46 m/s	47338	68855	89107	108201	126235

**Channel length (L) vs. Required Slope for different velocities,
Head losses = elevation gain (Current ARID-HV slope = 1%)**

Water depth in channels d = 0.1m

L (m)	Velocity (m/s)								
	0.06	0.083	0.18	0.20	0.25	0.30	0.35	0.4	0.46
	Required slopes								
13	0.0001	0.0003	0.0016	0.0020	0.0031	0.0045	0.0062	0.008	0.0107
50	0.0002	0.0005	0.0025	0.0031	0.005	0.0072	0.0097	0.012	0.0169
100	0.0004	0.0008	0.0038	0.0047	0.0076	0.0107	0.0145	0.019	0.0252
150	0.0005	0.0010	0.0051	0.0063	0.0098	0.0142	0.0193	0.025	0.0334

Water depth in channels $d = 0.15\text{m}$

L (m)	Velocity (m/s)								
	0.06	0.083	0.18	0.20	0.25	0.30	0.35	0.4	0.46
	Required slopes								
13	0.0001	0.0003	0.0015	0.0018	0.0029	0.0042	0.0057	0.007	0.0099
50	0.0002	0.0004	0.0020	0.0025	0.0040	0.0057	0.0078	0.010	0.0136
100	0.0003	0.0005	0.0028	0.0035	0.0055	0.0079	0.0108	0.014	0.0186
150	0.0003	0.0007	0.0036	0.0044	0.0069	0.0100	0.0137	0.017	0.0237

Water depth in channels $d = 0.20\text{m}$

L (m)	Velocity (m/s)								
	0.06	0.083	0.18	0.20	0.25	0.30	0.35	0.4	0.46
	Required slope								
13	0.0001	0.000	0.0014	0.001	0.0028	0.0040	0.0055	0.0072	0.0095
50	0.000	0.000	0.0018	0.002	0.0035	0.0051	0.0070	0.0092	0.0121
100	0.000	0.000	0.0024	0.002	0.0046	0.0066	0.0091	0.0119	0.0157
150	0.000	0.000	0.0029	0.003	0.0056	0.0082	0.0111	0.0146	0.0193

Water depth in channels $d = 0.25\text{m}$

L (m)	Velocity (m/s)								
	0.06	0.083	0.18	0.20	0.25	0.30	0.35	0.4	0.46
	Required slope								
13	0.0001	0.0003	0.00142	0.0017	0.00275	0.0039	0.00540	0.00706	0.0093
50	0.00019	0.00036	0.00173	0.0021	0.00336	0.0048	0.00658	0.00860	0.0113
100	0.00023	0.00045	0.00215	0.0026	0.00416	0.0060	0.00816	0.01067	0.0141
150	0.0002	0.0005	0.0025	0.003	0.0049	0.007	0.0097	0.01276	0.01688

Water depth in channels $d = 0.3\text{m}$

L (m)	Velocity (m/s)								
	0.06	0.083	0.18	0.20	0.25	0.30	0.35	0.4	0.46
	Required slope								
13	0.000	0.000	0.0013	0.00172	0.0027	0.0039	0.0053	0.006	0.009
50	0.000	0.000	0.0016	0.00204	0.0031	0.0046	0.0062	0.008	0.010
100	0.000	0.000	0.0019	0.00247	0.0038	0.0055	0.0076	0.009	0.013
150	0.000	0.000	0.0023	0.00288	0.0045	0.0065	0.0088	0.011	0.015

Algae production, algae concentration, and temperature simulation using the temperature model (Waller et al., 2012).

Channel Depth= 0.1m

Figure 1a.

Figure 1b.

Figure 1c.

Figure1. January 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.65 \text{ g/m}^2/\text{day}$, average conventional = $0.11 \text{ g/m}^2/\text{day}$, Pump on time = 9 am, Pump off time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure 2a.

Figure 2b.

Figure 2c.

Figure 2. February 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.88 \text{ g/m}^2/\text{day}$, average conventional = $0.128 \text{ g/m}^2/\text{day}$, Pump on time = 9 am, Pump off time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure3a.

Figure 3b.

Figure 3c.

Figure3. March 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 9.78 g/m²/day, average conventional = 2.9 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 0.5 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 4a.

Figure 4b.

Figure 4c.

Figure 4. April 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 11.85 g/m²/day, average conventional = 7.104 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 5a.

Figure 5b.

Figure 5c.

Figure 5c. May 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $12.8 \text{ g/m}^2/\text{day}$, average conventional = $8.78 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 6a.

