Michigan Agri Business Association
Soil Fertility Workshop
St. Johns, Michigan
19 March 2015

IPNI
INTERNATIONAL PLANT NUTRITION INSTITUTE

Soil Properties and Reactions

Tom Bruulsema, Director, Northeast Region, IPNI

Twitter

Formed in 2007, the **International Plant Nutrition Institute** is supported by leading fertilizer manufacturers.

Its mission is to promote scientific information on responsible management of plant nutrition.

A fertile soil is not necessarily a productive soil

External Factors Control Plant Growth

Influencing a crop's potential

- Air
- Light
- Temperature
- Water
- Nutrients
- Mechanical support

C H O

N P K

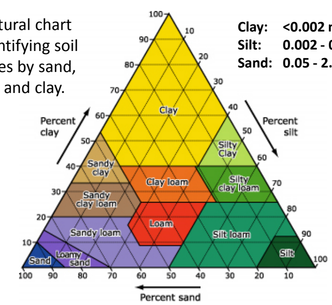
17 Essential Elements

Ca Mg S

B Cl Cu Fe

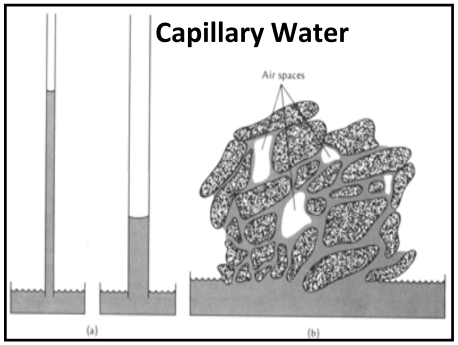
Mn Mo Ni Zn

Textural chart identifying soil types by sand, silt, and clay.



Clay: <0.002 mm
Silt: 0.002 - 0.05 mm
Sand: 0.05 - 2.0 mm

Capillary Water



Texture versus Structure

Soil Texture

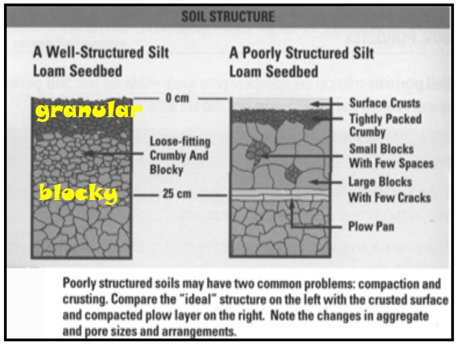
The proportion of primary particles in various size classes.
- influences CEC, water holding capacity, soil aeration
- may vary with depth
- not usually changeable by management

Soil Structure

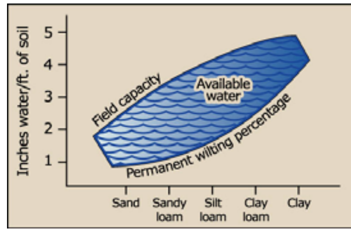
The arrangement of primary soil particles into aggregates (secondary units or peds).
- influences water holding capacity, soil aeration
- varies with depth
- influenced by soil organic matter, texture, compaction, weather
- easily destroyed, difficult to build
- influences nutrient availability

Bulk Density

The weight of soil per unit volume (g/cm^3, lb/ft^3, t/m^3)
- depends on both texture & structure
- clay soils can be heavier or lighter than sandy soils

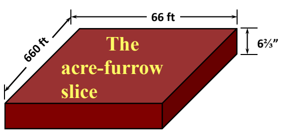


Relationship Between Soil Texture and Water Availability



The Ideal Soil for Crop Production

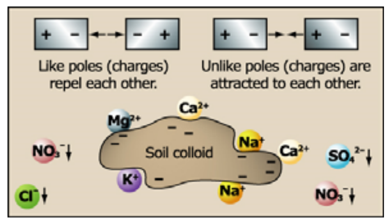
- Medium texture and organic matter for air and water movement
- Sufficient clay to hold soil moisture reserves
- Deep, permeable subsoil with adequate fertility levels
- Environment for roots to go deep for moisture and nutrients

