# Modeling Framework for Control of Bacterial Nitrification in Aquaponics-Inspired Hydroponics System: A Masters Thesis in Electrical Engineering at Colorado School of Mines

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# Outline

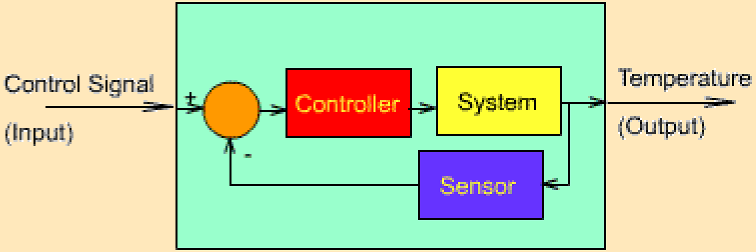
- About Me
- Intro to Control Engineering
- Thesis Project Overview:
    - Motivation
    - Goals
    - Modeling
    - Lab Design
    - Startup and Nominal Operation
    - Control Design
    - Experiment

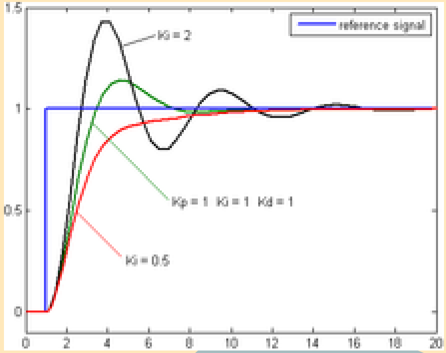
# About Me

- BA CS 12/2008
  - Oberlin College (OH)
- Software Engineer
  - Aerospace/Defense
- MS EE 8/2014
  - CSM
  - K-12 Outreach
- Aquaponics project since 6/2013
- Hobbies: hiking, skiing, (soil) gardening

# Intro to Control Systems

- Feedback control
- Dynamics
  - PID
- MIMO Systems
  - multiloop
  - state-space



# Thesis Project Overview

- Motivation
- Goals
- Modeling
- Lab Design
- Startup and Nominal Operation
- Control Design
- Experiment

# Motivation

- Water/Energy tradeoffs of Aquaponic Systems not well understood:
  - Assumed reduced water use of Aquaponics vs. traditional Aquaculture/Horticulture
  - Colorado Water Deliveries:
    - 86% Agriculture
    - 3% Recreation/Fisheries
- Control system designs absent in literature
- System level analysis absent in literature

# Goals

- Increase the **efficiency** of aquaponic systems through use of advanced control techniques.
- **Efficiency = Outputs/Inputs**
  - aggregation of terms using prices per unit
- For controlled system:
  - Efficiency = Outputs/ "Control Effort"

# Approach

- Modeling
  - identify key parameters & interactions
  - define inputs and outputs
- Lab Design
  - provide experimental data
- Experiment
  - inform/verify model
  - proof-of-concept control design
  - efficiency analysis

# Modeling

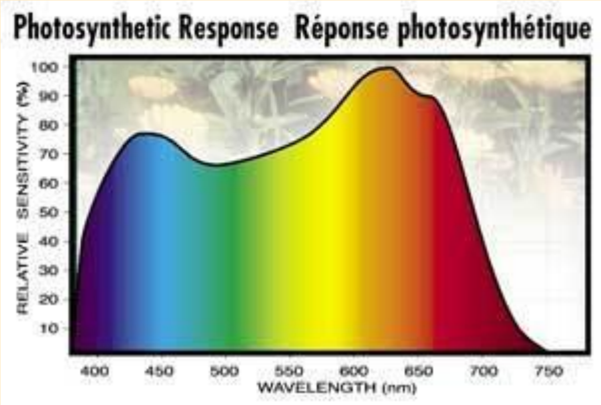
- Subsystem approach:
  - Biological
    - Aquatic Life (Fish)
    - Bacteria
    - Plants
  - Chemical
    - pH
  - Thermal (non-aqueous environment)
  - Fluidics (aqueous environment)

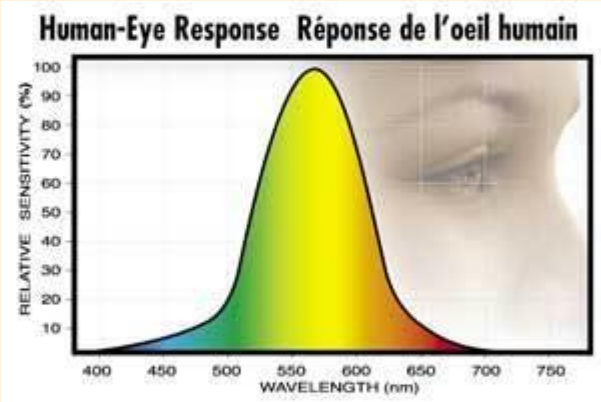
# Modeling (revised due to regulation)

- Subsystem approach:
  - Biological
    - Bacteria
    - Plants
  - Chemical
    - pH
    - Aquatic Life Simulation
  - Thermal (non-aqueous environment)
  - Fluidics (aqueous environment)

# Plants

- Inputs:
    - Micro/Macro Nutrients
        - H,C,O from air & water
    - PAR (light)
- Processes:
    - Photosynthesis
    - Cellular Respiration
    - Nitrogen Assimilation
- Environmental Parameters



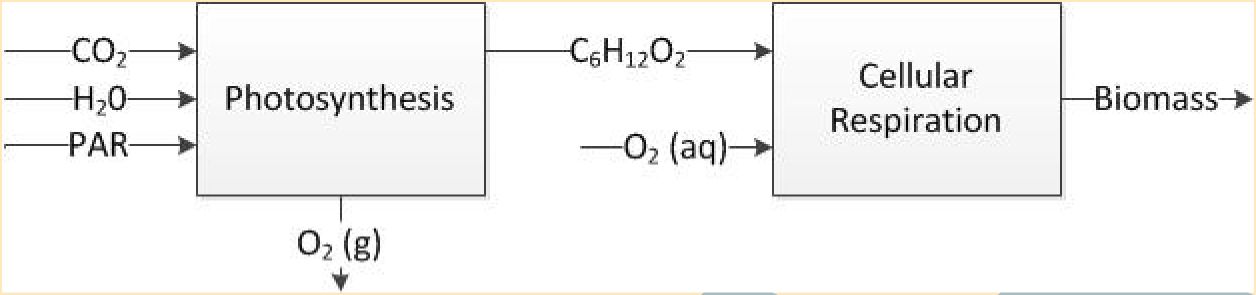
# Photosynthesis & Cellular Respiration

## Photosynthesis:

$$6CO_2(g) + 6H_2O + PAR \rightarrow C_6H_{12}O_6 + 6O_2(g)$$

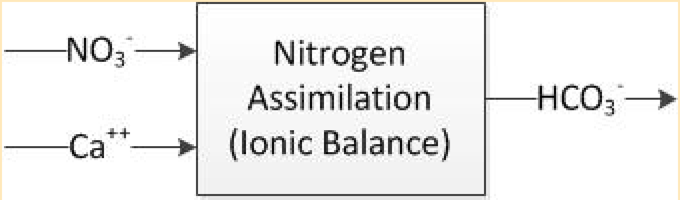
## Cellular Respiration:

