Bang for the Buck – Comparing Interventions For Conserving Phosphorus

AAEES Nutrient Recovery Workshop

NJWEA Annual Conference
Atlantic City, NJ

May 16, 2016

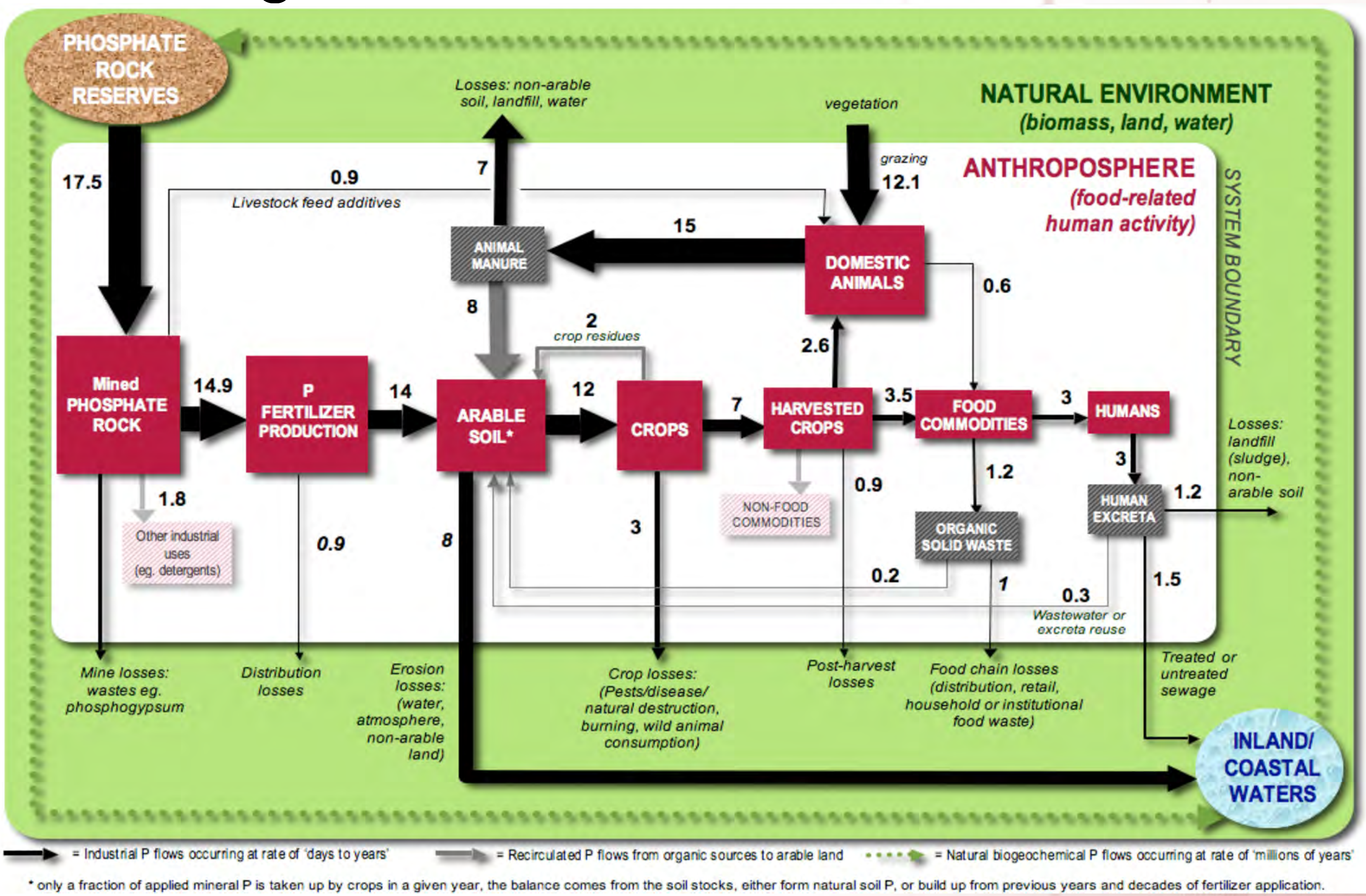
David A. Vaccari
dvaccari@stevens.edu

Outline

- **Substance Flow Analysis** (SFA or MFA)
- The **Dynamic** SFA (DSFA)
- The Substance Flow **Model** (SFM or MFM)
- An **Empirical** Substance Flow Model
  - Linear
  - Nonlinear (Multivariate Polynomial)
- A **Mechanistic** Substance Flow Model
  - Development
  - Sensitivity Analysis

