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Temperature modeling of a land-based aquaculture system for the production of *Gracilaria pacifica*: Possible system modifications to conserve heat and extend the growing season

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ABSTRACT

Temperature control is a major cost for numerous aquaculture systems. Solar thermal engineering techniques can be used to identify inexpensive methods for conserving and capturing heat. *Gracilaria pacifica*, also known as the culinary ingredient ogo, is currently grown in land-based tanks at a site in Goleta, CA where influent sea water temperatures infrequently reach the 21–28 °C range that provides for optimal growth. The major objective of this study was to explore various designs of a *G. pacifica* tank culture system that maintain optimal water temperature year round to maximize growth. A model was constructed and calibrated by comparing results to a one-third scale pilot system operated in Davis, CA. For model calibration the most sensitive parameter such as cover optical properties were adjusted first and less sensitive parameters were adjusted later. The pilot system consisted of six tanks, three insulated with foam and a clear polyethylene cover (experimental), and three uninsulated and uncovered (controls). The model had weather data inputs including air temperature, humidity, wind speed, and solar radiation. The model was then compared to a full-scale system operated in Santa Barbara during the winter. The experimental pilot system was 4.93 °C warmer than the control pilot system under optimal weather conditions. The full-scale experimental system was 2.80 °C warmer than the control system under non-ideal conditions. The model demonstrated predictive accuracy under most weather conditions. Furthermore the model is robust enough to accept estimated values for many inputs and still produce accurate results, this suggests a simpler model may be feasible. A polyethylene cover and insulation are not sufficient in general for raising the water temperature to the optimum range during the winter; they may be during other times of the year when more solar energy is available, thereby extending the growing season.

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1. Introduction

Seaweed aquaculture is a multibillion-dollar industry that is practiced worldwide (Titlyanov and Titlyanova, 2010). The red seaweed genus *Gracilaria* is most often grown for agar production, but has additional uses as the culinary ingredient ogo, as a dietary supplement for aquarium fish, and as a weaning feed for juvenile abalone (Armisen, 1995). Experimental tank culture of *Gracilaria* has been taking place for over 30 years and general culture methods are now well understood (Edelstein et al., 1976; Friedlander and Levy, 1995). Vigorous aeration is frequently used and serves a threefold purpose of rotating plants to reduce shadowing, increasing nutrient absorption by reducing boundary layers, and maintaining high dissolved CO_2 levels (Hanisak and Ryther, 1984). Neori et al. (1996) used *Gracilaria* as a biofilter for a fish producing system with a water residence time of 4.9 days. More recent biofilter research has maintained *Gracilaria* in a 900 l recirculating system for 120 days with no water exchange (Chaitanawisuti et al., 2011). Although *Gracilaria* is commonly cultured, very little work has been done in respect to growing *Gracilaria pacifica*, a species native to the Eastern Pacific Ocean. Preliminary growth experiments in Goleta, CA have demonstrated rapid growth of *G. pacifica* grown in tanks during late summer when air temperatures regularly reach 24 °C (D. Bush, personal communication). In the absences of a physiological study, a literature review of *Gracilaria* culture indicated an optimum growing temperature of 21 °C should be expected for *G. pacifica*, and that light would be a non-limiting factor in Goleta, CA during all seasons (Davison, 2014). Temperature was identified as the growth limiting factor since all other tank conditions, including nutrients, are carefully controlled.

