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Emergy Evaluation of Struvite Application as an Alternative to Conventional Phosphorus Fertilizer for Crop Production

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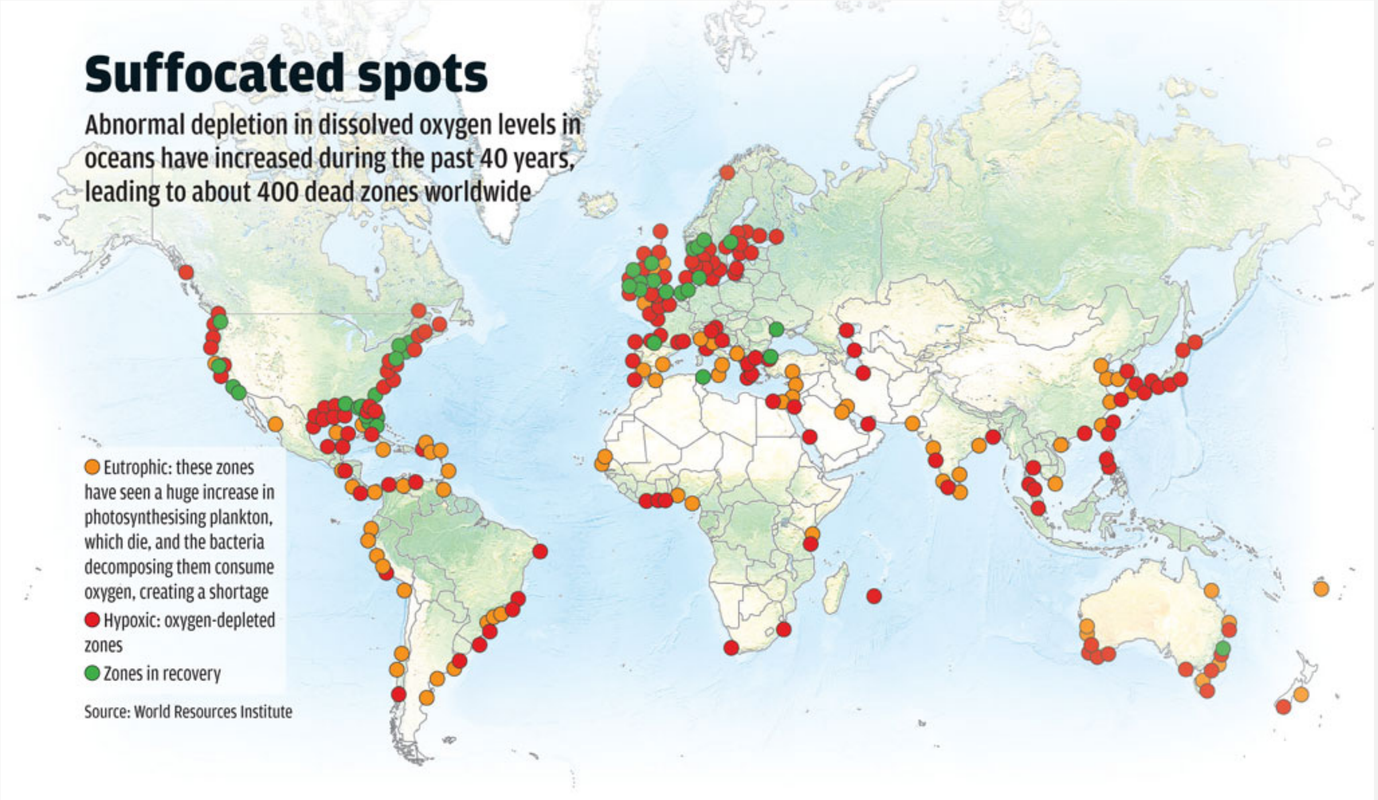
Title

Importance of Nutrient Management



Source: World Resources Institute, 2015

- Eutrophication - enrichment of an ecosystem with chemical nutrients, typically compounds containing nitrogen (N), phosphorus (P), or both.
- Clean Water Act (CWA) requires wastewater treatment plants (WWTPs) to reduce nutrient discharge levels to prevent eutrophication

Study Objectives and Approach

- Aims to address
  - 1) how regulations drive system changes;

    2) how conventional systems can be transitioned to more cost effective and sustainable alternatives using nutrient management.

- Influent wastewater flow and nutrient levels, capital, and operational data were collected from previous nutrient removal studies and for nutrient recovery from Ostara Nutrient Recovery Technologies, Inc.

- Use emergy accounting to provide system analysis

- All UEVs used and given hereafter (including those referenced in the text) were normalized to the **1.20 E25 sej/yr (solar emjoules/year)** global emergy baseline (Brown et al., 2016)

Nutrient Recovery and Benefits

- Nutrient recovery - practice of recovering nutrients (N and P) from wastewater and converting them into an environmental friendly fertilizer
- Industrial phosphate (PO_4^{3-}) fertilizers - manufactured using PO_4^{3-} rock (non-renewable resource)
- Nutrient recovery provides a self-sustainable solution to WWTPs
  - revenue generation from fertilizers
  - reduces fouling of equipment with involuntary precipitation of struvite
  - helps meet discharge limits
- PO_4^{3-} precipitation from wastewater is less energy intensive and economical compared to manufacture of phosphate fertilizers

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Struvite Formation and Production

- Recovered from municipal wastewater (MWW)/urine source - slow-release mineral fertilizer given by the simplified equation

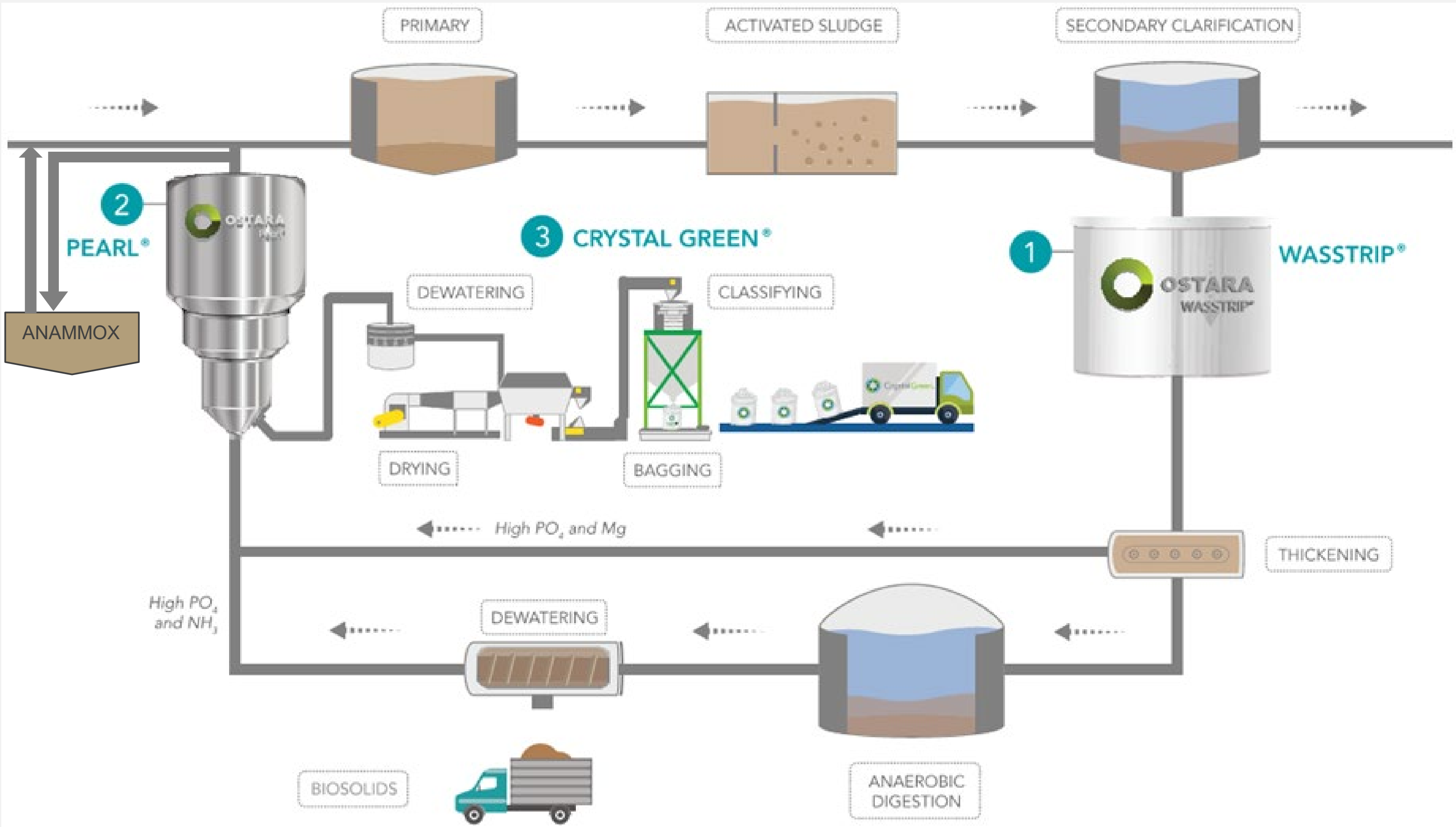
$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \bullet 6H_2O \text{ (solid)}$$

Magnesium Ammonium Phosphate

- Methods of struvite recovery from MWW have been under development, this study cites WASSTRIP™ and PEARL® process by Ostara Nutrient Recovery Technologies, Inc.