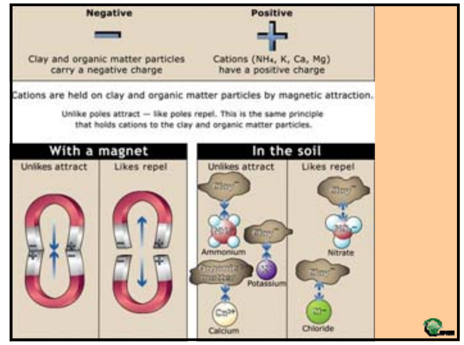


6⅔" x 660' x 66' = 24,200 ft^3
If bulk density = 83 lb/ft^3
then one acre has 2,008,600 lb of soil
(rule of thumb: one acre = 2 million pounds)

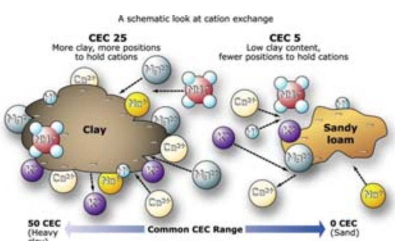
One ppm = two pounds per acre

Negatively Charged Colloids Attract Cations





Cation Exchange Capacity



Clay and Organic Matter Have Greatest Influence on CEC

Clay	Organic matter
10-150 cmol(+)/kg	200-400 cmol(+)/kg

Organic matter has a higher CEC

1 cmol/kg = 1 meq/100 g

Understanding Equivalents for Cation Exchange

Nutrient Element		Atomic[1] Weight	Positive Charges	Equivalent[2] Weight
H	hydrogen	1	1	1
N	nitrogen	14	1 (NH_4^+)	14
Mg	magnesium	24	2	12
K	potassium	39	1	39
Ca	calcium	40	2	20

1/ atomic weight is the weight in grams of $6x10^{23}$ atoms.
2/ equivalent weight is the weight in grams of $6x10^{23}$ positive charges.

Soil Organic Matter Benefits Soil in Many Ways:

- Improves physical condition
- Increases water infiltration
- Improves soil tilth
- Decreases erosion losses
- Contains plant nutrients
- Increases CEC

Soil Organic Matter and Available Water Capacity

Inches of Water/One Foot of Soil			
Percent SOM	Sand	Silt Loam	Silty Clay Loam
1	1.0	1.9	1.4
2	1.4	2.4	1.8
3	1.7	2.9	2.2
4	2.1	3.5	2.6
5	2.5	4.0	3.0

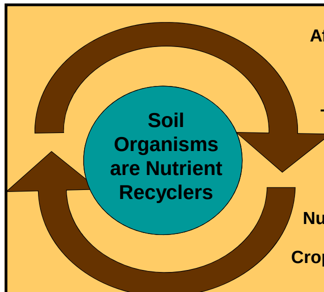
Berman Hudson
Journal Soil and Water Conservation 49(2) 189-194
March – April 1994
Summarized by:
Dr. Mark Liebig, ARS, Mandan, ND
Hal Weiser, Soil Scientist, NRCS, Bismarck, ND

NCAT The National Center for Appropriate Technology • www.ncat.org • 1-800-275-6228 (1-800-ASK-NCAT)

Average corn yields (1989-1993) and soil organic matter levels for a Brookston clay loam soil under different management practices since 1959.

Management Practice	Fertilization $N-P_2O_5-K_2O$ (lb/A)	Grain Yield bu/A	Organic Matter %
Continuous corn	115-70-30	104	3.6
Continuous corn	0-0-0	13	3.1
Rotation corn	115-70-30	145	4.4
Rotation corn	0-0-0	65	3.3

Gregorich & Drury, 1996



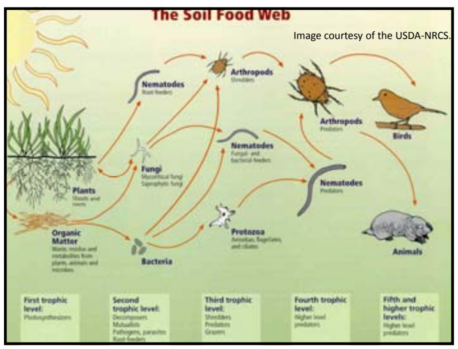
Affected by:

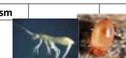
- Moisture
- Temperature
- Soil pH
- Aeration
- Nutrient supply
- Cropping system

Nitrogen-fixing Bacteria

Nodules formed where *Rhizobium* bacteria infected soybean roots.

Image courtesy of the USDA-NRCS.



