Activated Algae: Basic Concepts and Pilot-scale Results of Using Algae to Remove Nutrients

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Overview – Production of Biodiesel

Feedstocks for biodiesel production….

What do all of these have in common?

Overview – Production of Biodiesel

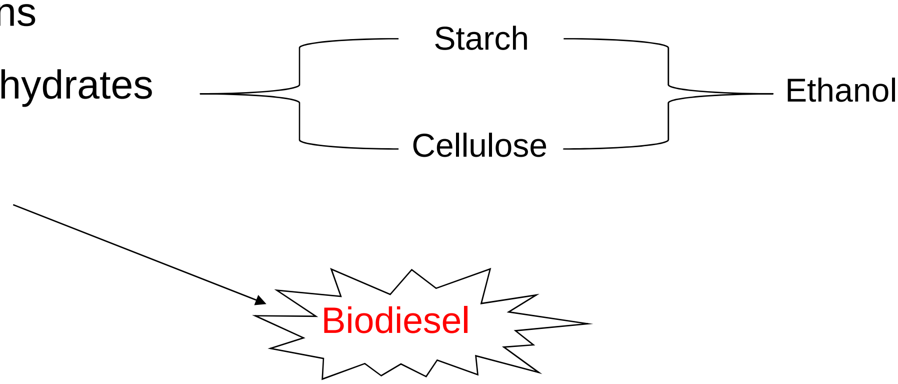
Biomass is comprised of four major chemical classes:

(1) Nucleic Acids (DNA, RNA)

(2) Proteins

(3) Carbohydrates

(4) Lipids



Overview – Production of Biodiesel

Biodiesel is typically produced via a transesterification reaction.

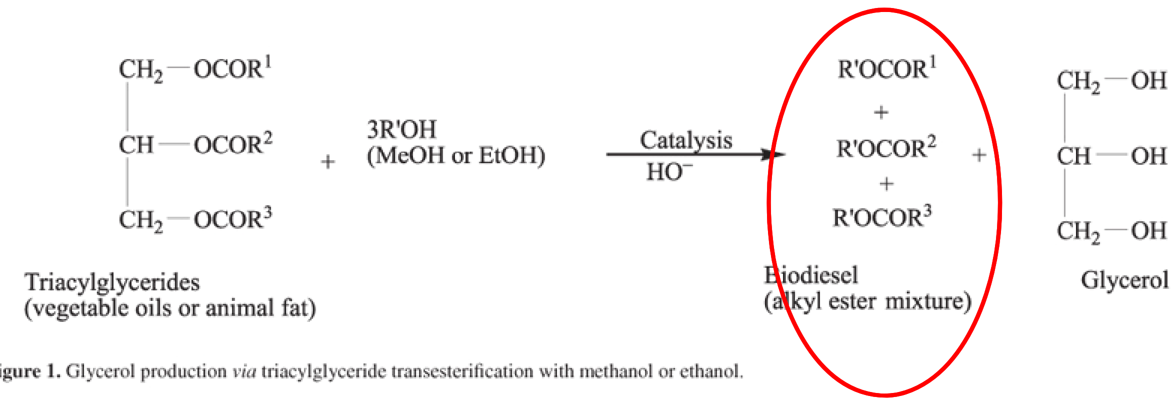


Figure 1. Glycerol production *via* triacylglyceride transesterification with methanol or ethanol.

Specific methyl esters (“R”) will vary depending on the source!

http://www.scielo.br/img/revistas/jbchs/v24n1/a04fig01.jpg

Hydrothermal Liquefaction of Microalgae

- Converts wet biomass to biocrude
- High pressure and high temperature
  - Subcritical temperatures (250-350˚C)

- Advantages
  - Uses entire algal biomass
    - No lipid extraction
  - Lowers need for dewatering
  - Biocrude yields 5 to 30% higher than the lipid content
  - Biocrude properties are similar to petroleum crude

Algae as a Biomass Feedstock

Oil Yield / Acre Per Year
(gallons / acre)

Algae*	**4,000-38,000**
Oil Palm	635
Coconut	287
Jatropha	207
Rapeseed/Canola	127
Peanut	113
Sunflower	102
Safflower	83
Soybean	48
Hemp	39
Corn	18

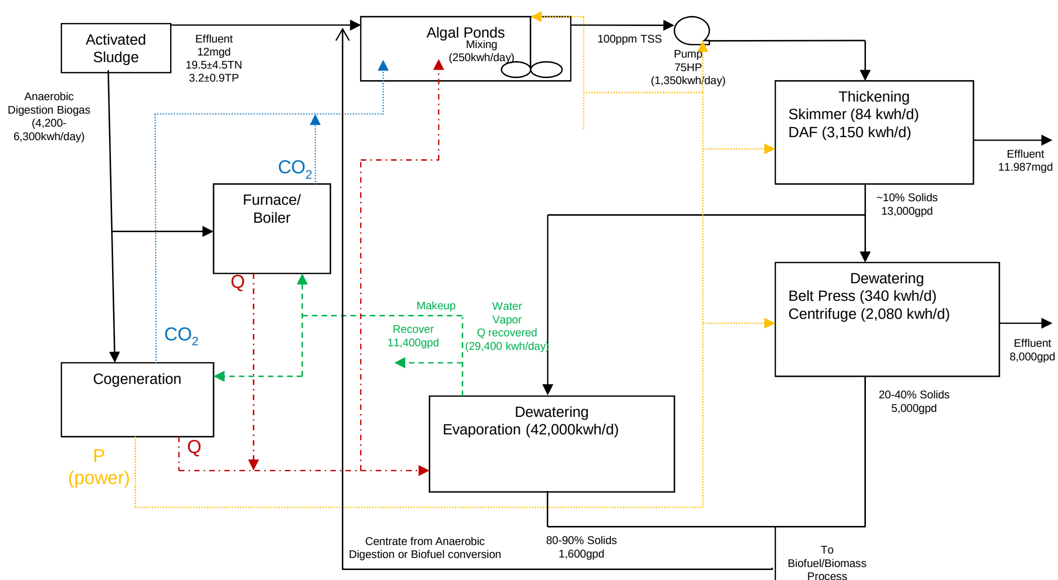
* 4,000 is the range for the best cases; 38,000 is the theoretical maximum (Weyer et al., *Bioenergy Res* 2009).