- Marketed fertilizer - 5% N, 28% PO_4^{3-}, and 0% potash, with 16.6% MgO (10% Mg)

Nutrient Recovery Technology Considered

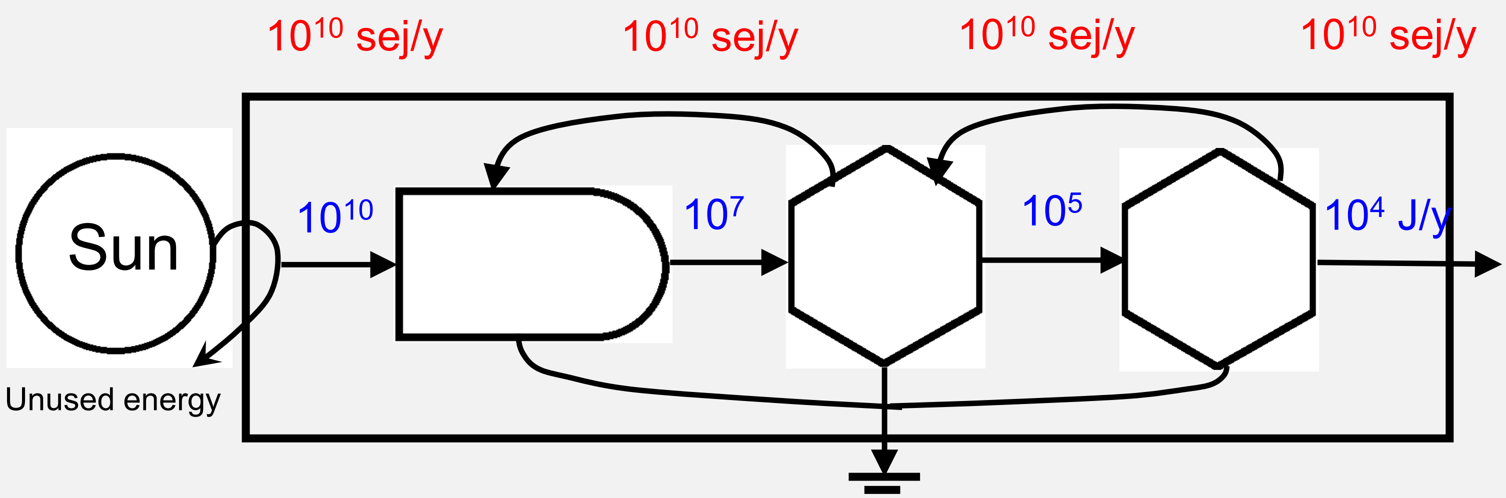


PEARL® process by Ostara Nutrient Recovery Technologies, Inc, 2016

- In addition to P precipitation, partial nitration anammox was considered for nitrogen reduction in the nutrient recovery alternative.

What is Emergy

- Available energy of any kind previously used both directly and indirectly to make another form of energy, product or service (H.T. Odum, 1996)



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Unit Emergy Value (UEV)