$$C_6H_{12}O_6 + 6O_2(aq) \rightarrow 6CO_2 + 6H_2O + Energy$$



# Nitrogen Assimilation (Ionic Balance)

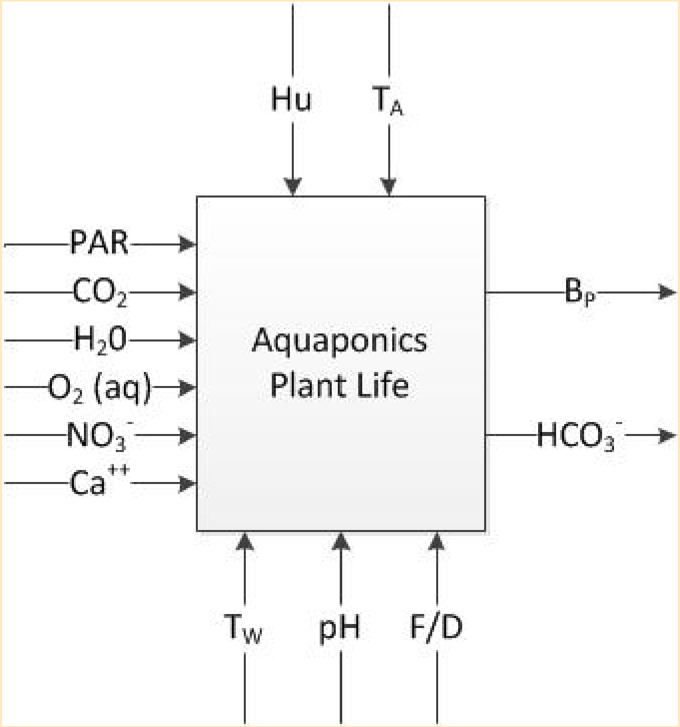
- Plant must maintain a neutral charge
- In order to absorb negatively charged Nitrate, the plant will either:
  - absorb positively charged nutrient ion (Calcium)
  - release negatively charged ion (Bicarbonate)



# Plant Life Model

Non-Aqueous Parameters

Chemical Inputs




Outputs

Aqueous Parameters

# Bacteria

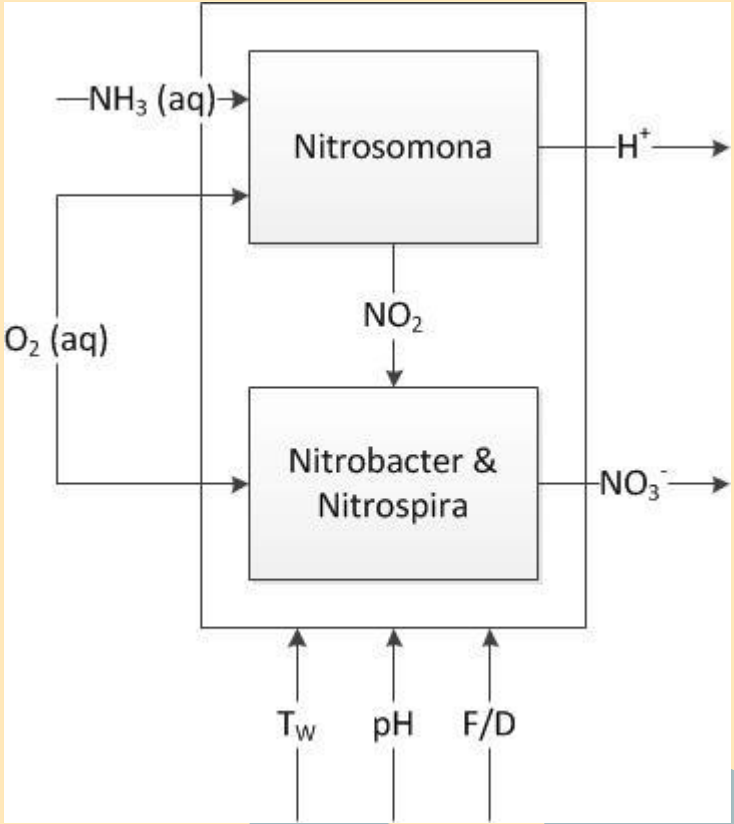
Nitrosomona:

$$2NH_4^+ + 3O_2 \rightarrow$$

$$2NO_2^- + 2H_2O + 4H^+$$

Nitrobacter and Nitrospira:

$$2NO_2^- + 1O_2 \rightarrow 2NO_3^-$$



# pH

Hydrogen ions released by Nitrosomona cause a drop in pH.  Buffer chemical needed to maintain pH at desirable level:

Table 2.4: Considerations for pH Set-Point Selection

| Measurement | Organism | Minimum | Nominal | Maximum |
|---|---|---|---|---|
| pH | Nitrosomonas[23] | 6.0 | 7.8-8.0[24] | 9.0 |
| | Nitrobacter[24] | | 7.3-7.5 | |
| | Fish[2] | | 6.5-8.0 | |
| | Plants[2] | 5.0 | 5.0-6.6[20] (spinach) | 7.0 |
| | Combined System[2] | 6.8 | 6.8-7.0 | 7.0 |

$$KHCO_3 + H^+ \rightarrow H_2O + CO_2 + K^+$$

# Aquatic Life Simulation

Simulate aquatic life with manual addition of ammonia (chemical form of fish waste). Same idea as "Fishless Cycling" method.

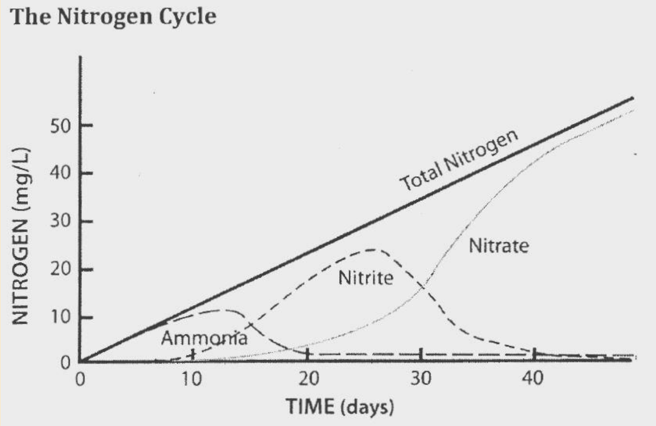



Table 2.5: Maximum Nitrogen Levels for Fish Health

| Nitrogen Form | Maximum Level (For Fish Health) | | | |
|---|---|---|---|---|
| Total Ammonia ($NH_3 + NH_4^-$) | W. Temp. | 68° F | 75° F | 82° F |
| | pH = 7.0 | 0.4 ppm | 0.52 ppm | 0.7 ppm |
| Nitrite ($NO_2^-$) | 10 ppm | | | |
| Nitrate ($NO_3^-$) | N/A (100 ppm desirable for plants) | | | |

# Thermal (non-aqueous parameters)

Thermal system designed to maintain desirable **non-aqueous** parameters (may require external energy):

Table 2.6: Optimal Non-aqueous set-points for Hydroponic Spinach Production

| Measurement | Set-point |
|---|---|
| Air Temperature | 75° F day |
| | 65° F night |
| Relative Humidity | 50% (max 70%) |
| Carbon Dioxide | 1000-1500 ppm with light |
| | 390 ppm (ambient) without light |
| Light | 17-22 $mol/m^2/d$ |

# Fluidics (aqueous parameters)

Fluidics system designed to maintain desirable **aqueous** parameters (may require external energy and water):

Table 2.7: Considerations for Water Temperature Set-Point Selection

| Measurement | Organism | Minimum | Nominal | Maximum |
|---|---|---|---|---|
| Water Temperature | Nitrosomonas[23] | 68° F | 77-86° F[24] | 86° F |
| | Nitrobacter[24] | 32 ° F | | 120° F |
| | Tilapia[2] | 60° F | 74-80° F | 95° F |
| | Trout[2] | 38° | 55-65° | 68° |
| | Goldfish[2] | 45° F | 65-75° F | 90° F |
| | Spinach[20] | | 77° F | |
| | Combined System | Highly dependent on (fish) species | | |