Advantages of Algae

- Higher potential lipid yields than other biomass feedstocks
- May produce high value co-products
- Can utilize N and P-rich wastewater as a nutrient source
- Does not compete with food markets
- Has potential to sequester CO_2

Algal Growth & Wastewater Treatment

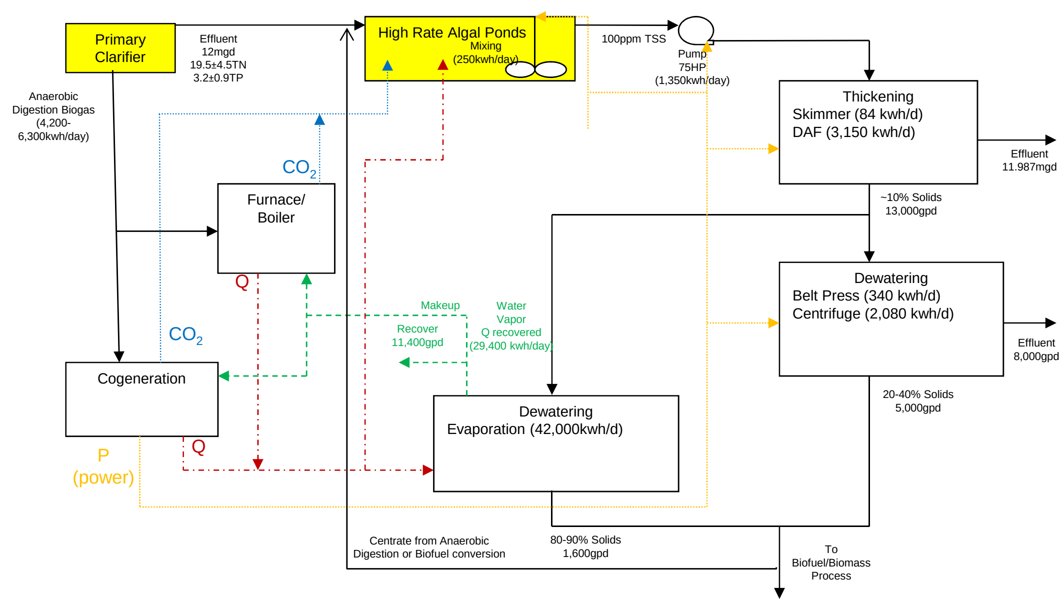
Flow diagram of coupling algal biomass production with a municipal WWTP treating an average 12 mgd.



Sturm and Lamer (2011) *Applied Energy* 88, p.3499–3506

Algal Growth & Wastewater Treatment

Alternate: Utilize High Rate Algal Ponds (HRAP)



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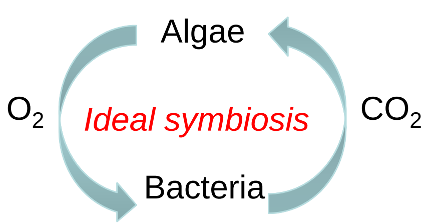
Sturm and Lamer (2011) *Applied Energy* 88, p.3499–3506

Algal Growth & Wastewater Treatment

Primary Effluent
(Organics, NH_4^+, PO_4^{3-})

A mixture of bacteria and algae are selected, potentially utilizing a synergistic relationship.

Mixed biomass would be digested.



Secondary Effluent
(Inorganic Carbon, NO_3^{2-}, PO_4^{3-})

Mainly algae will produced.

Algae cultivated with wastewater have had low lipid contents, so biomass would likely be digested or thermochemically converted to crude oil.

Thickened Algae (5-10% solids) →

Algal Growth & Wastewater Treatment

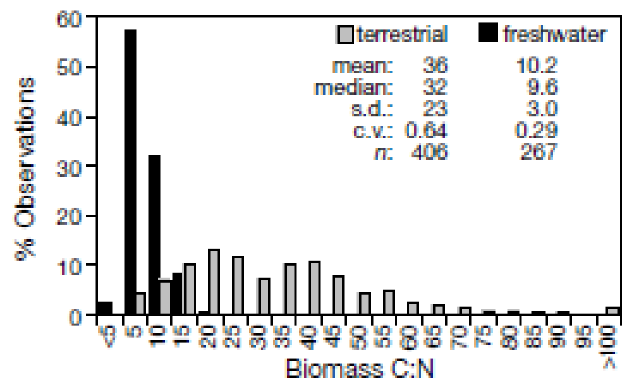
How do algae perform nutrient removal?

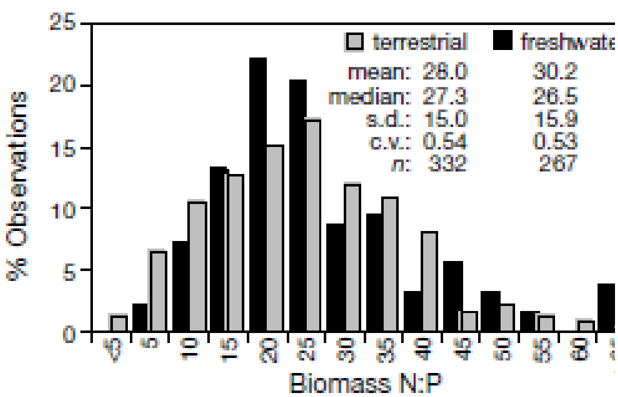
- Biomass growth $C_{106}N_{16}P_1$
  - N and P are incorporated into new biomass
  - “Removal” occurs when biomass is wasted
- Luxury Phosphorus uptake
  - There have been some reports of algae performing luxury P uptake in waste stabilization ponds

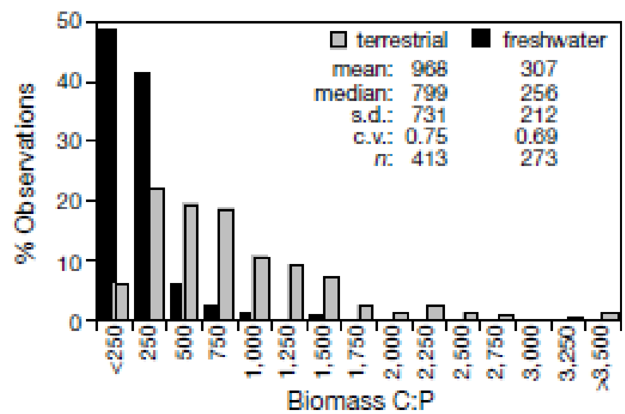
Algal Growth & Wastewater Treatment

Worldwide empirical analysis of algal biomass in freshwater lakes (Elser, *Nature*, 2006):

N:P averages 30:1
C:N averages 10:1
C:P averages 307:1 by moles







Nutrient Removal Goals for WWTPs

Wastewater Effluent Nutrient Concentration Goals

	Nutrient Concentration (mg/L)			
	EPA	**COE**	**KDHE**	**BAT**
TN	0.56-2.18	6.0	8.0	3.0
TP	0.020-0.067	1.5	1.5	0.3

EPA's 2001 Ecoregional Nutrient Criteria Range (Kansas)

US Army Corp of Engineers (2001)

Lab-scale to Pilot-scale Experimentation

Pure cultures: affects of varying N:P ratio and CO_2 % feed on lipid productivity

Pure cultures: Heterotrophic vs Mixotrophic growth using waste glycerine from biodiesel production

Inhibition tests of algal growth with industrial waste sources: glycerine and hydrothermal liquefaction waste

Wastewater Effluent-fed Open Ponds

- WWTP average flowrate of 12 mgd
- Nitrification is performed in aeration basins
- TN ave 21 mg/L
- TP ave 3.5 mg/L
- Ave aerial productivity 12 g/m^2-d
- Lipid content is always relatively low (~10% dry weight)