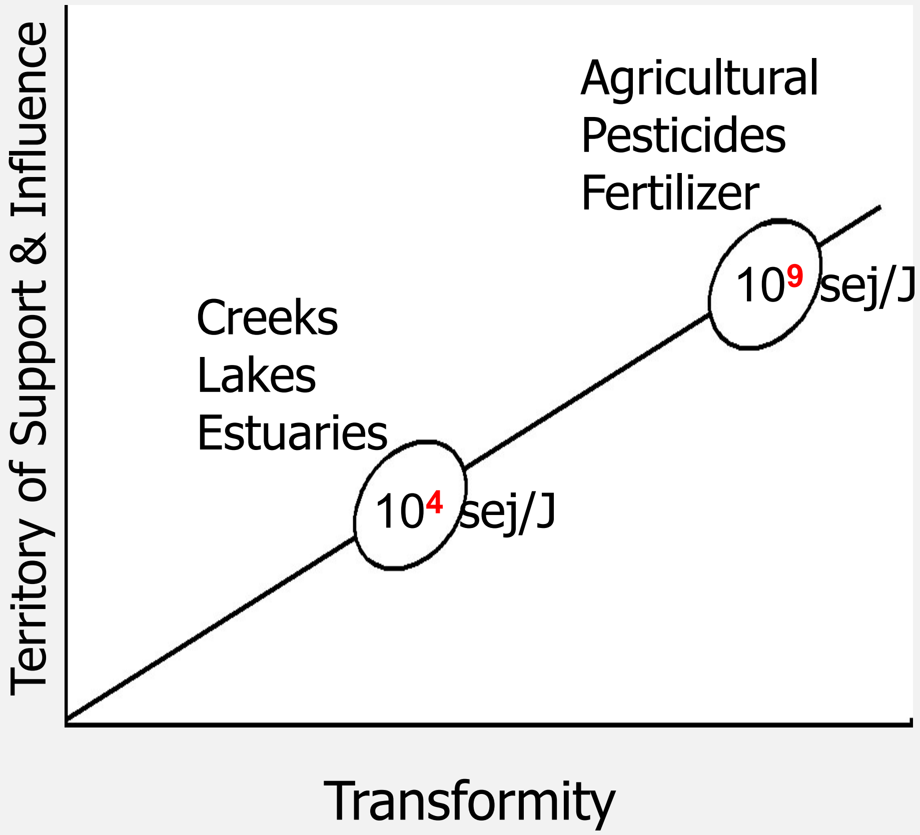
- Material (per mass) – specific emergy

$$\frac{\text{total emergy input}}{\text{mass output}} = \text{sej/g}$$

- Energy (per joule) –Transformity

$$\frac{\text{total emergy input}}{\text{energy output}} = \text{sej/J}$$

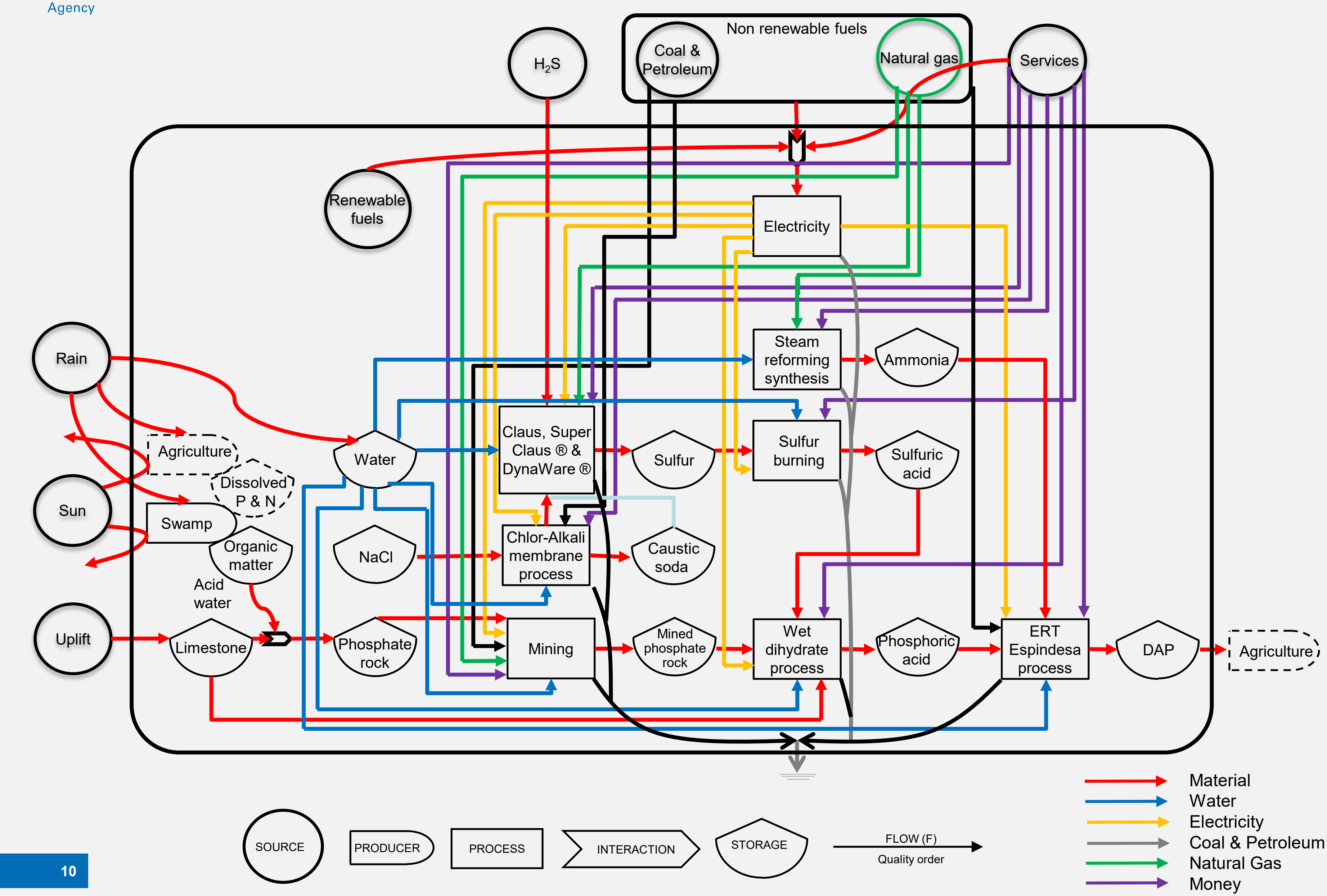
Transformity



- High transformity = high hierarchical order
- High transformity = high territory of influence
- High transformity = more emergy required to make product flow
- High transformity = less efficient