Table 2.8: Considerations for Dissolved Oxygen Set-Point Selection

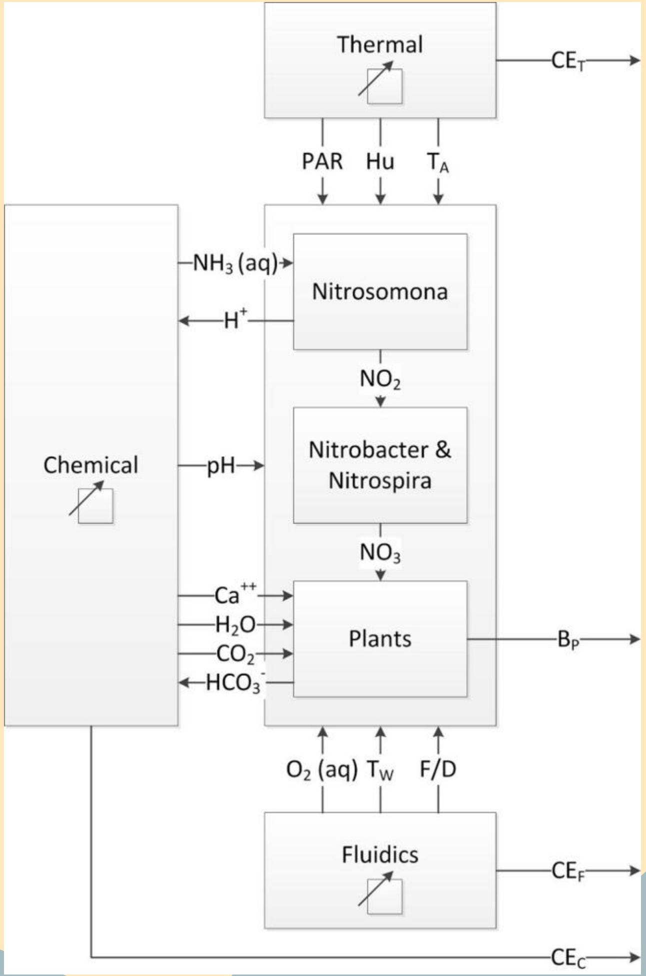
| Measurement | Organism | Minimum | Nominal | Maximum |
|---|---|---|---|---|
| Dissolved Oxygen | Nitrosomonas[24] | 2 ppm | 80% saturation | N/A |
| | Nitrobacter[24] | | | |
| | Fish[2] | 3 ppm (stress)<br>2 ppm (death) | 6 ppm | N/A |
| | Spinach[20] | 3 ppm | 7 ppm | N/A |
| | Combined System | 3 ppm | 7 ppm | N/A |

# Control Objectives

1. Maintain Desirable Set-points
   a. Possible death of organisms if parameters fall out of range
2. Maximize/Increase Efficiency
   a. Explore energy/water tradeoffs
3. Secondary objectives:
   a. reliability
   b. ease of use
   c. preservation of equipment

# Abstract Model

- Subsystem approach to controlling parameters
- Measure "Control Effort" used for variable manipulation



# Lab Design

Considerations:

1. Physical Design
2. Species Selection
3. Actuators
4. Sensors
5. Integration
6. Maintenance
7. Source of materials

Constraints:

1. Small space
2. Shared space
3. No natural light
4. Undefined ambient conditions
5. Limited budget and timeframe

# Physical Design

Japan Aquaponics Micro System Design:

- IKEA shelving units
- Hydroton media bed
- Siphon drain
- Continuous pump
  - manual bypass valve

Modified to include:

- Mylar enclosure
- Artificial lighting
- Ventilation fan

# Actuators

Table 3.1: Actuators Used During Experimental Iterations

| | Actuator | Power Rating | Manipulated Variable |
|---|---|---|---|
| Pump | Hydrofarm AAPW160 | 9.5 W | *Flow* |
| Light | Hydrofarm FLCDG125D | 125 W | *PAR* |
| Water Heater | Aqueon 13" | 150 W | $T_W$ |
| Aerator | Petco AC-9904 | 5 W | *DO* |
| Fan | Minuteman F-11 | Unspecified | $T_A$ (attempted) |
| Failsafe Aerator | Penn-Plax Silent Air B11 | N/A (2x "D" Cell Batteries) | *DO* (failsafe) |

Considerations:

- Light: Color Temperature, Lux to PAR conversion
- Heater and Aerator: Saturation
- Pump: Flow rate, siphon actuation

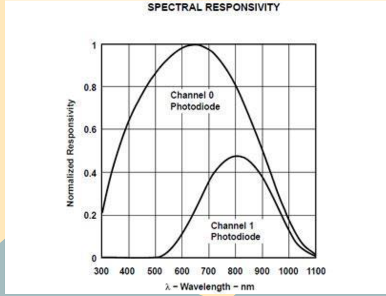
# Sensors (non-aqueous)

Table 3.5: Sensors for Exogenous Inputs

| System Variable | Description | Sensor | Interface | Max Sample Rate |
|---|---|---|---|---|
| $T_A$ | Air Temperature | TMP36 | Analog | N/A |
| $PAR$ | Light | TSL2561 | $I^2C$ | 400 ms |
| $CO_2$ | Carbon Dioxide | MG-811 | Analog | N/A |
| $Hu$ | Humidity | HIH-4030 | Analog | N/A |
| $\rho$ | Atmospheric Pressure | MPL115A2 | $I^2C$ | 8 ms |

## Considerations:

- Light: Spectral sensitivity (PAR)
- CO2: sourcing



# Sensors (aqueous)

Table 3.6: Sensors for Intermediate Measurements

| System Variable | Description | Sensor | Interface | Max Sample Rate |
|---|---|---|---|---|
| $NH_3$ | Ammonia | API Freshwater Master Test Kit | Manual | 1 day |
| $NO_2^-$ | Nitrite | API Freshwater Master Test Kit | Manual | 1 day |
| $NO_3^-$ | Nitrate | API Freshwater Master Test Kit | Manual | 1 day |
| $pH$ | pH | Atlas Scientific pH sensor | Serial | 378 ms |
| $EC$ | Salinity (Electrical Conductivity) | Atlas Scientific Conductivity Sensor | Serial | 1000 ms |
| $DO$ | Dissolved Oxygen | Atlas Scientific Dissolved Oxygen Sensor | Serial | 650 ms |
| $ORP$ | Oxygen Reduction Potential | Atlas Scientific ORP Sensor | Serial | 320 ms |
| $Flow$ | Flow | TurboFlow-226000 | Serial | 200 ms |
| $T_W$ | Water Temperature | ENV-TMP | Analog | N/A |

Considerations:

- Manual Nitrogen measurements
- Atlas Scientific sensors with serial interface boards
- Flow sensor pre-filter clogged

# Sensors (outputs, control effort)

Table 3.7: Sensors for Outputs

| System Variable | Description | Sensor | Interface | Max Sample Rate |
|---|---|---|---|---|
| $B_P$ | Plant Biomass | Scale | Manual | 17 days (harvest iteration) |
| $NH_3(in)$ | Powdered Ammonia | 0.25 tsp | Manual | 1 day |
| $CaHCO_3$ | pH buffer | 0.5 tsp | Manual | 1 day |
| $W_{in}$ | Water In | 1 G | Manual | 1 day |
| $E$ | Electric Energy | Kill-a-Watt | XBEE | 2 s |