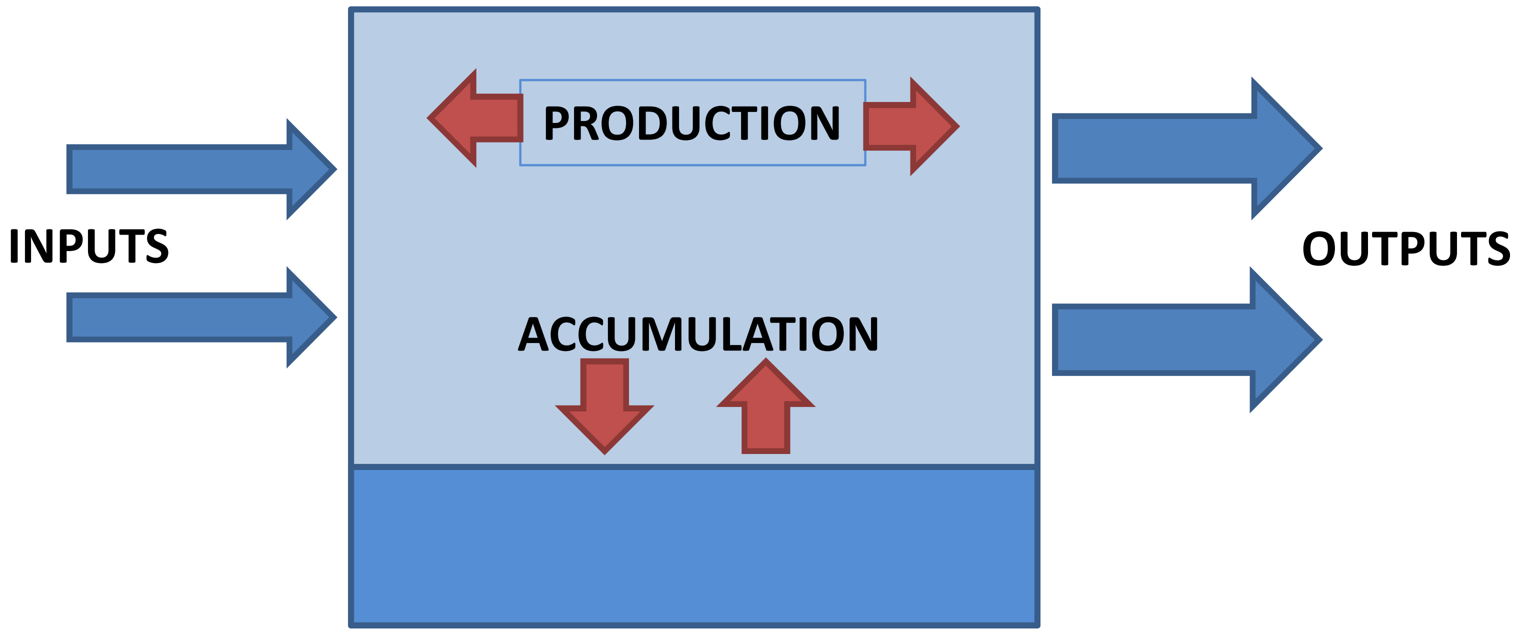
Global Substance Flow Analysis for P

Cordell, Drangert and White, 2009



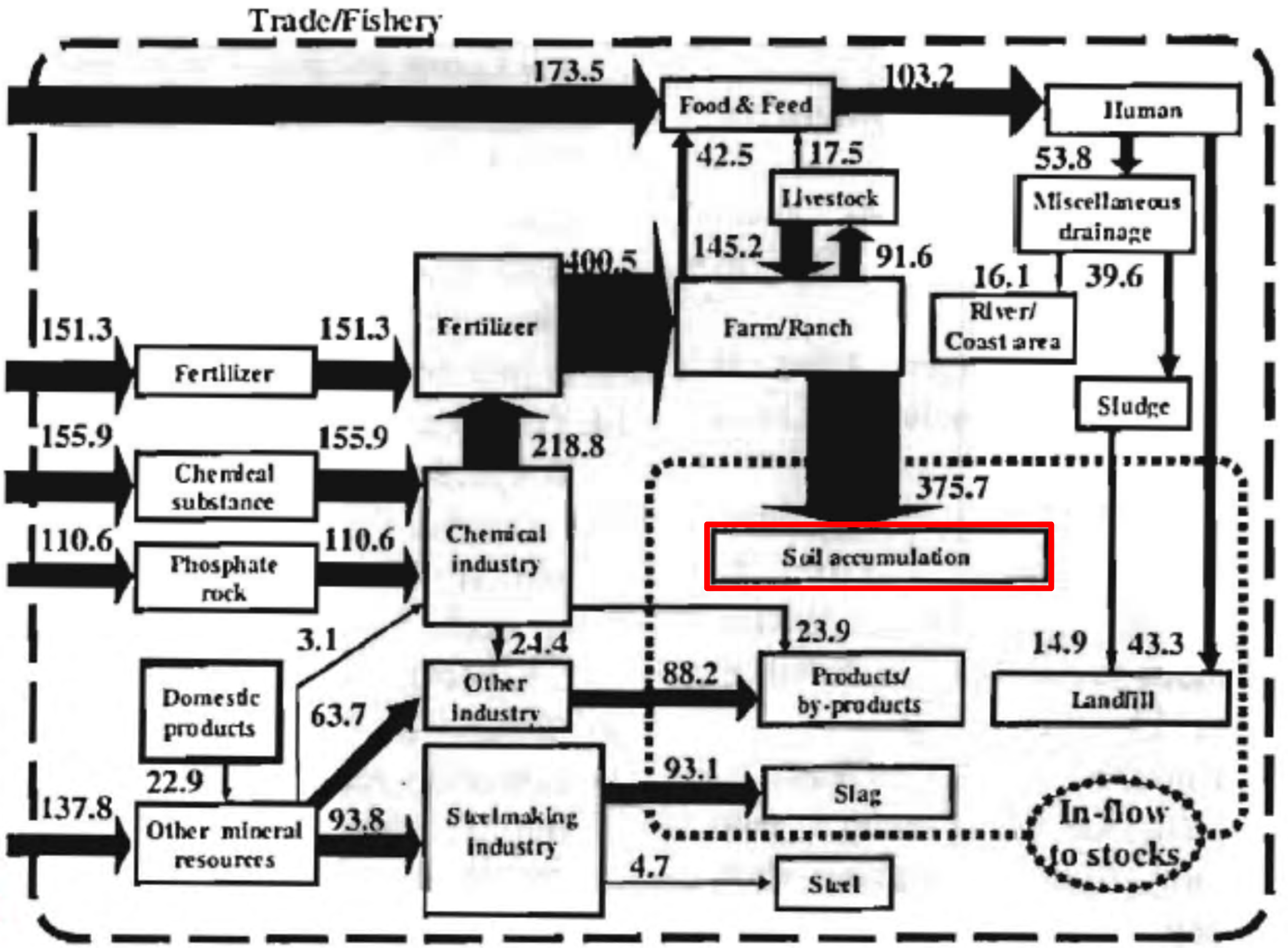
General Balance

$$ACCUMULATION = \sum INPUTS - \sum OUTPUTS + PRODUCTION$$

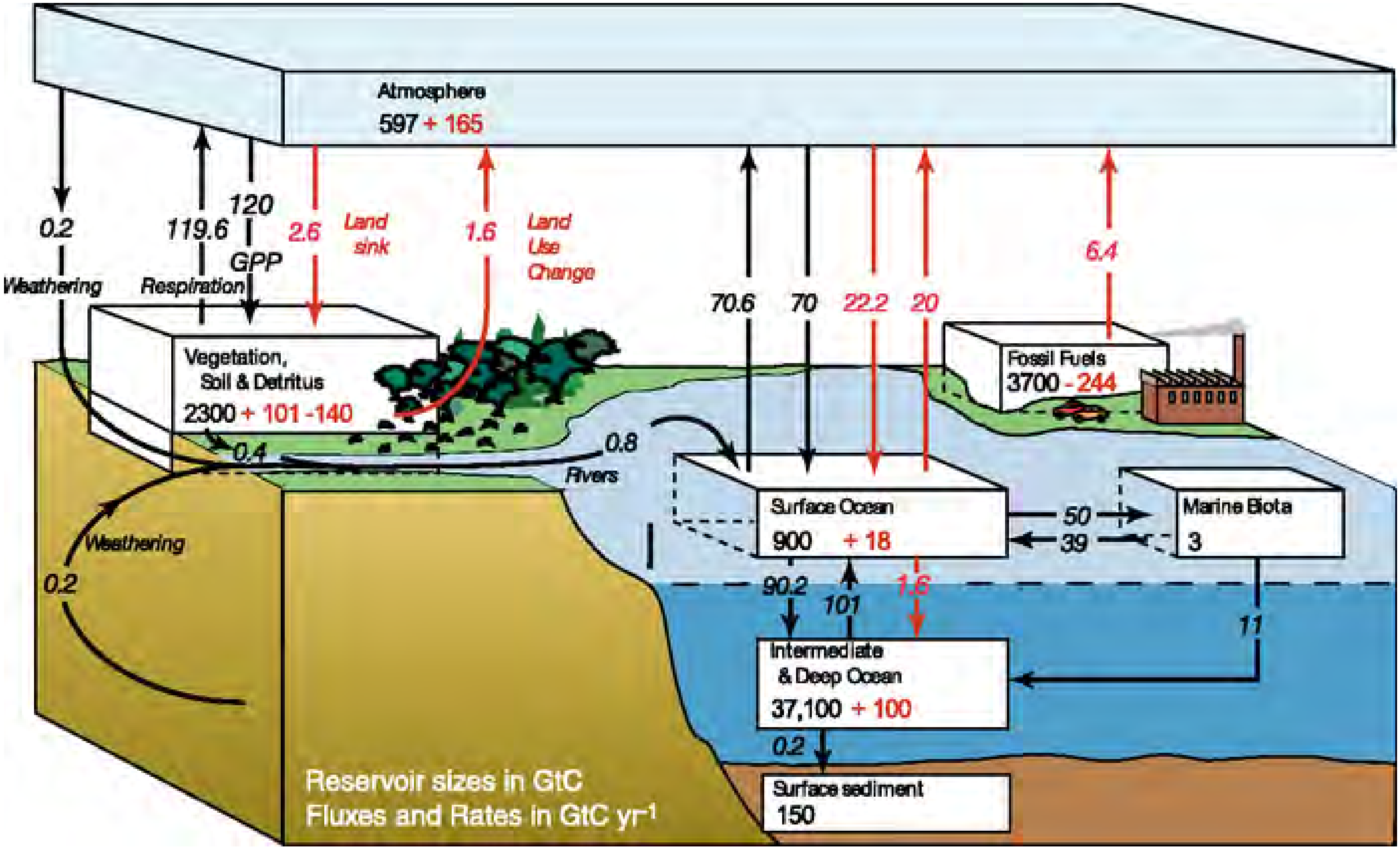


Phosphorus MFA for Japan

– all flows in Mt P/y (Kubo, et al, 2008)

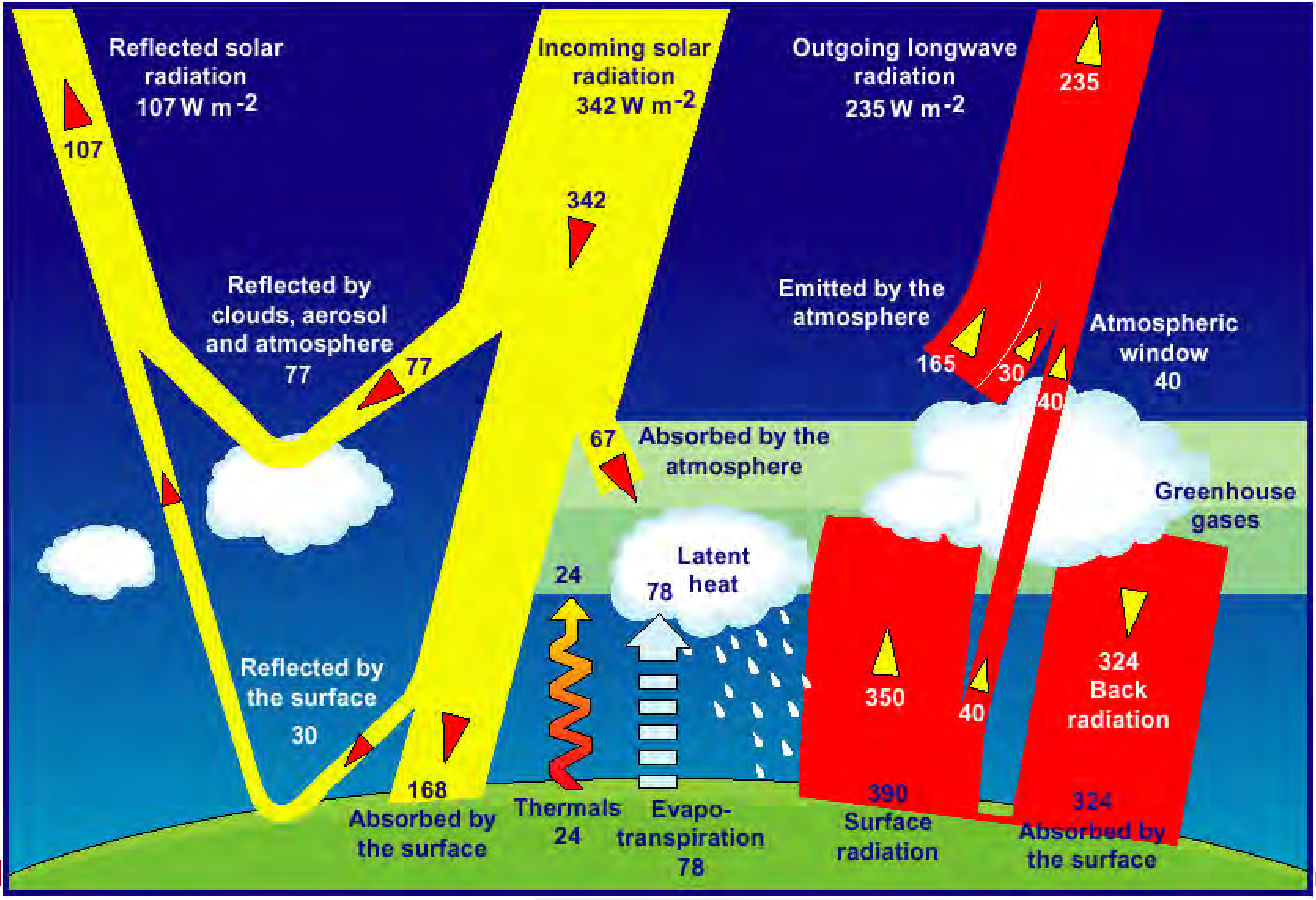


Global Carbon Cycle (Tg)