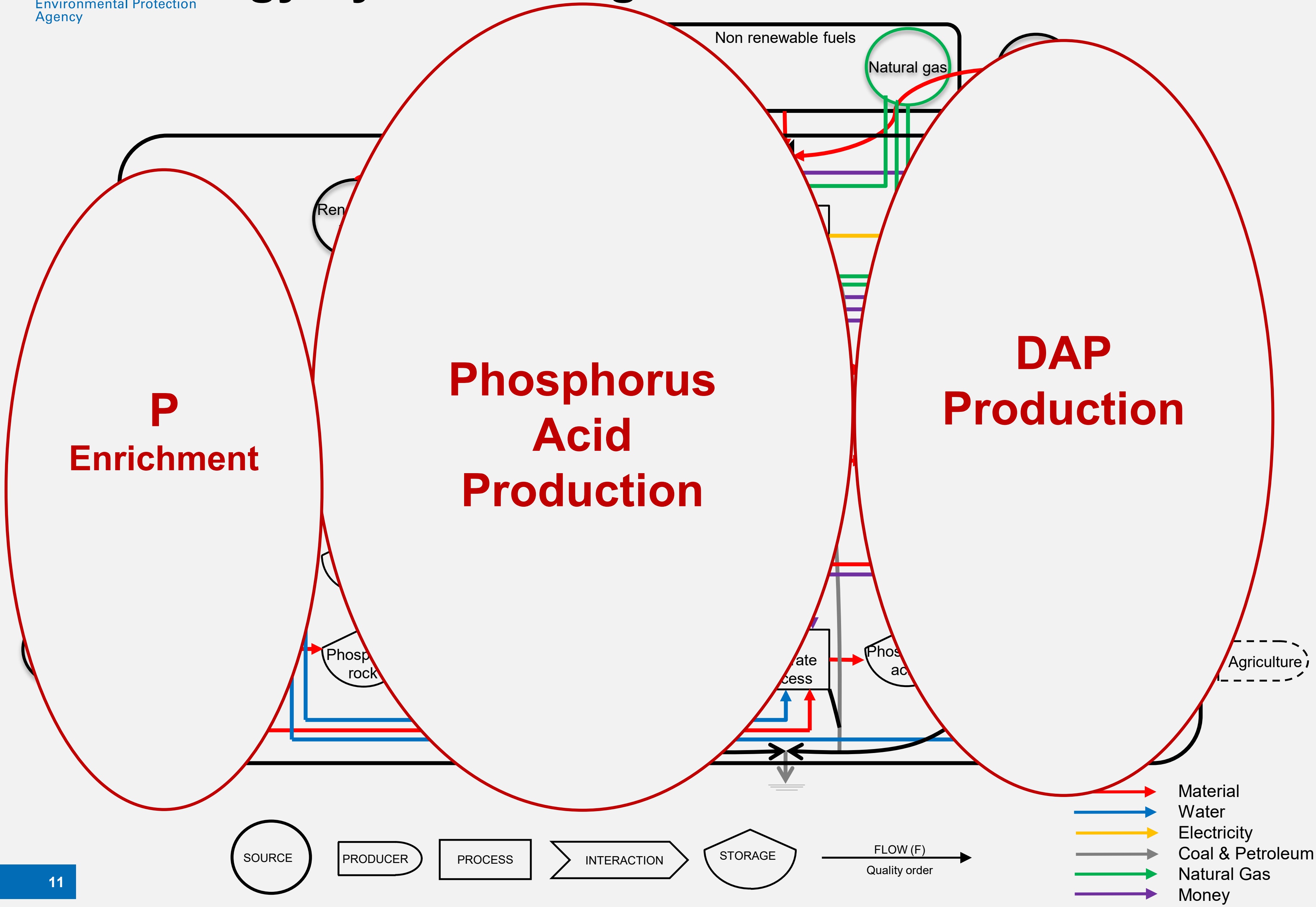
Transformity measures energy quality

Energy Systems Diagram for DAP Production



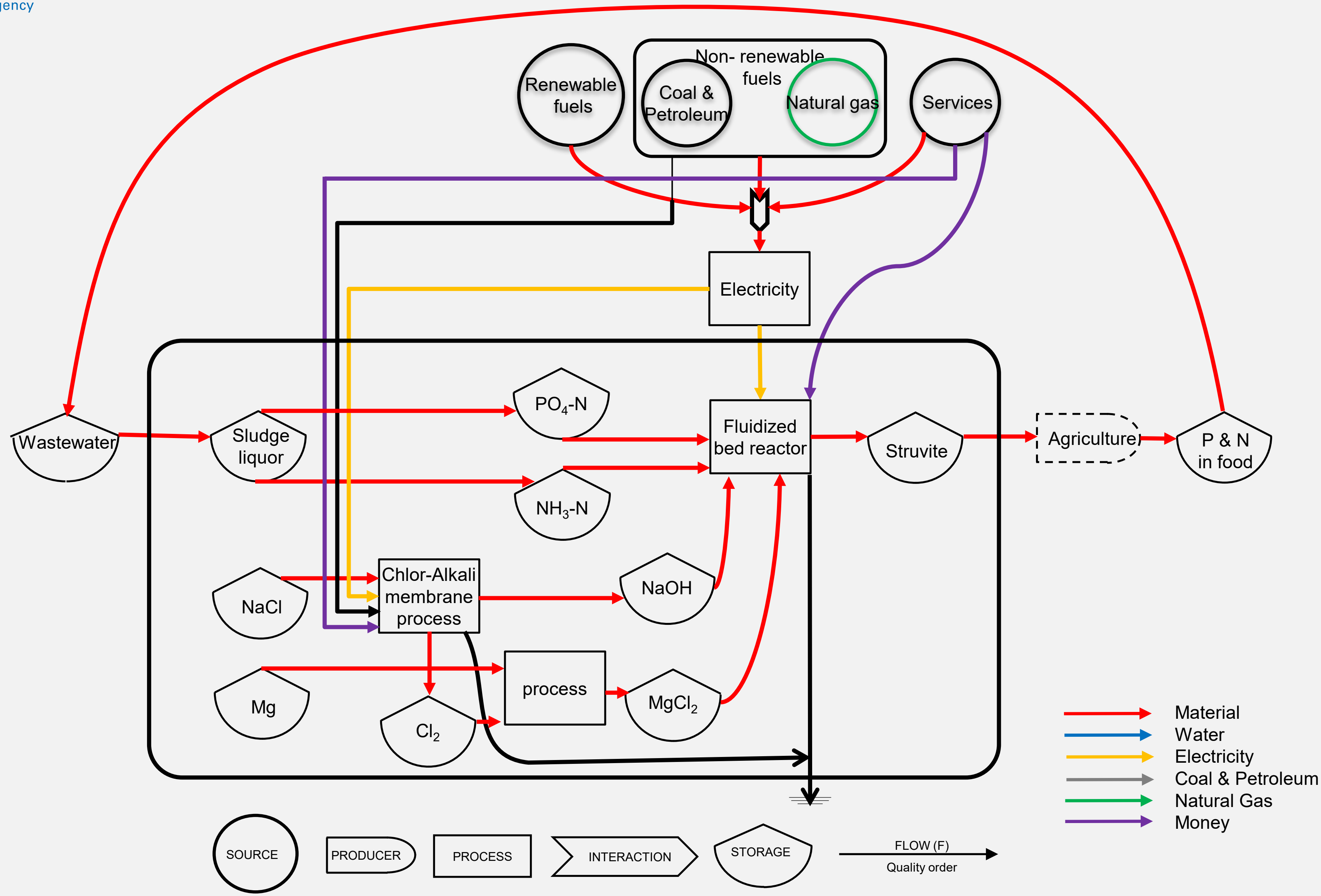
External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown

Energy Systems Diagram for DAP Production



External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown

Emergy Systems Diagram for Nutrient Recovery



External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown

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Results of Traditional Fertilizer Vs. Nutrient Recovery

Diammonium Phosphate (DAP)

Chemical formula: $(NH_4)_2HPO_4$ Composition: 18% N, 46% P_2O_5 (20% P)						
			Data	Unit	UEV	EMERGY
Note	Description				(sej/unit)	(E sej/yr)
Infrastructure input						
*	Capital		1.14E+01	$	2.02E+12	2.31E+13
Operational inputs per year (2013)						
1	Materials					
1a	Phosphate Rock		1.50E+06	g	3.61E+09	5.40E+15
1b	Ammonia		1.44E+05	g	6.48E+09	9.35E+14
1c	Sulfur		3.97E+05	g	9.50E+10	3.77E+16
1d	Limestone		3.02E+04	g	2.20E+08	6.65E+12
2	Energy					
2a	Electricity		1.16E+08	J	7.26E+05	7.85E+12
2b	Fuels		4.34E+08	J	6.13E+05	4.01E+13
3	Services		5.12E+02	$	2.02E+12	1.04E+15
4	Water		3.56E+01	m^3	8.22E+11	1.23E+13
	Total EMERGY					5.03E+16
5	Transformity	w/o capital invest			5.03E+10	sej/g DAP
		with capital invest			5.03E+10	sej/g DAP
		w/o capital invest			1.18 E+10	sej/g P

Struvite

Chemical Formula: Crystal Green®, $NH_4MgPO_4 \cdot 6H_2O$ (5-28-0 +10% Mg)						
			Data	Unit	UEV	EMERGY
Note	Description				(sej/unit)	(E sej/yr)
Infrastructure input						
*	Capital		2.47E+02	$	2.02E+12	5.01E+14
Operational inputs per year (2013)						
1	Materials					
1a	Phosphate, eq. to elemental phosphorus (PO_4-P)		1.40E+05	g		0.00E+00
1b	Ammonia, equivalent to elemental Nitrogen (NH_3-N)		2.10E+05	g		0.00E+00
1c	Sodium hydroxide (NaOH)		4.90E+04	g	4.14E+09	2.03E+14
1d	Magnesium chloride ($MgCl_2$) as Mg		1.47E+05	g	4.34E+10	6.38E+15
2a	Electricity		6.40E+08	J	2.21E+05	1.41E+14
3	Services		5.33E+01	$	2.02E+12	1.08E+14
4	Wastewater		2.63E+02	g	3.26E+05	8.56E+07
	Total EMERGY					7.10E+15
5	Transformity	w/o capital invest			7.10E+09	sej/g CG
		with capital invest			7.60E+09	sej/g CG
		w/o capital invest			8.96 E+08	sej/g P

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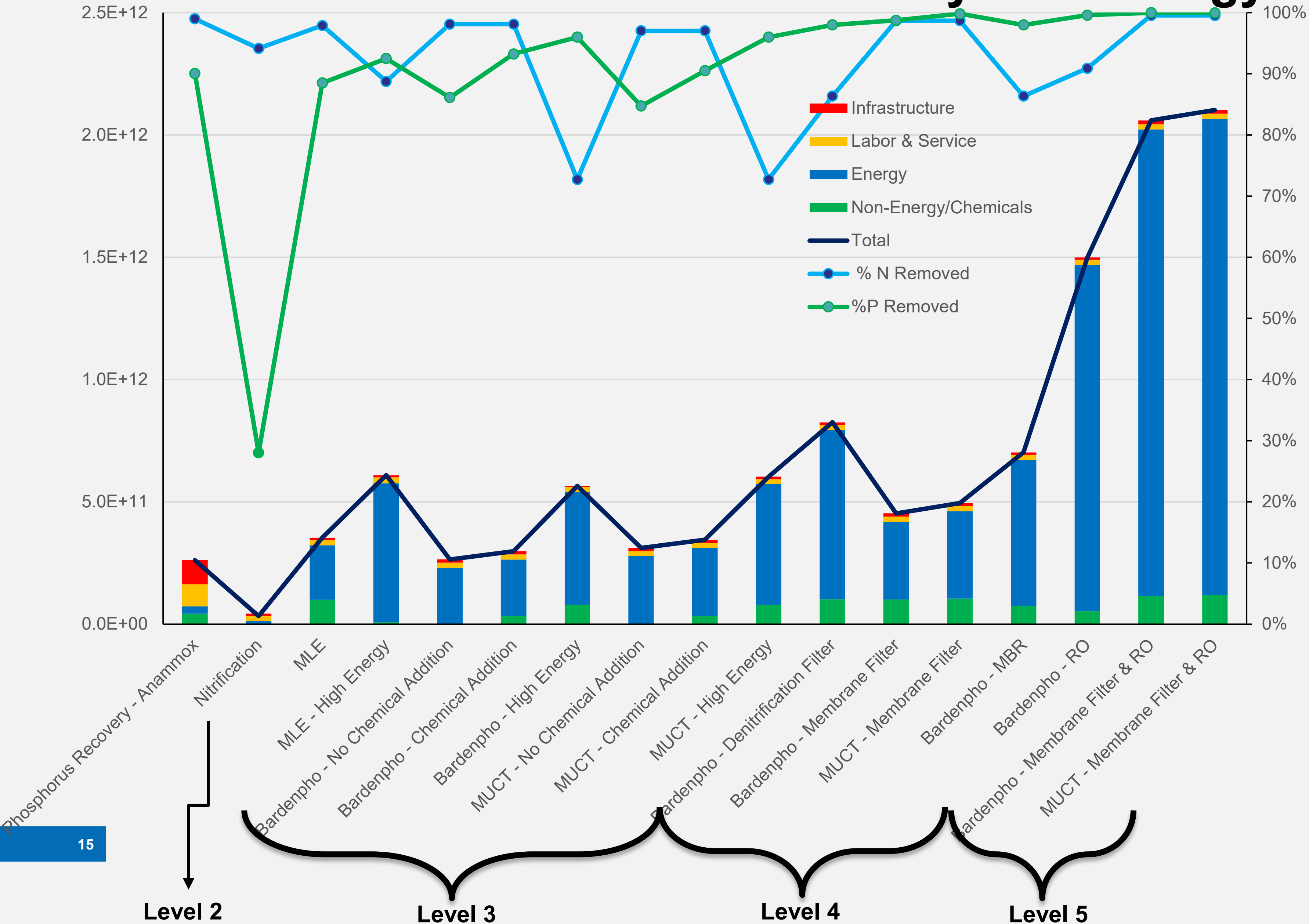
Processes Considered for the Study