Soil organism		Benefit to plant growth or soil health
Mites, collembola		Break up larger pieces of organic matter, regulate microbial populations (predators of fungi and microfauna), nutrient turnover
Earthworms, termites, ants, beetles		Create biopores , fragment organic residues, increase water infiltration and soil porosity Redistribute SOM and mix it with soil particles
Arbuscular mycorrhiza, rhizobium, algae,		Increase nutrient availability and capture, some have symbiotic relationship with plant roots enable crops or pastures to obtain additional nutrients
Fungi, bacteria		Break down SOM, cycle nutrients, bind soil particles, compete with disease organisms for food sources. May be free living or symbiotic. Chemical degradation, bio-filters.
Trichoderma, nematode spp.		Some attack harmful pathogens, regulate microbial populations, mineralize nutrients
Actinomycetes		Specific wax degrading bacteria able to degrade the organic waxes that cause non-wetting, others are symbiotic with roots and increase nutrient availability and uptake

Source: Soil Science Society of America

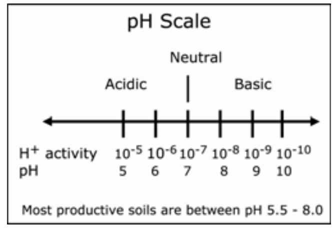
Night crawlers and tillage

Without *Lumbricus terrestris* With *Lumbricus terrestris*

Image courtesy of the USDA-NRCS.

Soil pH describes a soil's relative acidity or basicity (alkalinity)

What is Soil pH?



chemical equilibrium of water

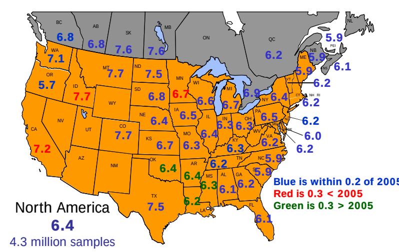
$$H_2O \rightleftharpoons H^+ + OH^-$$

$$[H^+][OH^-]=10^{-14}$$

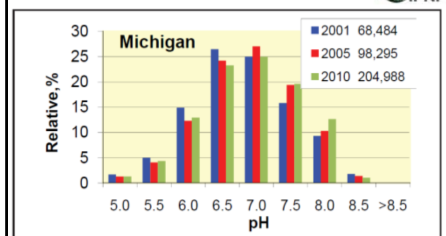
Soil pH Measures Hydrogen Ion Activity in Soil Water

Soil pH		Magnitude of the Acidity/Basicity compared to pH 7.0
9.0	Basicity	100x
8.0		10x
7.0		Neutral
6.0	Acidity	10x
5.0		100x
4.0		1,000x

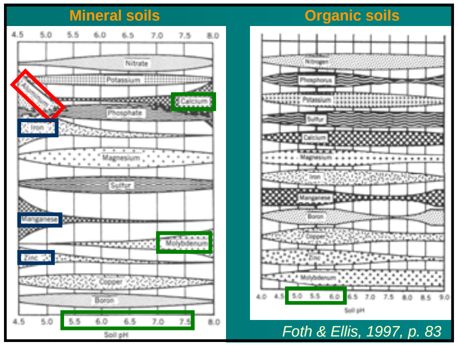
Figure 11. Median soil pH in 2010 and change from 2005.



Soil pH Distribution



Mineral soils | Organic soils



Foth & Ellis, 1997, p. 83

Why Acid Soils Should Be Limed

- Reduces Al and other metal toxicities
- Improves the physical condition of the soil
- Stimulates microbial activity in the soil
- Increases CEC in variable charge soils
- Increases availability of several nutrients
- Supplies Ca and Mg to plants
- Improves symbiotic N fixation in legumes
- Improve crop yields

Fertilizer N & Acidity

Pounds calcium carbonate per pound of N:

- AN, AA, UAN, urea 1.8
- ammonium sulfate 3.6 - 5.2
- MAP 5.4
- DAP 3.6
- KNO_3 -2.0

How Lime Reduces Soil Acidity

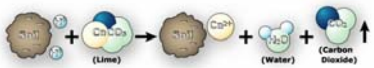
- Ca^{2+} ions from aglime replaces H^+ and Al^{3+} at the exchange sites. The Al^{3+} reacts with water releasing H^+…

$$Al^{3+} + H_2O \longrightarrow Al(OH^{2+}) + H^+$$

- Carbonate ions (CO_3^{2-}) from aglime react in the soil solution, creating excess OH^- (hydroxyl) ions which combine with H^+ ions forming water

$$CO_3^{2-} + H^+ \rightarrow HCO_3^- \; ; \; HCO_3^- + H^+ \rightarrow H_2O + CO_2$$