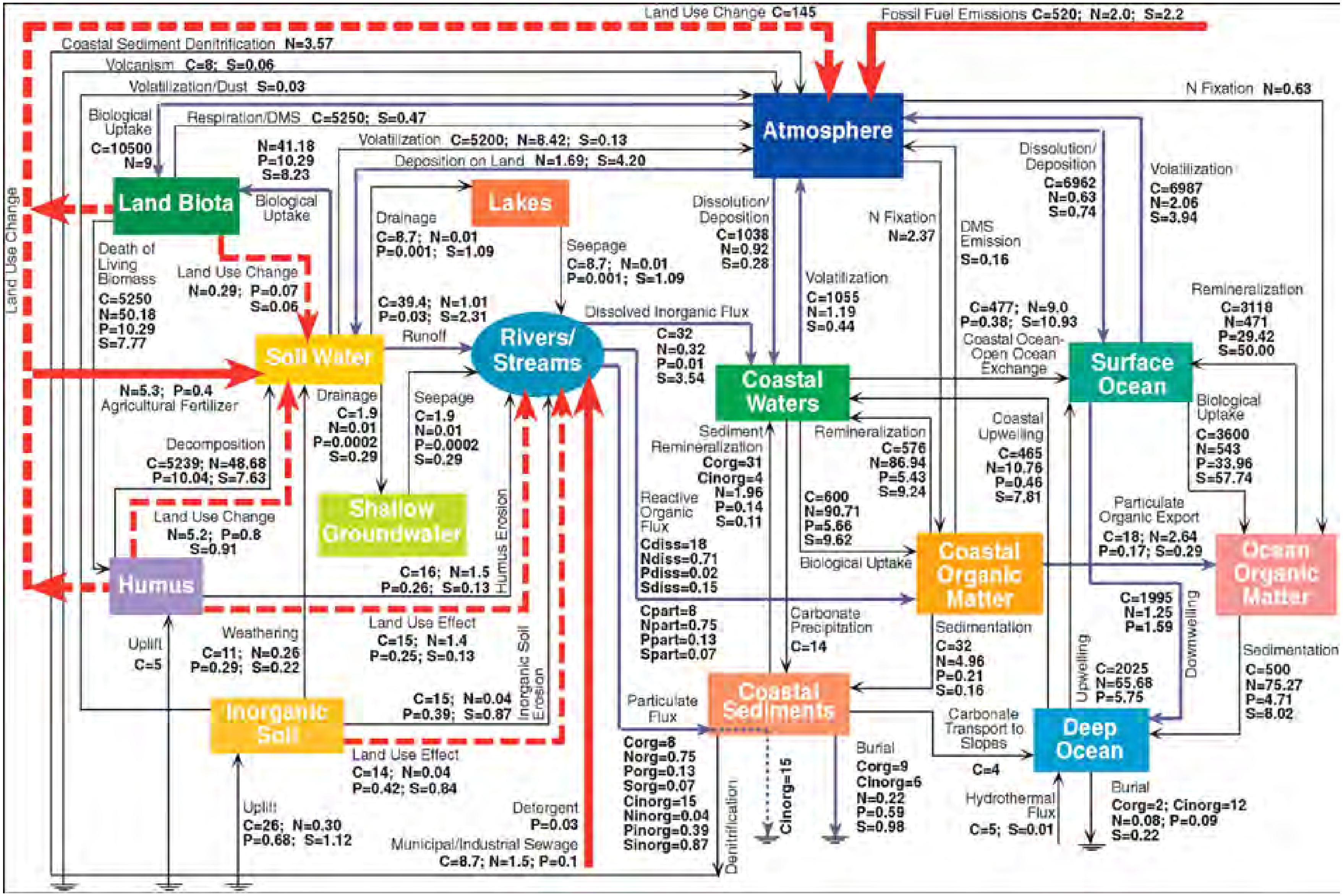


https://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-7-3.html

Atmospheric radiation balance

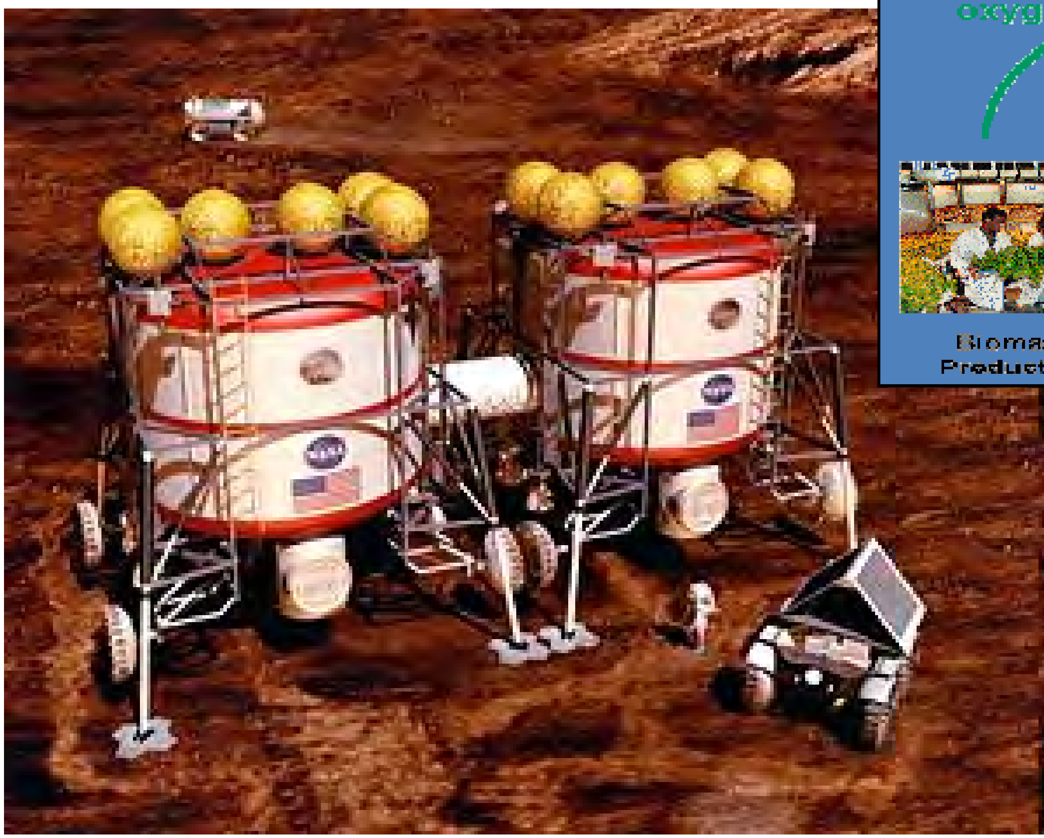


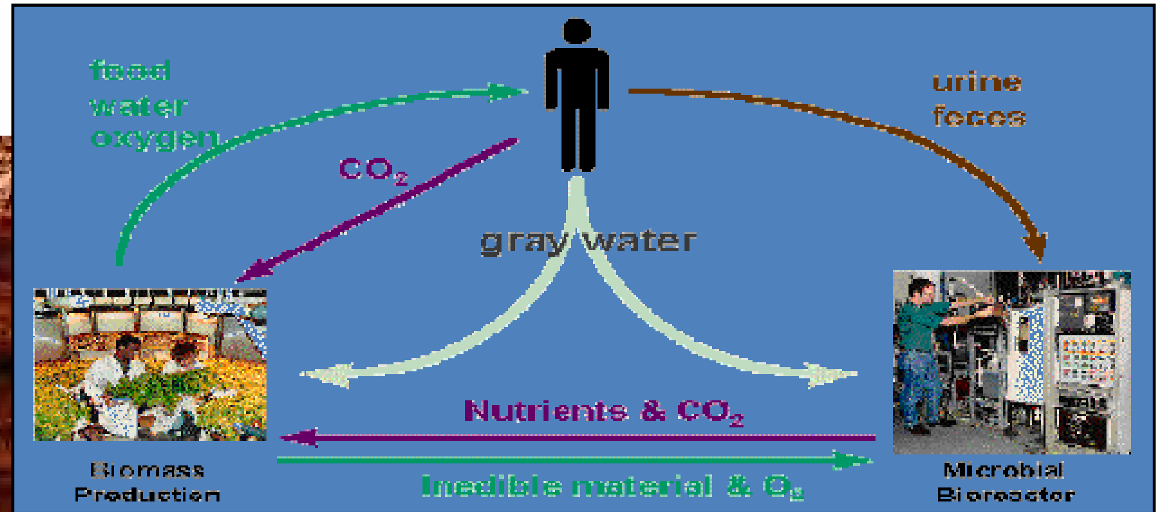
COUPLED MASS BALANCES: C-N-P-S, 13 Reservoirs: TOTEM (Terrestrial-Ocean-aTmosphere Ecosystem Model)