Figure 6b.

Figure 6c.

Figure 6. June 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 14.99 g/m²/day, average conventional = 11.41 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 7a.

Figure 7b.

Figure 7c.

Figure 7. July 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 13.89 g/m²/day, average conventional = 12.65 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure8a

Figure 8b.

Figure 8c.

Figure 8. August 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 12.78 g/m²/day, average conventional = 12.15 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 9a.

Figure 9b.

Figure 9c.

Figure 9. September 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 12.13 g/m²/day, average conventional = 10.41 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover

Figure 10a.

Figure 10b.

Figure 10c

Figure 10. .October 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 7.68 g/m²/day, average conventional = 5.96 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 30 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, no cover

Figure 11a.

Figure 11b.

Figure 11c.

Figure 11. November 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.70 \text{ g/m}^2/\text{day}$, average conventional = $0.338 \text{ g/m}^2/\text{day}$, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.5 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Figure 12a.

Figure 12b.

Figure 12c.

Figure 12. December 2011, 0.1 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $3.39 \text{ g/m}^2/\text{day}$, average conventional = $0.095 \text{ g/m}^2/\text{day}$, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.4 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am.

Figure 1a

Figure 1b.

Figure 1c.

Figure 1. January 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.70 \text{ g/m}^2/\text{day}$, average conventional = $0.128 \text{ g/m}^2/\text{day}$, Pump on time and cover off time = 9 am, Pump off time and cover on time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, cover from 5 pm to 9 am.

Figure 2a.

Figure 2b.

Figure 2c.

Figure 2. February 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 5.705 g/m²/day, average conventional = 0.179 g/m²/day, Pump on time = 9 am, Pump off time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure 3a.

Figure 3b.

Figure 3c.

Figure 3. March 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $10.07 \text{ g/m}^2/\text{day}$, average conventional = $1.57 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 0.5 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 4a.

Figure 4b.

Figure 4c.

Figure 4. April 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $12.16 \text{ g/m}^2/\text{day}$, average conventional = $6.91 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 5a.

Figure 5b.

Figure 5c.

Figure 5. May 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 13.18 g/m²/day, average conventional = 9.12 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 6a.

Figure 6b.

Figure 6c.

Figure 6. June 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $15.18 \text{ g/m}^2/\text{day}$, average conventional = $12.3 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 7a.

Figure 7b.

Figure 7c.

Figure 7. July 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 14.2 g/m²/day, average conventional = 13.01 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 8a.

Figure8b

Figure 8c.

Figure 8c. August 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $13.12 \text{ g/m}^2/\text{day}$, average conventional = $12.4 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 9a.

Figure 9b.

Figure 9c.

Figure 9. September 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 12.31 g/m²/day, average conventional = 10.75 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover

Figure 10a.

Figure 10b.

Figure 10c.

Figure 10. October 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $7.8 \text{ g/m}^2/\text{day}$, average conventional = $5.88 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 30 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, no cover

Figure 11a.

Figure 11b.

Figure 11c. November 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.77 \text{ g/m}^2/\text{day}$, average conventional = $0.33 \text{ g/m}^2/\text{day}$, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.5 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Figure 12a.

Figure 12b.

Figure 12c.

Figure 12. December 2011, 0.15 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 3.39 g/m²/day, average conventional = 0.12 g/m²/day, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.4 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Figure 1a

Figure 1b.

Figure 1c.

Figure 1. January 2011, 0.20 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.64 \text{ g/m}^2/\text{day}$, average conventional = $0.238 \text{ g/m}^2/\text{day}$, Pump on time and cover off time = 9 am, Pump off time and cover on time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure 2a.

Figure 2b.

Figure 2c.

Figure 2. February 2011, 0.20 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 5.64 g/m²/day, average conventional = 0.238 g/m²/day, Pump on time = 9 am, Pump off time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure 3a.

Figure 3b.

Figure 3c.

Figure 3. March 2011, 0.20 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 10.28 g/m²/day, average conventional = 1.431 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 0.5 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 4a.

Figure 4b.

Figure 4c.

Figure 4. April 2011, 0.20 m ARID and conventional raceways, canal at same depth as channels during day, average ARID = $12.42 \text{ g/m}^2/\text{day}$, average conventional = $6.96 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 5a.

Figure 5b.

Figure 5c.

Figure 5. May 2011, 0.2 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $13.5 \text{ g/m}^2/\text{day}$, average conventional = $9.53 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 6a.

Figure 6b.

Figure 6c.