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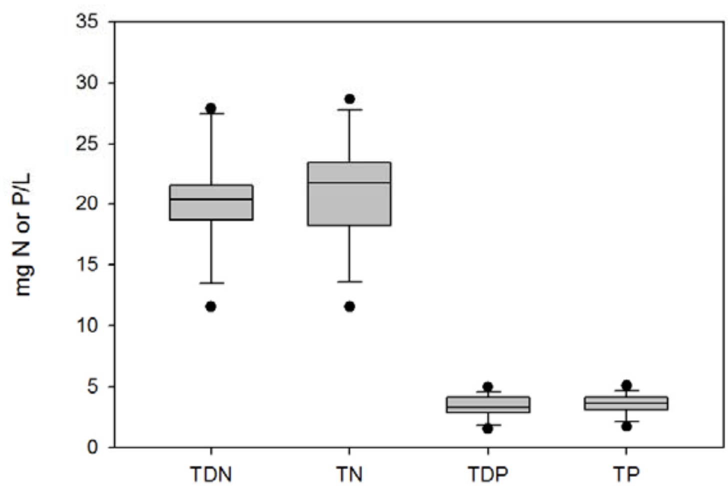
Operated since Fall 2009

Lab-scale to Pilot-scale Experimentation

Wastewater Effluent-fed Open Ponds

Current Lawrence WWTP Discharge:

- TN ave 21 mg/L
- TP ave 3.5 mg/L

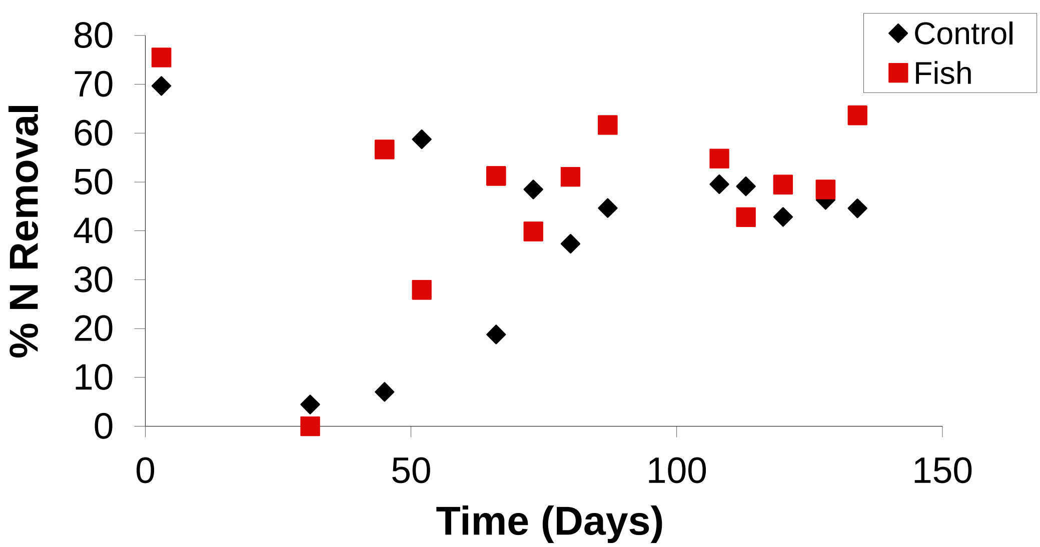


Sturm, B.S.M., Peltier, E., Smith, V. and deNoyelles, F. (2012) Controls of microalgal biomass and lipid production in municipal wastewater-fed bioreactors. *Environmental Progress & Sustainable Energy 31*(1), 10-16.

Wastewater Effluent-fed Open Ponds

Average ± Std Dev % Nitrogen Removal:

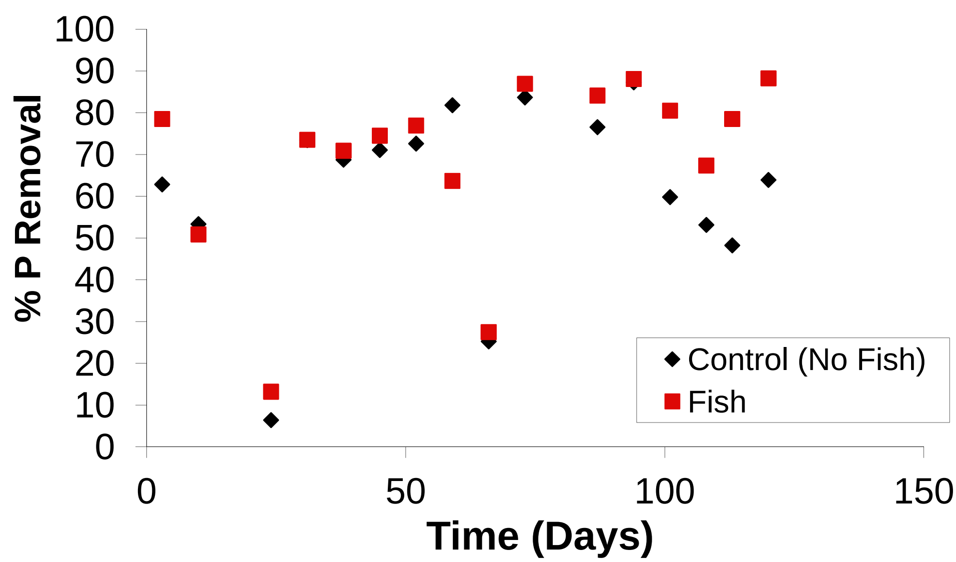
- Control Tanks – 48 ± 6 %
- Fish Tanks – 53 ± 7 %



Wastewater Effluent-fed Open Ponds

Average ± Std Dev % Phosphorus Removal:

- Control Tanks – 65 ± 16 %
- Fish Tanks – 83 ± 7 %

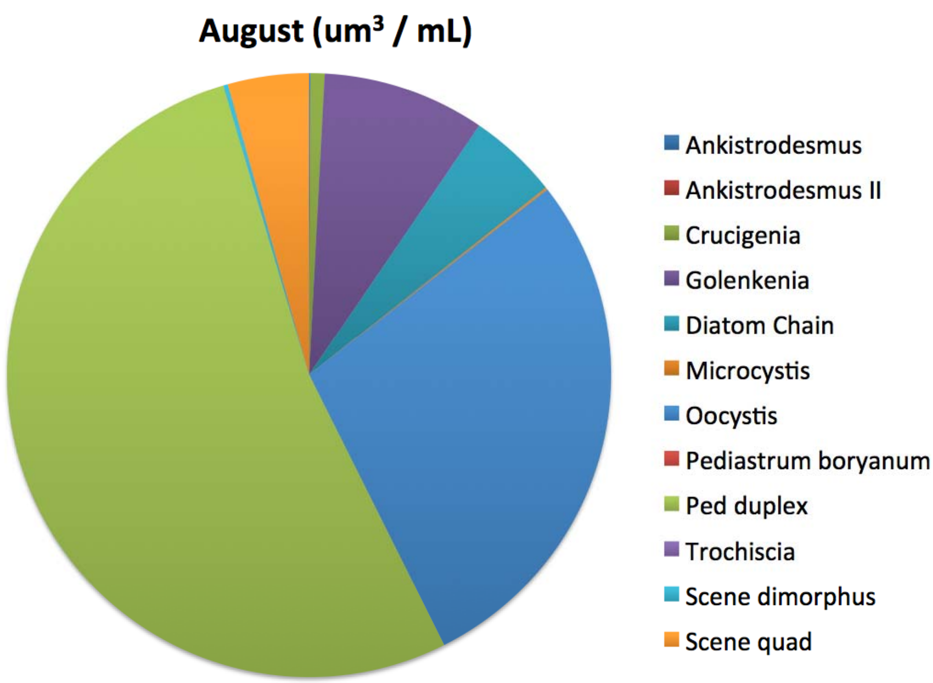


Algal Diversity

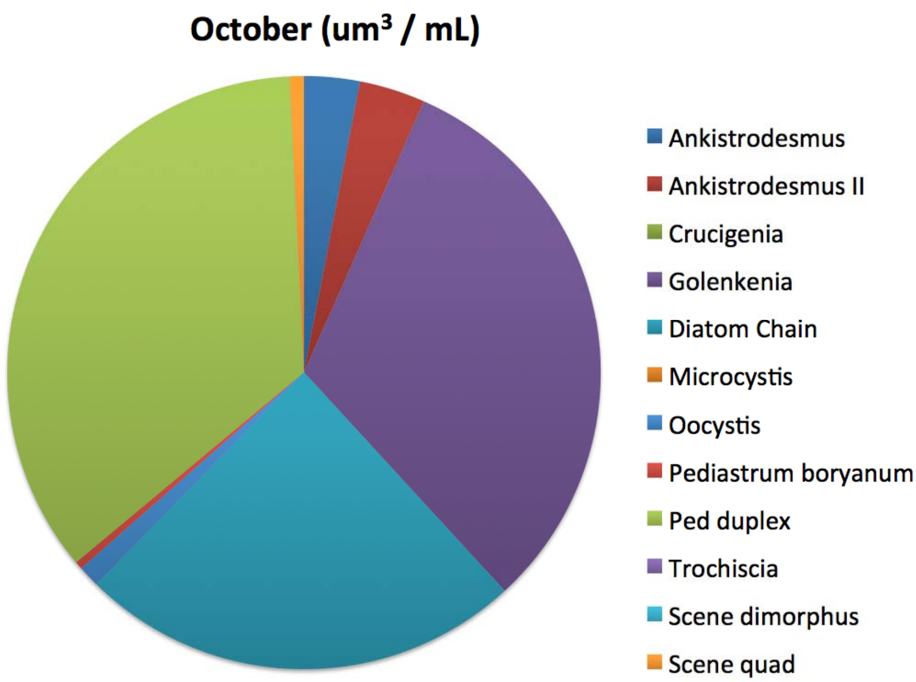
Wastewater fed systems will be diverse and dynamic.

Maintaining pure cultures from wastewater feeds is not realistic.

Algal Diversity – Biovolume Measurements



Algal Diversity – Biovolume Measurements



Algal Grazing

A *Daphnia* showing algal consumption and egg sacs

Food Web Manipulation

Establish that the growth of multi-species assemblages of algae can be maximized by manipulating food web structure.

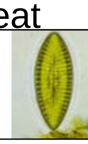
Secondary consumers (fish)

↓ eat

Primary consumers (zooplankton)

↓ eat

Primary producers (algae)

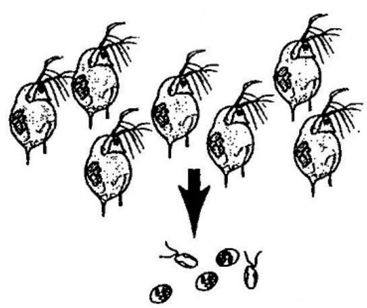


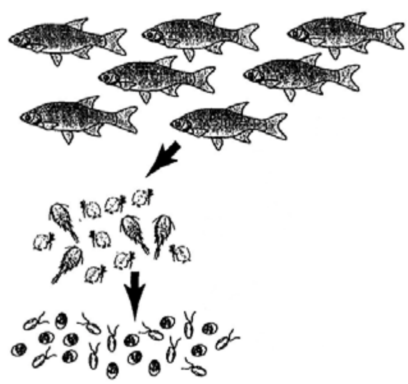
↓ consume

Nutrients, Carbon Dioxide, and Light

Food Web Manipulation

Key goal: Establish that the growth of multi-species assemblages of algae can be maximized by manipulating food web structure: **adding fish will remove large herbivores that limit algal growth**.



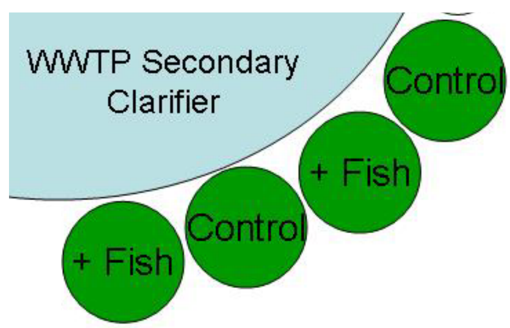


In the **absence** of fish, large *Daphnia* should be abundant, and the algal standing crop should be limited by grazing.

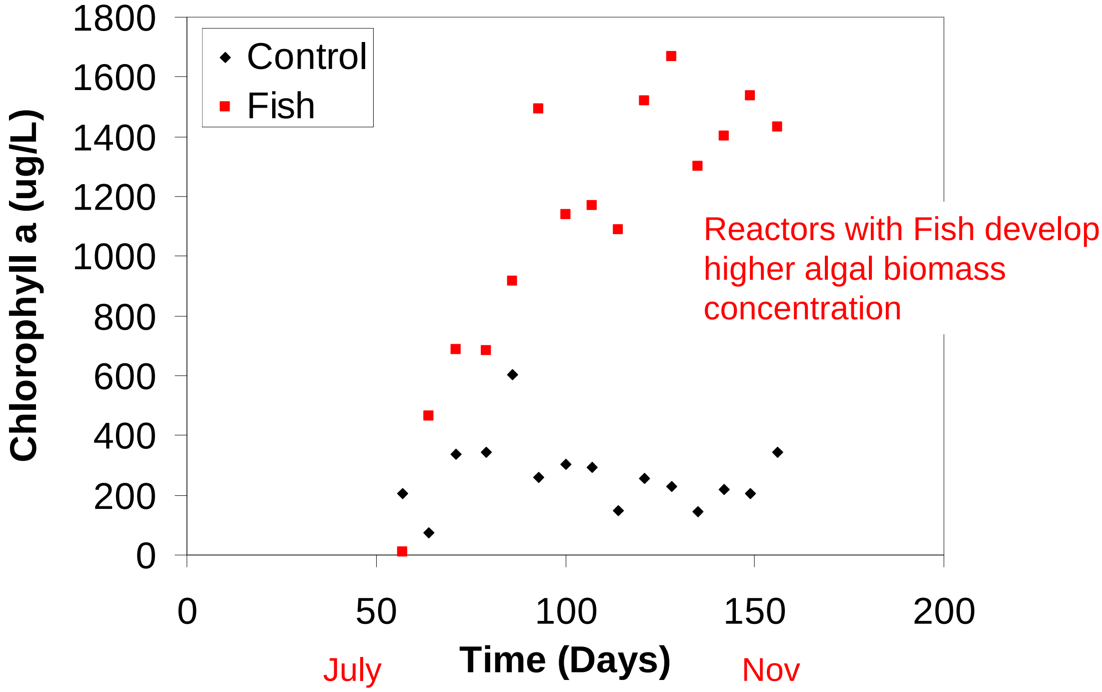
But if fish are **added**, large *Daphnia* will be eliminated, and the algal standing crop (and fuel production) should be ***maximized***.