http://www.soest.hawaii.edu/oceanography/faculty/mackenzie/mackenzie_TOTEM.html

Cooking in Space – Advanced Life Support





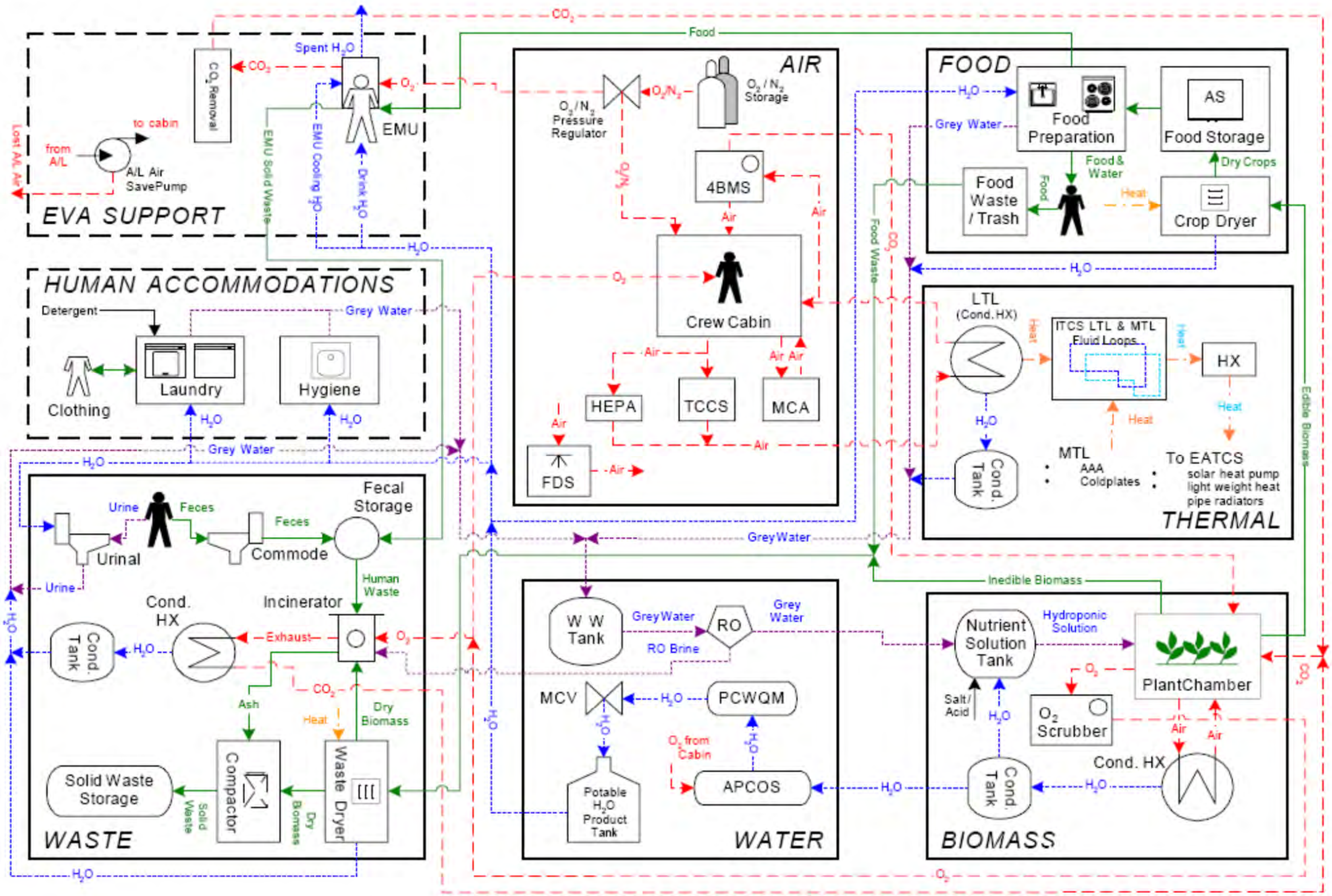


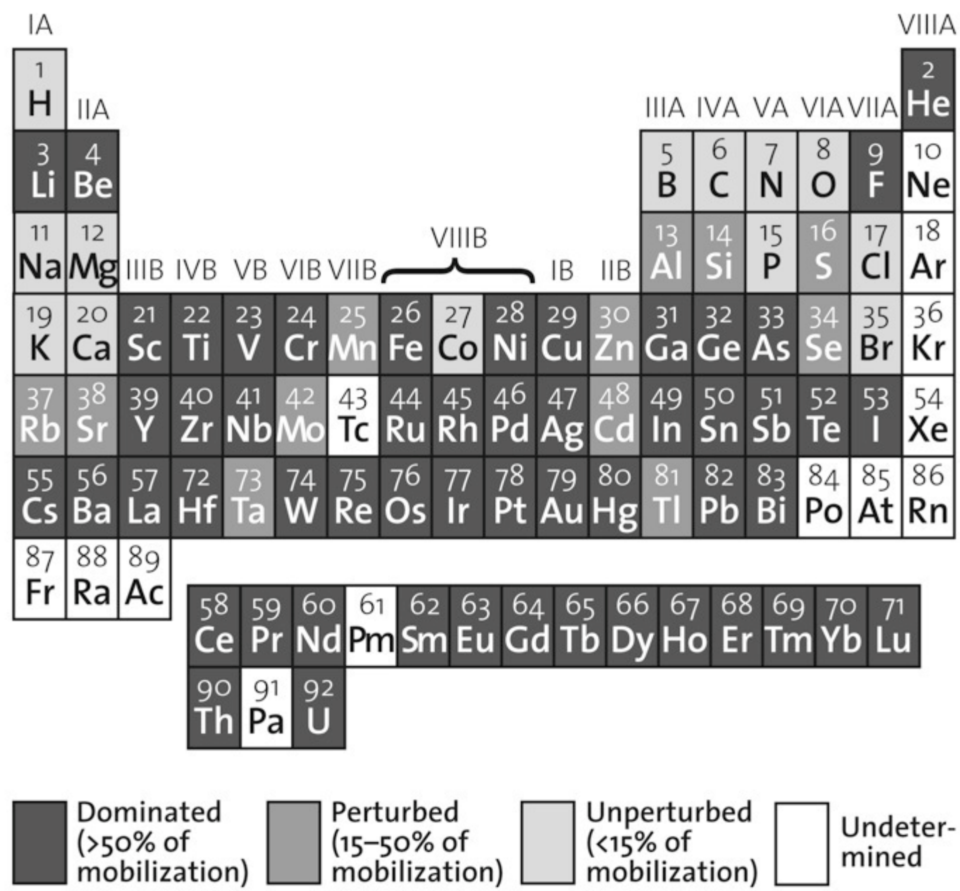
Figure 3.6 Life Support Concept for an **Evolved Mars Base** Using **ALS Technologies** (without ISRU)

Biosphere I

Human activities are dominating many biogeochemical cycles!

Dining at the periodic table
(Johnson et al. 2007:

For more than half of the elements human is responsible for more than 50% of the bio-geo-chemical cycle (the black ones)

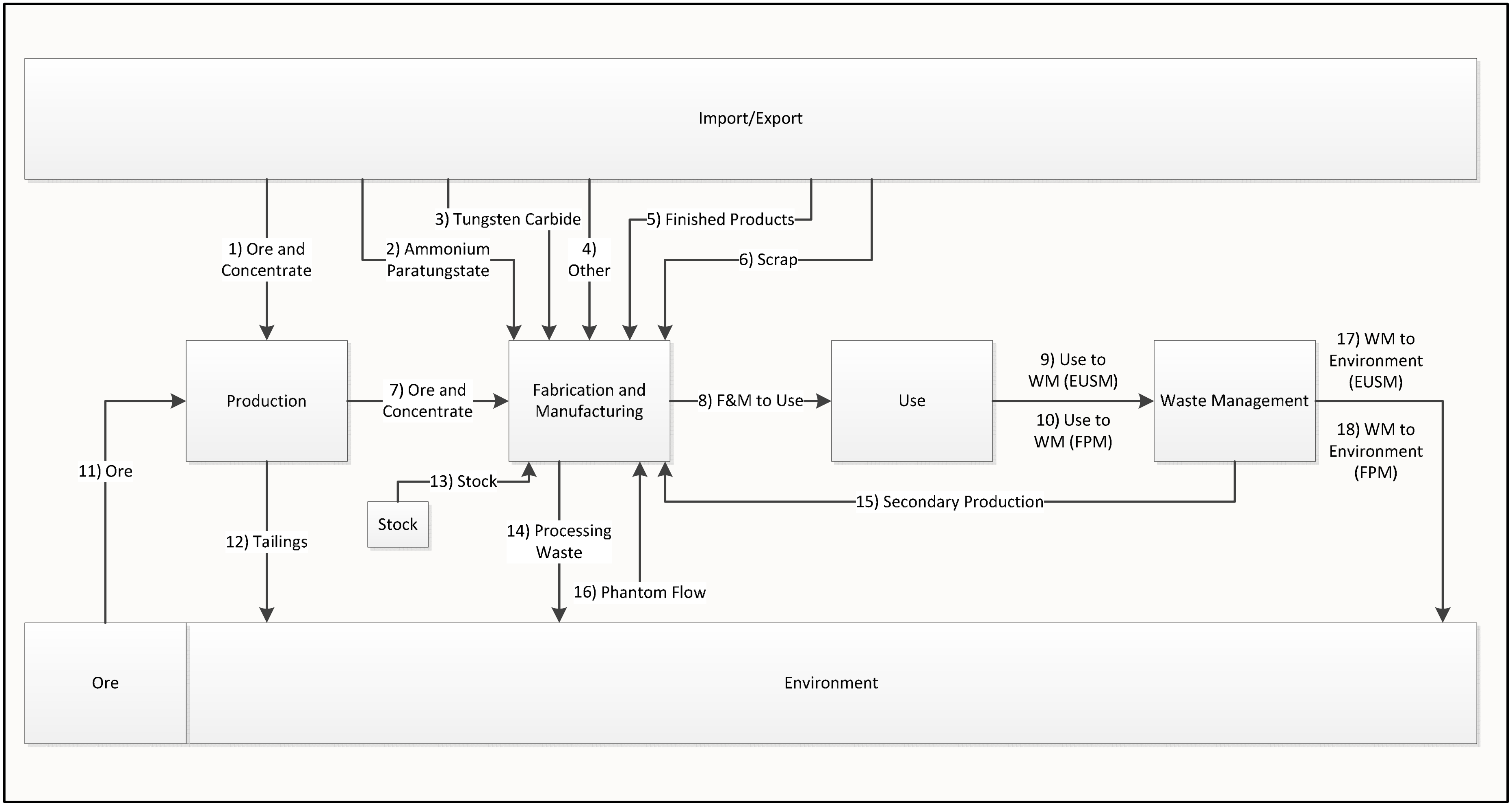


Source: AGS 2001 Goteborg, from Roland Scholtz

Elements that are essential to at least some living things (shaded)

Name	Sym	AN	Name	Sym	AN	Name	Sym	AN	Name	Sym	AN	Name	Sym	AN
Actinium	Ac	89	**Copper**	**Cu**	**29**	**Iron**	**Fe**	**26**	**Phosphorus**	**P**	**15**	Strontium	Sr	38
Aluminium	**Al**	**13**	Curium	Cm	96	Krypton	Kr	36	Platinum	Pt	78	**Sulfur**	**S**	**16**
Americium	Am	95	Darmstadtium	Ds	110	Lanthanum	La	57	Plutonium	Pu	94	Tantalum	Ta	73
Antimony	Sb	51	Dubnium	Db	105	Lawrencium	Lr	103	Polonium	Po	84	Technetium	Tc	43
Argon	Ar	18	Dysprosium	Dy	66	Lead	Pb	82	**Potassium**	**K**	**19**	Tellurium	Te	52
Arsenic	**As**	**33**	Einsteinium	Es	99	**Lithium**	**Li**	**3**	Praseodymium	Pr	59	Terbium	Tb	65
Astatine	At	85	Erbium	Er	68	Lutetium	Lu	71	Promethium	Pm	61	Thallium	Tl	81
Barium	Ba	56	Europium	Eu	63	**Magnesium**	**Mg**	**12**	Protactinium	Pa	91	Thorium	Th	90
Berkelium	Bk	97	Fermium	Fm	100	**Manganese**	**Mn**	**25**	Radium	Ra	88	Thulium	Tm	69
Beryllium	**Be**	**4**	**Fluorine**	**F**	**9**	Meitnerium	Mt	109	Radon	Rn	86	**Tin**	**Sn**	**50**
Bismuth	Bi	83	Francium	Fr	87	Mendelevium	Md	101	Rhenium	Re	75	**Titanium**	**Ti**	**22**
Bohrium	Bh	107	Gadolinium	Gd	64	Mercury	Hg	80	Rhodium	Rh	45	**Tungsten**	**W**	**74**
Boron	**B**	**5**	Gallium	Ga	31	**Molybdenum**	**Mo**	**42**	Roentgenium	Rg	111	Ununbium	Uub	112
Bromine	**Br**	**35**	**Germanium**	**Ge**	**32**	Neodymium	Nd	60	Rubidium	Rb	37	Ununhexium	Uuh	116
Cadmium	Cd	48	Gold	Au	79	Neon	Ne	10	Ruthenium	Ru	44	Ununoctium	Uuo	118
Cesium	Cs	55	Hafnium	Hf	72	Neptunium	Np	93	Rutherfordium	Rf	104	Ununquadium	Uuq	114
Calcium	**Ca**	**20**	Hassium	Hs	108	**Nickel**	**Ni**	**28**	Samarium	Sm	62	Uranium	U	92
Californium	Cf	98	Helium	He	2	Niobium	Nb	41	**Scandium**	**Sc**	**21**	**Vanadium**	**V**	**23**
Carbon	**C**	**6**	Holmium	Ho	67	**Nitrogen**	**N**	**7**	Seaborgium	Sg	106	Xenon	Xe	54
Cerium	Ce	58	**Hydrogen**	**H**	**1**	Nobelium	No	102	**Selenium**	**Se**	**34**	Ytterbium	Yb	70
Chlorine	**Cl**	**17**	Indium	In	49	Osmium	Os	76	**Silicon**	**Si**	**14**	Yttrium	Y	39
Chromium	**Cr**	**24**	**Iodine**	**I**	**53**	**Oxygen**	**O**	**8**	Silver	Ag	47	**Zinc**	**Zn**	**30**
Cobalt	**Co**	**27**	Iridium	Ir	77	Palladium	Pd	46	**Sodium**	**Na**	**11**	Zirconium	Zr	40