Figure 6. June 2011, 0.2 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 15.42 g/m²/day, average conventional = 12.95 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 7a.

Figure 7b.

Figure 7c.

Figure 7. July 2011, 0.2 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 14.42 g/m²/day, average conventional = 13.31 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 8a.

Figure 8b.

Figure 8c.

Figure 8. August 2011, 0.2 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $13.31 \text{ g/m}^2/\text{day}$, average conventional = $12.63 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 9a.

Figure 9b.

Figure 9c.

Figure 9. September 2011, 0.2 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 12.45 g/m²/day, average conventional = 11.05 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover

Figure 10a.

Figure 10b.

Figure 10c.

Figure 10. October 2011, 0.2 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 7.94 g/m²/day, average conventional = 5.98 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 30 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, no cover

Figure 11a.

Figure 11b.

Figure 11c.

Figure 11. November 2011, 0.20 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.82 \text{ g/m}^2/\text{day}$, average conventional = $0.41 \text{ g/m}^2/\text{day}$, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.5 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Figure 12a.

Figure 12b.

Figure 12c.

Figure 12. December 2011, 0.2 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $3.4 \text{ g/m}^2/\text{day}$, average conventional = $0.16 \text{ g/m}^2/\text{day}$, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.4 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Figure 1a

Figure 1b.

Figure 1c.

Figure 1. January 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.57 \text{ g/m}^2/\text{day}$, average conventional = $0.30 \text{ g/m}^2/\text{day}$, Pump on time and cover off time = 9 am, Pump off time and cover on time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, no cover.

Figure 2a.

Figure 2b.

Figure 2c.

Figure 2. February 2011, 0.25 m depth ARID and conventional raceways, canal at same depth as channels during day, average ARID = 5.60 g/m²/day, average conventional = 0.3 g/m²/day, Pump on time = 9 am, Pump off time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure 3a.

Figure 3b.

Figure 3c.

Figure 3. March 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 10.45 g/m²/day, average conventional = 1.49 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 0.5 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 4a.

Figure 4b.

Figure 4c.

Figure 4. April 2011, 0.25 m, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $12.63 \text{ g/m}^2/\text{day}$, average conventional = $7.11 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 5a.

Figure 5b.

Figure 5c.

Figure 5. May 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 13.8 g/m²/day, average conventional = 9.91 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 6a.

Figure 6b.

Figure 6c.

Figure 6. June 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 15.71 g/m²/day, average conventional = 13.43 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 7a.

Figure 7b.

Figure 7c.

Figure 7. July 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 14.62 g/m²/day, average conventional = 13.56 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 8a.

Figure 8b.

Figure 8c.

Figure 8. August 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 13.48 g/m²/day, average conventional = 12.85 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 9a.

Figure 9b.

Figure 9c.

Figure 9. September 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 12.6 g/m²/day, average conventional = 11.32 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover

Figure 10a.

Figure 10b.

Figure 10c.

Figure 10. October 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 8.10 g/m²/day, average conventional = 6.15 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 30 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, no cover

Figure 11a.

Figure 11b.

Figure 11c.

Figure 11. November 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $5.86 \text{ g/m}^2/\text{day}$, average conventional = $0.55 \text{ g/m}^2/\text{day}$, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.5 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Figure 12a.

Figure 12b.

Figure 12c.

Figure 12. December 2011, 0.25 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $3.36 \text{ g/m}^2/\text{day}$, average conventional = $0.20 \text{ g/m}^2/\text{day}$, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.4 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Channel Depth = 0.30 m

Figure 1a

Figure 1b.

Figure 1c.

Figure 1. January 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 5.62 g/m²/day, average conventional = 0.36 g/m²/day, Pump on time = 9 am, Pump off time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure 2a.

Figure 2b.

Figure 2c.

Figure 2. February 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 5.64 g/m²/day, average conventional = 0.36 g/m²/day, Pump on time = 9 am, Pump off time = 5 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.2 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5 pm to 9 am.

Figure 3a.

Figure 3b.

Figure 3c.

Figure 3. March 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $10.63 \text{ g/m}^2/\text{day}$, average conventional = $1.61 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 0.5 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 4a.

Figure 4b.

Figure 4c.

Figure 4. April 2011, 0.30 m, ARID and conventional raceways, canal at same depth as channels during day, average ARID = $12.86 \text{ g/m}^2/\text{day}$, average conventional = $7.29 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, radiant barrier, cover from 7 pm to 6 am.

Figure 5a.

Figure 5b.

Figure 5c.