- The pH increases because the acidity source (H^+) has been reduced



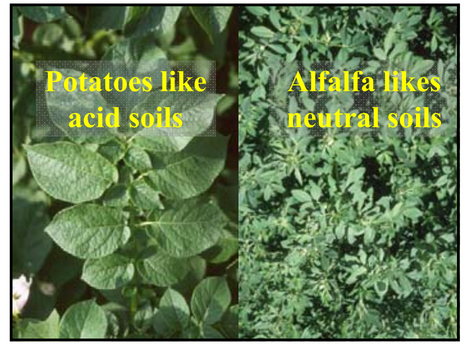
4R PNM 3-32

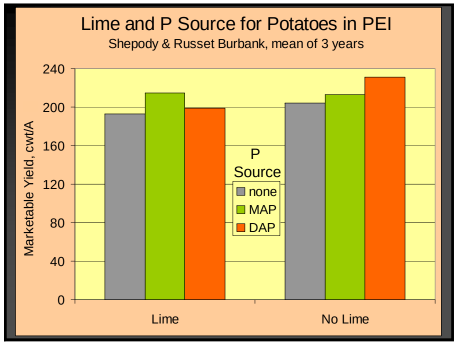
Reserve vs. Active Acidity

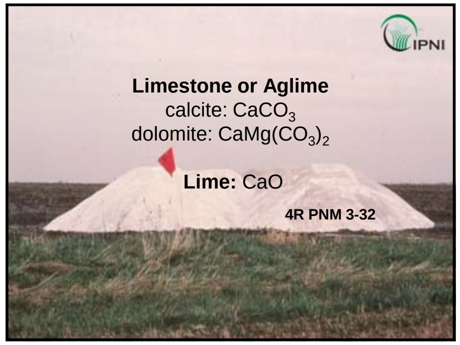
$$HA \rightleftharpoons A^- + H^+$$

reserve — *active*

- pH: whether to lime
- buffer pH: amount of lime

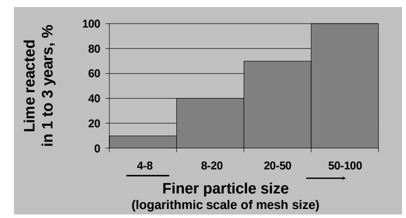






Selecting a Liming Material:

- neutralizing value (CCE) and fineness
- Particle Size Determines Lime Reactivity



Relative Neutralizing Values of Some Common Liming Materials

Liming material	Relative neutralizing value, %	Liming material	Relative neutralizing value*, %
Calcium carbonate	100	Burned oyster shells	90-110
Dolomitic lime	95-108	Hydrated lime	120-135
Calcitic lime	85-100	Basic slag	50-70
Baked oyster shells	80-90	Wood ashes	40-80
Marl	50-90	Gypsum	None
Burned lime (CaO)	150-179	By-products	Variable

*Relative neutralizing value is used interchangeably here with calcium carbonate equivalent

Key Points – Soil properties and pH

- Soil productivity involves nutrients, water, weather, structure, and biology
- Texture and organic matter influence water holding capacity
- Organic matter and CEC influence nutrient holding capacity
- Soil pH influences nutrient form and availability

4 nutrient stewardship

IPNI International Plant Nutrition Institute

Michigan Agri Business Association
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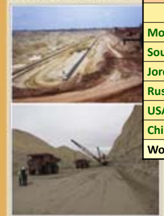
Phosphorus

Tom Bruulsema, Director, Northeast Region, IPNI

Twitter

Mining phosphate rock

IFDC World Phosphate Rock Reserves and Resources



Country	2011-12 Production	Reserves	Reserve Life
	Mt		Years
Morocco	28	50,000	1790
South Africa	2.5	1,500	600
Jordan	6.5	1,500	230
Russia	11	1,300	115
USA	29	1,400	49
China	85	3,700	43
World Total	204	67,000	328

Source: USGS, 2013

"No matter how much phosphate rock exists, it is a non-renewable resource"
IFDC, 2010

Ancaster, Ontario – 26 June 2009 – tilled corn
SOIL EROSION: LOSS OF PARTICULATE P

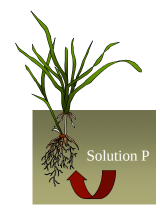
Northwest of Guelph, Ontario – 6 April 2014 – no-till
SURFACE RUNOFF: DISSOLVED P? INVISIBLE