Material Flow of Tungsten in the U.S. – Harper (2007)



Tungsten flows (t/y) – Harper (2007)

Year	1	2	3	4	5	6	7	8	10	11	13	14	15	16	18	CPI	IPI
1975	2380	320	-290	290	-400	30	4590	5690	1780	2770	730	240	910	-260	1330	53.8	113.4
1976	1620	180	-490	850	-330	70	3990	7140	2280	2950	2800	300	890	-520	1700	56.9	129.3
1977	2560	100	-470	-380	-230	140	4980	7850	2510	3030	2260	320	1250	510	1850	60.6	137.1
1978	3300	130	-510	-180	-220	70	6090	9490	3190	3480	2620	390	1290	600	2270	65.2	145.1
1979	4270	200	-380	-670	-380	300	6950	9340	3490	3340	2280	390	1200	220	2350	72.6	152.0
1980	4240	200	-420	-810	-360	180	6670	9200	5750	3050	1760	380	1740	620	3710	82.4	147.0
1981	5250	470	-210	-1490	-200	840	8400	9700	6210	3950	830	400	800	660	3920	90.9	150.9
1982	3220	760	-190	-540	50	770	4630	5870	4200	1750	-750	230	1150	210	2440	96.5	138.6
1983	2860	760	-100	-900	140	480	3770	6370	4500	1130	260	250	1600	640	2680	99.6	147.6
1984	5680	1160	3	-1540	460	950	6720	10270	6540	1300	720	390	930	1260	4260	103.9	163.3
1985	4620	1280	-240	-2060	420	430	5490	8310	5000	1090	1160	320	1190	960	3330	107.6	128.0
1986	2490	1150	30	-1380	400	250	3220	7870	4740	910	2330	300	1260	910	3250	109.6	125.2
1987	4410	1120	110	-1210	430	740	4440	8080	4810	30	970	310	870	920	3380	113.6	129.8
1988	7870	460	-40	210	410	1310	7870	10990	6170	0	-760	420	950	1000	4440	118.3	137.2
1989	7690	250	-720	-420	180	1020	7690	10080	5770	0	320	400	920	1250	4110	124	136.0
1990	6280	110	-390	-680	70	910	6280	8190	6100	0	270	320	1050	900	4240	130.7	109.2
1991	7820	70	-420	2170	-90	2280	7820	11440	8220	0	-610	450	0	620	5730	136.2	107.1
1992	2440	-90	-330	790	-3	1430	2440	6810	5340	0	1660	270	1200	-30	3590	140.3	108.6
1993	1660	1010	-960	1940	400	1150	1660	7250	5680	0	-60	270	910	1480	3820	144.5	111.0
1994	2920	600	-1060	2170	610	1960	2920	8240	6350	0	270	310	120	970	4290	148.2	117.8
1995	4660	1050	-1180	2240	660	1830	4660	10380	8540	0	-240	390	560	1180	5880	152.4	122.0
1996	4170	1430	-890	2320	450	1610	4170	10930	9000	0	280	420	1060	910	6180	156.9	122.2
1997	4840	1980	-420	2020	520	1310	4840	12250	10000	0	460	470	1620	390	6880	160.5	122.6
1998	4740	1630	-300	1570	770	1130	4740	12600	10310	0	-500	470	2220	1810	7090	163	130.0
1999	2840	1820	90	1530	1000	1100	2840	13410	10890	0	1000	500	3880	640	7460	166.6	136.0
2000	2300	2220	30	1600	1040	660	2300	14890	11930	0	2130	550	4550	910	8220	172.2	145.7

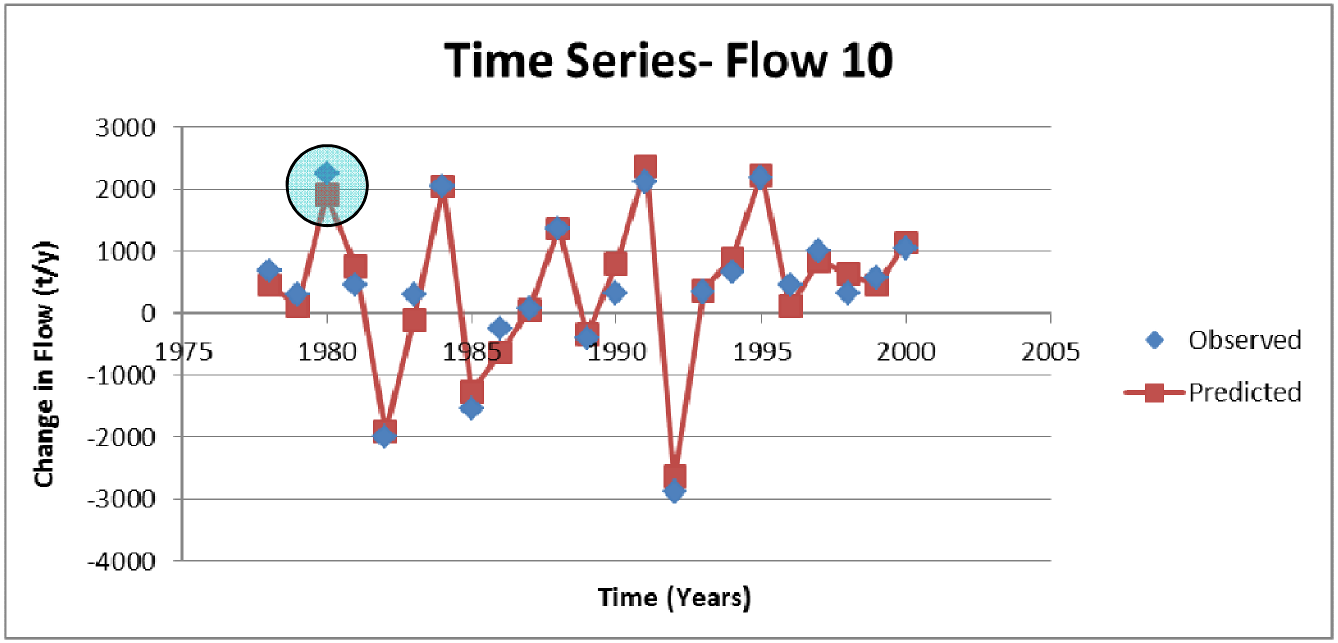
$$D_{i,k} = F_{i,k} - F_{i,k\text{-}1}$$

Example: MPX Model of #10 – Use to Waste Management

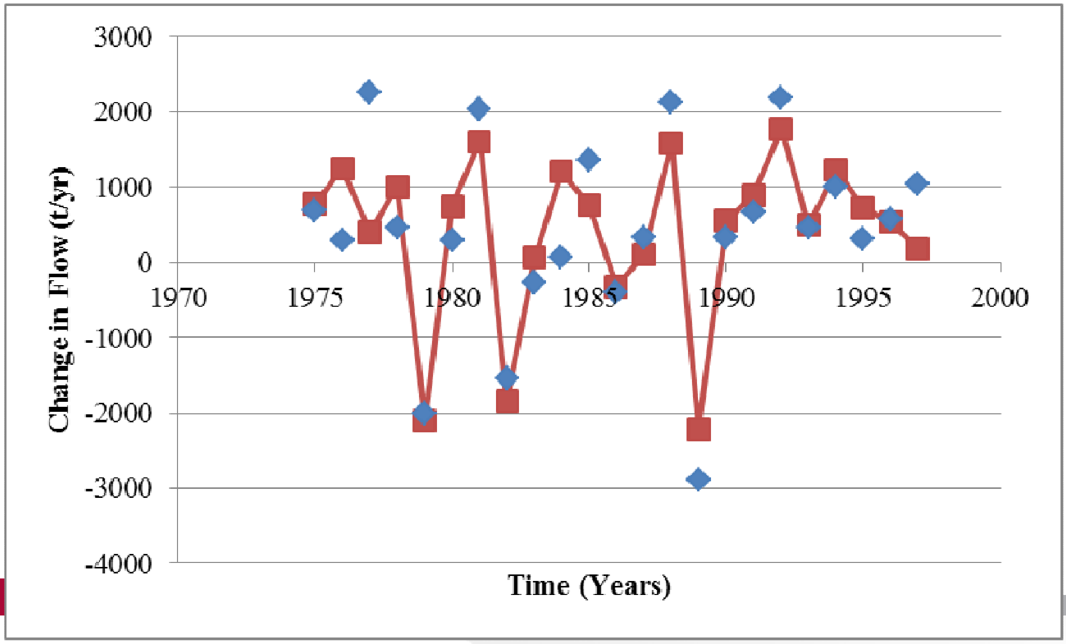
$$
\begin{aligned}
D_{10,0} = \\
-2.23 \cdot F_{11,1} \\
+2.28 \cdot 10^{-3} \cdot F_{3,3} \cdot F_{6,1} \\
-5.43 \cdot 10^{-3} \cdot F_{3,2} \cdot F_{11,3} \\
-2.33 \cdot 10^{-3} \cdot F_{3,3} \cdot F_{11,1} \\
+2.04 \cdot 10^{4} \cdot F_{2,1} \cdot F_{8,3}^{-1} \\
-444.8 \cdot F_{3,2} \cdot IPI_{3}^{-1} \\
-8.77 \cdot 10^{-7} \cdot F_{2,1} \cdot F_{6,1}^{2}
\end{aligned}
$$

Graphical Result for #10

MPX:



ML:

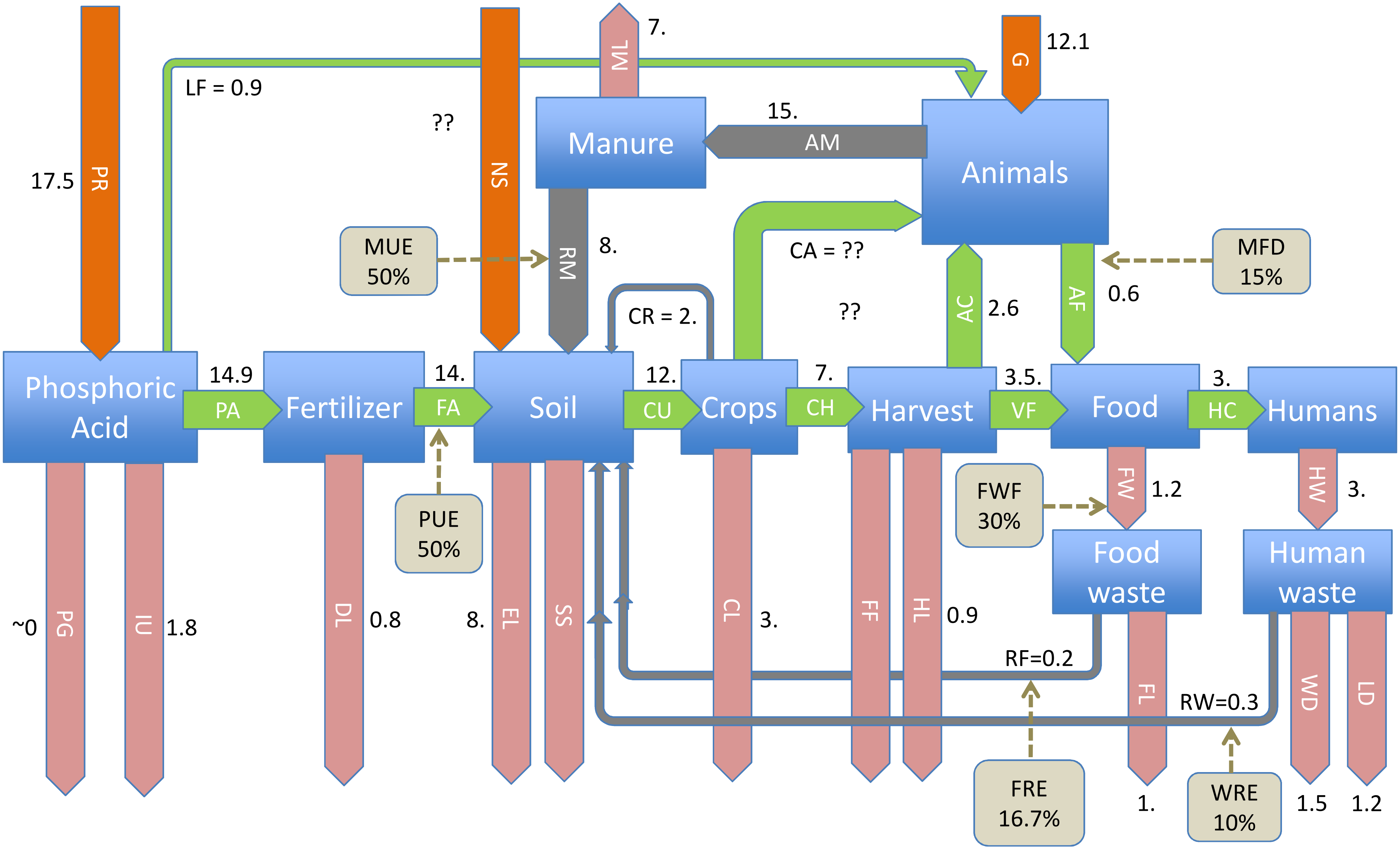


A Substance Flow Model for Global Phosphorus

- SFA (MFA) -- DSFA -- SFM -- DSFM
- Hypothetical/mechanistic SFM
- Based on Cordell, et al (2009, 2015)
- Goal: Determine sensitivity and interactions of global phosphate rock demand with various efficiency parameters, including:
  - MFD – Meat Fraction in the diet
  - PUE – Agricultural Phosphorus Use Efficiency
  - MUE – Manure Use Efficiency
  - FWF – Food Waste Fraction
  - FRE – Food Waste Recycling Efficiency
  - WRE – Human Waste Recycling Efficiency

Conceptual Model of Global Phosphorus Flows

(based on Cordell, et al, 2009)



Modeling Assumptions

- Major changes to Cordell et al: Natural source of P to soil
- Minor changes to Cordell et al scheme (e.g. beneficiation)
- **Grazing input is constant and does not use fertilizer**
- Nominal use and recycling efficiencies similar to Cordell et al
- **Basis: Fixed human consumption (1.25 grams/person/day)**
- Various flows in fixed ratios:

LD/HC,	WD/HC,	AF/(animal inputs),	LF/AC,
HL/(AC+VF),	CL/CU,	CR/CU,	FA/PA

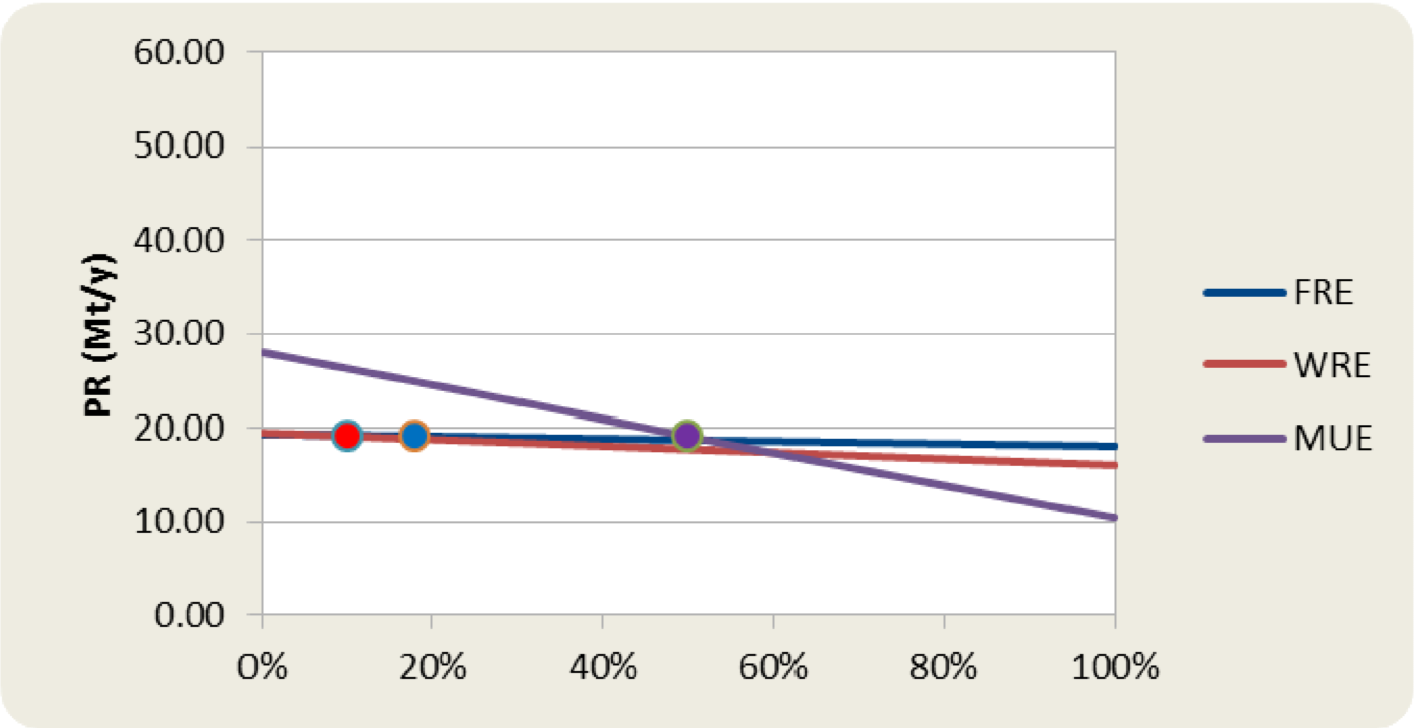
Spreadsheet Implementation of Model

A SUBSTANCE FLOW MODEL FOR GLOBAL PHOSPI		Version:	2.0		David A. Vaccari - Stevens Institute of Technology		
	Key efficiency factors:	**Model**	**Nominal**			**Fixed parameters**	**Model**
WRE	Human Waste Recycling Efficiency	10.0%	10%		b_LD	Landfill disposal ratio = LD/(HC-RW)	45%
FWF	Food Waste Fraction	27.0%	27%		b_WD	Waste discharge ratio = WD/(HC-RW)	55%
FRE	Food Waste Recycling Efficiency	18.0%	18.0%		Ym	Meat yield = AF/(AC+LF+G +CA)	3.8%
MFD	Meat Fraction in the diet (as P)	15.0%	15.00%		b_CA	Fert grazing ratio = CA/AC	0.25
MUE	Animal Manure Use Efficiency	50.0%	50%		b_LF	Feed additive ratio = LF/AC	0.35
PUE	Ag Phosphorus Use Efficiency	30.0%	30%		b_HL	Harvest loss ratio = HL/(VF+AC)	14.8%
	System Inputs:				b_CL	Crop loss ratio = CL/CU	25.0%
Gmax	Grazing maximum available (Mt/yr)	12.10	12.0		b_CR	Crop residue ratio = CR/CU	16.7%
IU	Fraction of PR to industrial uses (Mt/yr)	1.8	1.8		b_EL	Erosion loss ratio = EL/CU	50.0%
NS	Natural source of P to cropland (Mt/yr)	3.00	3.0		b-HR	Harvest ratio = CH/CU	65.0%
NP	Population (billion)	6.45	6.7		b_FF	Fuel and fiber ratio = FF/NP (Mt/yr/Gp)	0.16
PPC	Avg per-capita dietary P demand (g/cap/d)	1.25	% of PR:	17%	b-FPE	Fertilizer production efficiency = FA/PA	94.0%
Conv	Conversion factor (Mt/yr) / (g/cap/d):	2.36			b-PG	Fraction of PR to phosphogypsum	5.0%
		Mt/yr	**kg/cap/yr**	**g/cap/d**			**Mt/yr**
PR	**BENEFICIATED PHOSPHATE ROCK**	**17.11**	**2.65**	**7.3**			
	HUMANS AND WASTE					**HARVEST**	
HW	Excreta	2.94			AC	To animal feed	2.28
LD	Landfill	1.19			FF	Fuel and Fiber	1.00
WD	Surface water discharge	1.46			HL	To post-harvest losses	0.84
RW	Wastewater or excreta reuse (to ag soils)	0.29					
						CROPS	
	FOOD OUTPUTS				CL	Crop losses	3.12
HC	**P IN DIET (=HW)**	**2.94**	**0.46**	**1.25**	CR	Crop residues (recycled to soil)	1.26
FW	Food waste	1.09			CA	Fertilizer to pasture	0.57
FL	Food chain losses (food waste, distr. Etc.)	0.89			CH	Crop Harvest	**7.55**
RF	Organic solid waste input (from food)	0.20					
						ARABLE SOIL	
	FOOD SUPPLY				RI	Recycle inputs (CR+RM+RF+RW)	9.31
FS	Total food supply (before waste)	**4.03**			EL	Soil erosion losses	6.25
AF	Animal-based food supply (total)	0.61			SS	Soil storage	6.41
AFG	AF from natural G source only	0.47			CU	Crop uptake	**12.50**
VF	Vegetal-based food supply	3.43					
						FERTILIZER	
	DOMESTIC ANIMALS				FA	Fertilizer Applied to Soil	**12.84**
AI	Total animal P inputs (AC+LF+CA+G)	15.73			DL	Distribution losses	0.83
G	Grazing input utilized	12.10					
FI	Fertilized input to animals (AC+CA+LF)	3.63				**PHOSPHORIC ACID manufacturing**	
LF	Livestock feed additives	0.79			PG	Loss to phosphogypsum	0.68
	Straw recycled as Fodder				PA	Phosphoric Acid to Fertilizer	**13.67**
AM	**ANIMAL MANURE**	**15.13**			IU	Industrial uses	1.8
ML	Losses	7.56					
RM	Applied to soil	7.56			PR	**BENEFICIATED PHOSPHATE ROCK**	**17.11**