Treatment Level (Effluent Limits)	Nutrient Removal/Recovery Process	Energy (kWh/m³)	Influent Ammonia (mg/L as NH_3-N)	Influent P (mg/L as P)
Recovery	Phosphorus Recovery - Anammox	0.14	20	7
Level 2 (TN – 8 mg/L, TP – 1 mg/L)	Nitrification	0.23	24	10
Level 3 (TN – 4-8 mg/L, TP – 0.1-0.3 mg/L)	MLE	0.28	23	8
	MLE - High Energy	0.59	32	8
	Bardenpho - No Chemical Addition	0.29	23	8
	Bardenpho - Chemical Addition	0.29	23	8
	Bardenpho - High Energy	0.58	22	5
	MUCT - No Chemical Addition	0.35	23	8
	MUCT - Chemical Addition	0.35	23	8
	MUCT - High Energy	0.56	22	5
Level 4 (TN – 3 mg/L, TP – 0.1 mg/L)	Bardenpho - Denitrification Filter	0.53	22	5
	Bardenpho - Membrane Filter	0.4	23	8
	MUCT - Membrane Filter	0.45	23	8
	Bardenpho - MBR	0.53	22	5
Level 5 (TN - <2 mg/L, TP<0.02 mg/L)	Bardenpho - RO	0.60	22	5
	Bardenpho - Membrane Filter & RO	2.4	23	8
	MUCT - Membrane Filter & RO	2.45	23	8

Total Emergy Comparison between Different Nutrient Removal and Recovery Technology



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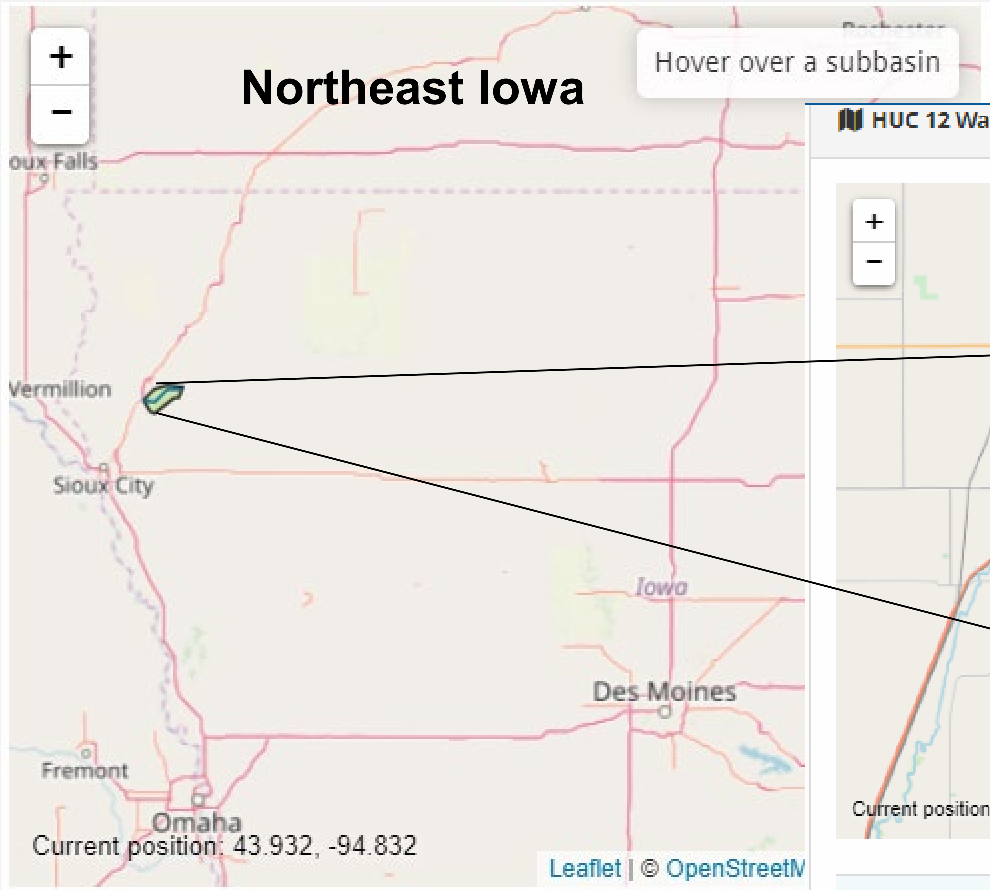
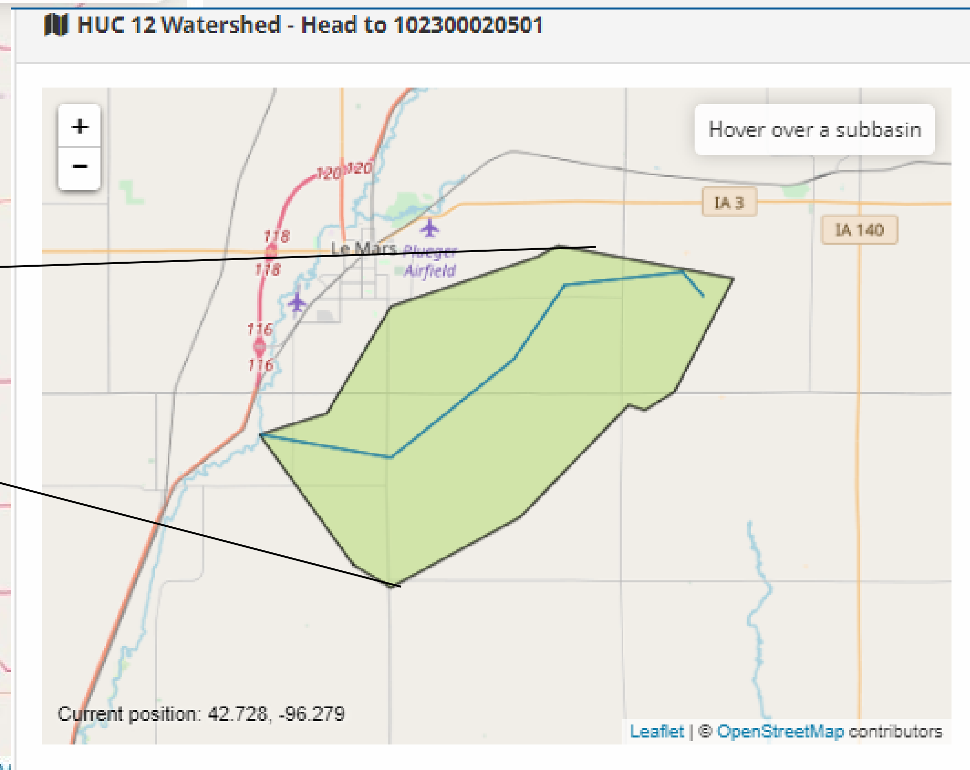
HAWQS/SWAT Tool and Study Area

- Hydrologic and Water Quality System (HAWQS) is a web-based interactive water quantity and water quality modeling system that employs Soil and Water Assessment Tool (SWAT) as its core modeling engine

- Enables use of SWAT to simulate the effects of management practices based on an extensive array of crops, fertilizers, soils, natural vegetation types, land uses, and climate change scenarios