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Nomenclature

α_i	absorptivity of component i
ε_i	emissivity of component i
θ_d	declination angle (°)
θ_z	zenith angle (°)
λ	latent heat of vaporization ($J\,kg^{-1}$)
ρ_i	density of component i ($kg\,m^{-3}$)
$\rho_{s,i}$	reflectivity of component i
σ	Stefan–Boltzmann constant
$\tau_{l,c}$	transmissivity of longwave radiation through the cover
$\tau_{s,c}$	transmissivity of shortwave radiation through the cover
A	surface area of top of tank (m^2)
A_{sb}	surface area of sides and bottom of tank (m^2)
B	Julian date to degrees conversion (°)
C	constant for converting from English to SI units ($W\,day\,cal^{-1}$)
cc	cloud cover fraction
Cp_i	heat capacity of component i ($J\,kg^{-1}\,°C^{-1}$)
$D_{w,t}$	tank sides and bottom heat transfer (W)
e_i	vapor density at temperature of component i ($kg\,m^{-3}$)
Eot	equation of time (min)
G_{sun}	global solar radiation, measured by pyranometer ($W\,m^{-2}$)
h_a	convective heat transfer coefficient of ambient air flow ($W\,m^{-2}\,°C^{-1}$)
h_{ap}	convective heat transfer coefficient of air pocket air flow ($W\,m^{-2}\,°C^{-1}$)
hf	humidity factor
h_L	latent convection coefficient ($W\,m\,kg^{-1}$)
h_n	natural convection coefficient ($W\,m^{-2}\,°C^{-1}$)
h_w	convective heat transfer coefficient of water flow ($W\,m^{-2}\,°C^{-1}$)
h_{wall}	natural convection coefficient used in Res calculation ($W\,m^{-2}\,°C^{-1}$)
k_a	thermal conductivity of air ($W\,m^{-1}\,°C^{-1}$)
L	characteristic length of a rectangle (m)
L_{ap}	latent heat transfer due to airflow out of air pocket (W)
lat	local latitude (°)
$L_{c,ap}$	latent heat transfer between the cover and the air pocket (W)
Le	Lewis number, dimensionless ratio of mass to thermal diffusivity
L_{loc}	local longitude (°)
L_{st}	standard longitude of current time zone (°)
$L_{w,a}$	latent heat transfer between the water and the ambient air (W)
$L_{w,ap}$	latent heat transfer between the water and air pocket (W)
$L_{w,at}$	latent heat transfer between the water and the aeration bubbles (W)
$L_{w,sw}$	latent heat transfer between the water and the ambient air due to swirling water motion
MBE	mean bias error statistic (°C)
M_w	molecular weight of water ($kg\,kmol^{-1}$)
m	total number of data points (used in statistics)
n	Julian date (day)
P_i	vapor pressure at temperature of component i (Pa)
Pr	Prandtl number
Q_{air}	rate of aeration air flow ($m^3\,s^{-1}$)
$Q_{s,c}$	shortwave solar energy absorbed by cover (W)
$Q_{s,w}$	shortwave solar energy absorbed by water (W)
Q_{wat}	rate of inlet water flow ($m^3\,s^{-1}$)
r	constant (°)
R	universal gas constant ($J\,kmol^{-1}\,K^{-1}$)
$R_{c,sky}$	longwave radiation between the cover and the sky (W)
Res	total thermal resistance of tank ($m^2\,°C\,W^{-1}$)
Res_{wall}	thermal resistance of tank plus insulation if present ($m^2\,°C\,W^{-1}$)
Rh_a	relative humidity of ambient air, measured by the weather station (%)
Rh_{ai}	relative humidity of aeration inlet air (%)
RMSE	root mean square error statistic (°C)
$R_{w,c}$	longwave radiation between the cover and the water (W)
$R_{w,sky}$	longwave radiation between the water and the sky (W)
S_{ap}	sensible heat transfer due to airflow out of air pocket (W)
STDEV	standard deviation statistic (°C)
$S_{w,at}$	sensible heat transfer between the water and the aeration bubbles (W)
t	time (s)
T_{dp}	dew point temperature, measured by weather station (°C)
T_i	temperature of component i (°C)
T_{sky}	sky temperature (K)
t_{sol}	solar time (h)
t_{st}	standard time (h)
V_a	velocity of ambient air, measured as wind speed by weather station ($m\,s^{-1}$)
V_{ap}	velocity of air pocket air, a constant value ($m\,s^{-1}$)
$V_{c,a}$	convection between the cover and the ambient air (W)
$V_{c,ap}$	convection between the cover and the air pocket (W)
V_i	volume of component i (m^3)
V_{sw}	velocity of water surface caused by aeration swirling, a constant value ($m\,s^{-1}$)
$V_{w,a}$	convection between the water and the ambient air (W)
$V_{w,ap}$	convection between the water and the air pocket (W)
w	solar time to angle conversion (°)
W_{ref}	heat transfer due to inlet water addition and outlet water drainage (W)
ν_a	kinematic viscosity of air ($m^2\,s^{-1}$)

Subscript

a	ambient air
ai	eration inlet air
ap	air pocket
c	cover
i	system component *i* can be any of the below subscripts
j	data point number (used in statistics)
k	tank number (used in statistics)
w	water
wi	inlet water

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