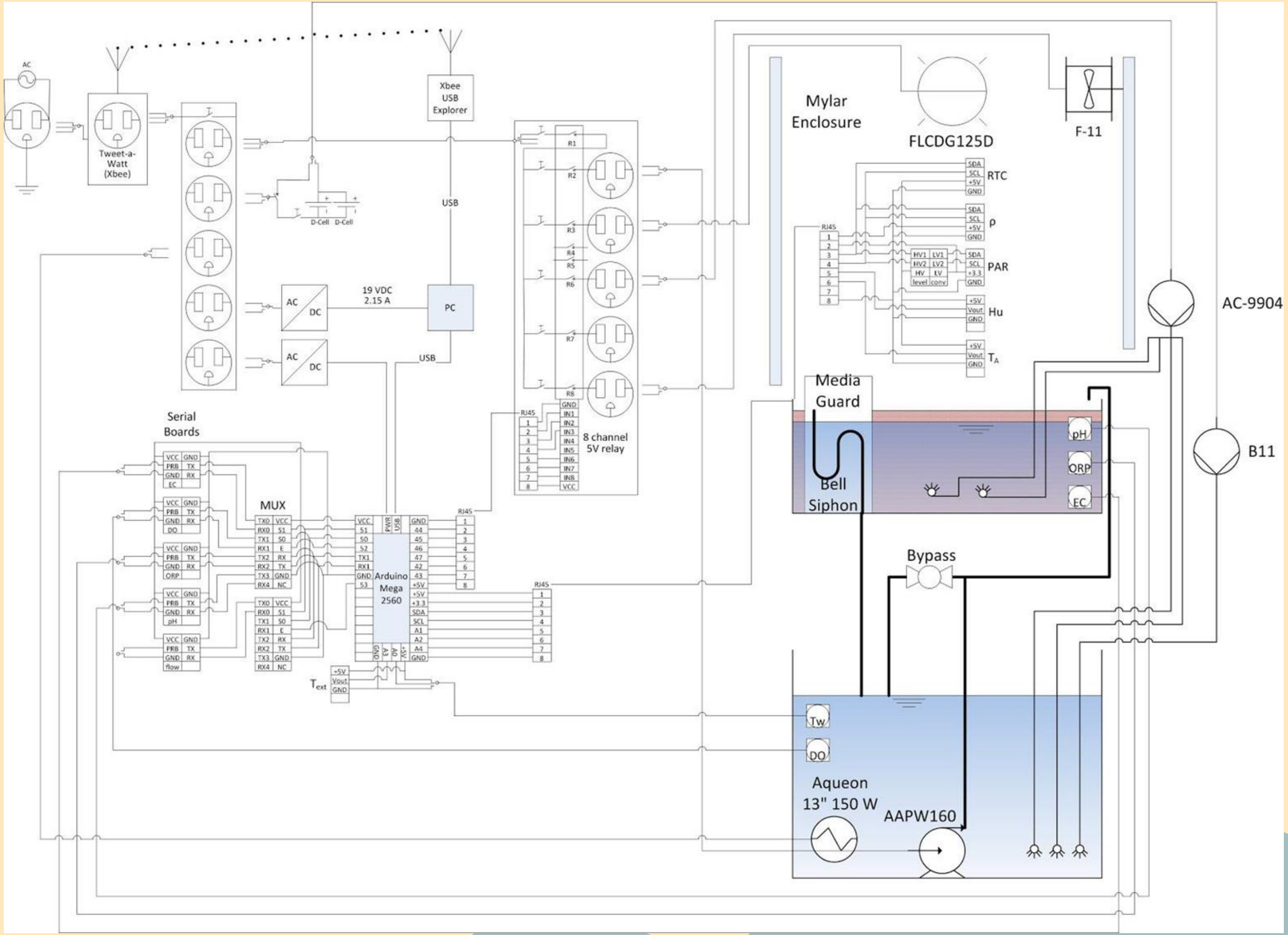
Considerations:

- (Lack of) High rate plant mass sample
- Manual additives
- Kill-a-Watt integration

# Integration

Arduino Mega 2560
Real Time Clock
Logic Level Converter
Serial Multiplexers
SainSmart 8 channel 5V relay

Tweet-a-Watt mod



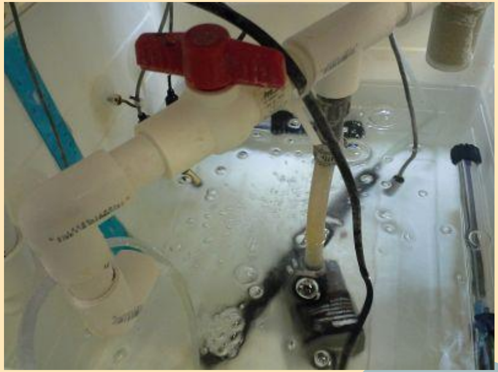
# Species Selection

Table 3.2: Thermal Set Points Versus Measured Outputs

| System Variable | Set Point | Measured |
|---|---|---|
| $PAR$ (Daily) | 4-4.8 $mol/day$ | 6.9 $mol/day$ |
| $PAR$ (Instantaneous) | 71-83 $\mu mol/s$ | 140 $\mu mol/s$ |
| $T_A$ (Day) | 75° F | 80° F |
| $T_A$ (Night) | 65° F | 75° F |

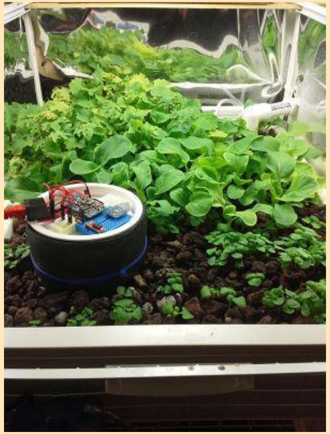
- Spinach and Goldfish intended
- Regulations -> No Goldfish!
- Crawfish possible (invertebrates)
  - Red claw too big
- Too hot for spinach -> "warm weather" crops: Pak Choi, Basil, Mesclun

# Lab photos

# Startup and Nominal Operation

| 2/24 | 3/3 | 3/10 | 3/17 | 3/24 | 3/31 | 4/7 | 4/14 | 4/21 | 4/28 | 5/5 |
|---|---|---|---|---|---|---|---|---|---|---|
| Cycling (unsuccessful) | | | Mesclun (4 wk) | | | | Mesclun | | | |
| | | | Pak Choi (6 wk) | | | | | | | |
| | | | Basil (6 wk) | | | | | | | |

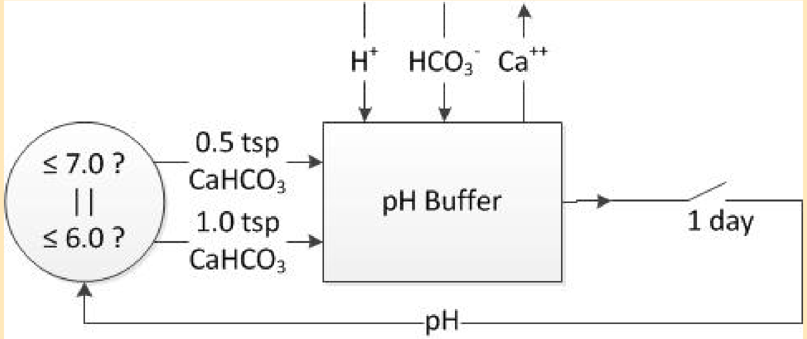
# Model Verification and Control

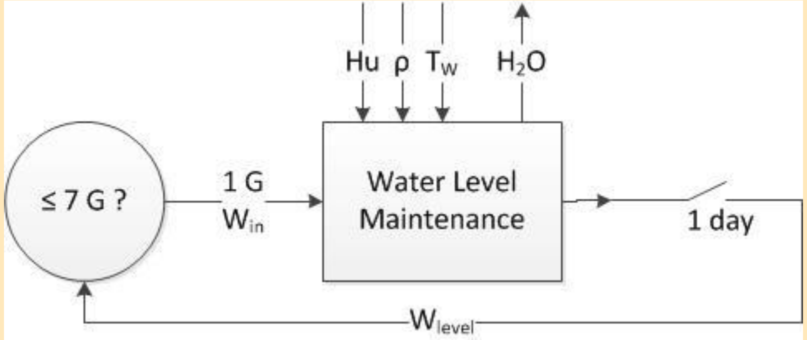
- Manual additives for chemical control
    - Combined “Biochemical” model
- Implementation specific models
    - Thermal
    - Fluidics
- “Nitrifying Hydroponics” model