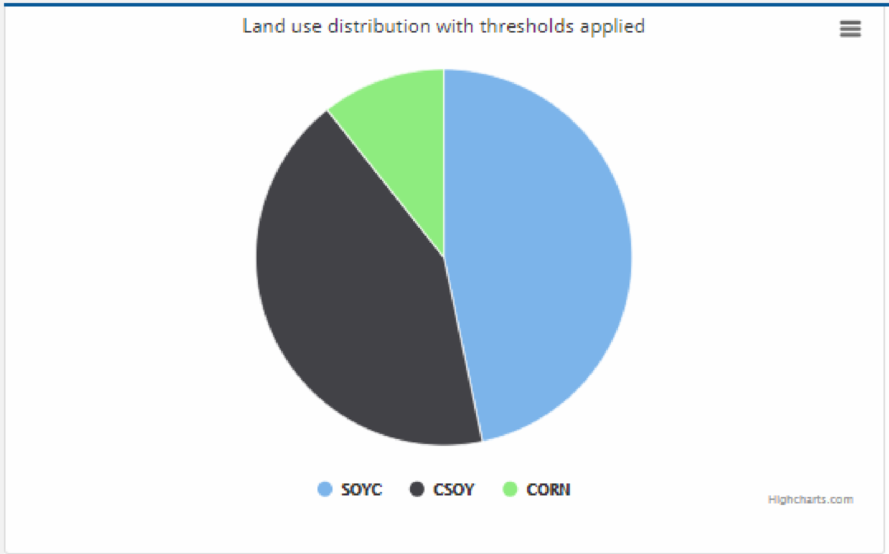
HAWQS/SWAT Tool and Study Area

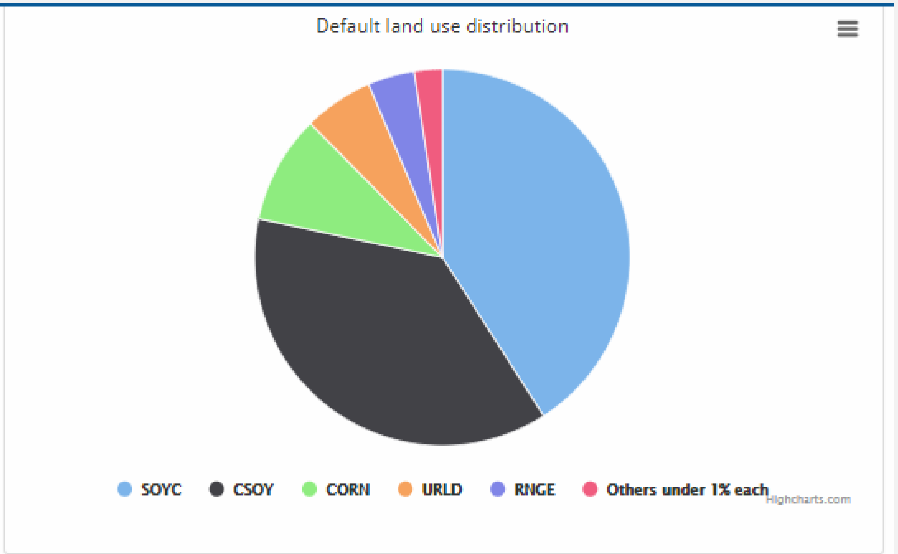




Project area:	94.95 km²	
Number of subbasins:	1	Download SWAT to HUC Mapping
Original number of HRUs:	38	Download
Number of HRUs:	9	Download

Hydraulic Response Unit (HRUs) Chosen





Land use distribution comparison

	With thresholds applied		Original	
Land Use	Area	% of Total Area	Area	% of Total Area
SOYC	44.37 km^2	46.73 %	38.88 km^2	40.95 %
CSOY	40.48 km^2	42.63 %	35.47 km^2	37.35 %
CORN	10.10 km^2	10.64 %	8.85 km^2	9.32 %

Soils and slope classes after applying thresholds

Soil Type	Area	% of Total Area
IA091	45.15 km^2	47.54 %
IA092	41.28 km^2	43.47 %
IA098	8.53 km^2	8.99 %

Slope Class	Area	% of Total Area
0-1	94.95 km^2	100.00 %

Crop rotation – Soybean-Corn (SOYC), Soil Type – IA-091 (Loess Ridges/Clay Paleosol), Slope >1%, HRU Area - 3.5 km^2

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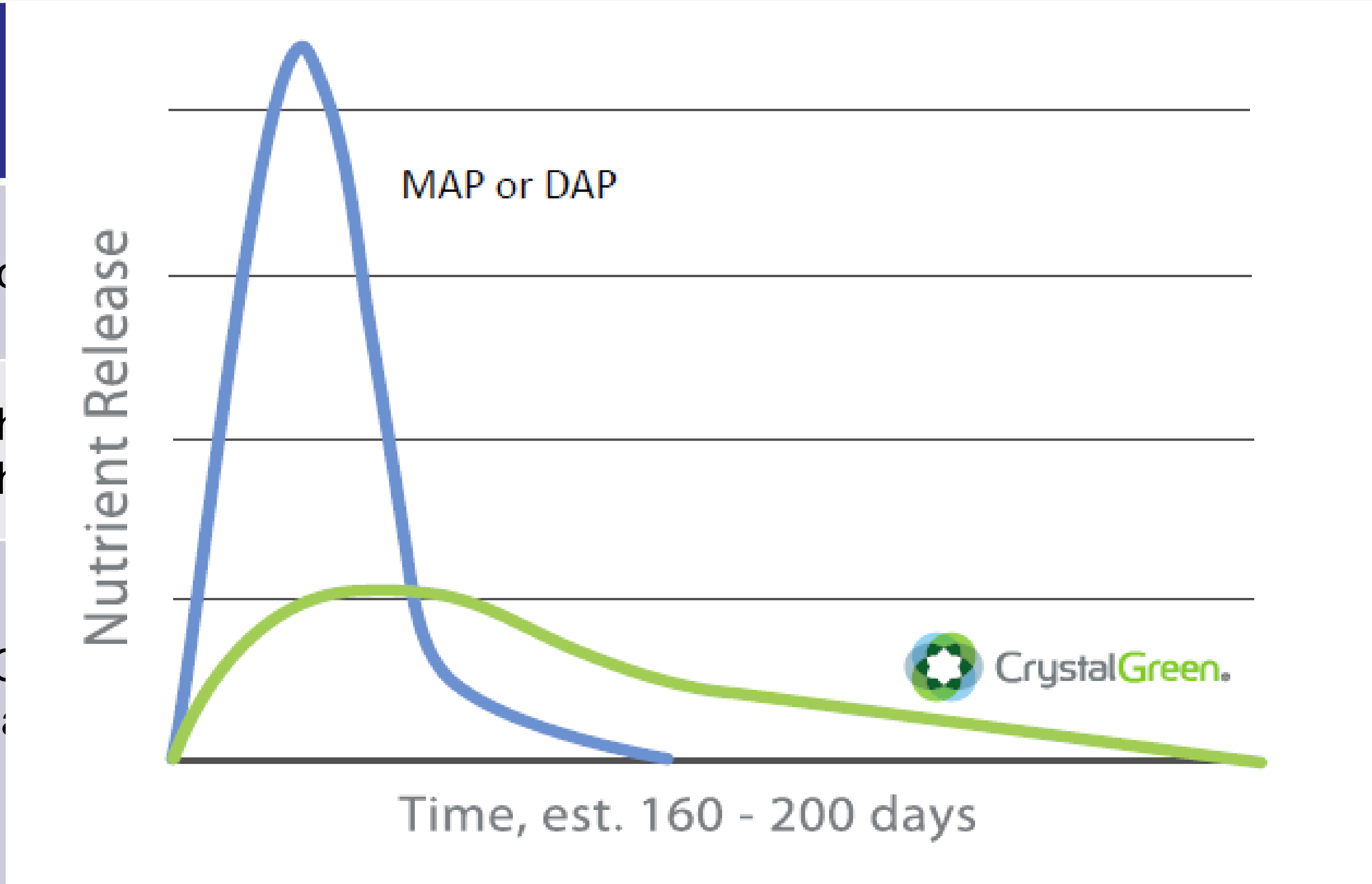
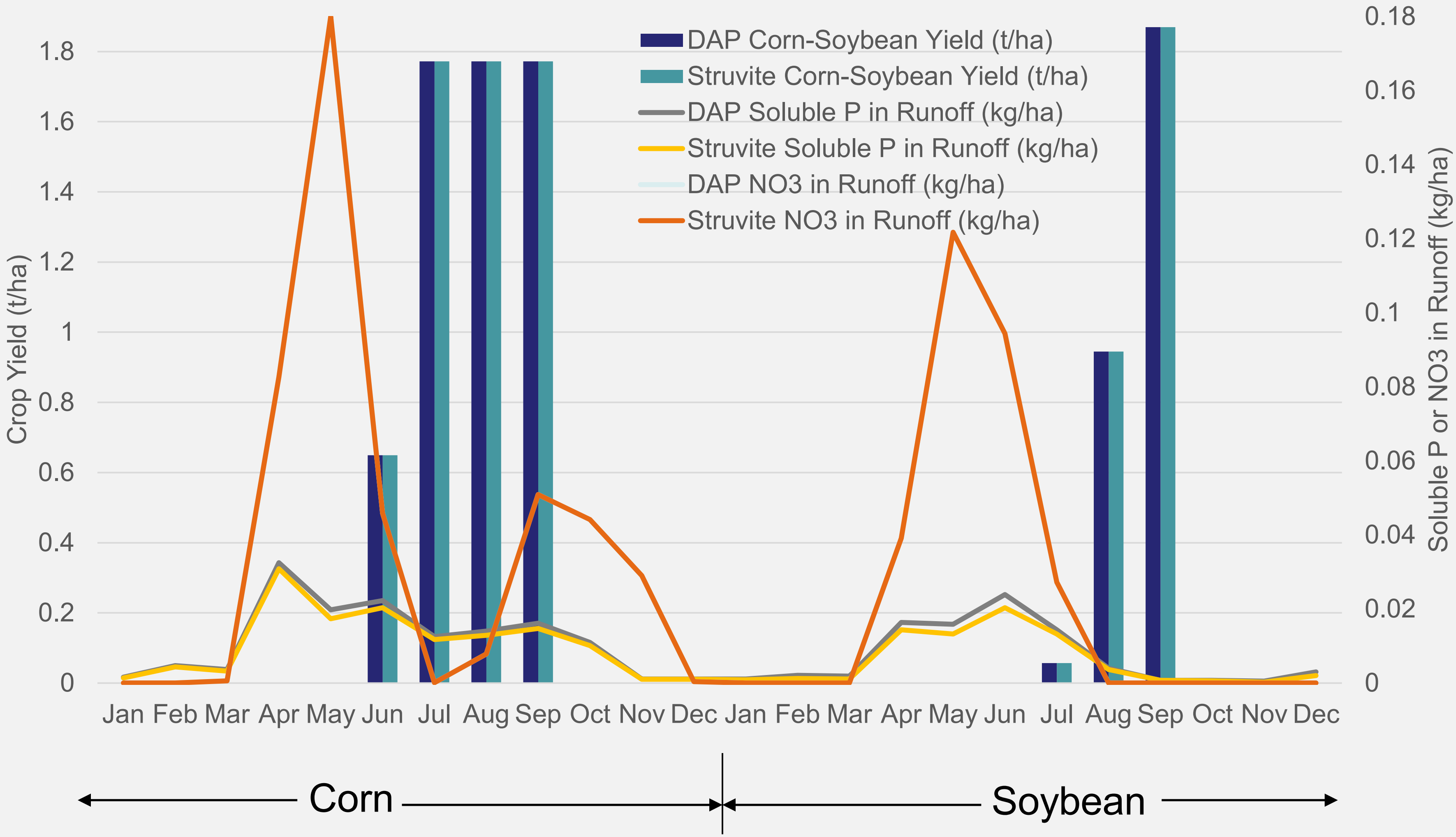
DAP and Struvite characteristics and quantity applied