Definitions of Use and Recycling Efficiency Factors

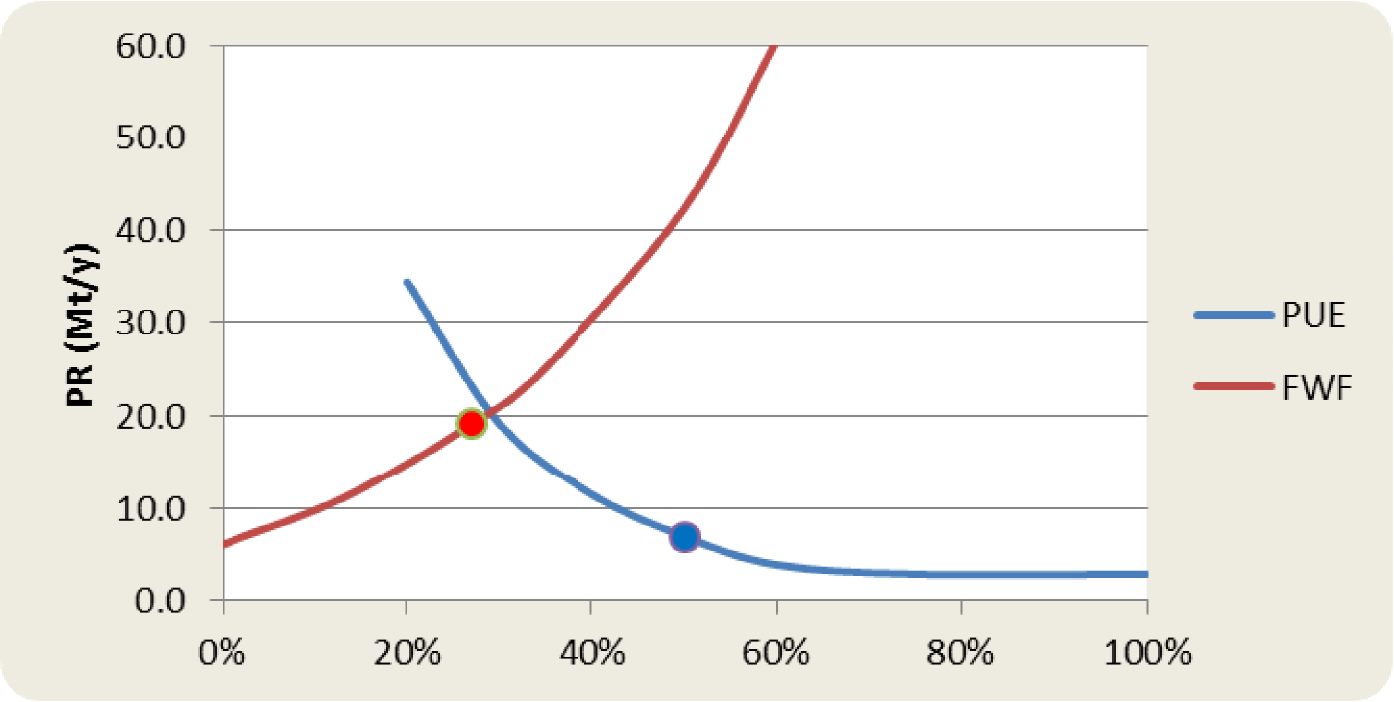
• Meat Fraction in the diet :	MFD = AF/(AF+VF)	= 15%
• Ag Phosphorus Use Efficiency:	PUE = CH/(All Crop Inputs)	= 30%
• Manure Use Efficiency:	MUE = RM/AM	= 50%
• Food Waste Fraction :	FWF = FW/(AF+VF)	= 27%
• Food Waste Recycling Efficiency:	FRE = RF/FW	= 18%
• Human Waste Recycling Efficiency:	WRE = RW/HC	= 10%

Effects of Manure Recycling, Food Waste, and Human Waste Recycling



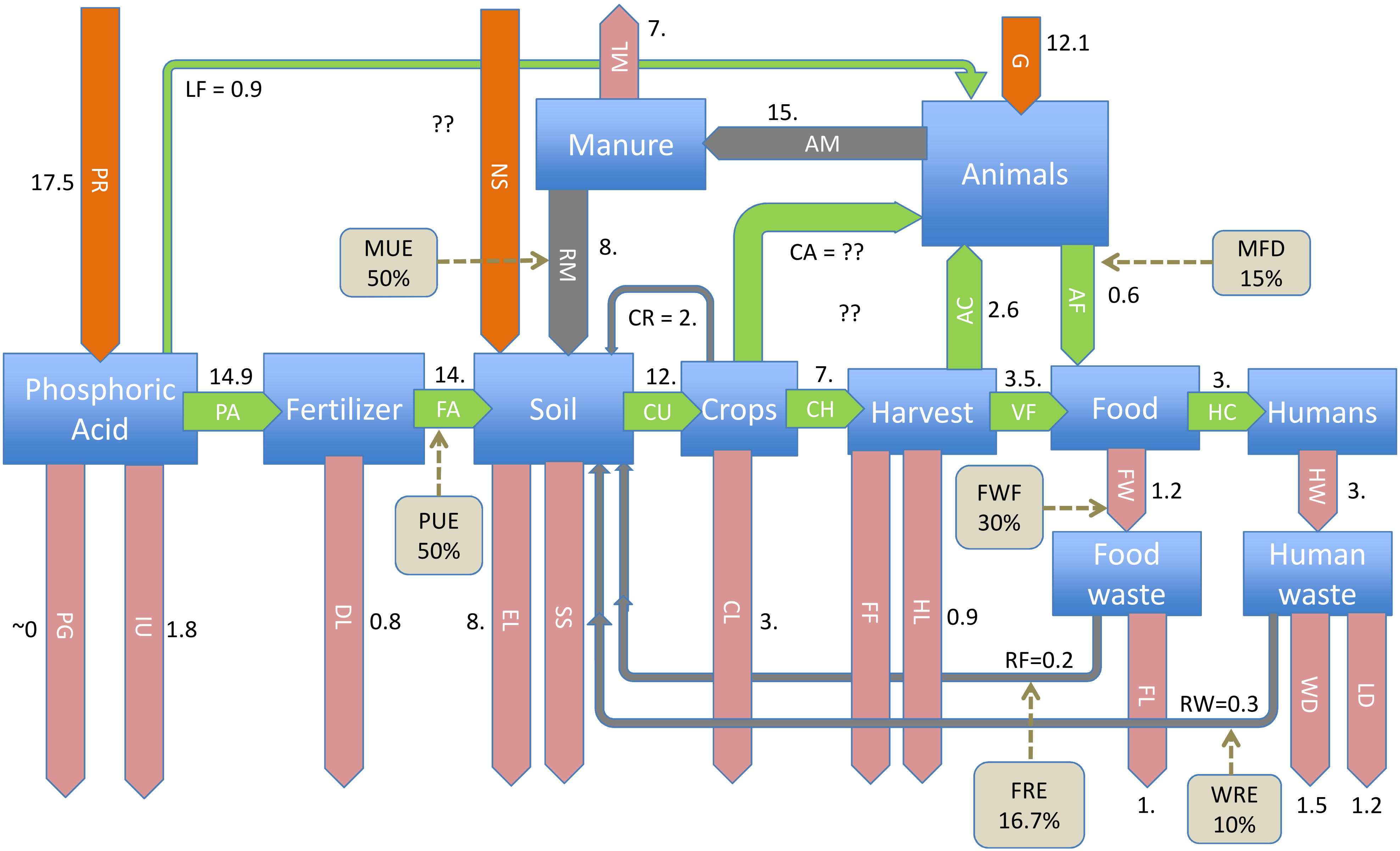
Nominal sensitivity	
MUE	-0.176
WRE	-0.034
FRE	-0.013