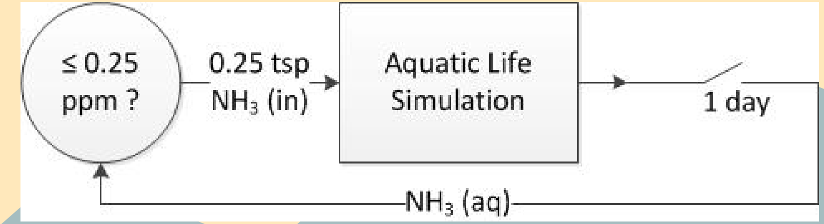
# Manual Control

1. pH Buffer
2. Water Level
3. Aquatic life simulation

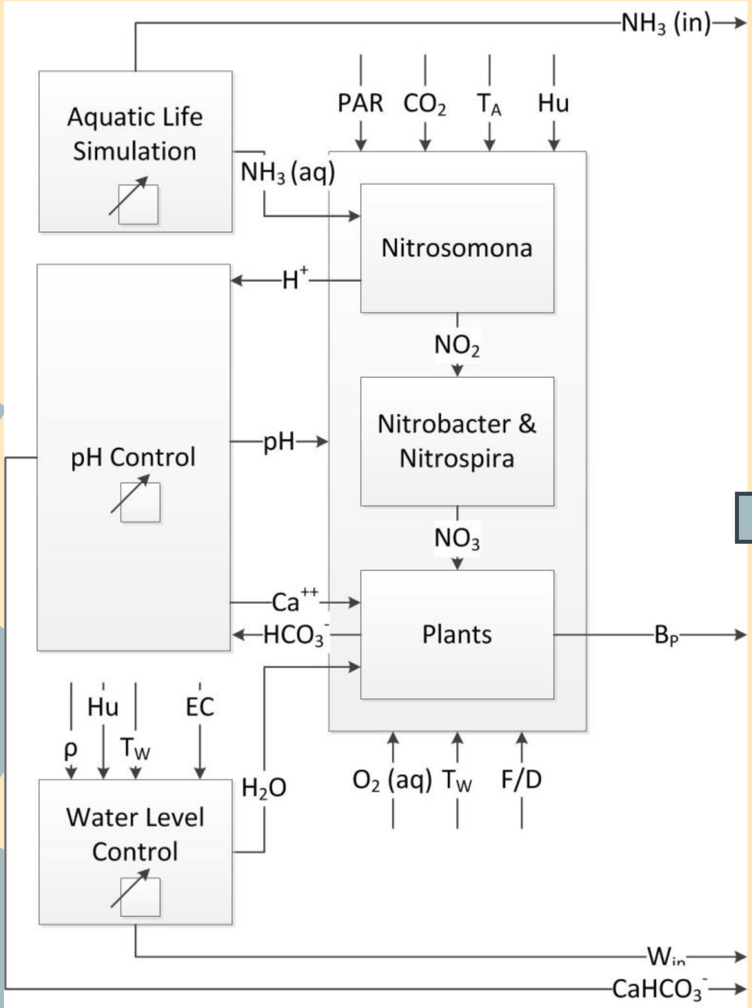
Note: difficulty manipulating small scale system