Nitrogen and Phosphorus in Runoff and Crop Yield Results (one-cycle of crop rotation)



- Simulation results shown here is only for the two year period, long term evaluation may indicated less Struvite demand with less loss via runoff

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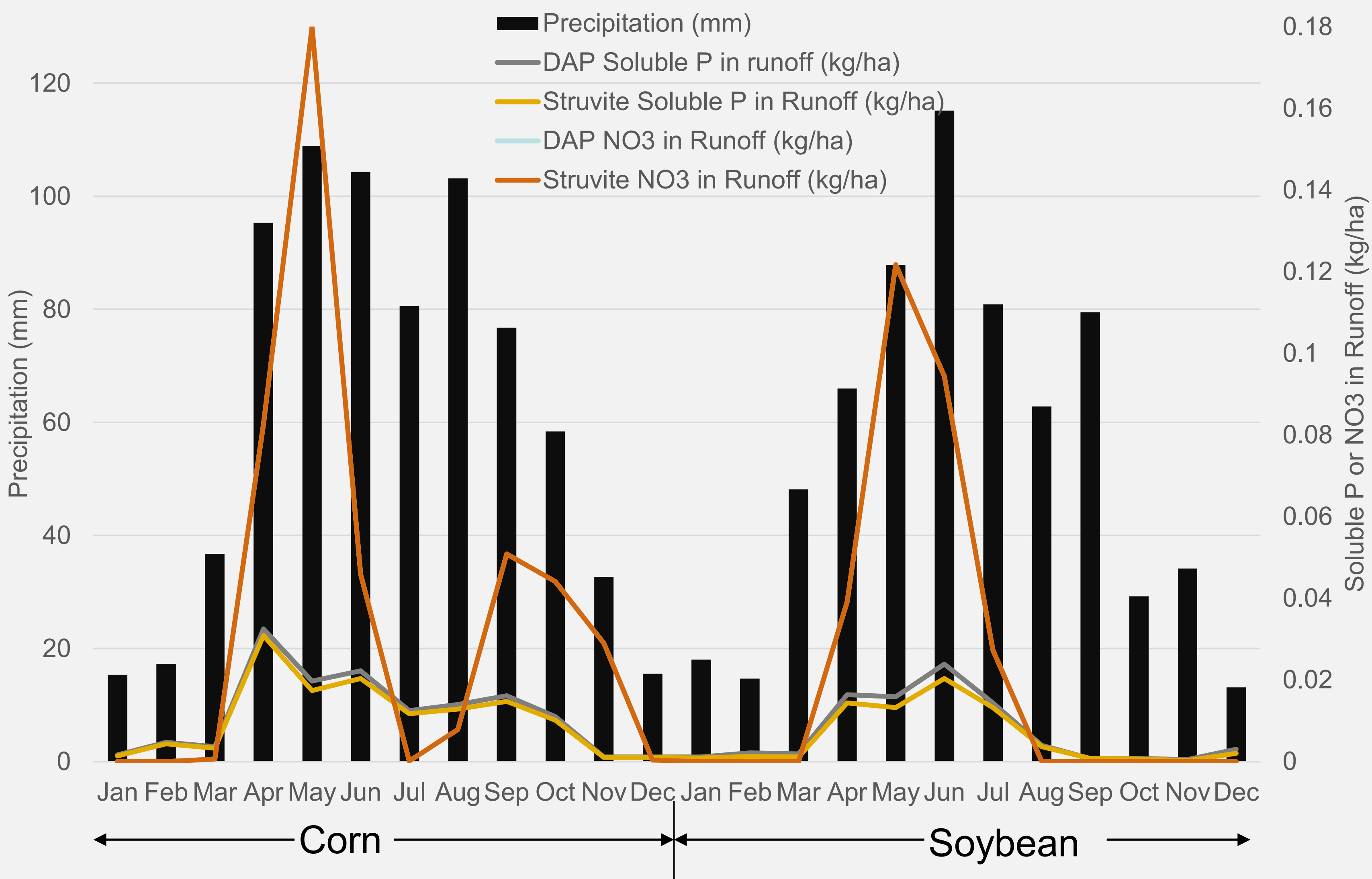
Nitrogen and Phosphorus in Runoff and Crop Yield Results (one-cycle of crop rotation)



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Total Emergy of DAP vs. Struvite via Field Application

Parameter	Diammonium Phosphate (DAP)	Magnesium Ammonium Phosphate (MAP) or Struvite
Crop Type/Rotation	Corn-Soybean	Corn-Soybean
Fertilizer Quantity (kg/ha)	100	170
P Applied via Fertilizer (kg P/ha)	18	20.4
Emergy of P Applied via Fertilizer (sej/kg P applied)	1.81E+14	1.96E+13
Runoff P (kg/ha)	0.24	0.20
Added Emergy due to Runoff (sej/kg P in runoff)	2.39E+12	1.93E+11
Runoff N (kg/ha)	0.72	0.72
Crop Yield (t/ha)	8.838	8.838
P Required (kg/t of Crop)	2.06	2.33
UEV of Fertilizer (sej/kg P)	1.01E+13	9.60E+11
Transformity/Yield (sej/t)	2.07E+13	2.24E+12