Figure 5. May 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 14.08 g/m²/day, average conventional = 10.24 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 6a.

Figure 6b.

Figure 6c.

Figure 6. June 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 15.94 g/m²/day, average conventional = 13.81 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 7a.

Figure 7b.

Figure 7c.

Figure 7. July 2011, 0.30 m depth ARID and conventional raceways, canal at same depth as channels during day, average ARID = $14.81 \text{ g/m}^2/\text{day}$, average conventional = $13.79 \text{ g/m}^2/\text{day}$, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1.5 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 8a.

Figure 8b.

Figure 8c.

Figure 8. August 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 13.62 g/m²/day, average conventional = 13.06 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover.

Figure 9a.

Figure 9b.

Figure 9c.

Figure 9. September 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 12.74 g/m²/day, average conventional = 11.55 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 1 OD, initial conventional concentration = 1 OD, ARID harvest percent/ day = 35 %, Conventional harvest percent/day = 35%, harvest time = 5 am from canal, no cover

Figure 10a.

Figure 10b.

Figure 10c.

Figure 10. October 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 8.26 g/m²/day, average conventional = 6.35 g/m²/day, Pump on time = 6am, Pump off time = 7 pm, initial ARID concentration = 0.8 OD, initial conventional concentration = 0.8 OD, ARID harvest percent/ day = 30 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, no cover

Figure 11a.

Figure 11b.

Figure 11c.

Figure 11. November 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 5.92 g/m²/day, average conventional = 0.73 g/m²/day, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.5 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

Figure 12a.

Figure 12b.

Figure 12c.

Figure 12. December 2011, 0.30 m depth, ARID and conventional raceways, canal at same depth as channels during day, average ARID = 3.395 g/m²/day, average conventional = 0.25 g/m²/day, Pump on time = 9am, Pump off time = 5 pm, initial ARID concentration = 0.4 OD, initial conventional concentration = 0.1 OD, ARID harvest percent/ day = 20 %, Conventional harvest percent/day = 20%, harvest time = 5 am from canal, radiant barrier, cover from 5pm to 9am

ARID Temperature Model (Waller et al., 2012)

The interface displays a schematic of the ARID Temperature Model, showing three basins (Basin 1, Basin 2, Basin 3) and a canal (Canal B). Each basin and canal is represented by a blue bar with 'water' and 'soil layers' indicated. The canal is shown as a blue bar with 'Upper canal (Filled at night)' and 'Lower canal (Always filled)' indicated.

Simulation Settings:

- Starting time in date format: 6/10/2012 14:45
- Starting time fraction: 0.615
- Simulation period (days): 30
- First simulation day (Jan 1 is 1): 30
- Decimal starting time: 30.000
- Days in dynamic simulation: 22
- # of times to show simulation: 100

Insulation and Radiation:

- Use Braden's temps for growth: FALSE
- Select insulation:
 - 1 No insulation in basins
 - 2 Radiant barrier in basins
 - 3 Polystyrene Ins. in basins
- Select source of radiation data:
 - 1 Braden's light data
 - 2 Theoretical data
 - 3 AZMET weather station data
- AZMET weather station: [Dropdown]

Basin and Canal Dimensions:

- Basin width: [Input field]
- Basin length: [Input field]
- Basin 1, Basin 2, Basin 3, Canal B. [Input fields]
- Canal top width: [Input field]

Initial Conditions and Parameters:

- Select comparison:
 - ☐ Compare to experimental data
 - ☒ Compare to conventional raceway
- Initial algae concentration:

ARID initial	OD Conventional	Specify here
0.5	0.1	TRUE
- ARID dilution (canal):

ARID dilution (canal)	Conventional	Time (hr)
0.3	0.1	5
- Initial ARID basin soil temperature (C): 20
- Initial ARID canal soil temperature (C): 20
- ARID deep soil temperature (C): 20
- ARID initial water temperature (C): 20
- Conventional RW deep soil temperature (C): 14
- Conventional initial water temperature (C): 14
- Conventional initial soil temperature (C): 14
- Decrease basin evaporation fract: 0.5
- DOY: 32

Pump and Cover Settings:

- Specify pump on and off time here: TRUE

Pump on time (hr)	Pump off time (hr)
8	17
- Specify cover on and off time here: TRUE

Cover off time (hr)	Cover on time (hr)
8	17

Buttons and Controls:

- Get weather, Output, Simulation, Algae temp, Thermal
- View weather, 21_X data, Canal, Basin soils
- Run button
- Move this slide bar to the right to slow down the dynamic simulation