Testing for Top-Down Ecological Control

Gambusia added to two of the four tanks to control the zooplankton population, and thus predation of algae.

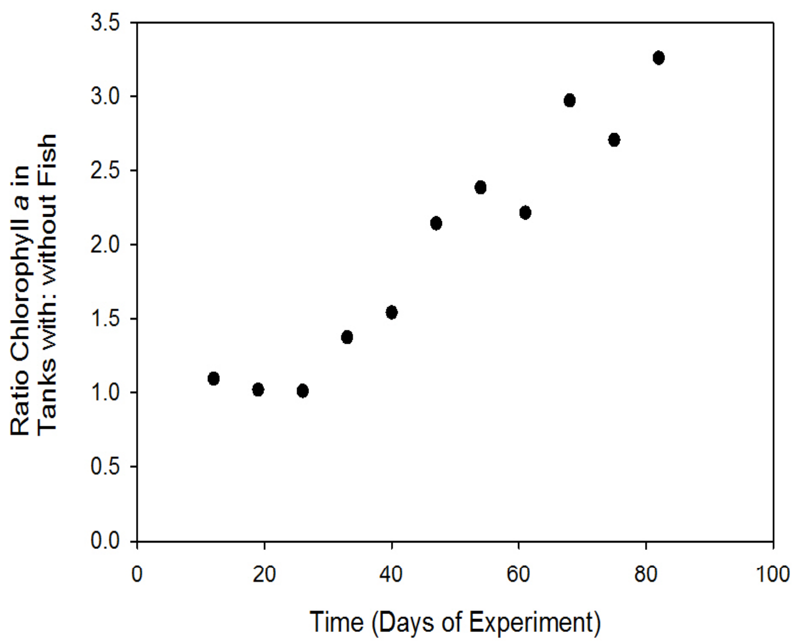


Algal Biomass Growth at NESA



Algal Productivity

Much higher algal productivity (measured by chlorophyll *a*) is exhibited in open ponds containing zooplanktivorous fish compared to those without.



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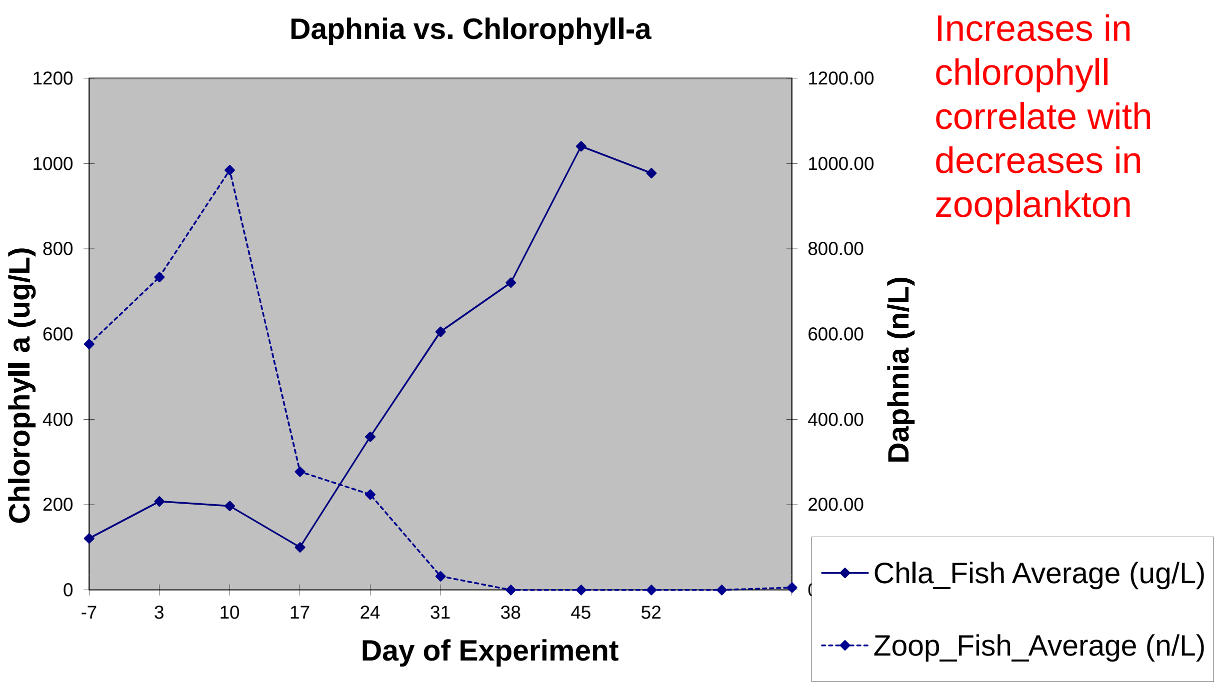
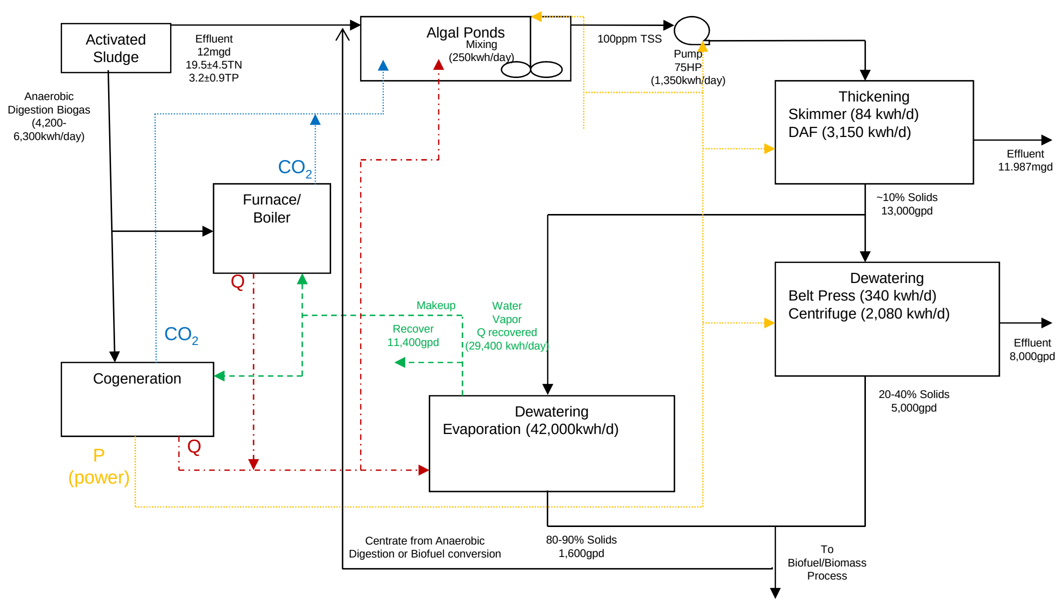
Algal Productivity