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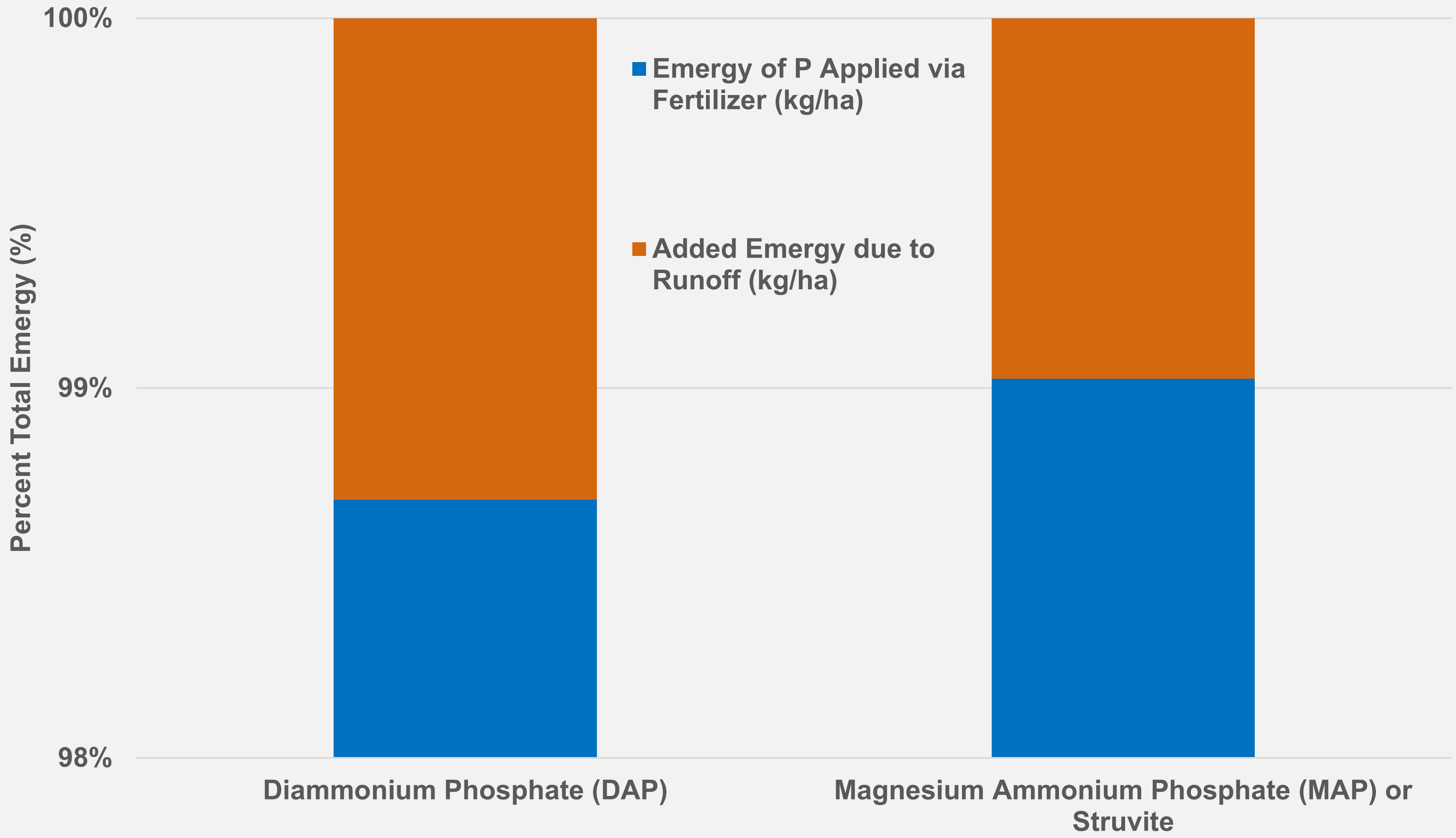
Total Emergy of DAP vs. Struvite via Field Application



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Results and Discussions

- Stringent nutrient reduction regulations lead to trade-offs that need further evaluation to choose the most sustainable treatment alternative

- Emergy analysis justifies nutrient recovery from wastewater sludge and provides sound economic and ecological comparison of removal and recovery treatment alternative independent of perceived monetary value

- Application of Struvite as a replacement/substitution to traditional phosphate fertilizers for crop growth over a long period of time can lead to substantial phosphorus and overall emergy reduction.

- DAP with an order of magnitude higher total emergy relative to struvite, displays a bigger environmental 'footprint'.

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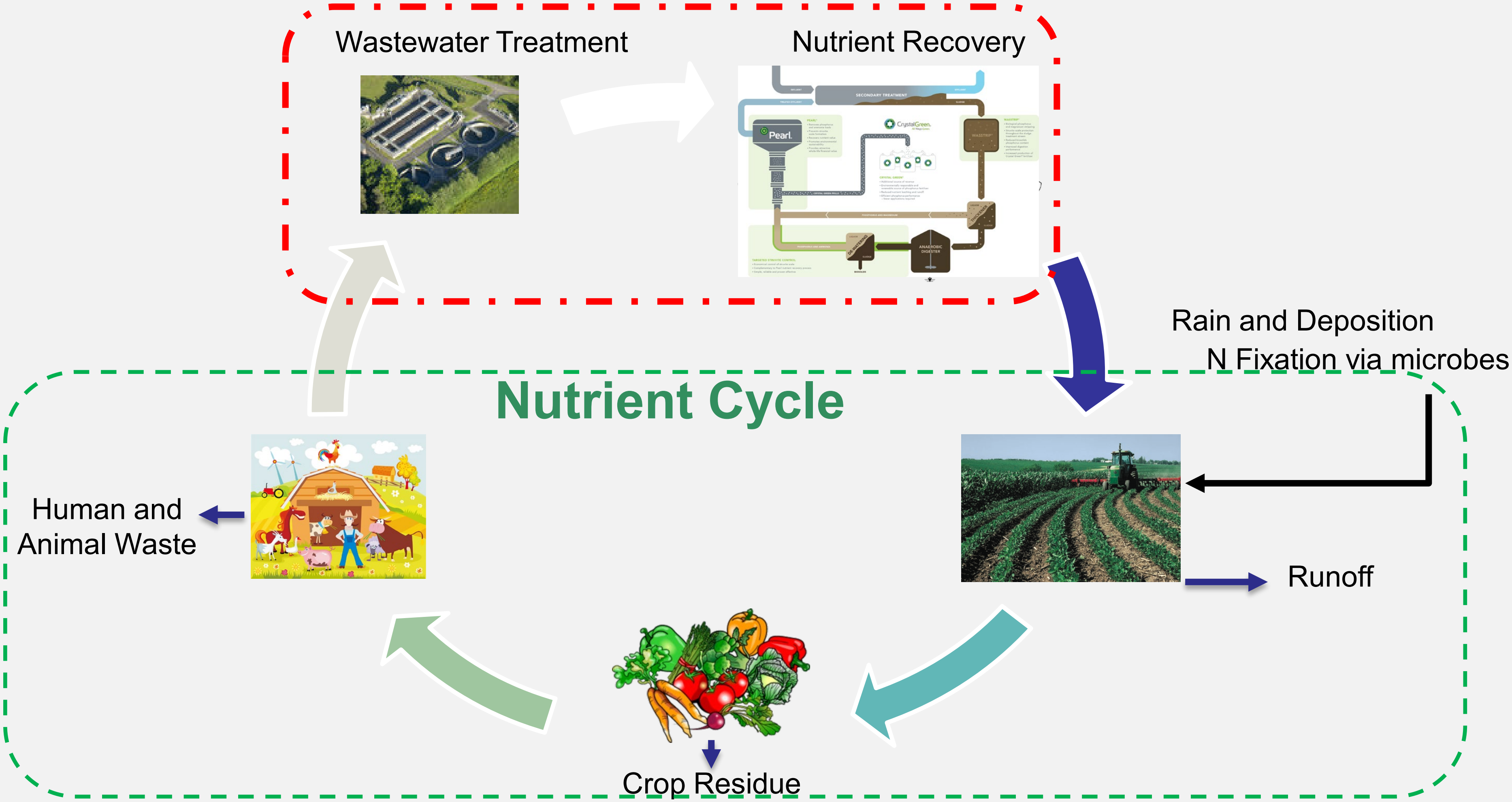
Future or Continued Work



Account for the benefits of nutrient recovery via efficient use of the struvite fertilizer and the flow of N and P nutrients in the food system, the economic, environmental and societal benefits of struvite recovery would be more perceptible.

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