Crops Take Up Large Quantities of Phosphorus

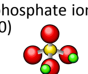
Crop	Yield level/A	Uptake	Removal
		------P_2O_5, lb/A------	
Alfalfa	5 ton	80	80
Corn	150 bu	90	60
Soybeans	50 bu	50	40
Wheat	75 bu	55	45
Potatoes	400 cwt	70	50

4R PNM 4-2

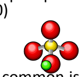
Phosphorus is Taken Up by Plants as:



- primary orthophosphate ion: $H_2PO_4^-$ (pH < 7.0)



- secondary orthophosphate ion: $HPO_4^=$ (pH > 7.0)



- The form most common is a function of soil pH – both equally present at neutral

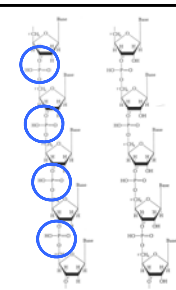
Seeds Contain More Phosphorus than Other Plant Parts

Crop	Plant part	P content, %
Corn	Grain	0.22
	Stover	0.17
Soybeans	Grain	0.42
	Straw	0.18
Wheat	Grain	0.42
	Straw	0.12
Potatoes	Petioles	0.2-0.4
	Tubers	0.18-0.25

P

Structure of DNA

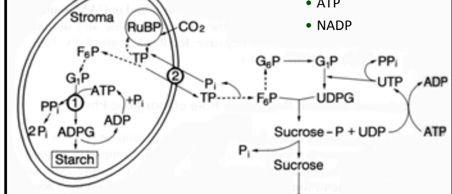
A phosphate molecule links each & every base in the DNA molecule



P

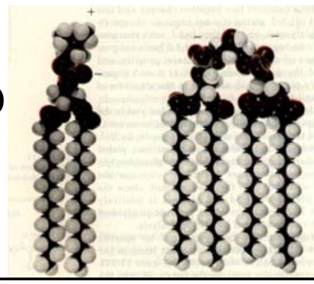
Photosynthesis & Respiration

- ATP
- NADP



Cell Membranes (phospholipids)

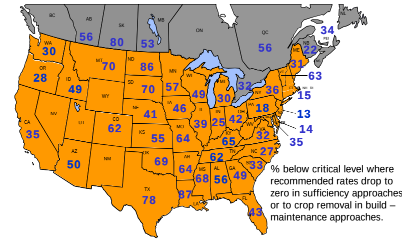
P



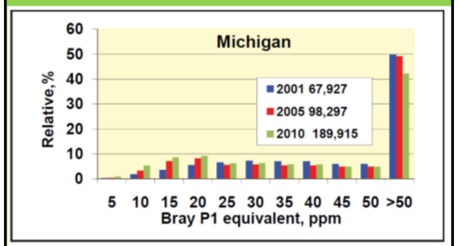
Some Roles Phosphorus Plays in Plant Growth

- Photosynthesis and respiration
- Energy storage and transfer
- Cell division and enlargement
- Early root formation and growth
- Improves quality
- Vital to seed formation
- Transfer of hereditary traits (DNA)

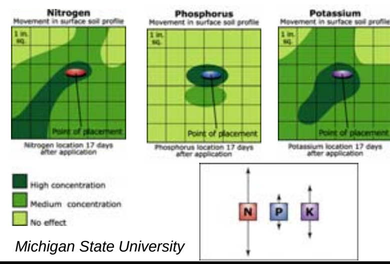
Figure 3. Percent of samples testing below critical levels for P for major crops in 2010.



Soil test P distribution, 2001-2010



Relative Movement of N, P, K in the Soil

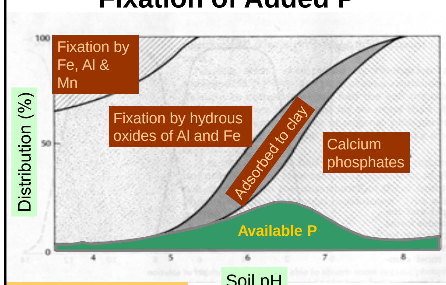


Michigan State University

Factors Influencing Availability of Added P

Soil pH	Aeration
Amount of clay	Moisture
Type of clay	Compaction
Time of application	Other nutrients
Crop grown	Soil P status
Temperature	Placement
Mycorrhizae	

Fixation of Added P



Source: NC Brady, 1990. The Nature and Properties of Soils.