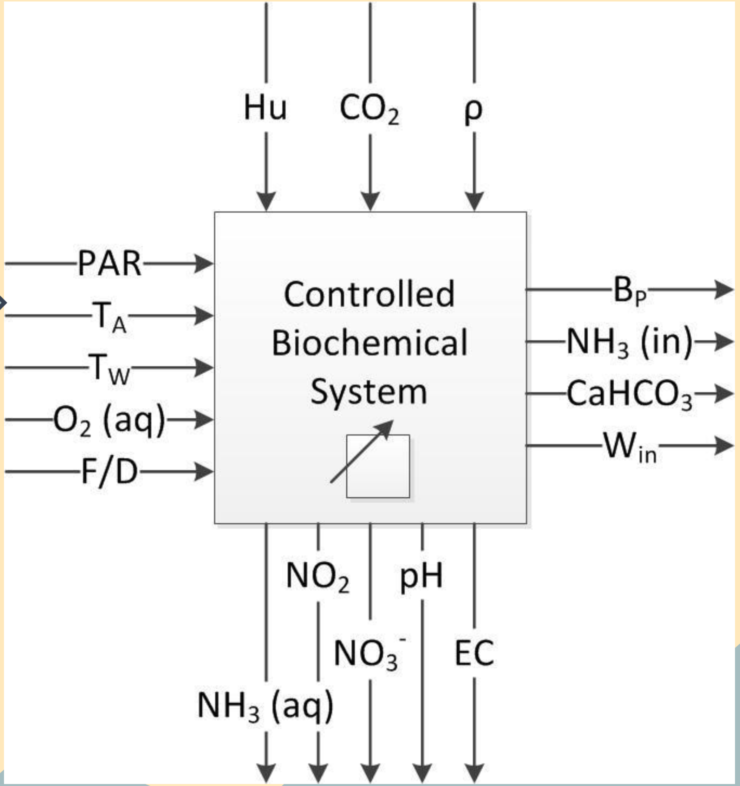


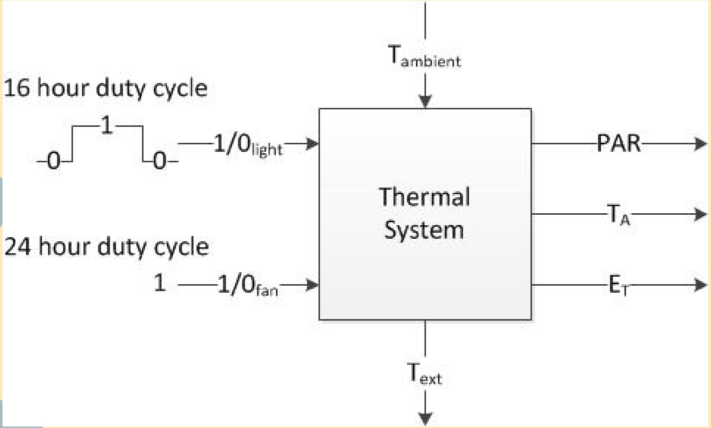



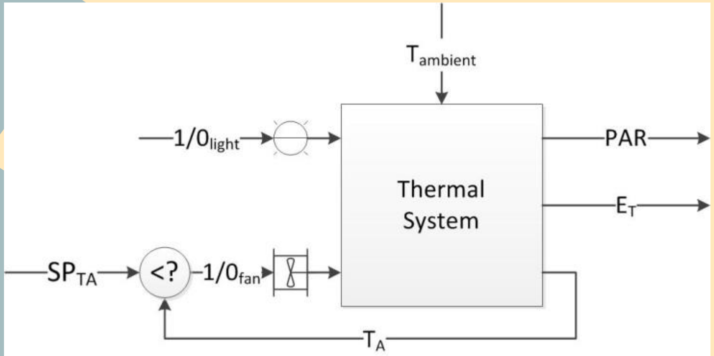
# Biochemical Model

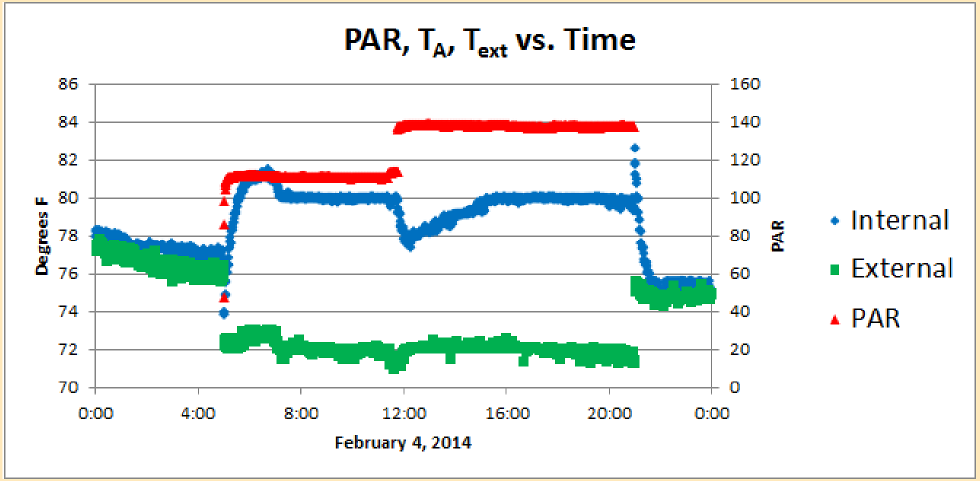


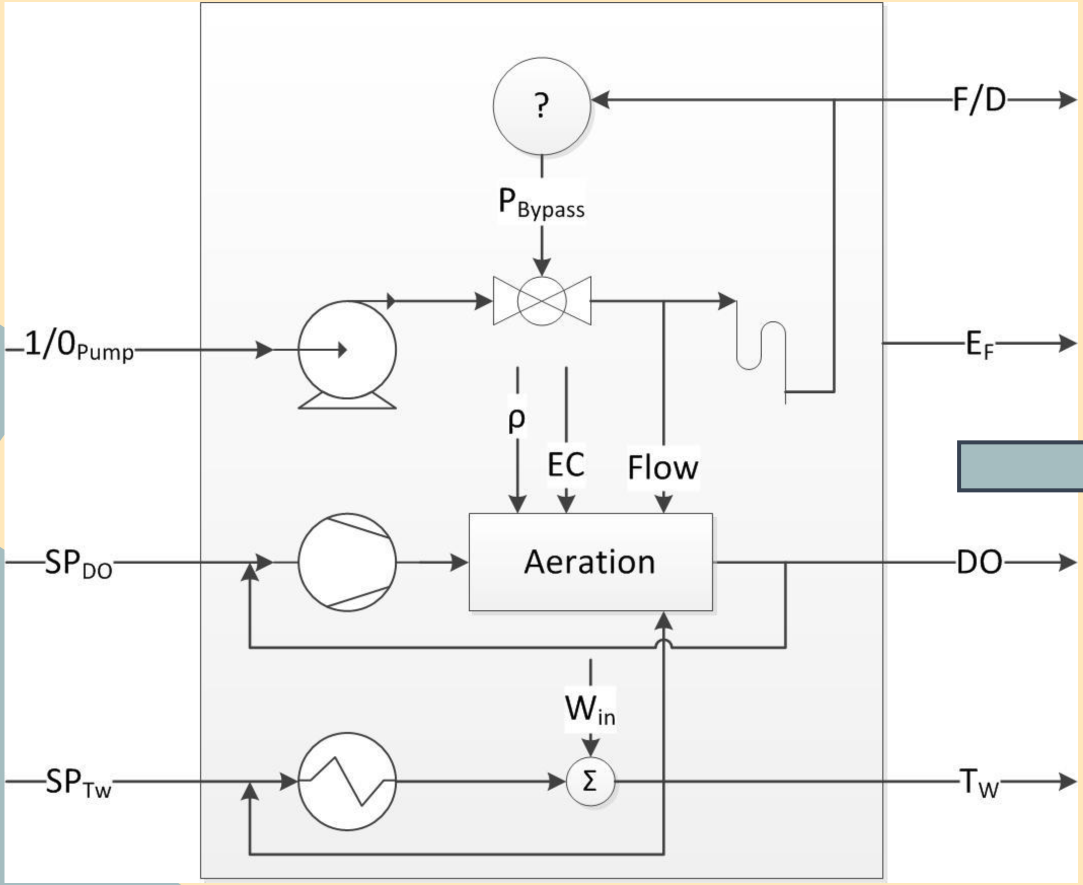
# Thermal Model

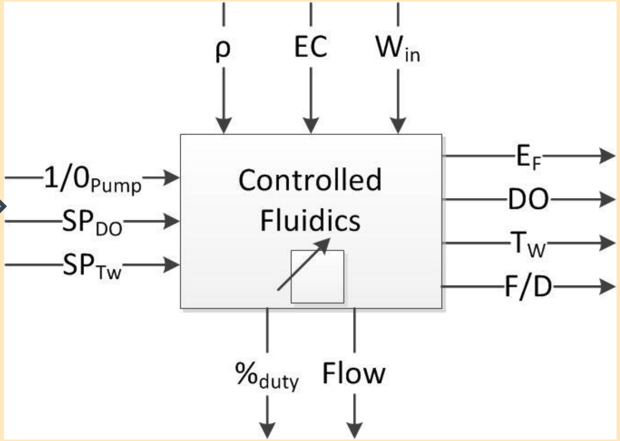