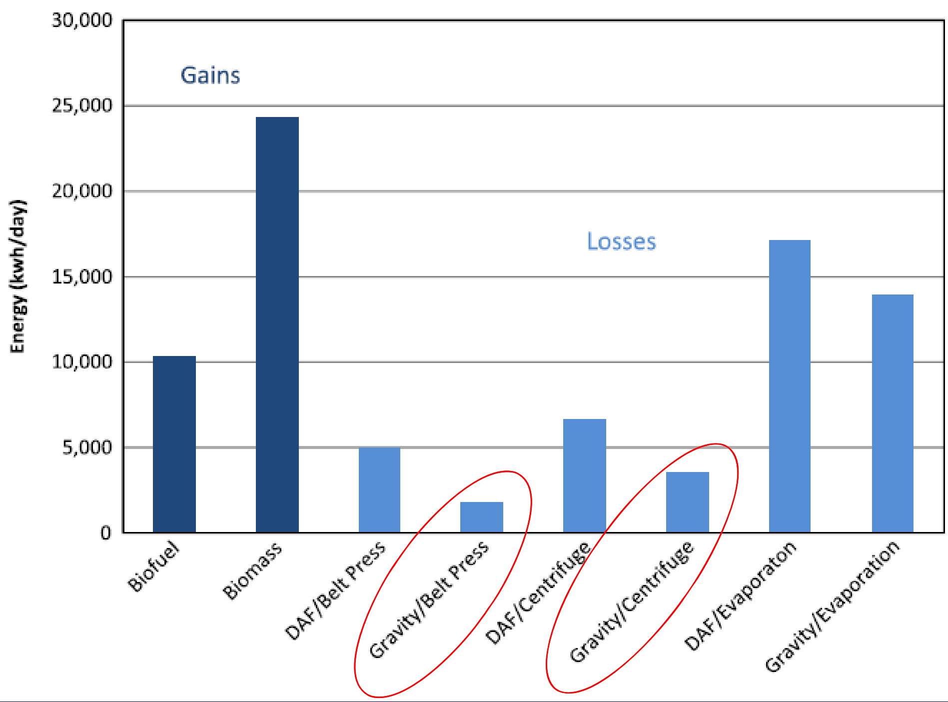
Increases in chlorophyll correlate with decreases in zooplankton

Algal Solids Separation

What about dewatering???



Energy Balance



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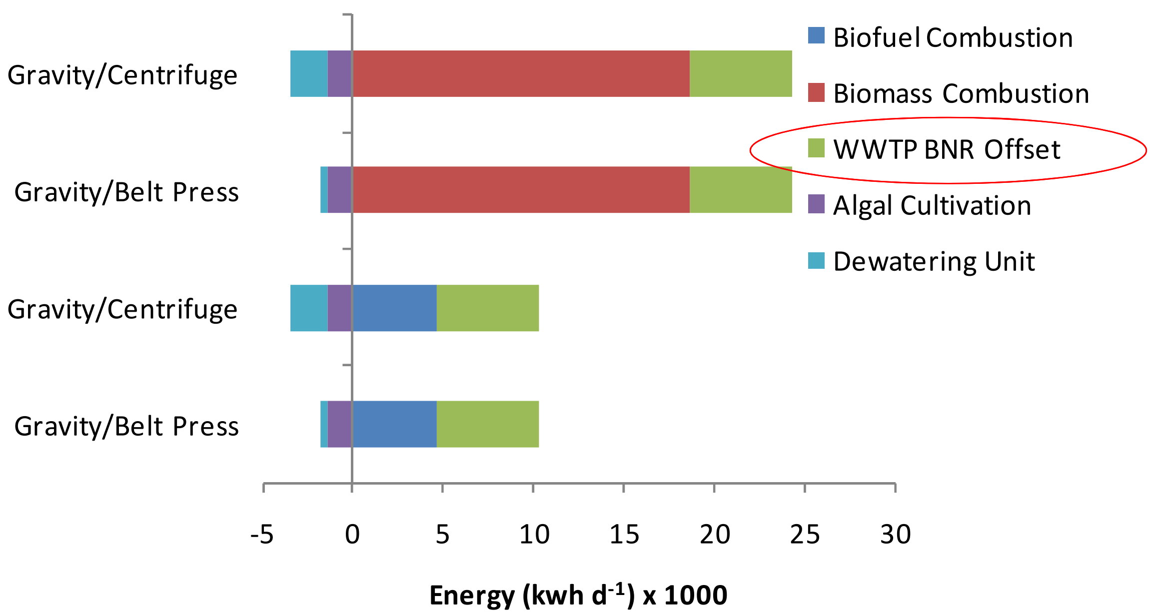

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Biomass Harvesting & Dewatering

- Algae Harvesting
  - Gravity sedimentation
    - No flocculent added
    - 47%-99% removals observed

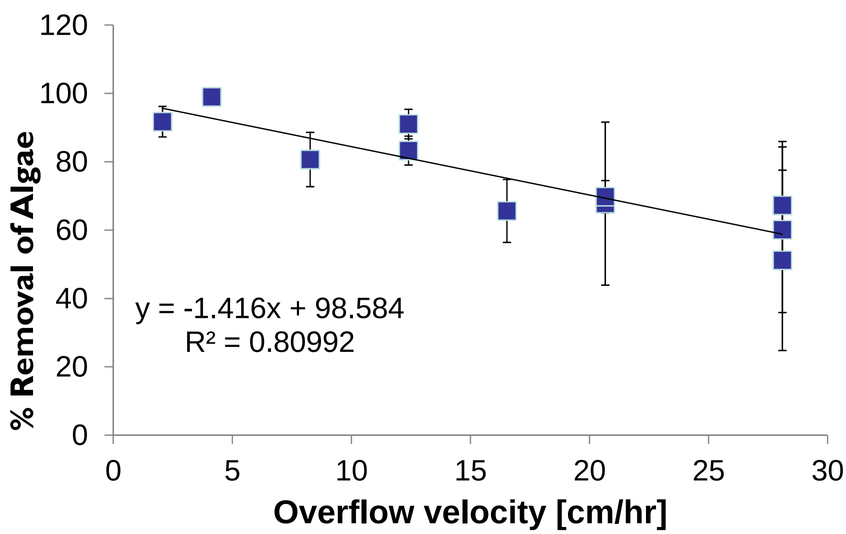
- Algae Dewatering: Two Readily Available Options
  - Solar Drying
    - No fossil energy required; manual labor
    - 5.7% solids
  - Centrifugation
    - Modeled with the power requirements of a Evodos 25 centrifuge
    - 10% solids

http://www.evodos.eu/products/evodos-25.html

Gravity Sedimentation Thickening

Sedimentation was performed with varying flowrates;
No Chemical coagulation.

