Phosphorus in Utah Lake

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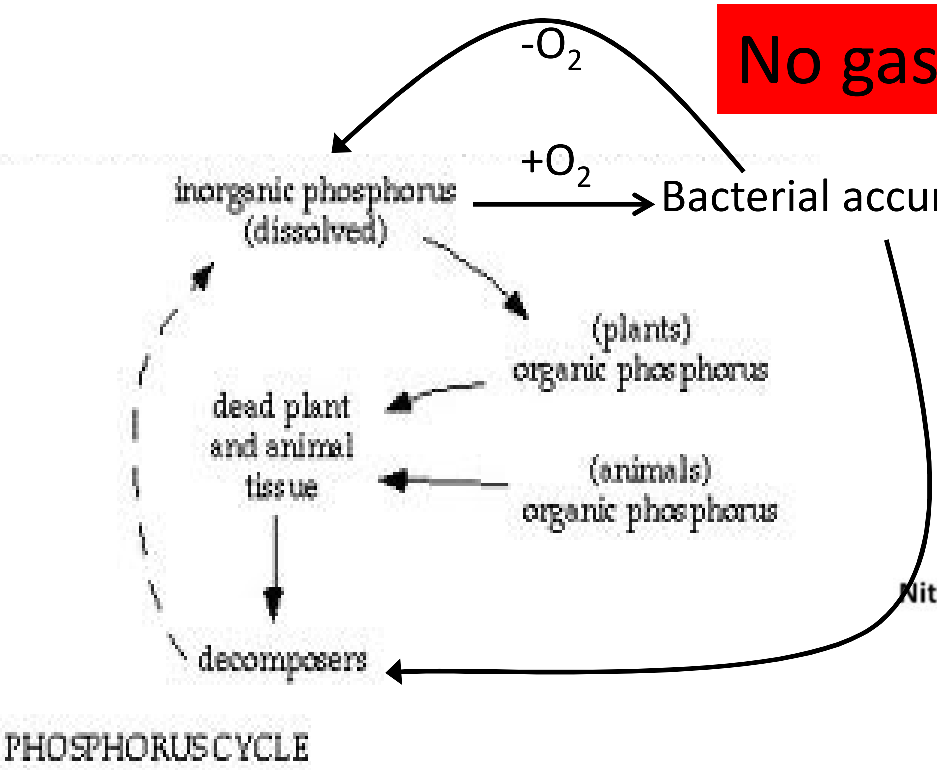
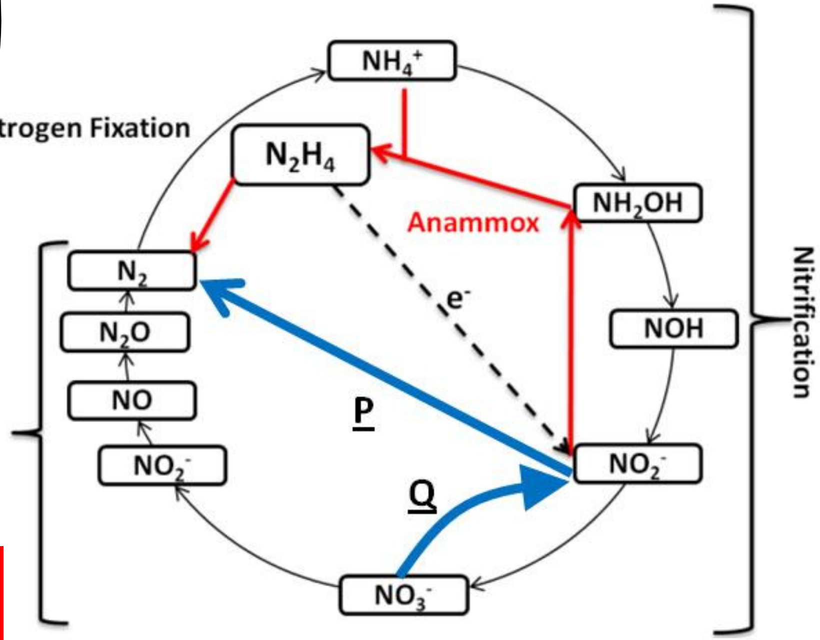
N and P Cycles-Comparison

No gaseous form



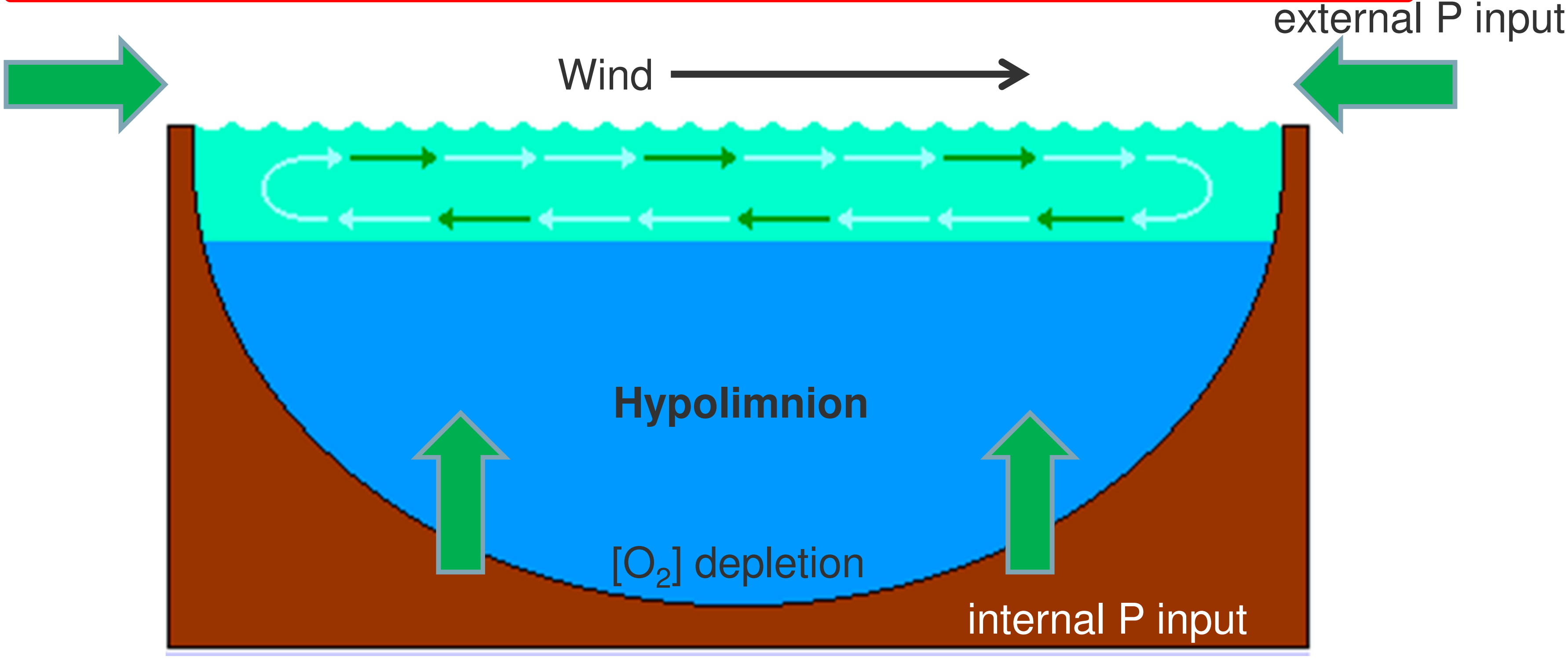


N_2 as end product

Motivation

- Lake and reservoir management challenge: Issues with [O_2] depletion and consequent detrimental effects on fish stocks and water quality
- Link between P and [O_2] depletion: “cause-effect related” or “two parallel symptoms of one common cause” (Gachter and Wehrli, 1998)

$O_2 \downarrow \longrightarrow F_{Pint} \uparrow$ or $F_{OM} \uparrow \longrightarrow O_2 \downarrow$ & $F_{Pint} \uparrow$



Summer stratification

Quantifying Oxygen Depletion

Muller et al. (2011) studied 55’000 O_2 measurements from 19 Swiss lakes and suggested 2 sinks for O_2:

1) Oxidation of reduced substances diffusing from deeper sediment layers
2) Mineralization of freshly settled OM at the sediment surface

It is quantified by Areal Hypolimnetic Mineralization (AHM) and expressed as $gO_2/m^2/d$:

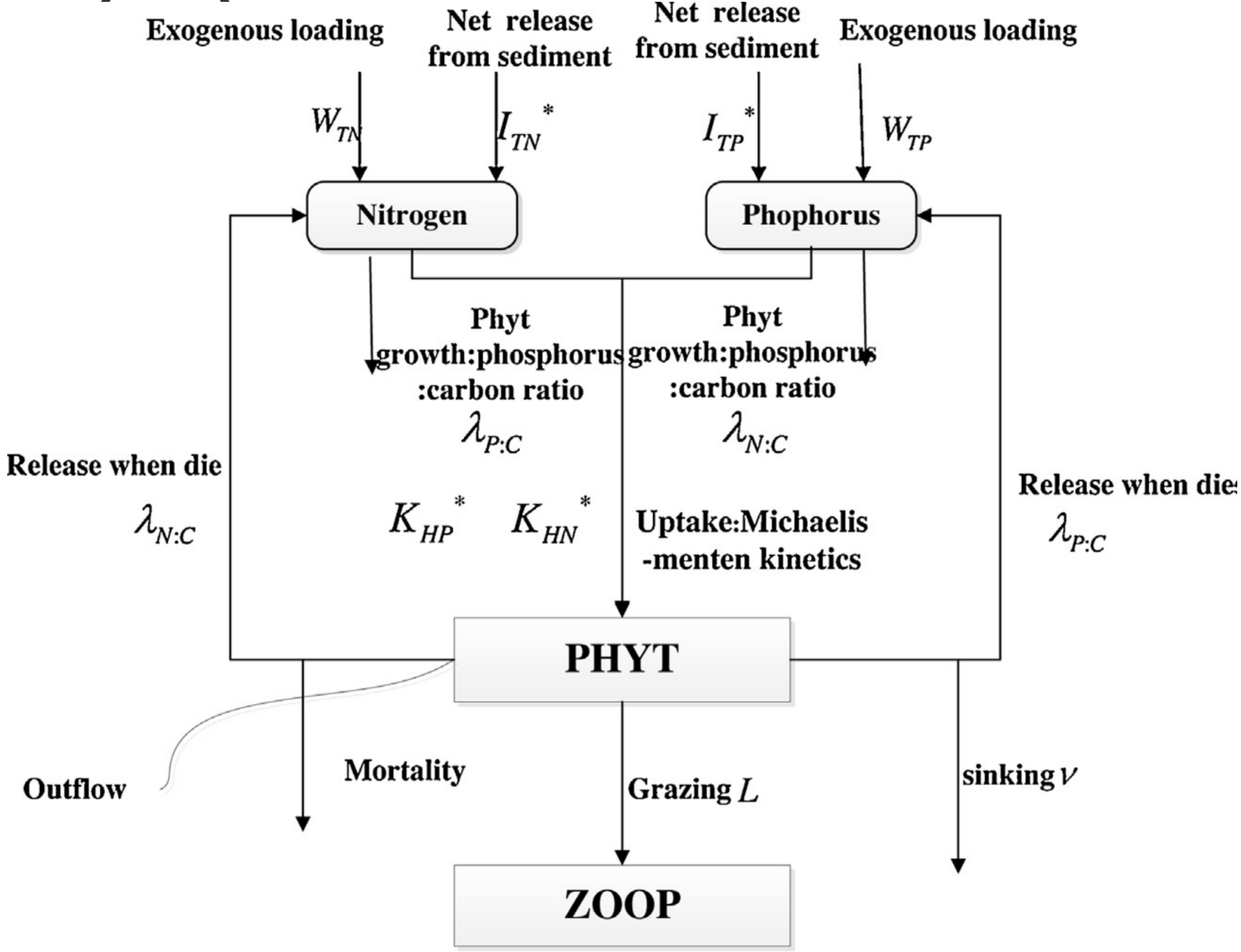
$$\boxed{AHM = F_{red} + \frac{D_{O_2}}{\delta \times \Delta t} \int_0^{200d} C(t)\,dt}$$

- F_{red} : flux of dissolved reduced substances from the sediment porewater expressed in equivalents of O_2 required for their oxidation i.e.

$$\boxed{\mathrm{Fred} = 2\times F_{CH4} + 2\times F_{NH4} + 2\times F_{H2S} + 0.5\times F_{Mn} + 0.25\times F_{Fe}}$$

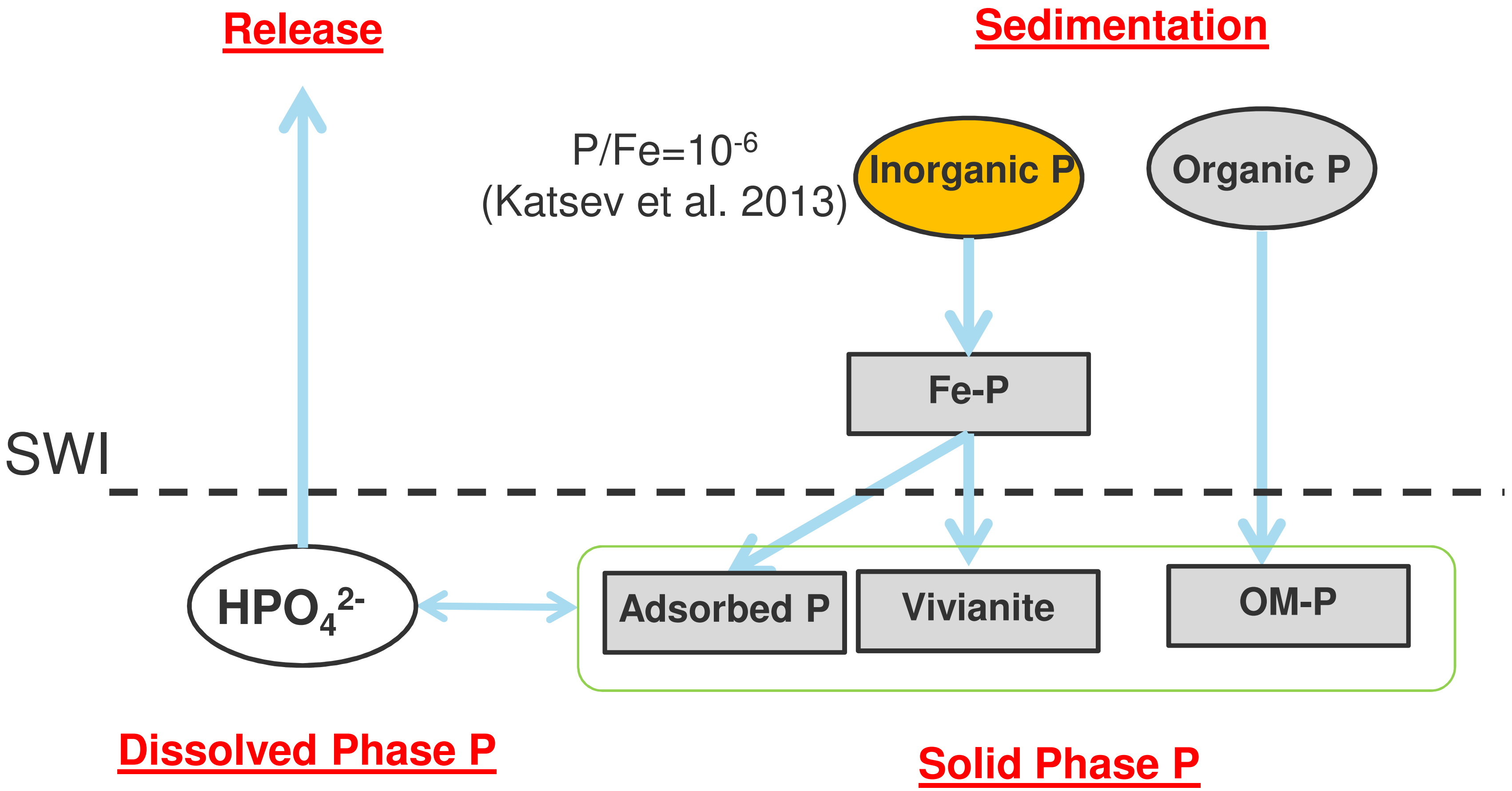
- Δt : stratification period (200 days) from Apr to Oct
- D_{O2} : molecular diffusion coefficient of O_2
- $C(t)$: volume-averaged hypolimnetic O_2 concentration as a function of time
- δ : thickness of the diffusive boundary layer (DBL) at sediment water interface. DBL is the region immediately above the SWI where turbulence is low.

Phytoplankton Growth Model

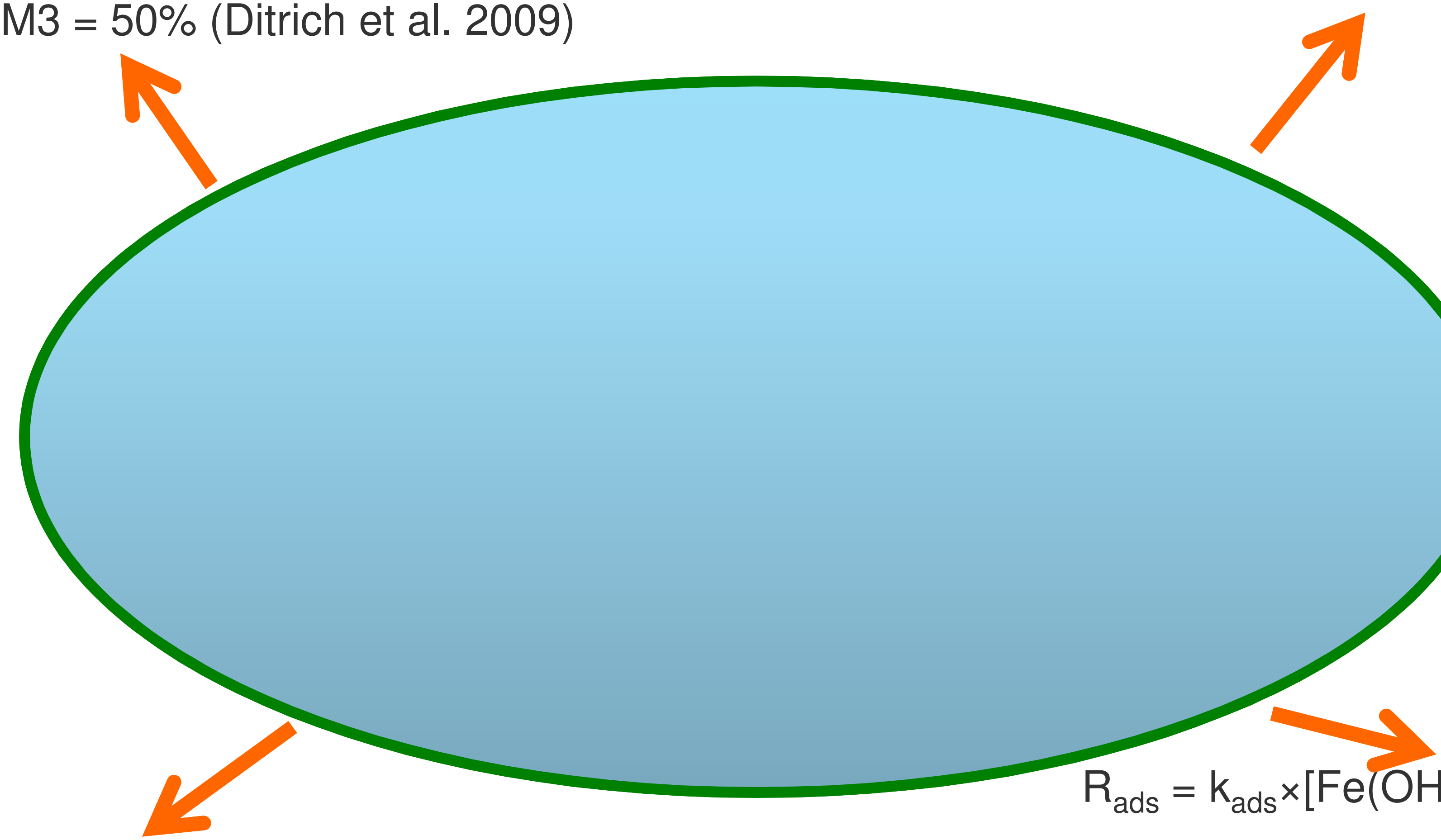


Li et al, 2015

Conceptual Model: P Phases



Conceptual Model: P Cycling



OM = $(CH_2O)_x(NH_3)_y(H_3PO_4)_z$
OM1 = 20%
OM2 = 30%
OM3 = 50% (Ditrich et al. 2009)