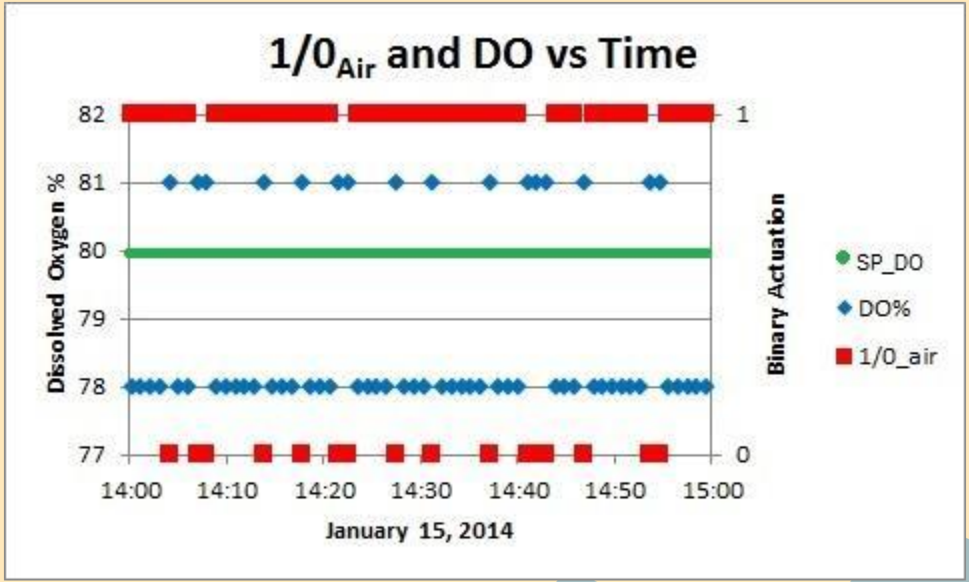
# Fluidics Model



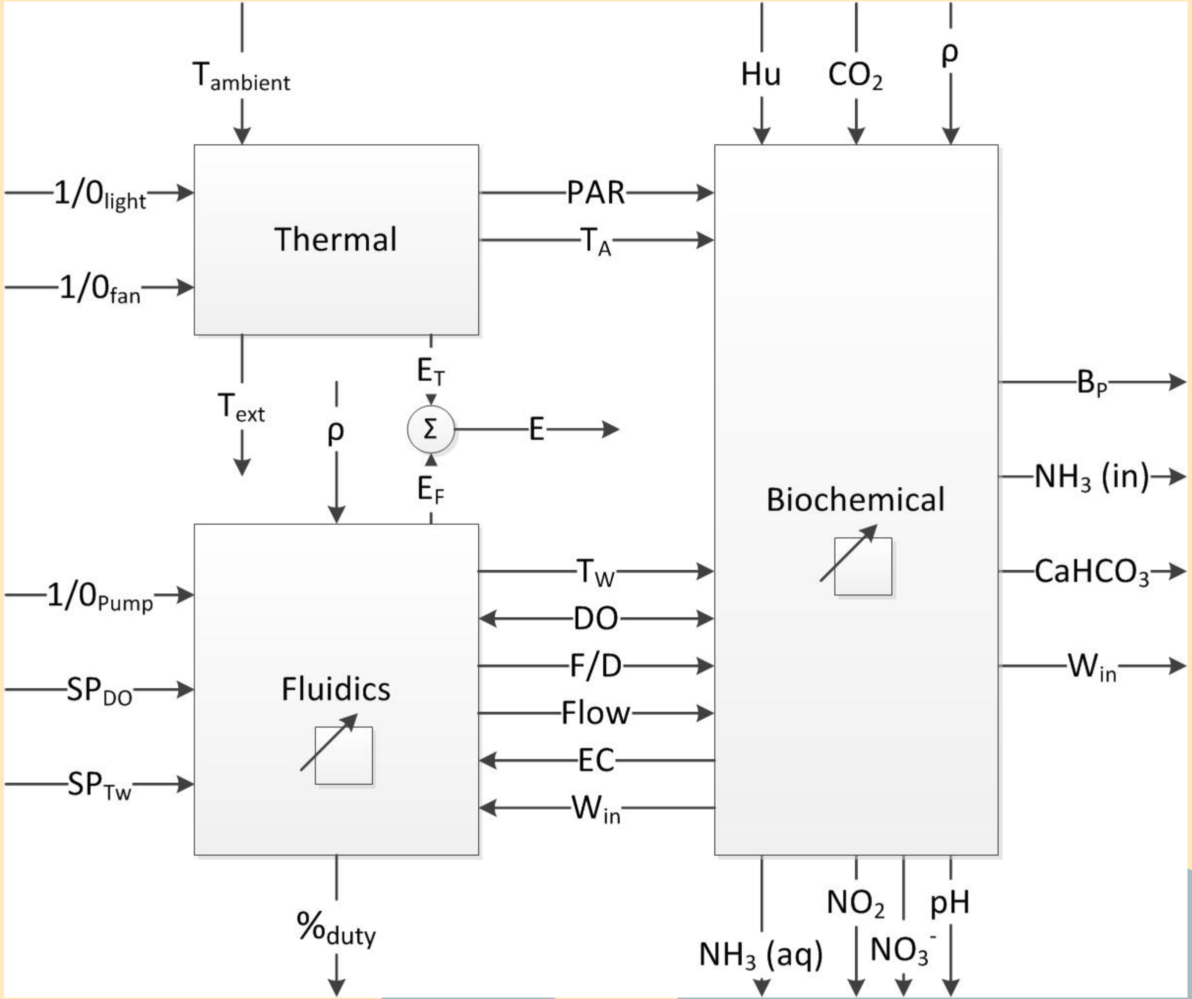



# Aeration Control Data

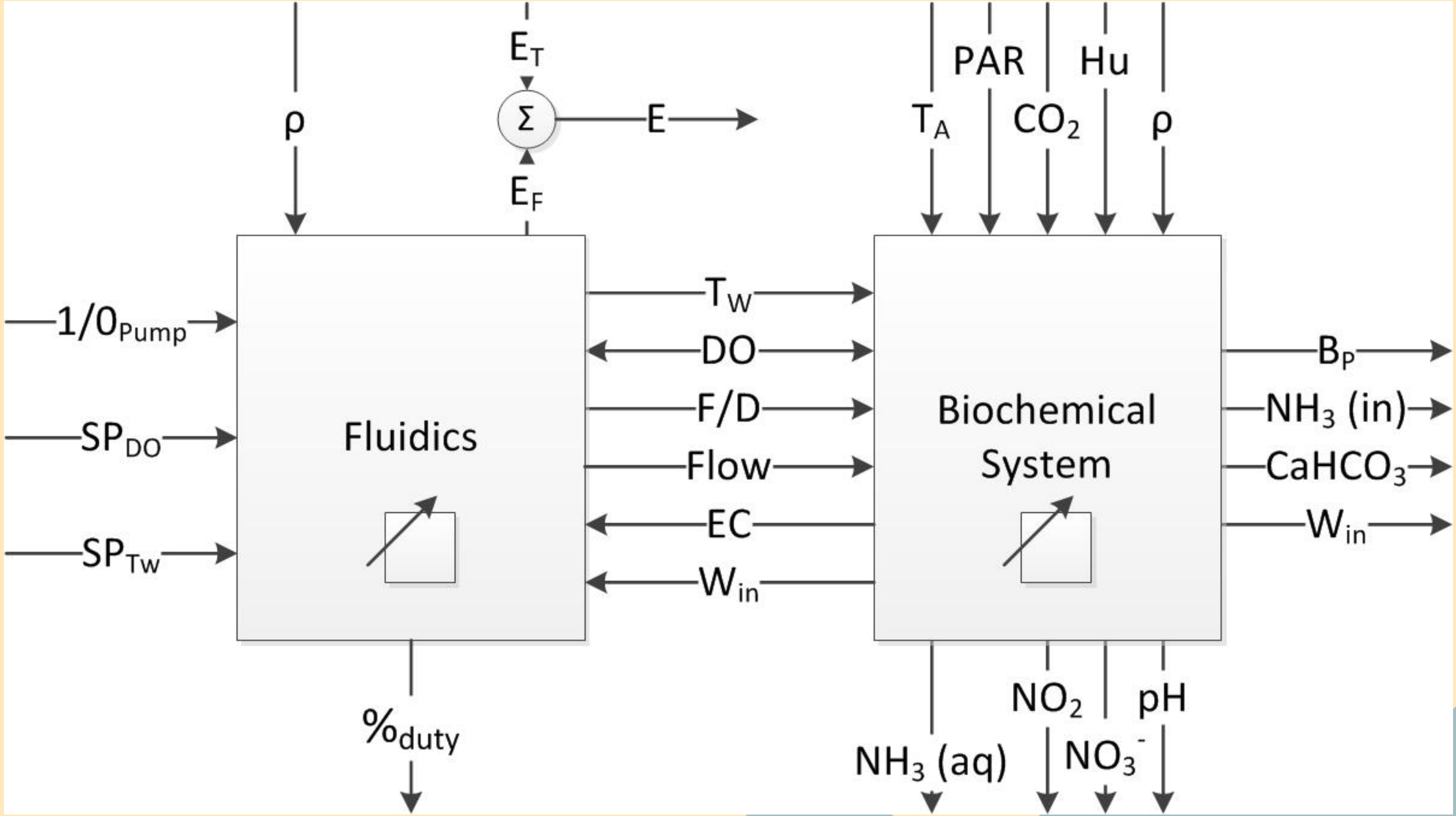
- Before cycling.
- DO set point realized
- ~75 deg F.
- Aeration duty:
  - 75%