Mycorrhizae

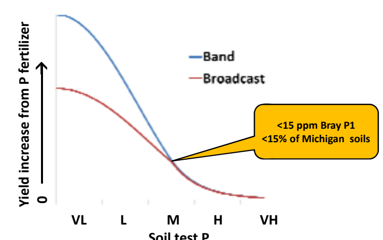
- "Fungus-root" – make glomalin
- Extend to absorb P from more soil
- Decline with increasing P fertility, fallow

Effect of fertilizer P on corn mycorrhizae.

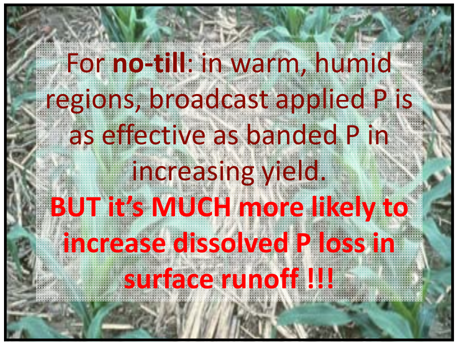
Fertilizer P_2O_5 Rate, lb/A	Hyphal Density (m/g)	Corn grain yield, bu/A
0	1.04	107
55	0.91	118
110	0.68	125

Mean of 2 years, 1997/98, Quebec. Soil test P (Mehlich 3) was 65 to 87 kg/ha. Adapted from Liu et al., 2003

Band is more efficient than broadcast at low to medium soil test levels and rates



Randall and Hoeft, 1988



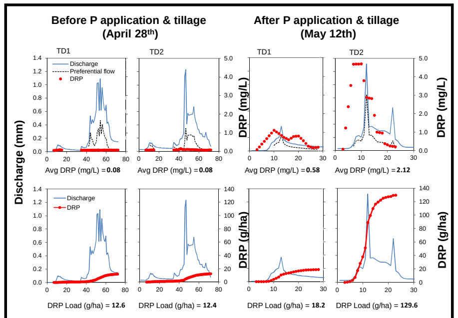
Effect of tillage on preferential flow and phosphorus transport

Soil type: Silt loam
Tile depth: 3 ft
Soil test P: 30 ppm Mehlich-3P
Tillage: No-till

2014 management
May 6th – Applied 175 lb/ac of MAP
May 8th – Tilled field TD1 (disc)
(TD2 remained no-till)

Study Objective
Compare P transport before and after tillage and between tilled and no-till fields

Kevin King, USDA-ARS, Columbus, Ohio



Kevin King, USDA-ARS, Columbus, Ohio

Practice	Advantages	Limitations
S – MAP or DAP R – rotation removal T – fall P – broadcast	Minimal soil compaction Allows timely planting in spring Low-cost fertilizer form Low cost of application	Risk of elevated P in runoff in late fall and winter Low N use efficiency
S – MAP or DAP R – rotation removal T – spring P – broadcast	Minimal soil compaction Better N use efficiency Low-cost fertilizer form Low cost of application	Risk of elevated P in spring runoff before incorporation Potential to delay planting Retailer spring delivery capacity
S – MAP or fluid APP R – one crop removal T – spring P – 2" x 2" band	Low risk of elevated P in runoff Most efficient use of N Less soil P stratification	Cost and practicality Potential to delay planting Retailer delivery capacity Cost of fluid versus granular P
S – MAP or DAP R – rotation removal T – fall P – banded in zone	Low risk of elevated P in runoff Maintain residue cover Allows timely planting in spring Less soil P stratification	Cost of RTK GPS guidance Cost of new equipment More time required than broadcast
S – fluid APP P – point injection	As above	As above, plus cost of fluid versus granular P

Choice of practice considers both advantages and limitations.

Fall Strip-till Banding

- Puts the P in the soil
- Keeps residue on the soil
- RTK GPS for precision planting

Greg LaBarge, Ohio State University Extension

Seed Placement: Small Amounts, Liquid or Granular

P_2O_5 rate, lb/A	Corn yield,[1] bu/A
0	137
5	151
10	146
21	148

[1] Mean of two hybrids at each of two Ontario sites; seed-placed 8-19-3

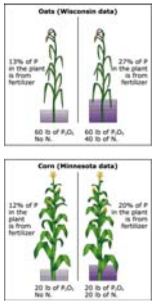
Rate, lb P_2O_5/A	Corn yield,[2] bu/A	
	Liquid[3]	Granular MAP, 13-52-0
0	145	145
10	156	156
21	152	157

[2] