CO_2 REMOVAL

RECENT CHALLENGES, EXPERIENCES, AND SOLUTIONS DEVELOPED FOR LAND BASED CLOSED CONTAINMENT AQUACULTURE SYSTEMS

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PR Aqua™
An In-Situ Inc. Company

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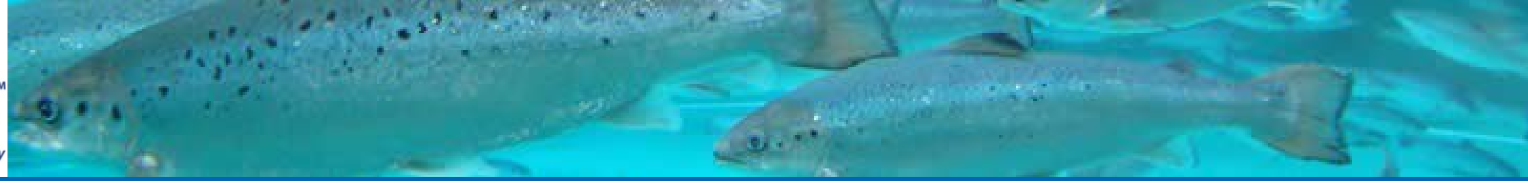
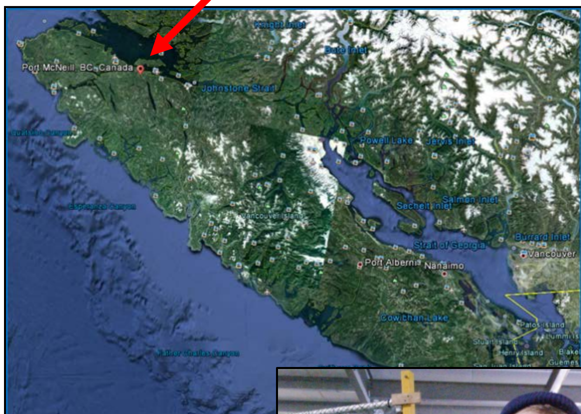


Presentation Objectives

- Review experiences and challenges related to CO_2 removal, focusing on the Kuterra Closed Containment facility as a case study
- Provide a summary of analysis performed, conclusions drawn, and solutions being developed to improve carbon dioxide levels
- Comment on potential design methodology for CO2 removal in large-scale, land based closed containment projects in the future.

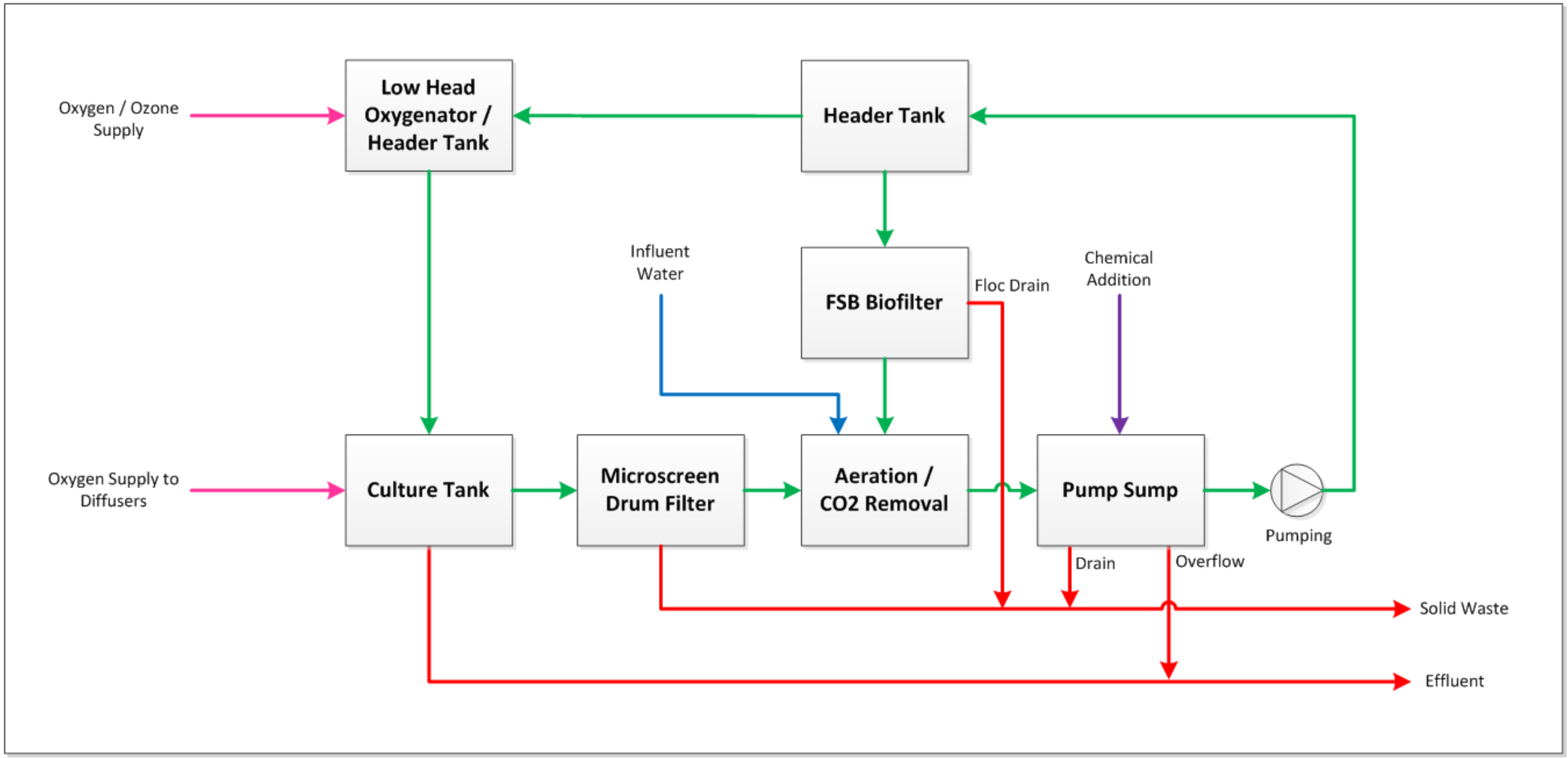
Project Background: Kuterra Closed Containment



- Located near Port McNeil on Vancouver Island, BC, Canada
- Target production of 390 mT/year of 6 kg Atlantic Salmon
- Smolt entry every 17 weeks
- Three modules:
  - Quarantine (360 m3)
  - Growout (2500 m3)
  - Purge (360 m3)
- RAS: 540 L/kg feed influent use
- Began production in 2013

Process Overview

Two process loops through a centralized, forced-air CO_2 stripper



Design Criteria Overview (Grow-out Module)

- Culture tank design criteria
  - Target CO_2 concentration <12mg/L at tank outlet
  - Culture tank HRT = 45 min
  - Maximum density (per tank) = 50 kg/m3 with 1.5 safety factor
  - Oxygen consumption rate = 330 g O2 / kg feed
  - CO2 production rate = 1 kg CO2 / 1 kg O2
  - Feeding 24 hour/day
- CO2 stripper design
  - HLR = 35 gpm / ft2
  - G:L ratio = 10:1 maximum
  - Orifice plate with crown nozzles
  - No gas transfer media

Changing Operating Conditions

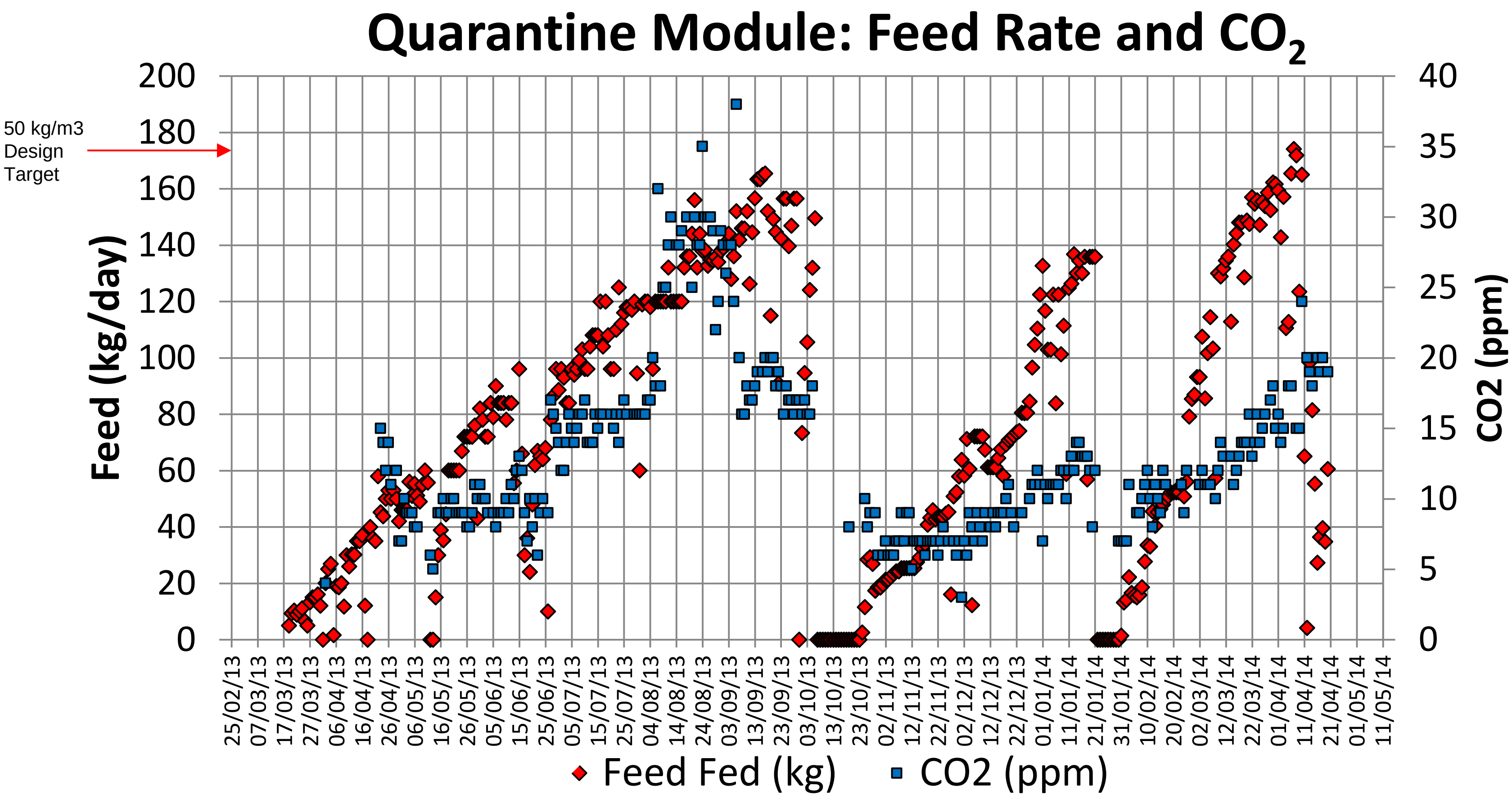
- Increased maximum density
  - Design = 50 kg/m3 (+1.5x safety factor)
  - New Target = 90 kg/m^3
- Feeding over a shortened day
  - Design = 24 hr feeding
  - Actual = 10 hr feeding
- Alkalinity reduced
  - Design = 100 mg/L as $CaCO_3$ minimum
  - Actual = 20-30 mg/L as $CaCO_3$
- CO_2 concentration target relaxed
  - Design = 12mg/L
  - New Target = 18 mg/L Growout, 15 mg/L Quarantine

Challenges Encountered

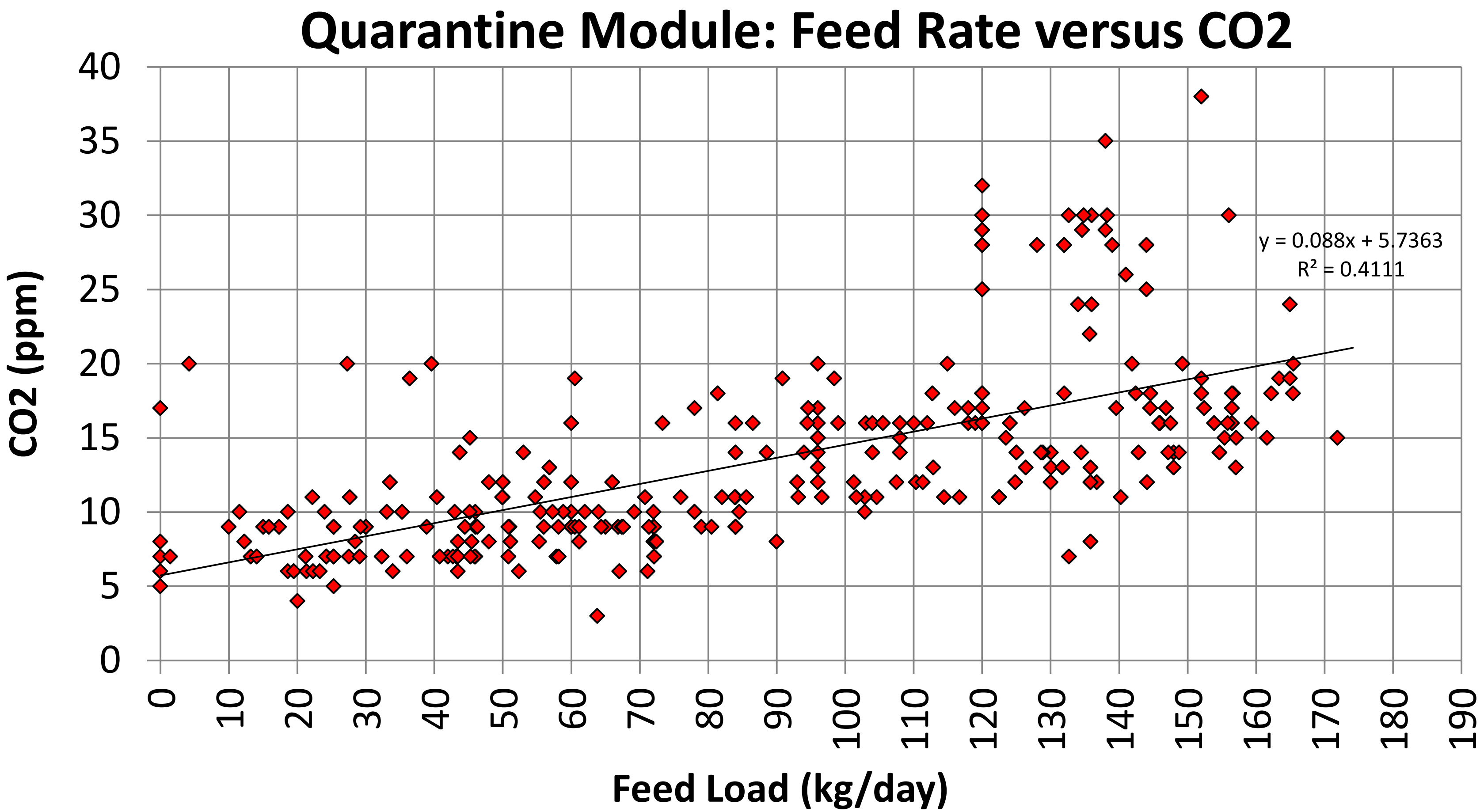
- CO_2 concentrations consistently higher than 12 mg/L target despite lower than target design density and feed load

- Issue is exacerbated by the desire to increase production by 20% over the safety factor design value (80% over design value)

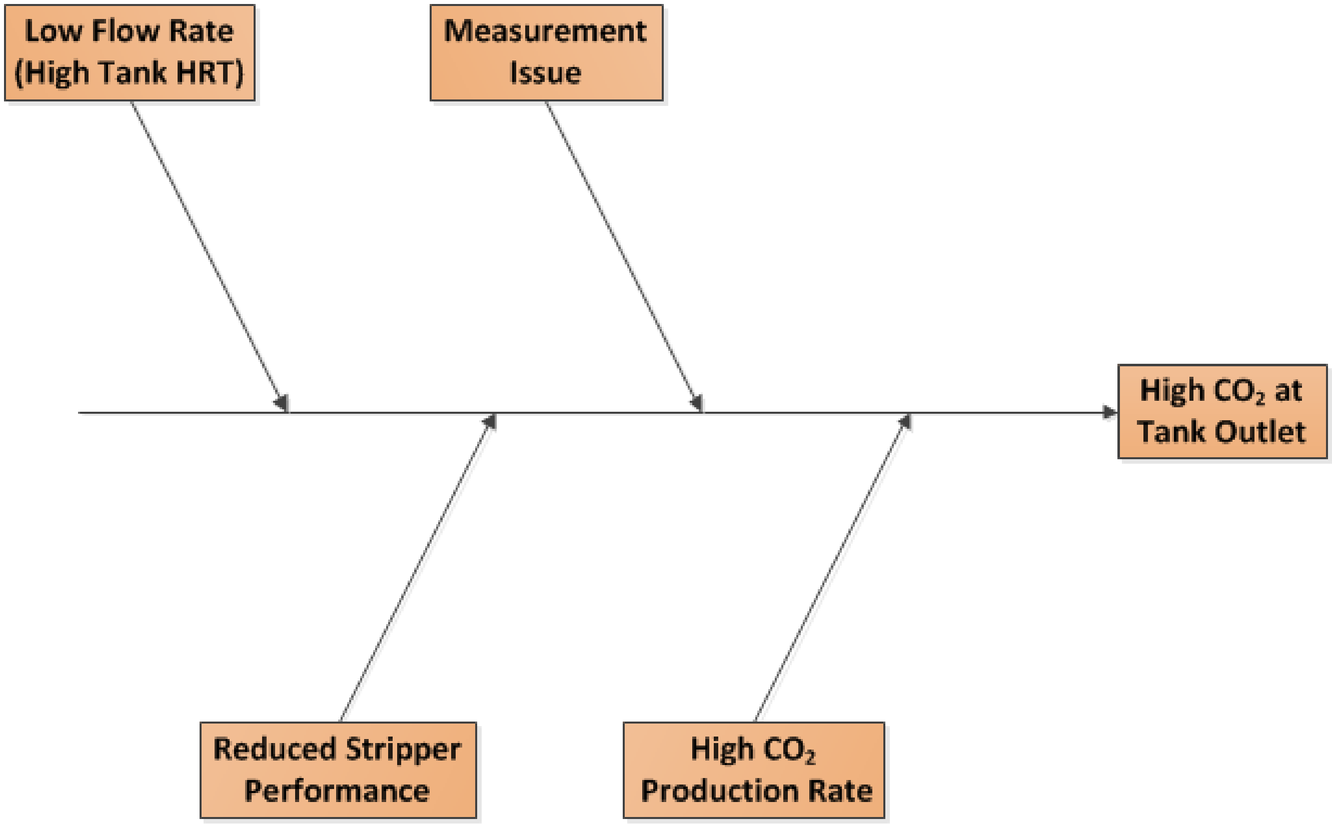
Data Measurement and Validation

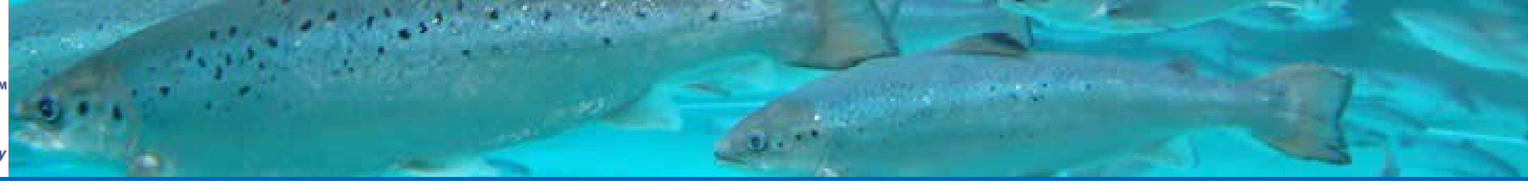


Data Measurement and Validation



Root Cause Analysis: Identify Potential Causes



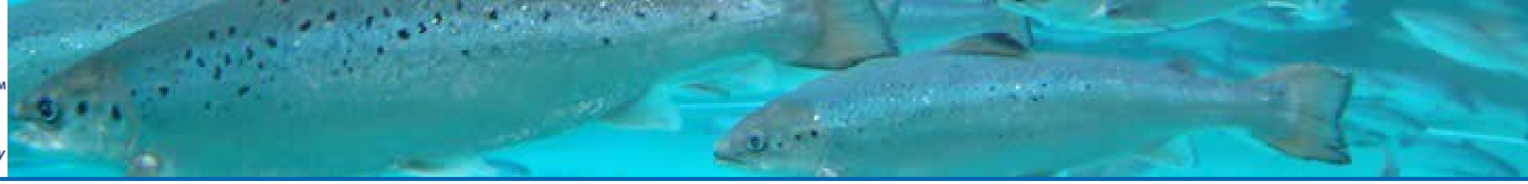


Potential Cause: Measurement Issue

- Potential Contributing Factors
  - Measurement at bottom drain rather than side drain of tank
    - Between 2 and 4 mg/L difference between bottom and side drain (bottom drain estimated to represent up to 15 to 25% of tank volume)
  - Measurement method / analytical instrument error
    - Measurements taken using multiple methods (2 meters, pH/Alk, lab titration)
    - Poor agreement between methods (up to 4 mg/L different)
    - Using pH and Alkalinity difficult also due to consistency of alkalinity data
    - Low alkalinity results in significant pH shifts throughout the system
    - Measurement with meter at multiple locations difficult due to long response time of meters
    - Ultimately, a calibration method using dry ice used to validate meter readings

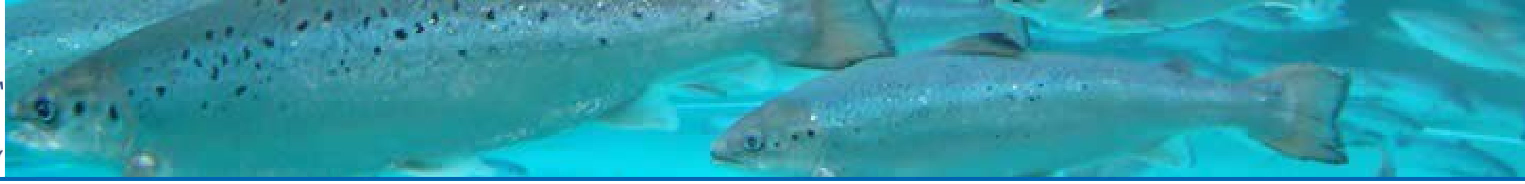
Potential Cause: Insufficient Flow Rate

- Potential Contributing Factors
  - Difficult to quantify flow rates
    - No flow meters in the system due to size and cost
    - Insufficient straight runs of exposed pipe for strap on flow meters
  - Pump flow rates not meeting specification
    - Pump curves checked
    - Flow stoppage test performed to evaluate sump fill rate
  - Too much flow allocated to biofilters
    - Due to split flow process design, potential for biofilters to steal water from tanks
    - More biofilter flow required to compensate for settling in biofilter corners



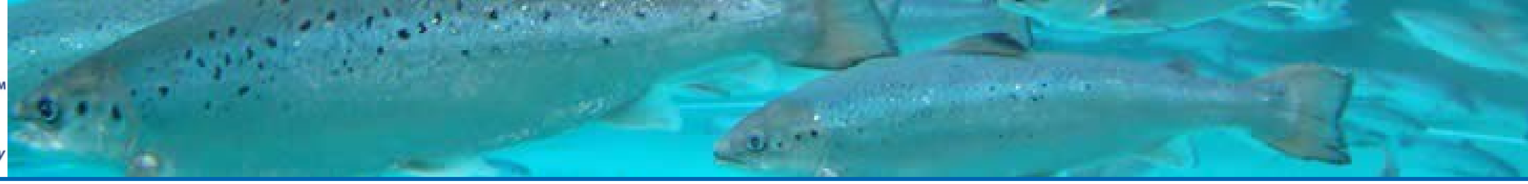
Potential Cause: Reduced Stripping Efficiency

- Potential contributing factors:
  - High ambient CO_2
    - Typically less than 700 ppm, deemed to be minimal impact
  - Insufficient air flow (low G:L ratio)
    - Blower operating pressures tested, within design range
  - Insufficient fall height
    - Impact of raising and lowering stripper fall height evaluated, trade off with flow
  - Insufficient exposed water surface area
    - Structured or random packed media not possible due to installation challenges
    - Opti-grid media trialled to evaluate impact
  - Dilution of inlet CO2 concentration by biofiltration side loop
    - Offset by higher stripper turnover, overall 29%-60% efficient (data varied)



Potential Cause: Increased CO_2 Production Rate

- March 2014 data:
  - 640 - 1000 g CO_2 / kg feed
- Aug-Sept 2014 data:
  - 550 g O2 consumed/kg feed
  - 0.87:1 kg CO2 produced per kg O2 consumed
  - therefore 480 g CO2/kg feed
- High delta CO_2 across culture tank
  - Requires very low CO_2 leaving treatment system to address most heavily loaded culture tank

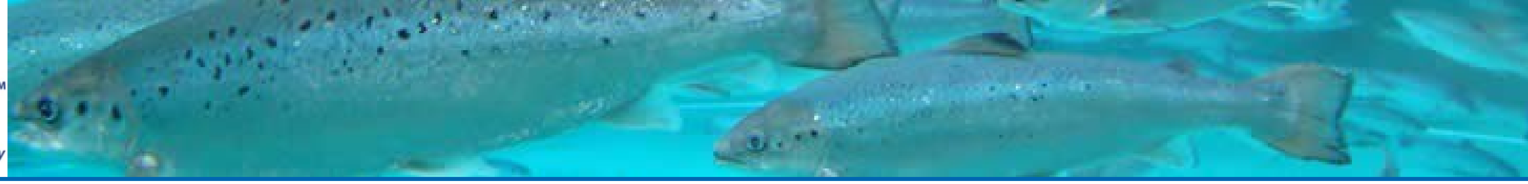


Root Cause Analysis: Conclusions

- Accurate, real-time measurement of CO_2 is challenging
- Low flow rate to culture tanks due to high flow rate to biofilters
- Central CO_2 stripper efficiency requires media to maximize removal
- Oxygen consumption by the fish is much higher than assumed in design (68% higher)