$3H_2S + Fe_3(PO_4)_2 \rightarrow 3FeS + 2\ HPO_4^{2-} + 4H^+$

$3Fe^{2+} + 2HPO_4^{2-} \leftrightarrows Fe_3(PO_4)_2 + 2H^+$

5 Pools of Solid Phase P:
OM1-P, OM2-P, OM3-P, Fe-P, $Fe_3(PO_4)_2$

$R_{ads} = k_{ads} \times [Fe(OH)_3] \times [HPO_4^{2-}]$

$k_{ads} = 1.35\ (\mu mol/cm^3/yr)^{-1}$

(Kraal et al. 2012)

Conceptual Model: Reaction Network

Primary Reactions

$OM + xO_2 + (-y+2z)HCO_3^- \rightarrow 0.4xN_2 + (x-y+2z)CO_2 + yNH_4^+ + zHPO_4^{2-} + (x+2y+2z)H_2O$	R1,R2
$OM + 0.8xNO_3^- \rightarrow 0.4xN_2 + (0.2x-y+2z)CO_2 + (0.8x+y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-} + (0.6x-y+2z)H_2O$	R3,R4
$OM + 2xMnO_2 + (3x+y-2z)CO_2 + (x+y-2z)H_2O \rightarrow 2xMn^{2+} + (4x+y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-}$	R5,R6
$OM + 4xFe(OH)_3 + (7x+y-2z)CO_2 \rightarrow 4xFe^{2+} + (8x+y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-} + (3x+y-2z)H_2O$	R7,R8
$OM + 0.5xSO_4^{2-} + (y-2z)CO_2 + (y-2z)H_2O \rightarrow 0.5xH_2S + (x+y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-}$	R9,R10
$OM + (y-2z)H_2O \rightarrow 0.5xCH_4 + (0.5x-y+2z)CO_2 + (y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-}$	R11,R12

Secondary Reactions

$NH_4^+ + 2O_2 + 2HCO_3^- \rightarrow NO_3^- + 2CO_2 + 3H_2O$	R13
$2Mn^{2+} + O_2 + 4HCO_3^- \rightarrow 2MnO_2 + 4CO_2 + 2H_2O$	R14
$Fe^{2+} + 0.25O_2 + 2HCO_3^- + 0.5H_2O \rightarrow Fe(OH)_3 + 2CO_2$	R15
$H_2S + 2O_2 + 2HCO_3^- \rightarrow SO_4^{2-} + 2CO_2 + 2H_2O$	R16
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	R17
$NH_4^+ + 4MnO_2 + 6H^+ \rightarrow 4Mn^{2+} + NO_3^- + 5H_2O$	R18,R19
$2Fe^{2+} + MnO_2 + 2HCO_3^- + 2H_2O \rightarrow 2Fe(OH)_3 + Mn^{2+} + 2CO_2$	R20,R21
$H_2S + 4MnO_2 + 6CO_2 + 2H_2O \rightarrow 4Mn^{2+} + SO_4^{2-} + 6HCO_3^-$	R22,R23
$H_2S + 8Fe(OH)_3 + 14CO_2 \rightarrow 8Fe^{2+} + SO_4^{2-} + 14HCO_3^- + 6H_2O$	R24
$3H_2S + Fe_3(PO_4)_2 \rightarrow 3FeS + 2\ HPO_4^{2-} + 4H^+$	R25
$SO_4^{2-} + CH_4 + CO_2 \rightarrow 2HCO_3^- + H_2S$	R26

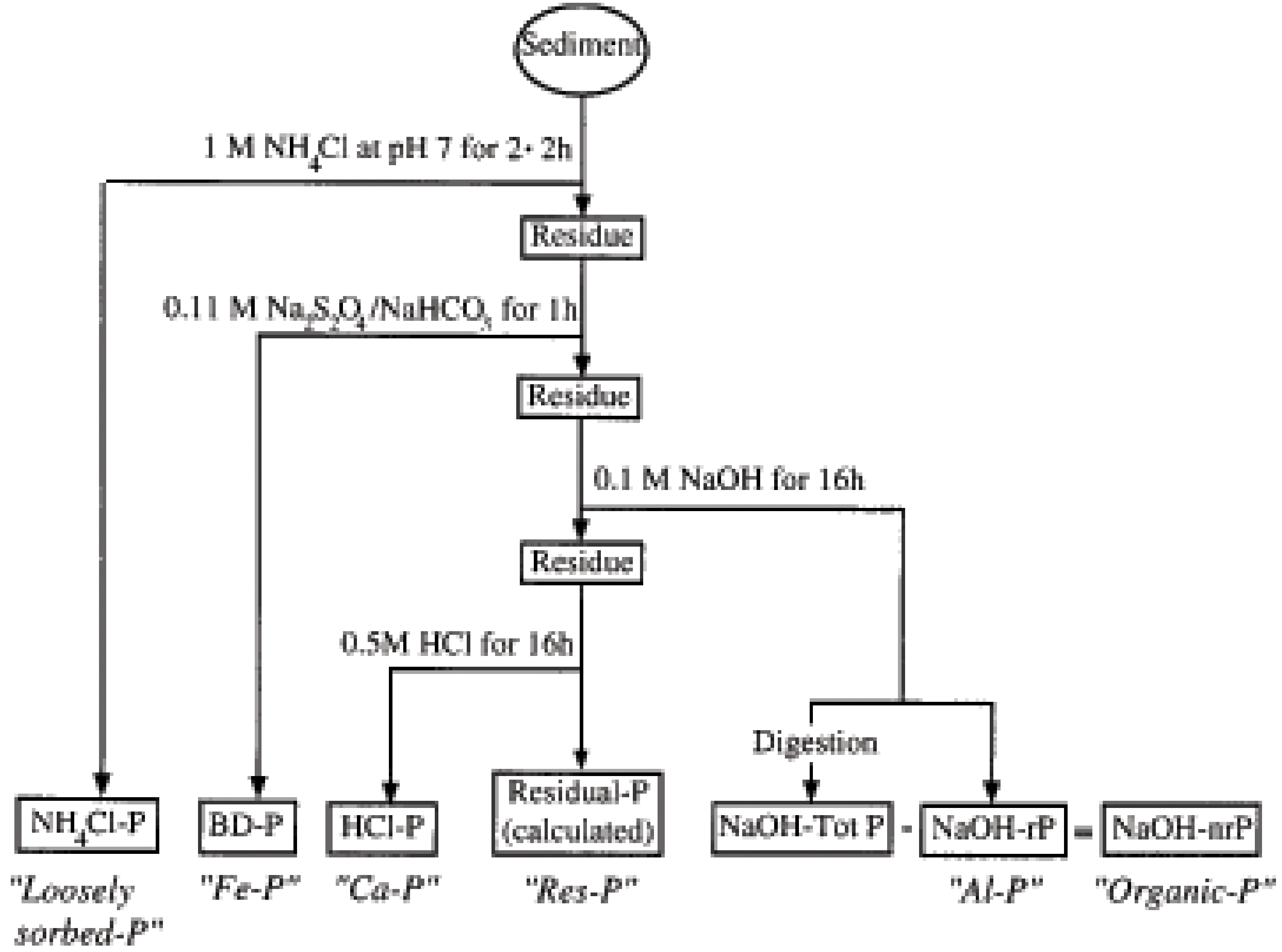
Dissolution and Precipitation Reactions

$FeS + 2H^+ \rightarrow Fe^{2+} + H_2S$	R27
$Fe^{2+} + H_2S \rightarrow FeS + 2H^+$	R28
$FeS + H_2S \rightarrow FeS_2 + H_2$	R29
$Fe_3(PO_4)_2 + 2H^+ \rightarrow 3Fe^{2+} + 2HPO_4^{2-}$	R30
$3Fe^{2+} + 2HPO_4^{2-} \rightarrow Fe_3(PO_4)_2 + 2H^+$	R31