# System Model

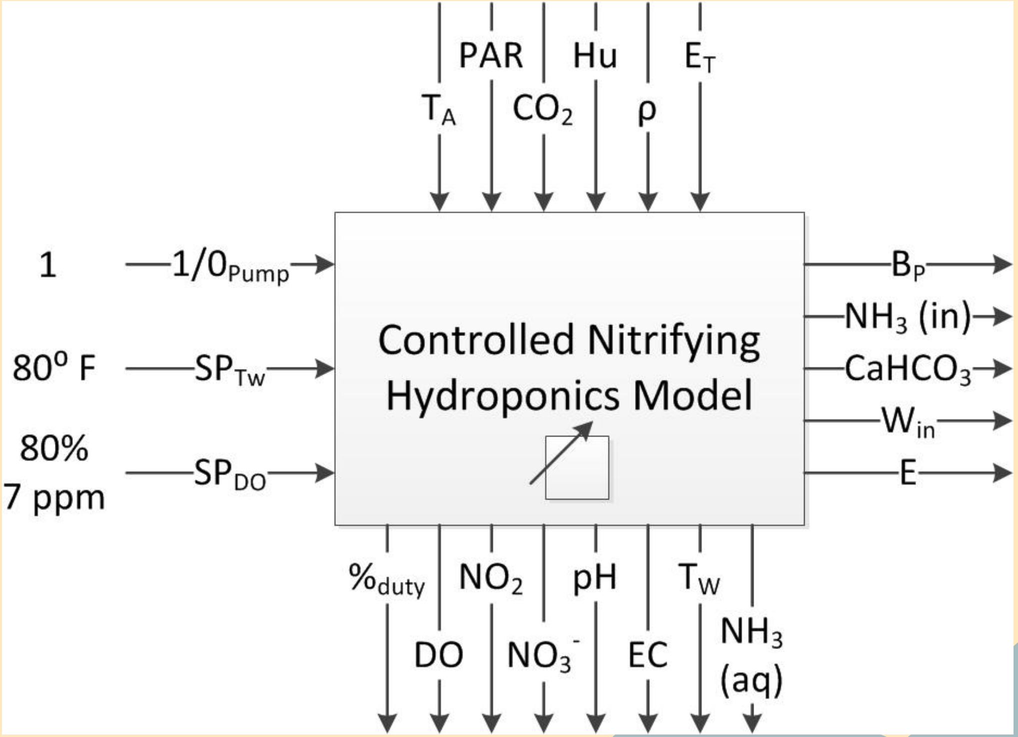


# Thermal System Ignored



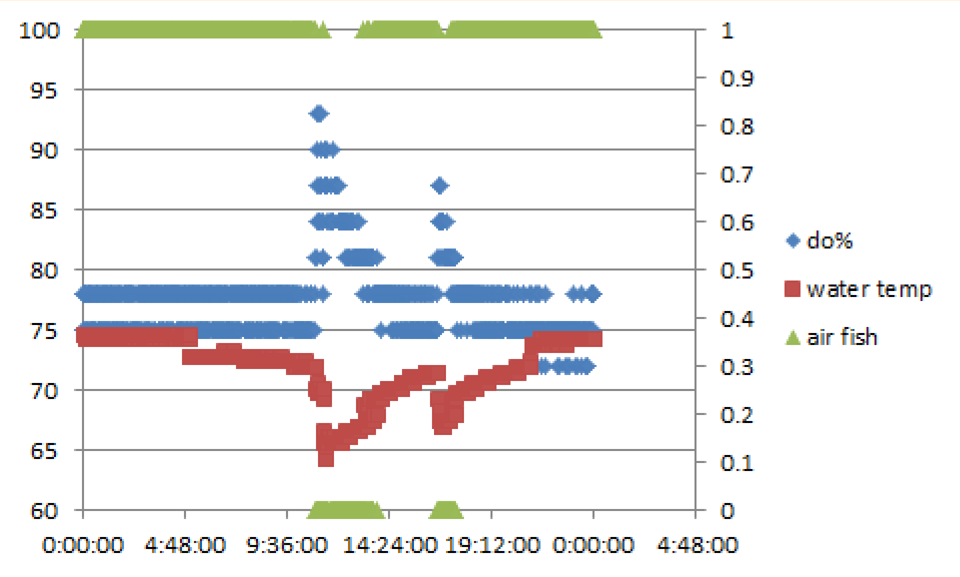
# Simplified "Top-level" Model

$$\text{Efficiency} = \frac{P_{Bp}(\Sigma B_P)}{P_W(\Sigma W_{in}) + P_{NH3}(\Sigma NH_3(in)) + P_{CaHCO3}(\Sigma CaHCO_3) + P_E(\Sigma E)}$$



# Experiment

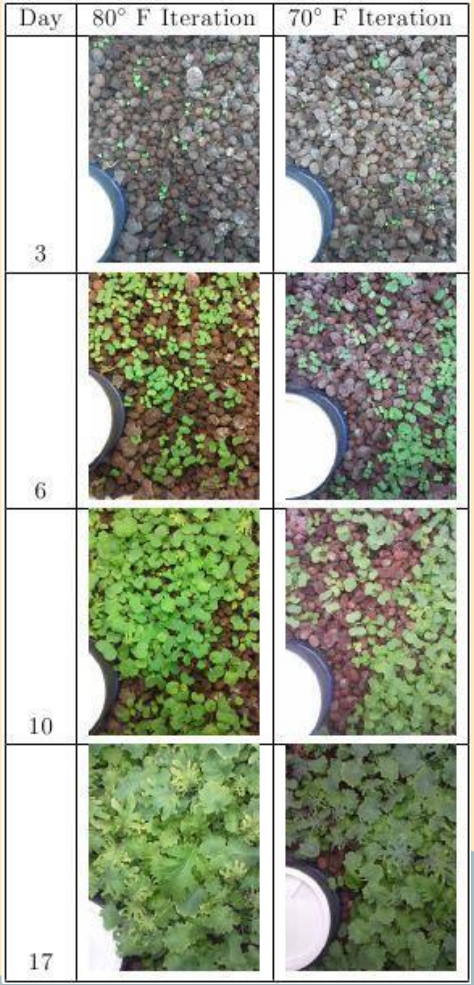
- Motivation:
  - “negative” relationship between DO and Tw observed
- Design:
  - Grow mesclun at different water temperatures
  - Seed to harvest
- Outcomes:
  - impact on DO?
  - impact on **efficiency**?



# Results

| Output | 80° F Iteration | 70° F Iteration | % Change |
|---|---|---|---|
| $B_P$ | 8 oz. | 6 oz. | -25% |
| $W_{in}$ | 11 G | 4 G | -67% |
| $NH_3(in)$ | 2.5 tsp | 2.75 tsp | +10% |
| $CaHCO_3$ | 4.5 tsp | 8 tsp | +44% |
| $E$ | 73.44 kWh | 48.14 kWh | -34% |

| | | |
|---|---|---|
| Set-point Tw | 80 deg F | 70 deg F |
| Water Temp. | 80.3 deg F | 71.0 deg F |
| Set-point DO | 80% saturation | 80% saturation |
| DO | 30.3% saturation | 38.5% saturation |
| %duty (air) | 100% | 100% |



# Analysis

$$\text{Efficiency} = \frac{P_{Bp}(\Sigma B_P)}{P_W(\Sigma W_{in}) + P_{NH3}(\Sigma NH_3(in)) + P_{CaHCO3}(\Sigma CaHCO_3) + P_E(\Sigma E)}$$

| Output | 80° F Iteration | 70° F Iteration | % Change |
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| Output | Stream Type | Description | Price/Unit |
|---|---|---|---|
| $B_P$ | Output | Plant Mass | $3/oz. |
| $W_{in}$ | Input | Water In | $1/G |
| $NH_3(in)$ | Input | Ammonia In | $0.35/tsp |
| $CaHCO_3$ | Input | pH Buffer | $0.12/tsp |
| $E$ | Input | Energy Consumed | $0.10/kWh[16] |

Efficiency(80) = 1.214
Efficiency(70) = 1.677

# Conclusions

1. Efficiency increased at lower temperature
    a. less energy used (by heater)
    b. less water used (evaporation and absorption)
    c. less plant mass produced
2. Nitrification increased
    a. more additives used
    b. higher dissolved Oxygen
3. Feedback of DO not effective
    a. saturation
        i. exogenous parameters (salinity?)

# Future Directions

1. Reduce additive quantities:
   a. Sub-optimal nitrification rates
      i. saturation of Nitrate
2. Exploration of thermal subsystem
   a. PAR and $CO_2$ coupling
3. High rate plant sampling desired
   a. image processing
   b. IR reflectometry

# Summary

- Aquaponic system model developed:
  - Subsystem approach
- Lab designed
- Control system designed
- Experiment:
  - Water Temperature changed
- Efficiency Analysed

# Questions?

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