Options Evaluated

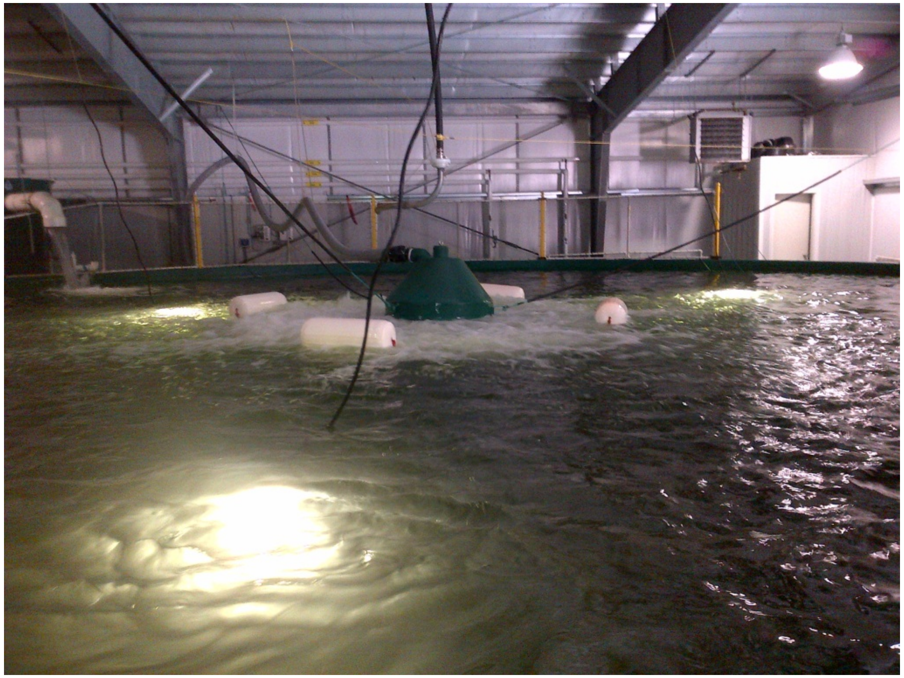
- Flow Rate Increase (reduce delta CO_2 at tank): Rejected
  - Limitations of existing piping
- Centralized CO_2 treatment: Rejected
  - 90 kg/m3 loading (351kg/d feed peak tank) (1323kg/d feed system)
    - 12.2mg/L across the peak tank requires 5.8mg/L CO_2 inlet condition
    - Requires 61.5% CO2 removal efficiency at central treatment (does not include FSB CO2 production)
  - Can't shut down flow to make modifications
- Decentralized CO_2 treatment beside tank: Rejected
  - large flow and footprint required
  - major tank modifications required (screened inlet / outlet)



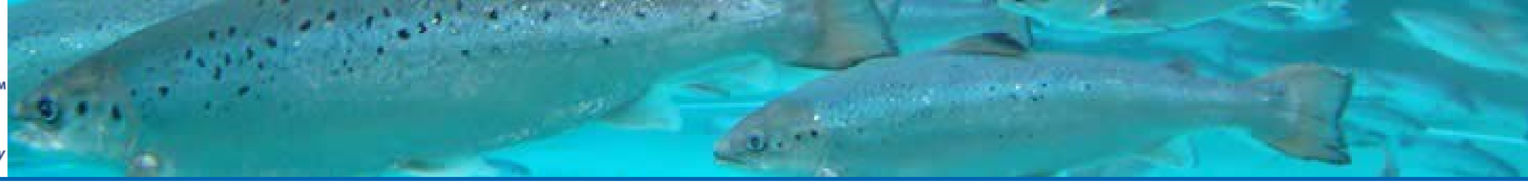
Options Evaluation

- In-tank aeration: Selected
  - Advantages:
    - Strips CO_2 at source
    - More stripping on highest loaded tanks
    - Minimal infrastructure change
    - No additional footprint
  - Disadvantages:
    - Potential disruption to tank hydrodynamics
    - Potential for suspension and shearing of solid waste
    - Operational challenges

In-tank Aeration Pilot



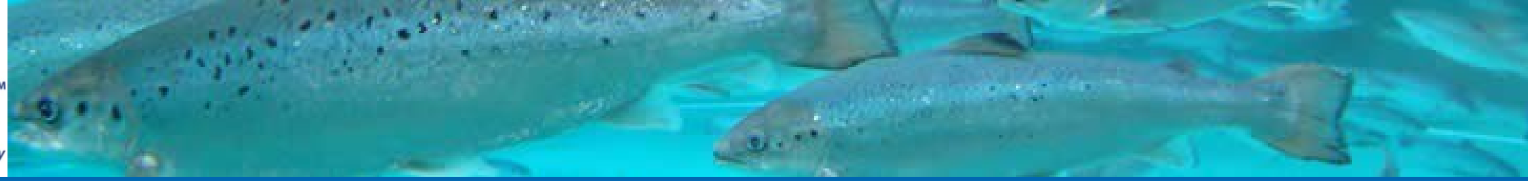
- Sized based on diffuser testing at PR Aqua
- Occupies <2% of tank volume
- Located in top 1/3 of tank depth
- Low rise velocity, minimal solids entrainment
- Floating design
- Minimized hard edges and flat surfaces
- 10 HP regenerative blower



In-tank Aeration Pilot: Preliminary Results

- Effectively removes CO2 (up to 5 mg/L delta achieved)
- CO2 removal efficiency less than small scale testing suggested (approx. 50%)
  - possible cause includes geometry, water impurities, salinity
- No observable solids entrainment or increase in turbidity
- No observable negative reaction from fish
- No observable impact to tank hydrodynamics
- Scalable performance = flexibility
- Cumbersome for operators during fish handling