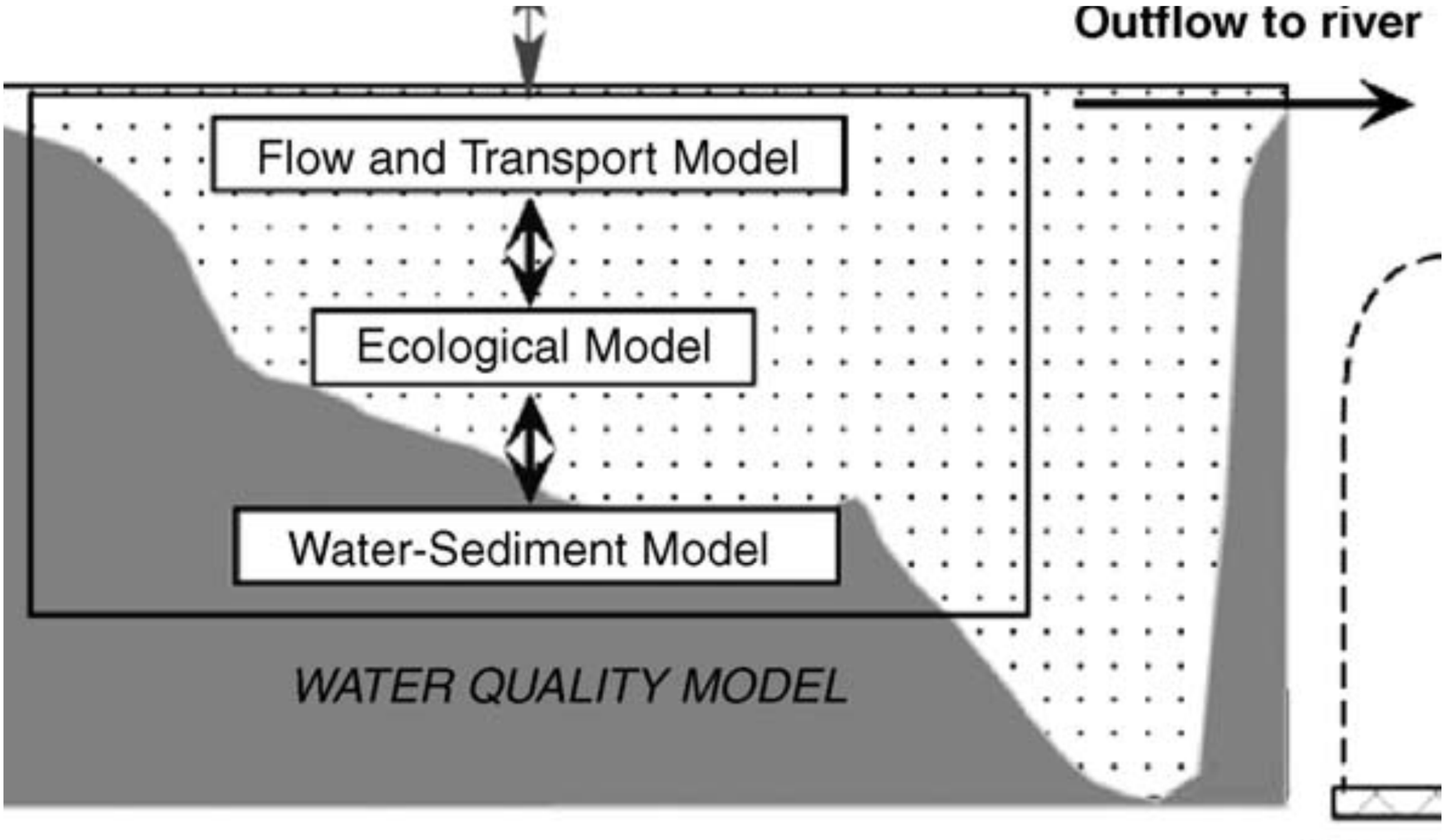
Adsorption and Desorption Reactions

$Fe(OH)_3 + HPO_4^{2-} \rightarrow Fe\text{-}P$	R32
$Fe\text{-}P \rightarrow HPO_4^{2-}$	R33

P Fractionation scheme



Conceptual Modeling Framework



Specific to Utah Lake
Past research funded by UDWQ

Past Scope of Work

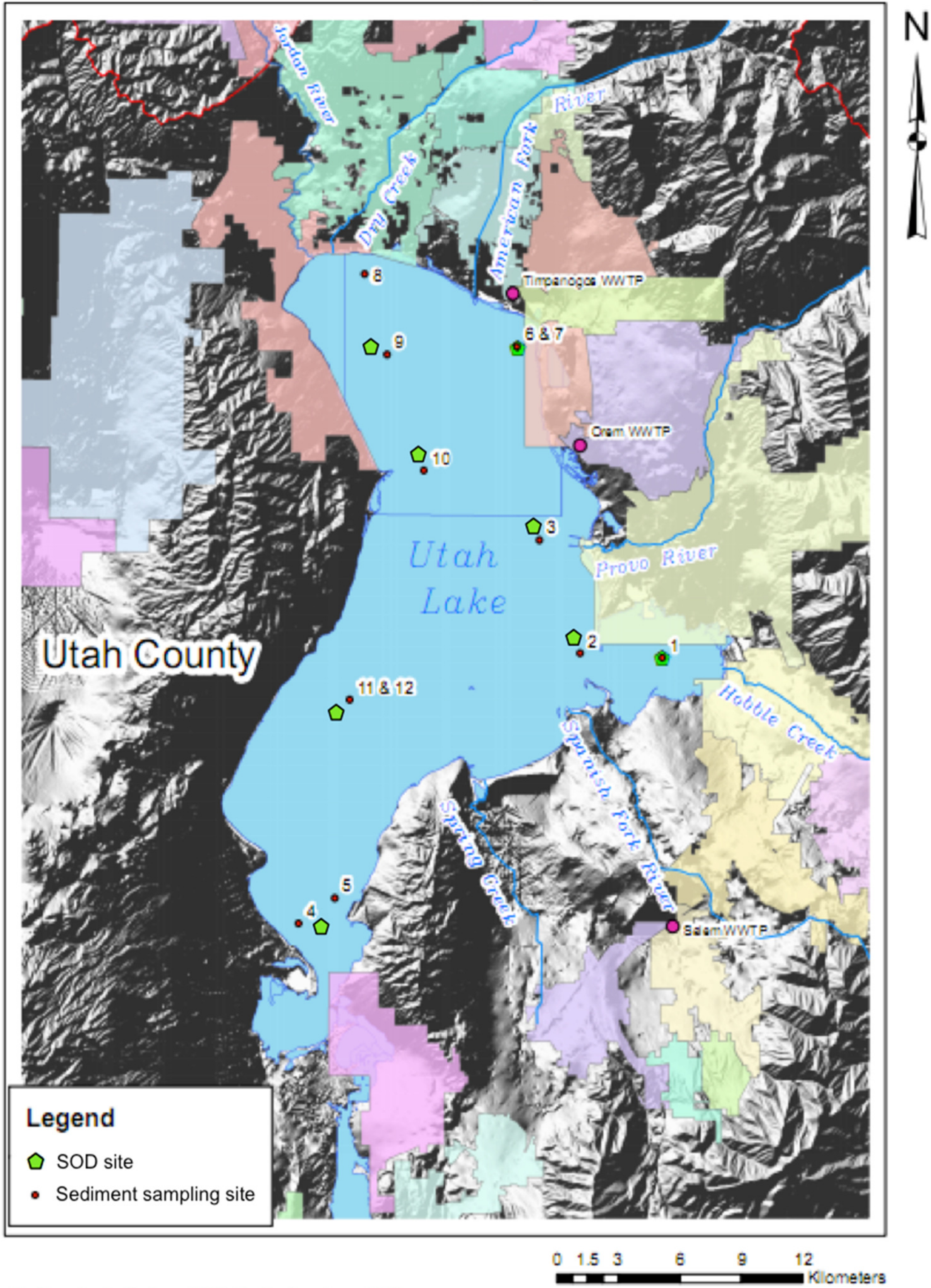
Task 1: Phosphorus speciation in lake sediments at 10~15 locations

Task 2: Evaluate mineralogy using X-ray defraction at 12 locations.

Task 3: One time in situ measurement of nutrient flux and sediment oxygen demand at selected 3 shallow sites in the lake using four chamber instead of originally proposed 1 chamber. In chambers, DO and pH will be varied.

Project ended January 31, 2012

Utah Lake, Sampling Locations

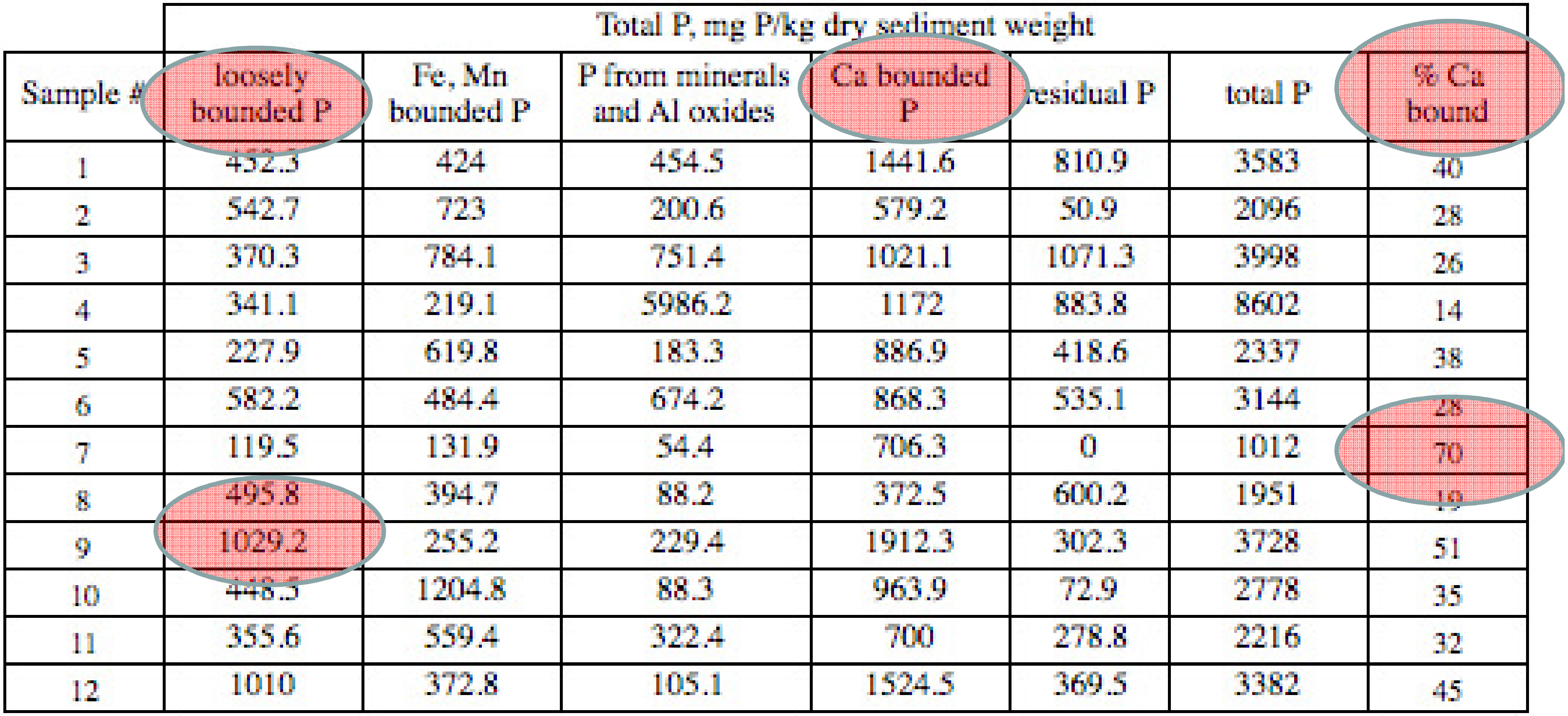


Geographic Coordinate System: GCS_North_American_1983

Observed SOD, WC and estimated ambient DO depletion rates

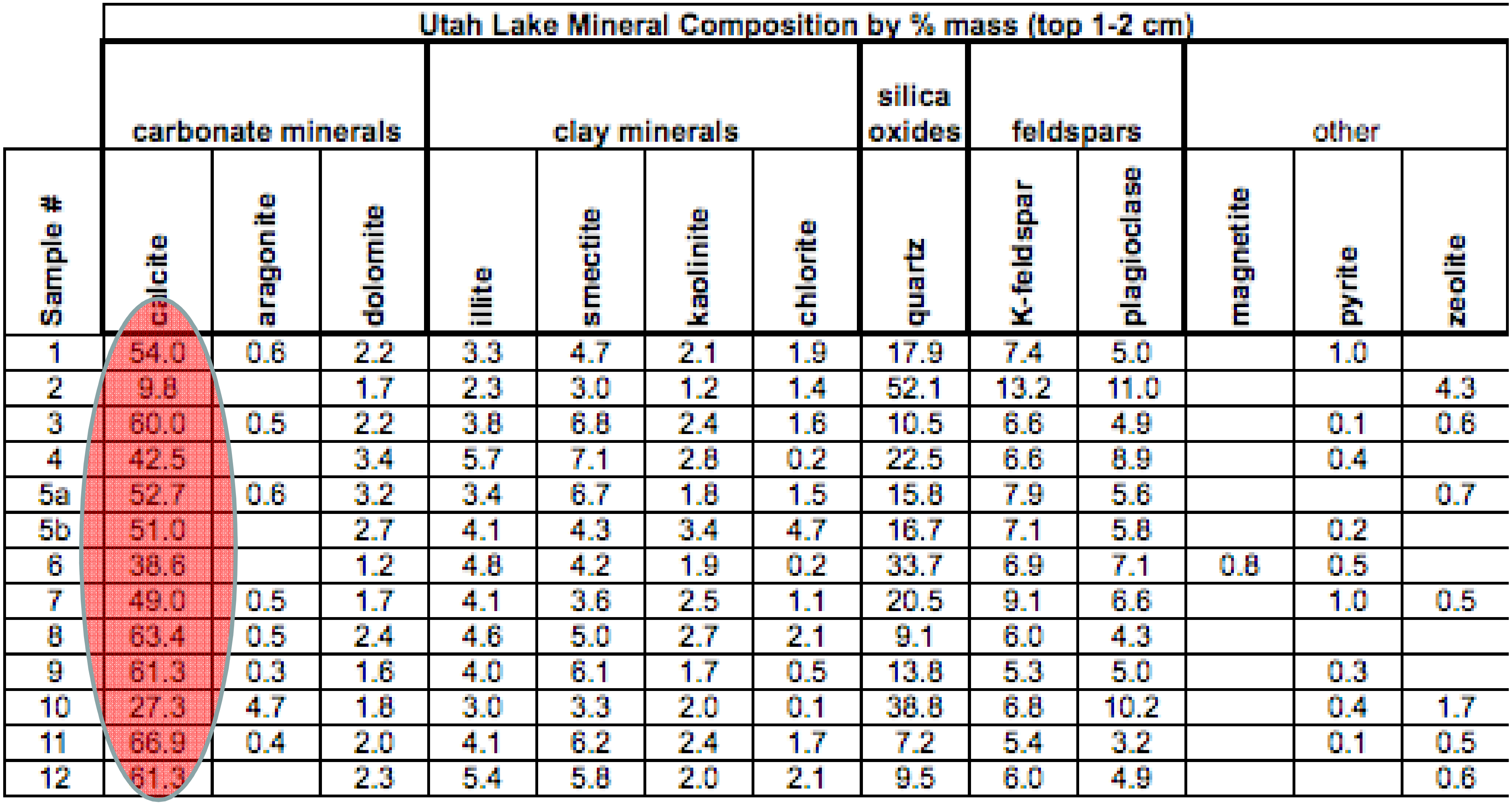
site	SOD_{avg} g/m²/d	WC g/m³/d	ambient g/m²/d	ambient g/m³/d	depth m
Provo Bay	-4.61	-6.66	-11.3	-11.3	1
Provo Bay entrance	-1.42	-3.45	-4.9	-4.9	1
outside marina	-1.49	-2.28	-8.3	-2.8	3
Goshen Bay	-1.67	-3.4	-5.1	-5.1	1
Geneva Steel	-2.04	-1.9	-5.8	-2.9	2
Utah Lk. Outlet	-1.03	-1.28	-3.8	-1.7	2.2
Pelican Point	-1.06	-4.17	-13.6	-4.5	3
Goshen Bay entrance	-0.90	-1.11	-4.2	-1.4	3

Phosphorus Speciation



	Total P, mg P/kg dry sediment weight						
Sample #	loosely bounded P	Fe, Mn bounded P	P from minerals and Al oxides	Ca bounded P	residual P	total P	% Ca bound
1	432.3	424	454.5	1441.6	810.9	3583	40
2	542.7	723	200.6	579.2	50.9	2096	28
3	370.3	784.1	751.4	1021.1	1071.3	3998	26
4	341.1	219.1	5986.2	1172	883.8	8602	14
5	227.9	619.8	183.3	886.9	418.6	2337	38
6	582.2	484.4	674.2	868.3	535.1	3144	28
7	119.5	131.9	54.4	706.3	0	1012	70
8	495.8	394.7	88.2	372.5	600.2	1951	19
9	1029.2	255.2	229.4	1912.3	302.3	3728	51
10	448.5	1204.8	88.3	963.9	72.9	2778	35
11	355.6	559.4	322.4	700	278.8	2216	32
12	1010	372.8	105.1	1524.5	369.5	3382	45

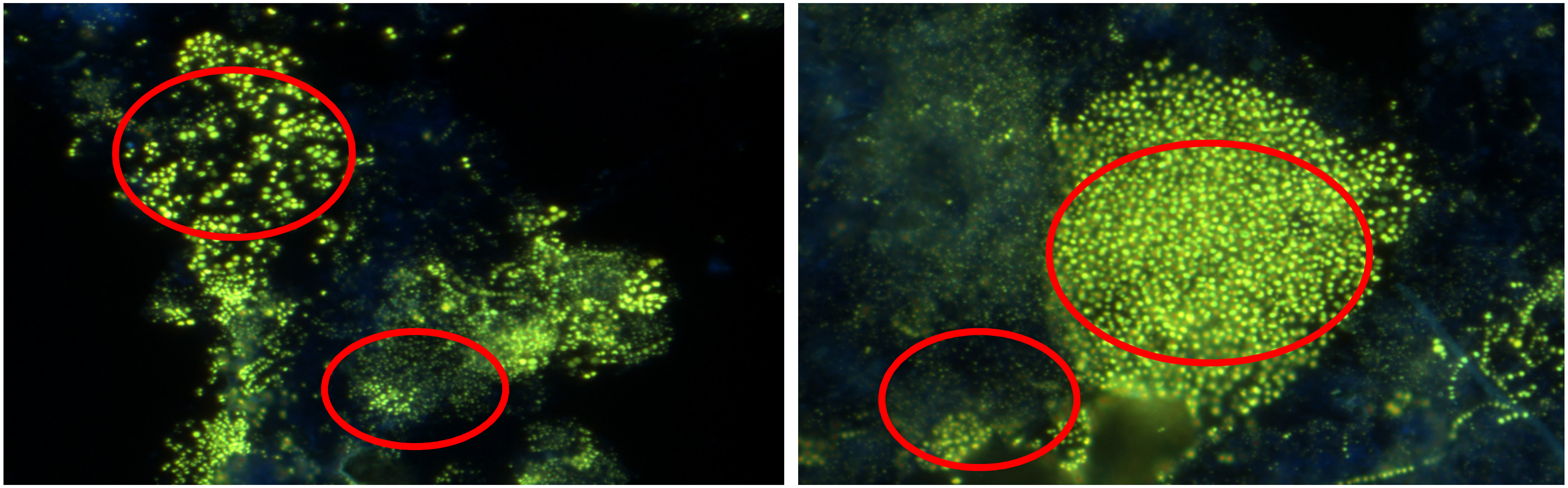
Utah Lake Sediment Minerology



Utah Lake Mineral Composition by % mass (top 1-2 cm)

	carbonate minerals			clay minerals				silica oxides	feldspars		other		
Sample #	calcite	aragonite	dolomite	illite	smectite	kaolinite	chlorite	quartz	K-feldspar	plagioclase	magnetite	pyrite	zeolite
1	54.0	0.6	2.2	3.3	4.7	2.1	1.9	17.9	7.4	5.0		1.0	
2	9.8		1.7	2.3	3.0	1.2	1.4	52.1	13.2	11.0			4.3
3	60.0	0.5	2.2	3.8	6.8	2.4	1.6	10.5	6.6	4.9		0.1	0.6
4	42.5		3.4	5.7	7.1	2.8	0.2	22.5	6.6	8.9		0.4	
5a	52.7	0.6	3.2	3.4	6.7	1.8	1.5	15.8	7.9	5.6			0.7
5b	51.0		2.7	4.1	4.3	3.4	4.7	16.7	7.1	5.8		0.2	
6	38.6		1.2	4.8	4.2	1.9	0.2	33.7	6.9	7.1	0.8	0.5	
7	49.0	0.5	1.7	4.1	3.6	2.5	1.1	20.5	9.1	6.6		1.0	0.5
8	63.4	0.5	2.4	4.6	5.0	2.7	2.1	9.1	6.0	4.3			
9	61.3	0.3	1.6	4.0	6.1	1.7	0.5	13.8	5.3	5.0		0.3	
10	27.3	4.7	1.8	3.0	3.3	2.0	0.1	38.8	6.8	10.2		0.4	1.7
11	66.9	0.4	2.0	4.1	6.2	2.4	1.7	7.2	5.4	3.2		0.1	0.5
12	61.3		2.3	5.4	5.8	2.0	2.1	9.5	6.0	4.9			0.6

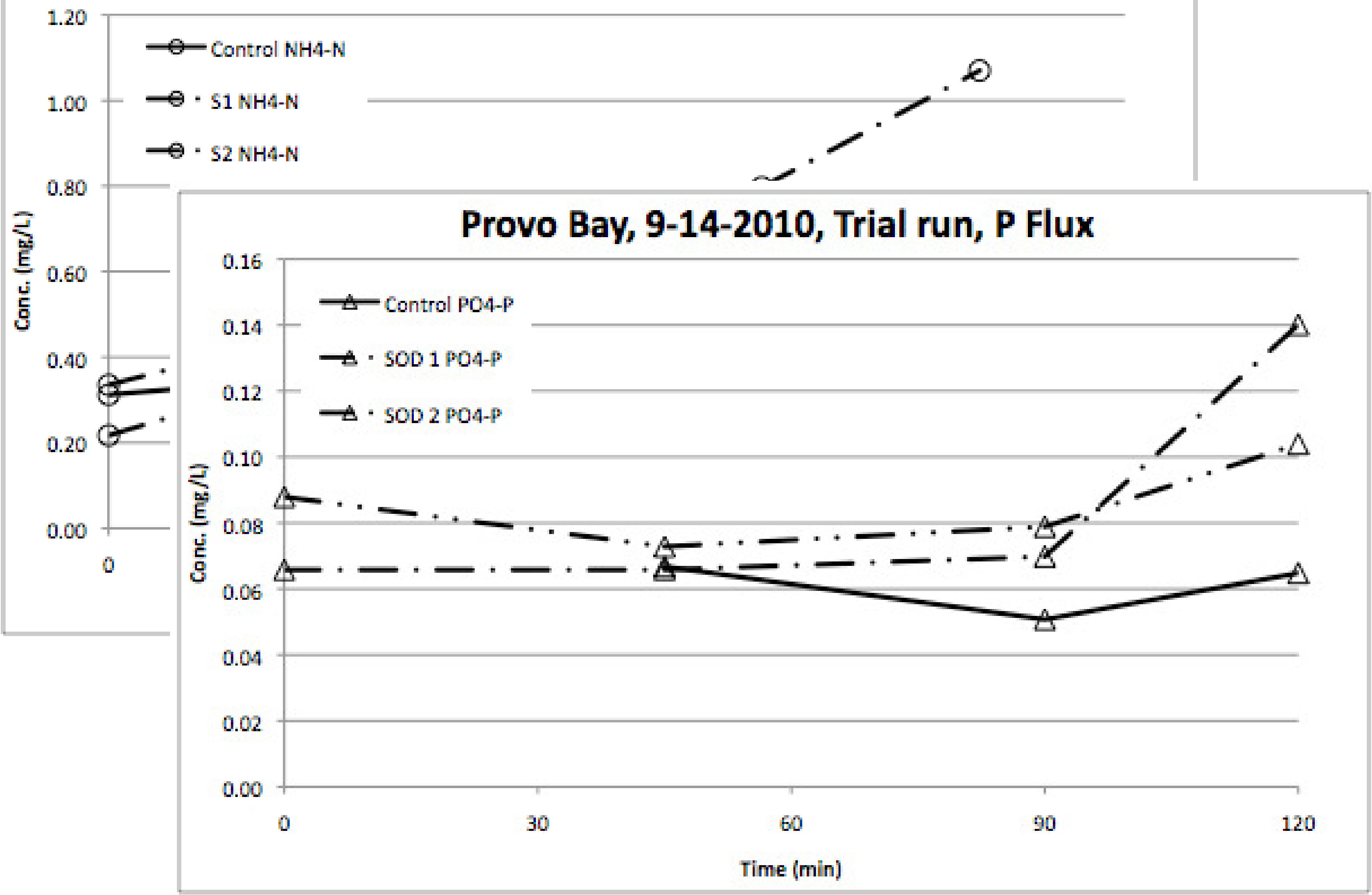
Phosphorus Accumulating Organisms



Poly-P Positive cells (stained with DAPI)

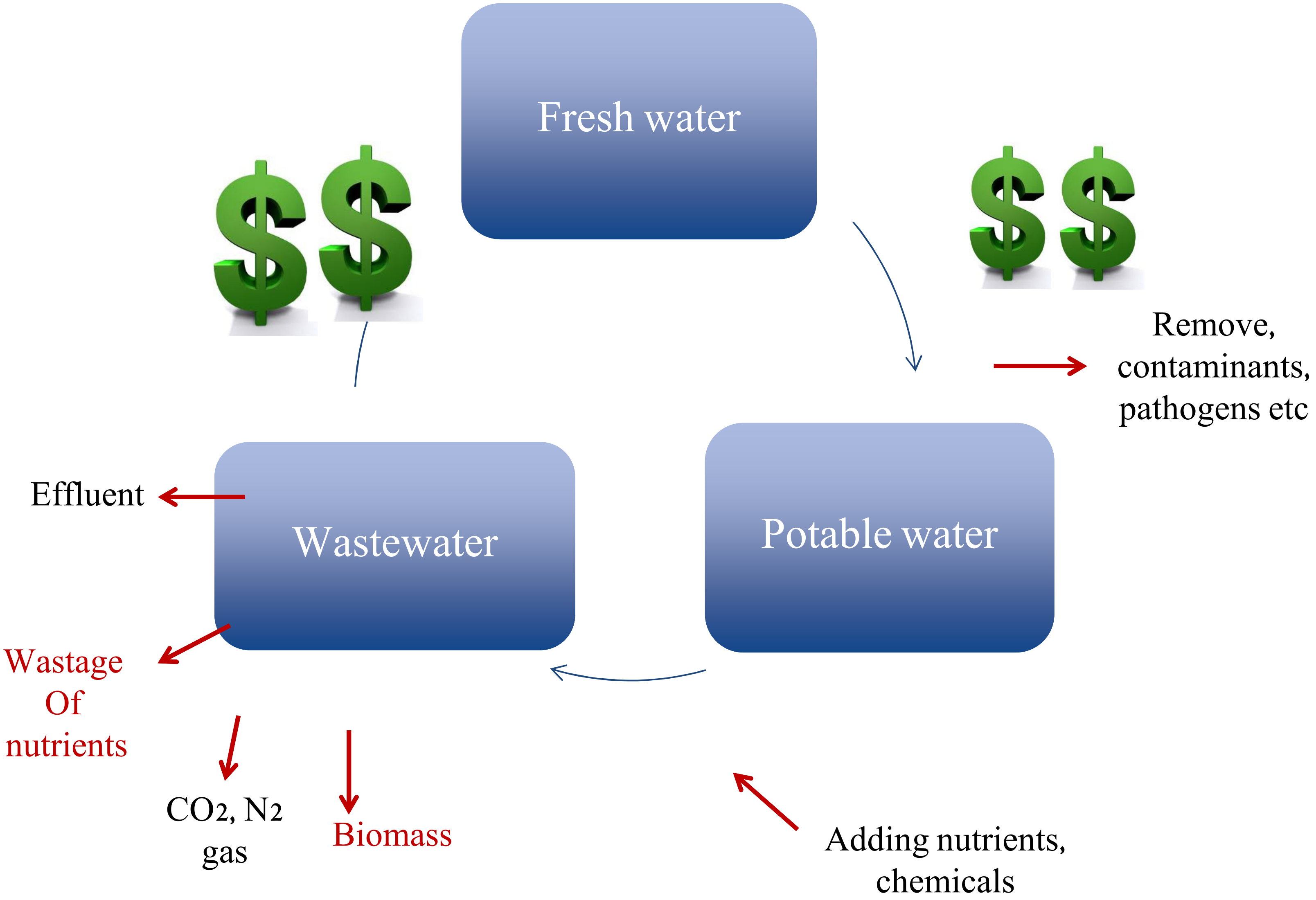
Let us not forget about their contribution in Utah Lake

Nutrients Flux Provo Bay



Some social aspects
P removal versus recovery

Waste of Money and Resources



Fresh water

Remove,
contaminants,
pathogens etc

Potable water

Adding nutrients,
chemicals

Wastewater

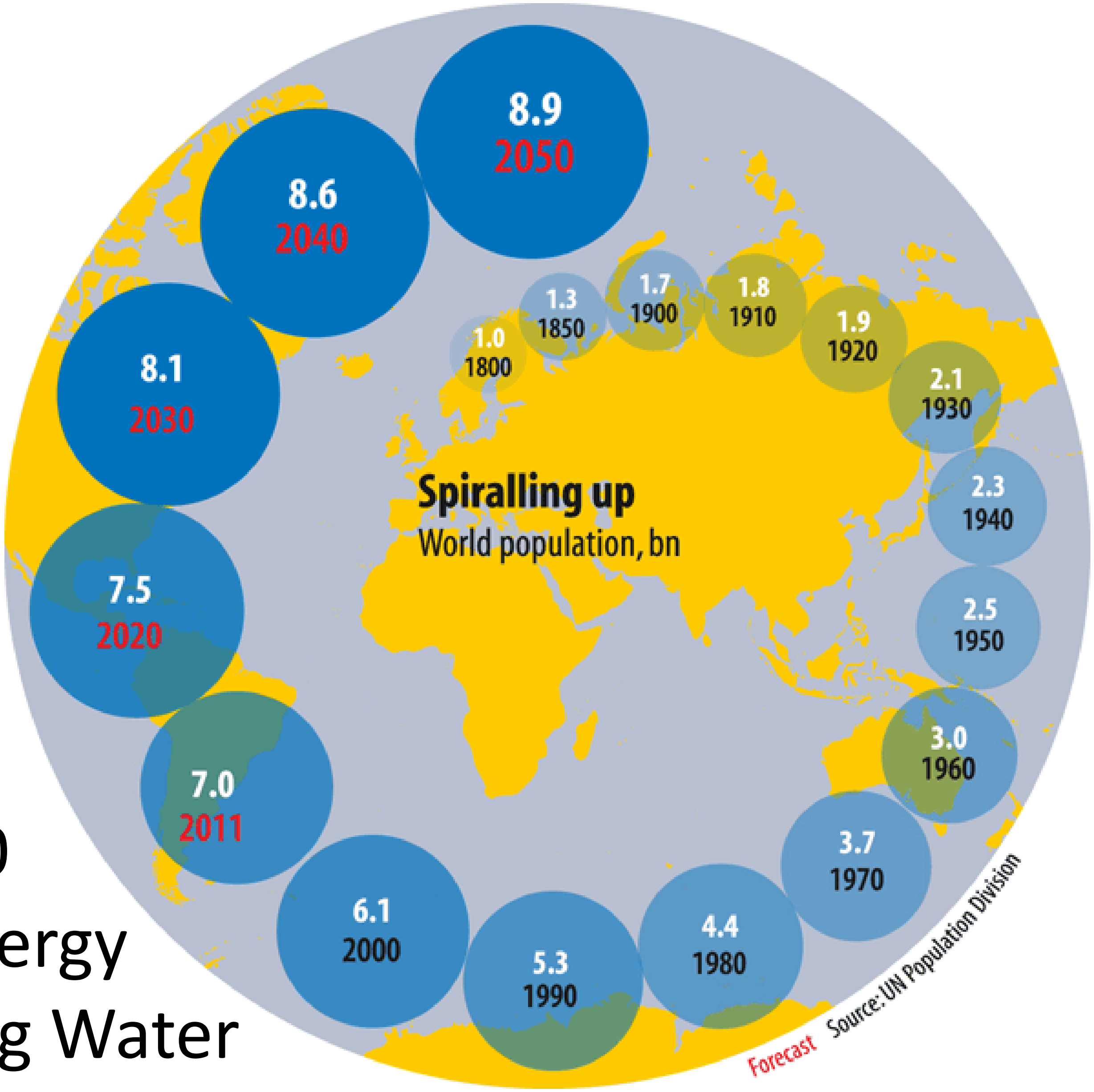
Effluent

Wastage
Of
nutrients

CO_2, N_2
gas

Biomass

How To Feed the Growing Population



Source: UN Population Division

8.9 Billion by 2050

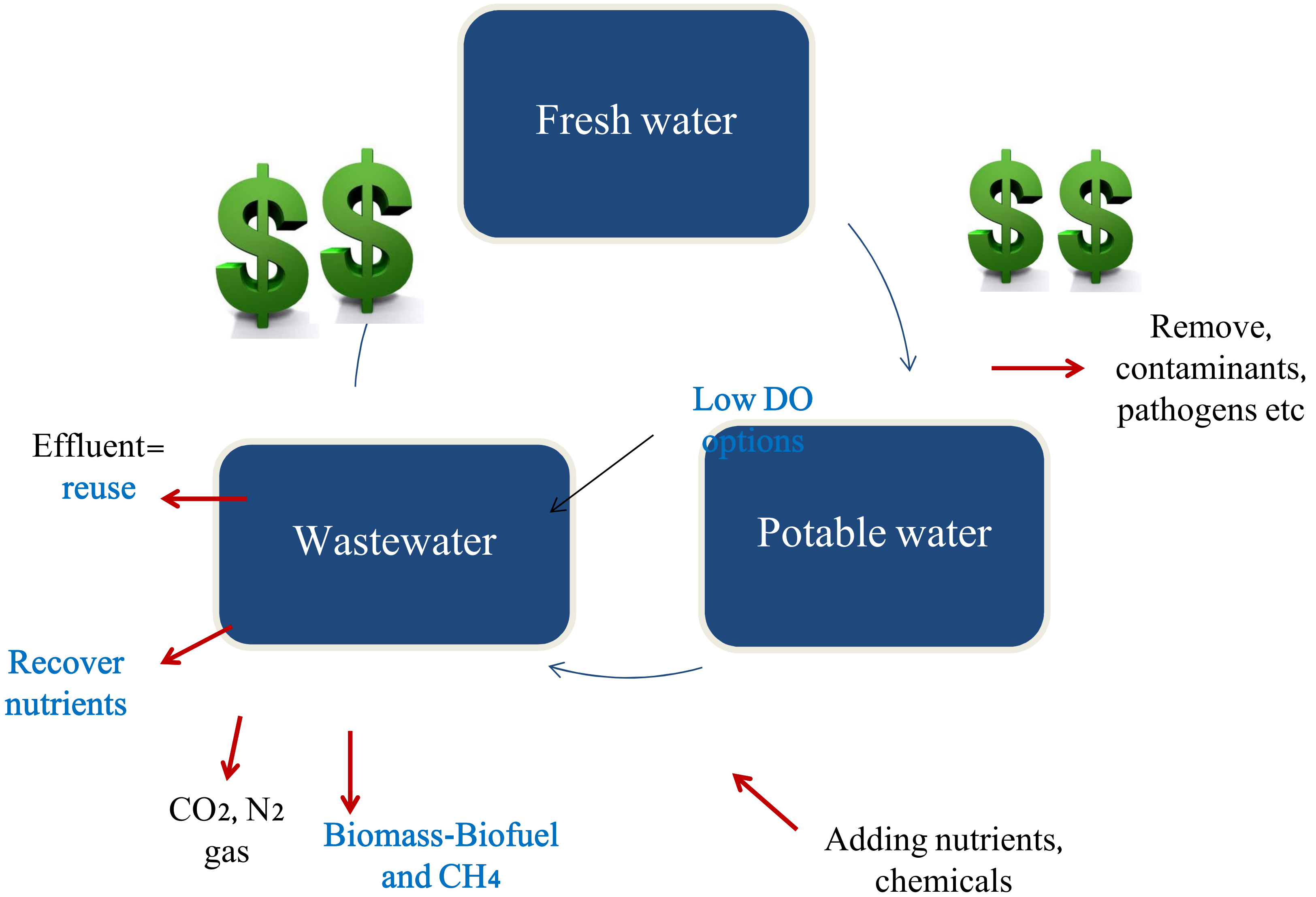
Running out of Energy

Stress on Receiving Water

P scarcity

- P reserves could become scarce
- P scarcity causes increased prizes to farmers
- P increase causes environmental stresses
- P pollution exacerbate public health problems
- Introduces sociopolitical tension because nearly 90 % of P supply is control by 5 countries.

From removal to Recovery and Reuse



Fresh water

Remove, contaminants, pathogens etc

Low DO options

Effluent= reuse

Wastewater

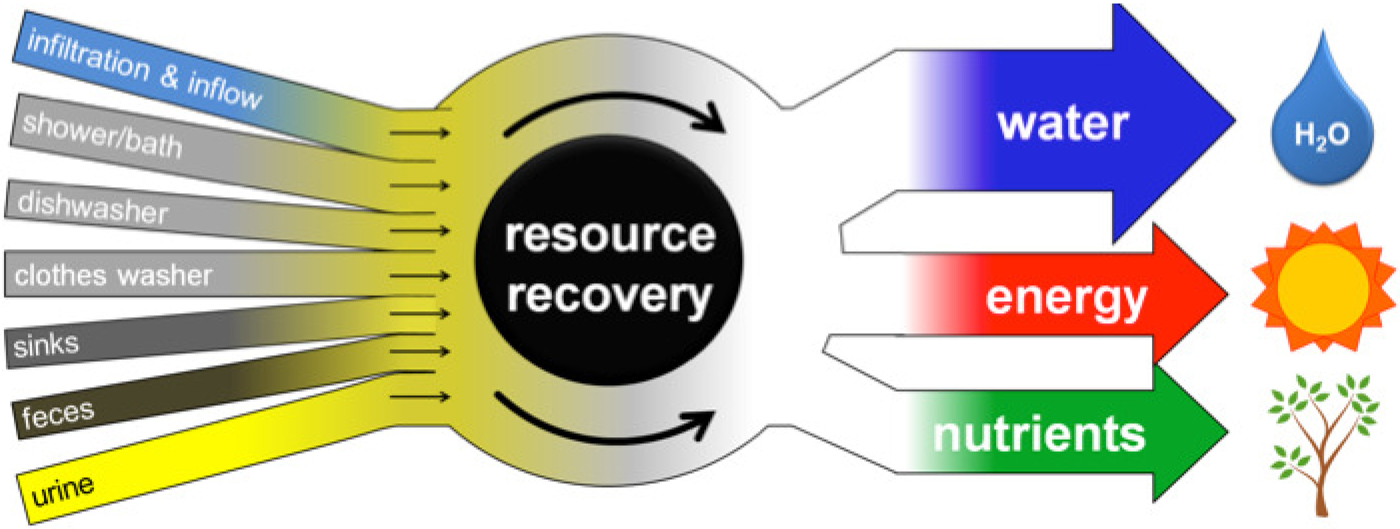
Potable water

Recover nutrients

CO_2, N_2 gas

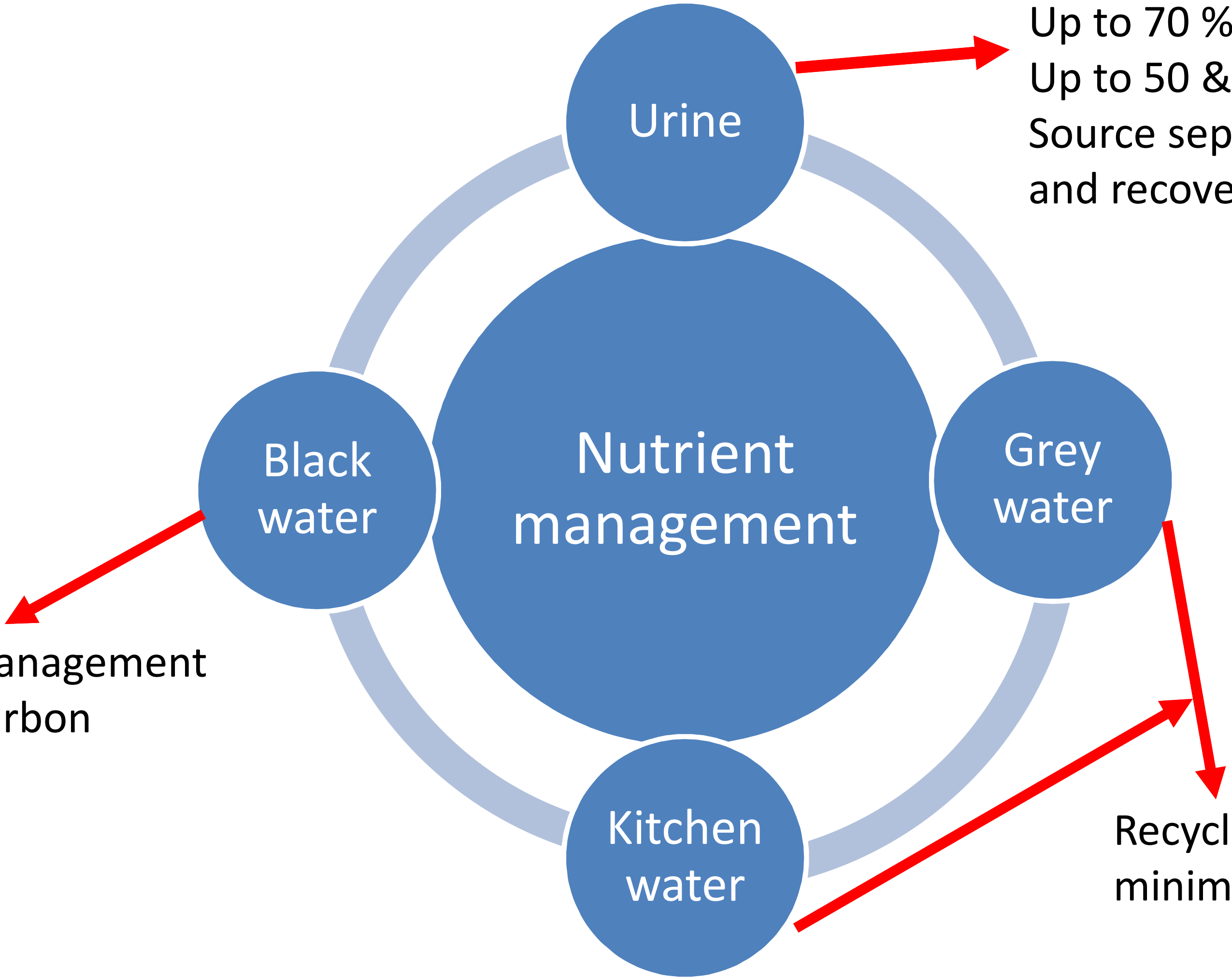
Biomass-Biofuel and CH_4

Adding nutrients, chemicals



- The increase in population and decrease in resources (i.e. freshwater, phosphorus, energy) requires reuse and recovery of current resources.
- The current reliance on mined phosphate rock is economically, environmentally, and socially unsustainable
- China, Morocco, and USA account for 70% of the world’s phos-phate rock supply (INRA, 2014).
- Water Reuse can be achieved through better treatment.

Nutrient management-closer Look



Nutrient management

Urine

Up to 70 % N
Up to 50 & P
Source separate urine
and recover nutrients

Grey water

Recycle with
minimum treatment

Kitchen water

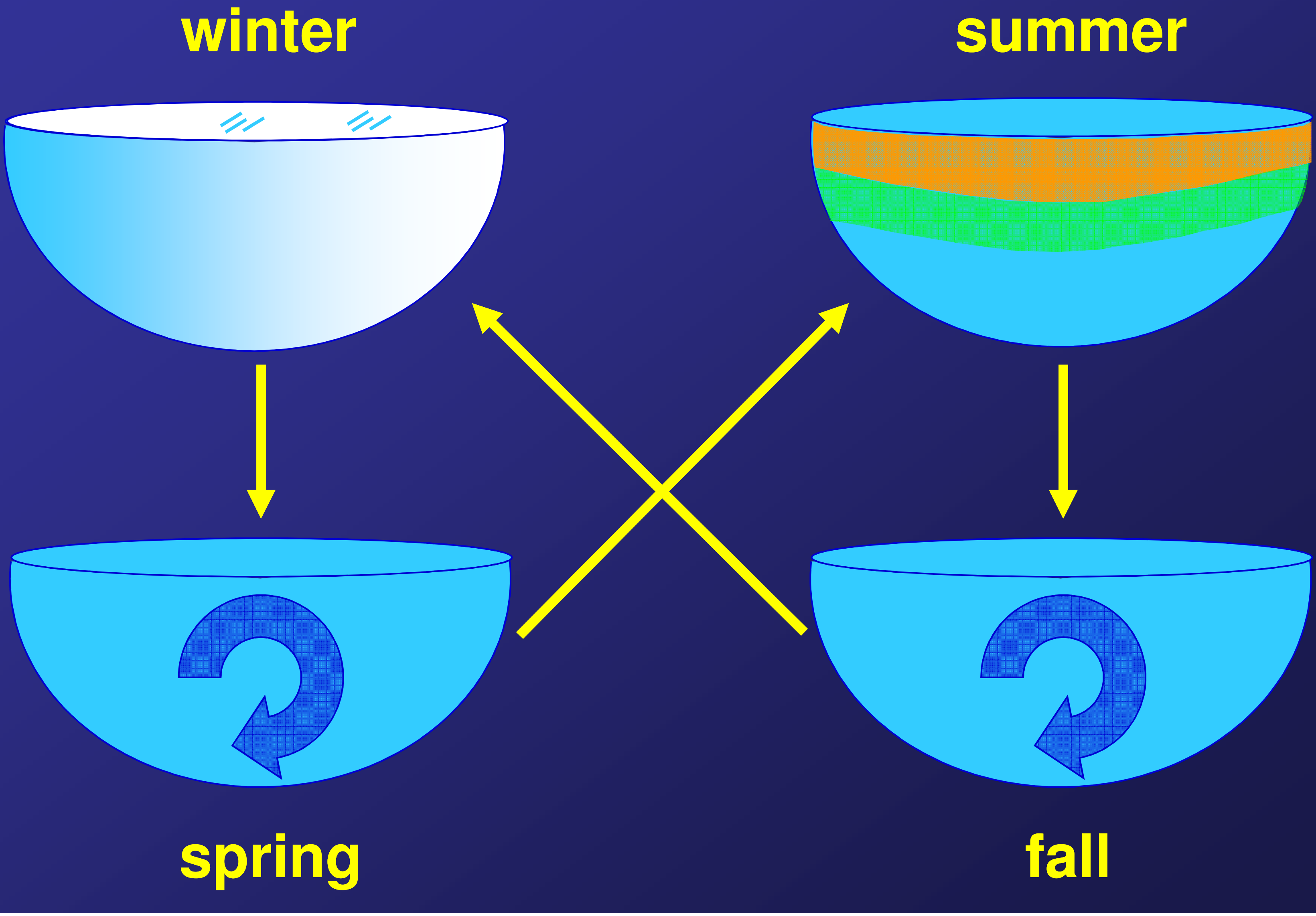
Black water

Carbon management
Smaller carbon
footprints

Decentralized treatment

QUESTIONS

Temporal variation: seasonal events



winter

summer

spring

fall