Effects Ag P Use Efficiency and Fraction of Food Wasted

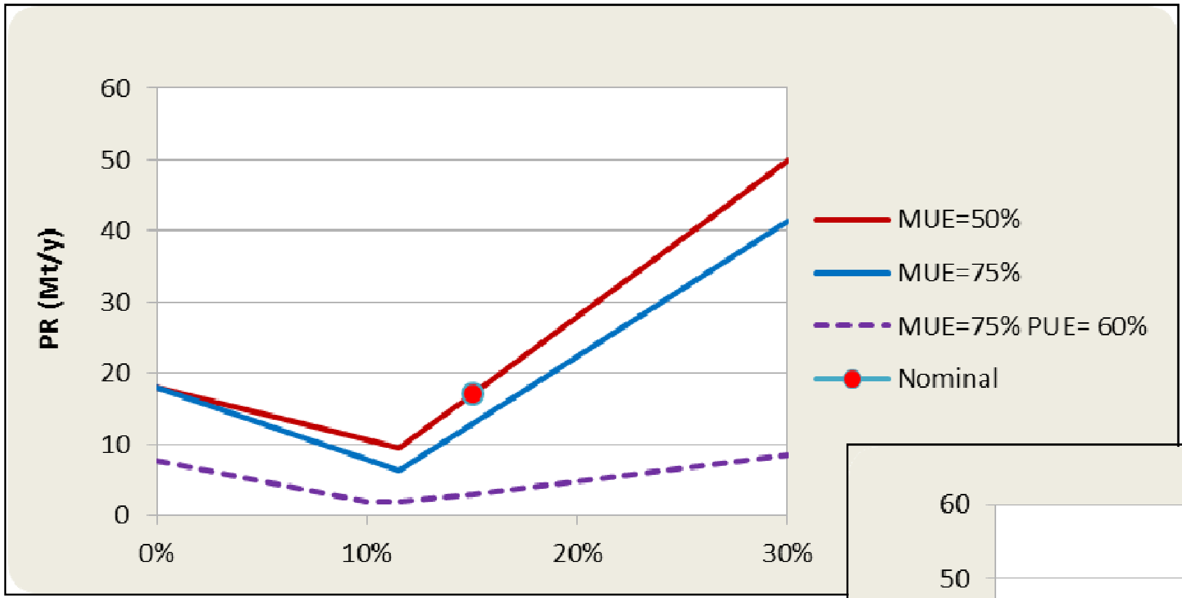


Nominal sensitivity	
FWF	0.65
PUE	-0.38

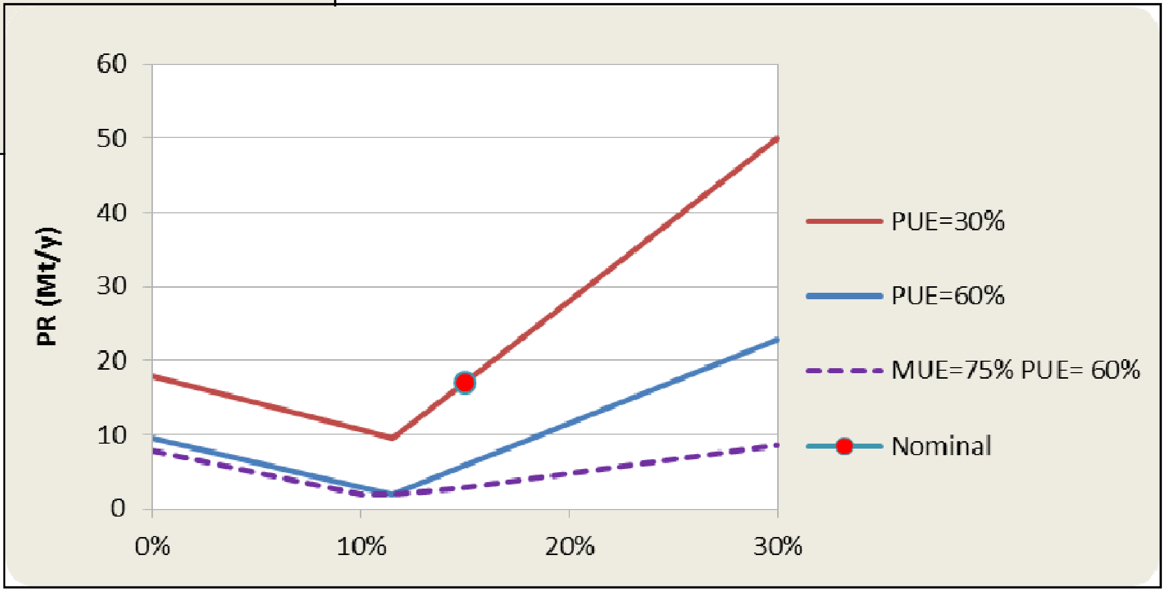
Conceptual Model of Global Phosphorus Flows
(based on Cordell, et al, 2009)



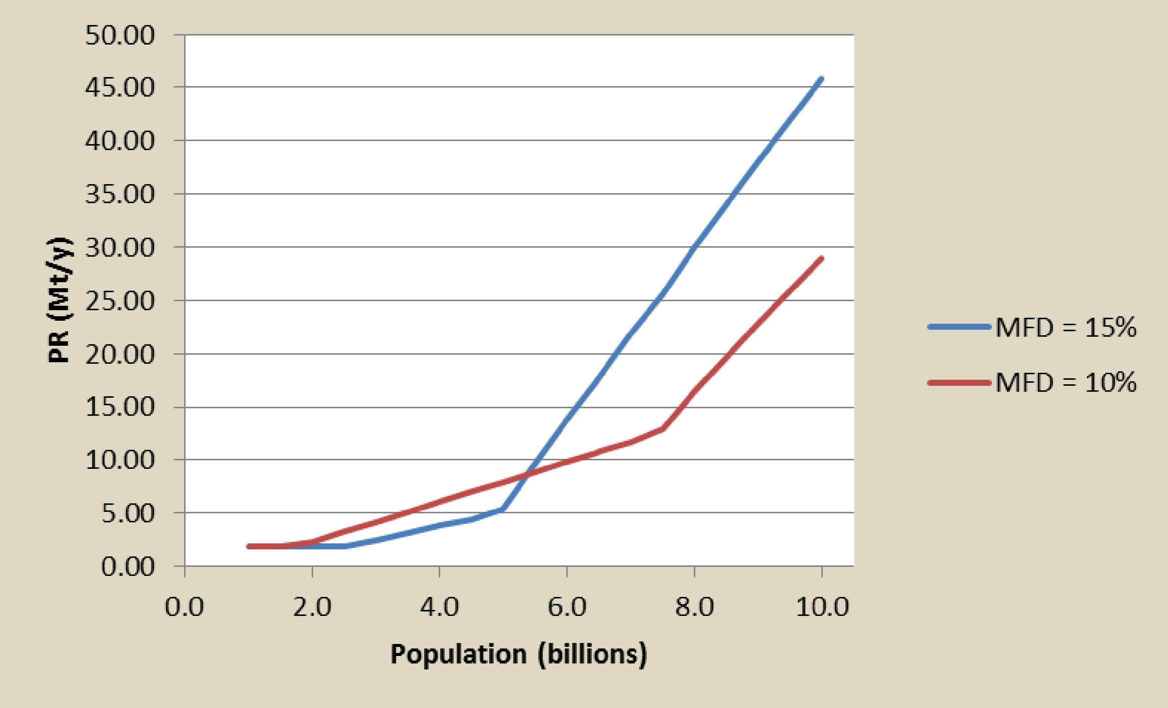
Effects of Meat Fraction in Diet Interacting with MUE and PUE



Nominal sensitivity	
MFD	2.19
FWF	0.65
PUE	-0.38
MUE	-0.176
WRE	-0.034
FRE	-0.013



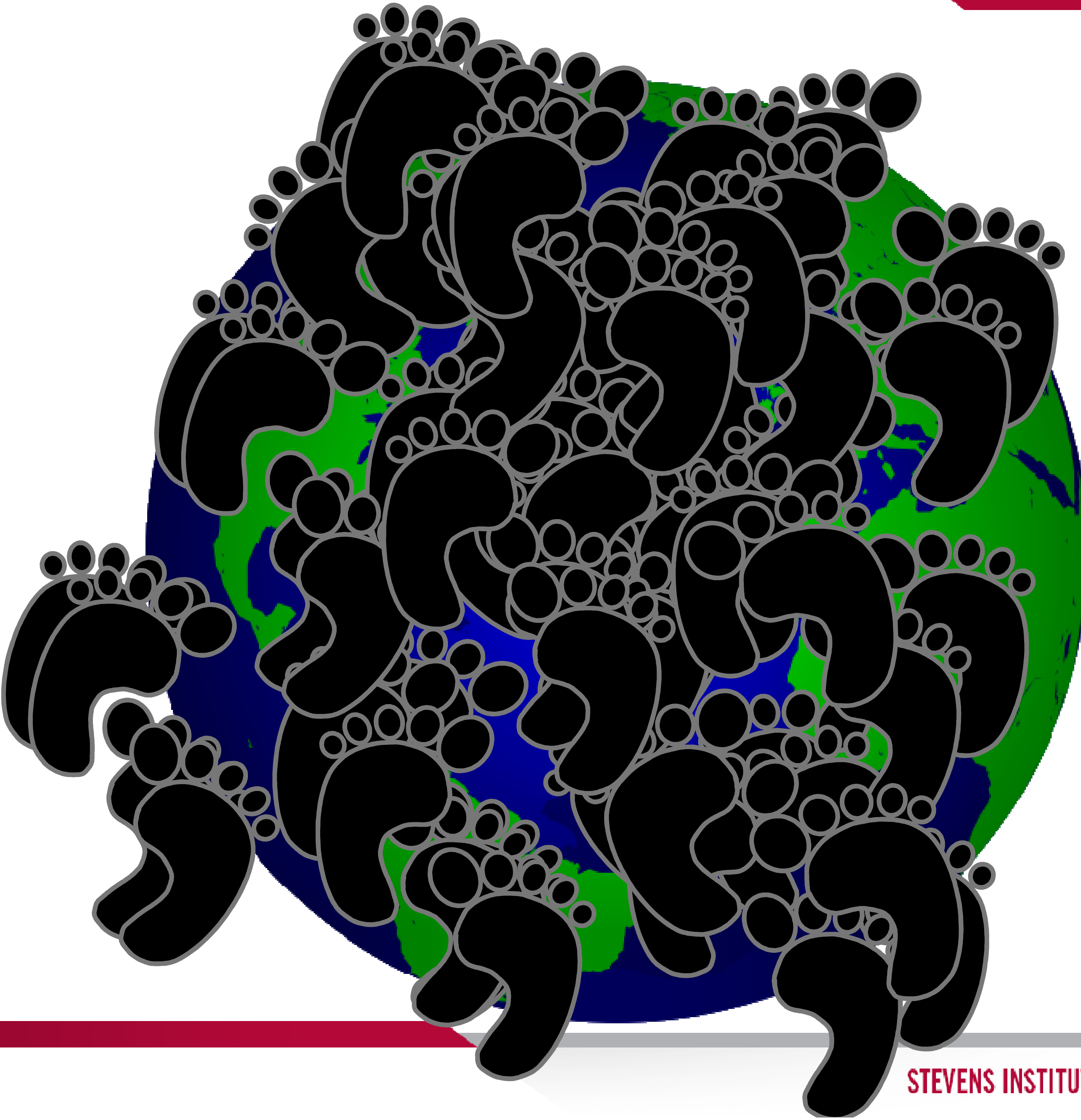
Effect of Population Interacting with % meat in diet



Pop (B)	MFD	Sensitivity
	10%	15%
4.0	1.88	1.32
6.0	1.88	8.09
8.0	6.40	8.09

Conclusions

- The sensitivity is MFD > FWF > PUE > MUE > WRE > FRE
- MFD interacts significantly with MUE and PUE, but retains its high sensitivity
- Meat in the diet has a non-zero optimum due to grazing input
- PUE and FWF exhibit diminishing returns
- Food waste fraction is much more significant than food waste recycling
- Population is significantly affected by MFD
- Sensitivity must be interpreted in terms of costs of implementation
- **Substance Flow Modeling is a viable planning tool for resource sustainability**



Thank you, and Save the P!

David A. Vaccari

dvaccari@stevens.edu

Department of Civil, Environmental and Ocean Engineering