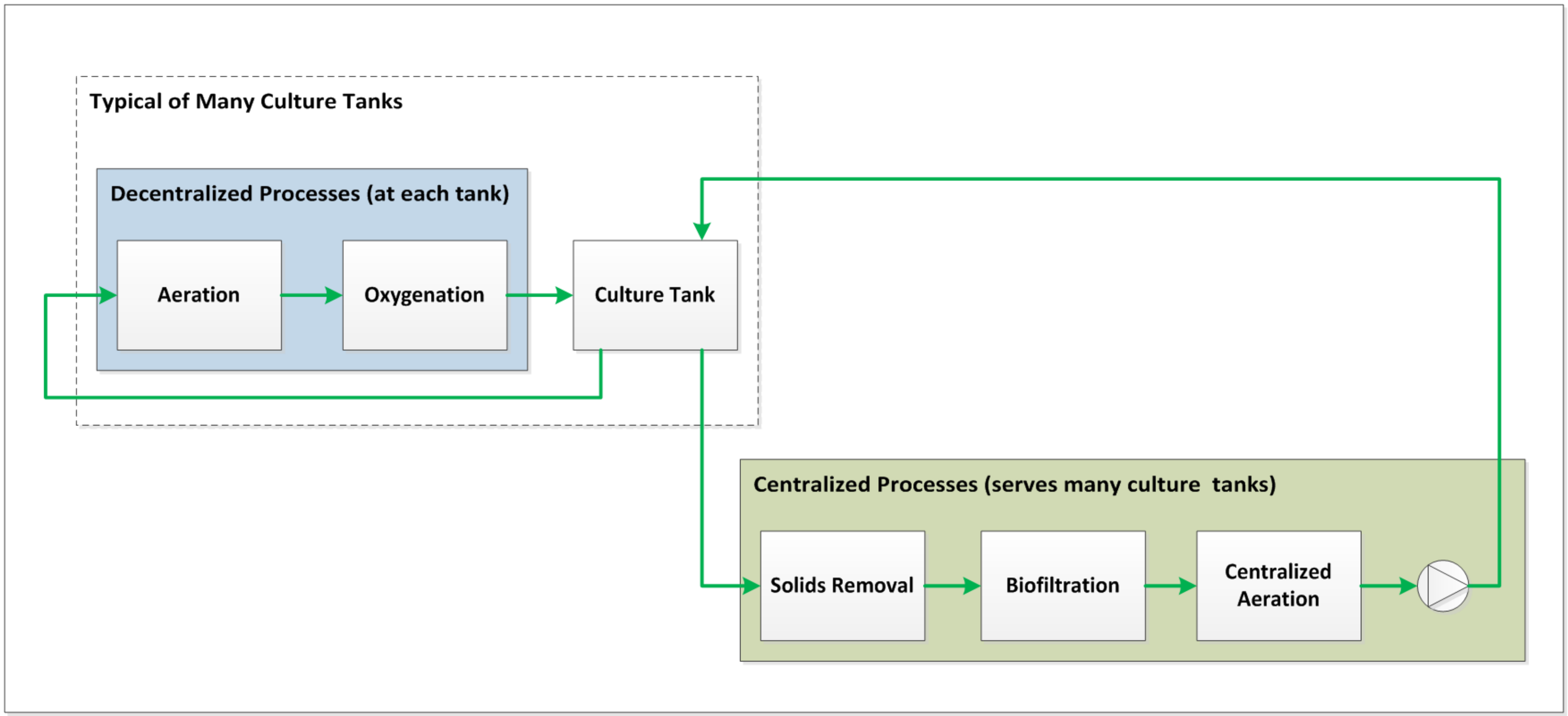
In-tank aeration appears to be viable solution



Impacts to Future Design Methodology

- Centralized treatment strategy:
  - System flow rates (for all processes) are driven by the needs of one limiting water quality criteria
  - At high density culture, and at low CO_2 design concentrations, CO_2 is likely to be the limiting factor setting tank HRT
- Combination of centralized and decentralized treatment makes sense:
  - Allows for peaks to be dealt with at highest loaded tank
  - Allows “right-sizing” of flows for other treatment processes
  - Reduces flows that need to be conveyed to centralized treatment
  - Longer actual tank HRT with shorter effective HRT
  - Redundancy of process

Impacts to Future Design Methodology



Combination of centralized and decentralized treatment

Lessons Learned

- Design in the ability to measure / troubleshoot systems

- Use much higher oxygen consumption / CO_2 production rates in design for large fish swimming at velocity

- Do not mistake production safety factor for design criteria safety factor.

- Innovation can result in uncertainty
  - consider contingencies for modification or improvement of system post commissioning

Future Work Required

- Improve understanding of the factors impacting oxygen consumption and CO_2 production rates
  - Quantify impacts of swim speed, lighting, stress, and feed loads

- Determine optimal design limits for CO_2
  - Balance between production optimization and cost

- Continue to develop distributed treatment solutions for carbon dioxide removal
  - Develop designs to mitigate impacts to tank operation
  - Beta testing proceeding at Kuterra facility