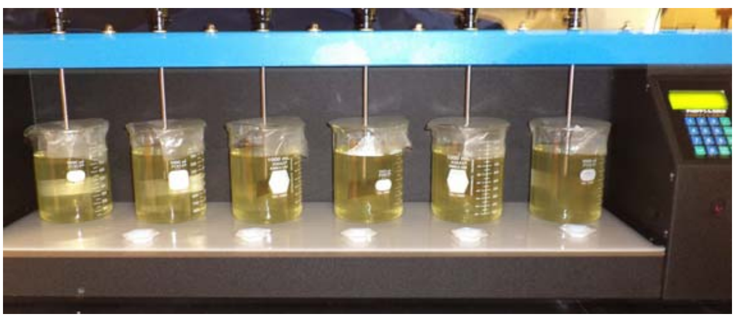
% Solids ranged from 1-3%



Work performed by NSF REU student Tess Murray

Coagulation-Aided Thickening

Jar Tests have been performed with a variety of coagulants; and larger reactions with 100 L have been tested.



0 mg/L Clay

100 mg/L Clay

Work performed by NSF REU students Brandon Westemeyer and Tess Murray

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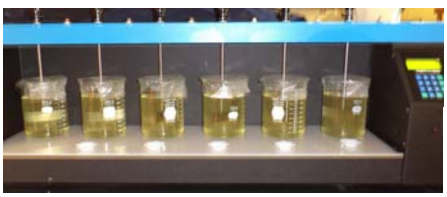
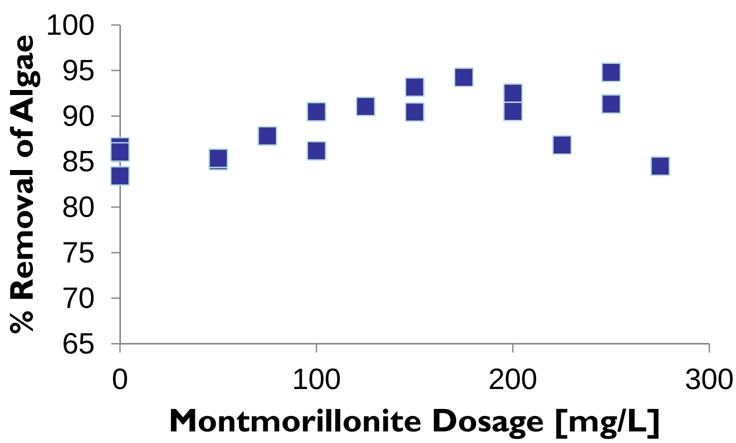




Work performed by NSF REU student Tess Murray

Is Auto-Flocculation Possible?

Algae have been reported to auto-flocculate under certain pH conditions and wastewater composition conditions.

If auto-flocculation can be performed consistently, then chemical coagulants would not need to be added, and gravity harvesting processes can be utilized.

*** Auto-flocculation needs to be consistently demonstrated, and overflow rates need to be determined for sedimentation unit design.

Work performed by undergraduate Emily Cook

Biomass Harvesting & Dewatering

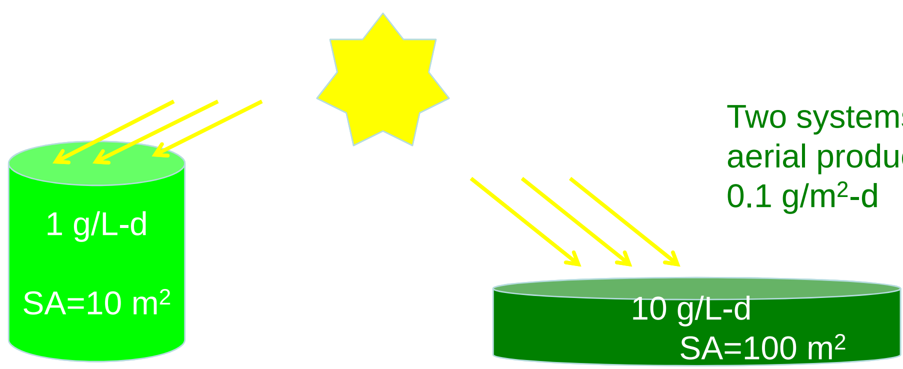
Centrifugation

- The Evodos research-scale centrifuge (T10) consistently yields an algal cake of 17-21% solids without coagulant or polymer addition
- Trials have been performed with a 0.01% feed (directly from the algal pond) and 3% solids (from the gravity sedimentation unit)

http://www.evodos.eu/products/evodos-25.html

Algal Growth Needs Light

Algal productivity is typically compared using the variable <u>aerial productivity</u> (g/m^2-d), which considers the footprint required. Land-use is significant to economic, life-cycle, and social implications of adoption.



Two systems with equal aerial productivity 0.1 g/m^2-d

Algal Growth Needs Light

Sapphire Energy's Existing Facility in New Mexico
(25 acre demonstration facility)

http://www.phillips66.com/EN/newsroom/feature-stories/Pages/Sapphire.aspx

Algal Growth Needs Light

Sapphire Energy's Planned Algae Plant in San Diego

http://sdcab.blogspot.com/2011/08/sapphire-energy.html

Algal Growth Needs Light

It does not have to be a raceway pond....

Sapphire Energy

Iowa State

Algae Wheel

http://domesticfuel.com/2010/10/26/sapphire-energys-4-pillars-to-success/

Algal Growth Needs Light

It does not have to be a raceway pond....

Hydromentia Algal Turf Scrubber

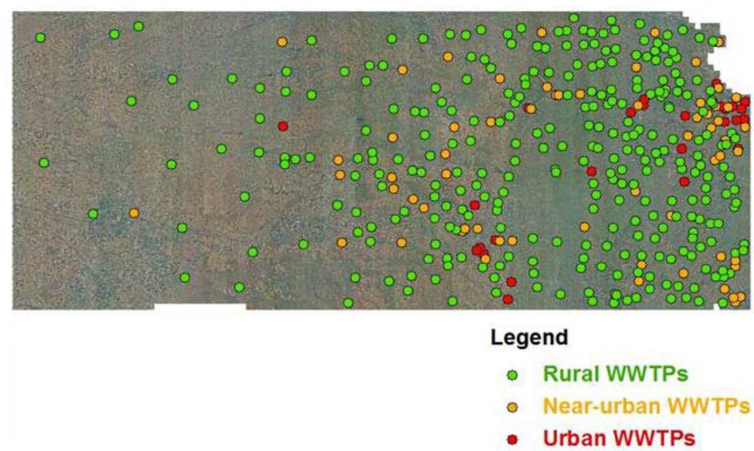
GIS Analysis of Algal Wastewater Potential

Wastewater treatment plants in Kansas with at least 50% municipal flow and a National Pollution Discharge Elimination System (NPDES) permit were selected.

n=387 WWTPs

Cumulative existing flow of 232.8 MGD

Kansas Wastewater Treatment Plants



Each WWTP classified as urban, near-urban, and rural, based on 2000 census classifications.

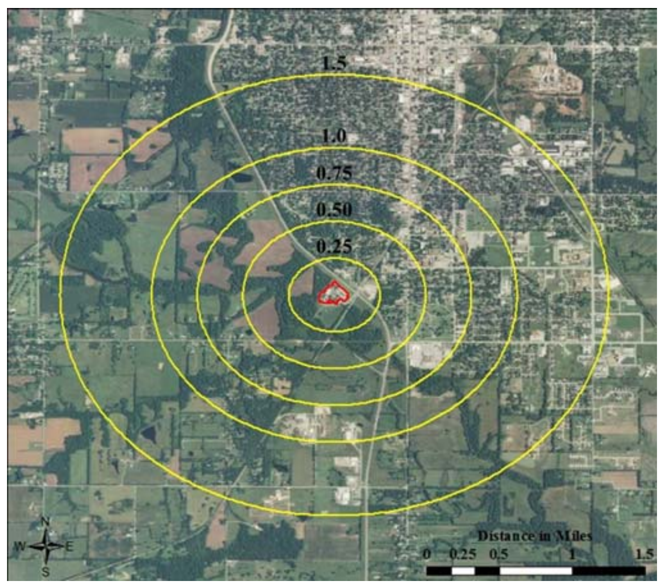
Fortier and Sturm (2012). *Environmental Science & Technology 46*(20), 11426-11434

GIS Analysis of Algal Wastewater Potential

The "available" land surrounding each WWTP was calculated at varying radial extents from 0.25 to 1.5 miles

• "available land" was defined as land with a slope less than 5%

• Land currently occupied by WWTP infrastructure and water bodies were omitted

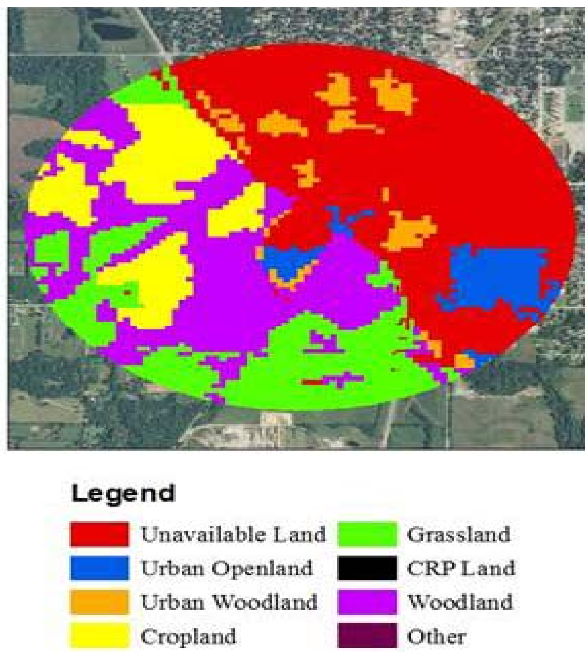


Radial extents in miles around the Pittsburg, KS WWTP

GIS Analysis of Algal Wastewater Potential

"Available land" was also limited to certain land use categories, using a land cover map from the Kansas Applied Remote Sensing Program.

Unavailable land categories included urban residential, urban commercial, or urban industrial land cover types



GIS Analysis of Algal Wastewater Potential

Assumptions for Calculating Algal Productivity per Land Area:

(1) A **baseline algal production (BAP)** scenario

- Based on pilot-scale data from Lawrence WWTP
- Algal areal productivity of 12 g m^{-2} d^{-1}
- Lipid content of 10% dry weight

(2) A **high algal production (HAP)** scenario

- Based on many algal biofuel life cycle analyses whose assumptions are informed by lab-scale data
- Algal productivity of 25 g m^{-2} d^{-1}
- Lipid content of 30%

GIS Analysis of Algal Wastewater Potential

Results for production under land and wastewater volume limitation:

	potential algal biodiesel production (thousand barrels/year)		percent of Kansas[1] liquid fuel demand met (%)	
	BAP	HAP	BAP	HAP
Land-Limited Production				
RE = 0.25 miles	183	1.14×10^3	0.29	1.83
RE = 0.50 miles	733	4.58×10^3	1.17	7.30
RE = 0.75 miles	1.63×10^3	1.02×10^4	2.61	16.3
RE = 1.00 miles	2.86×10^3	1.79×10^4	4.58	28.6
RE = 1.50 miles	6.49×10^3	4.06×10^4	10.4	65.0
Wastewater-Limited Production				
avg TN and TP	20.5	61.5	0.0328	0.0985
min TN and TP[a]	8.28	24.8	0.0133	0.0398
max TN and TP	32.3	96.9	0.0518	0.1553

[1]The percentage of the Kansas annual fuel consumption of 62.44 million barrels

Final Thoughts

Research for algal production has been driven by biofuel research and development.

The conditions that yield maximum lipid content are not the same that yield maximum nutrient removal.

Optimal nutrient removal rates, and optimum algal reactor design for N&P removal, still need to be determined.

If efficient algal solids removal can be achieved, the first applications can be rural lagoon systems.

* Very little biofuel can be produced from these systems, but efficient nutrient removal will lessen the environmental impact of these systems.

Acknowledgements

- City of Lawrence WWTP
- Dr. Susan Williams
- Dr. Jerry deNoyelles
- Dr. Val Smith
- Scott Campbell
- Jay Barnard
- Marie-Odile Fortier
- Emily Cook
- Dr. Ted Peltier
- Tess Murray

Funding Sources:

- NSF C-CHANGE IGERT
- NASA EPSCoR
- Kansas NSF EPSCoR
- KU Transportation Research Institute
- US Department of Energy

Thank you!
Questions?

Selected KU publications related to algae:

- Fortier, M.-O.P., Roberts, G.W., Stagg-Williams, S.M., and Sturm, B.S.M. (2014) Life cycle assessment of bio-jet fuel from hydrothermal liquefaction of microalgae. *Applied Energy* 122, 73-82.
- Roberts, G.W., Fortier, M.-O.P., Sturm, B.S.M. and Stagg-Williams, S.M. (2013) Promising Pathway for Algal Biofuels through Wastewater Cultivation and Hydrothermal Conversion. *Energy & Fuels 27*(2), 857-867.
- Fortier, M.-O.P. and Sturm, B.S.M. (2012) Geographic Analysis of the Feasibility of Collocating Algal Biomass Production with Wastewater Treatment Plants. *Environmental Science & Technology 46*(20), 11426-11434.
- Sturm, B.S.M., Peltier, E., Smith, V. and deNoyelles, F. (2012) Controls of microalgal biomass and lipid production in municipal wastewater-fed bioreactors. *Environmental Progress & Sustainable Energy 31*(1), 10-16.
- Sturm, B.S.M. and Lamer, S.L. (2011) An energy evaluation of coupling nutrient removal from wastewater with algal biomass production. *Applied Energy 88*(10), 3499-3506.
- Smith, V.H., Sturm, B.S.M., deNoyelles, F.J. and Billings, S.A. (2010) The ecology of algal biodiesel production. *Trends in Ecology & Evolution 25*(5), 301-309.

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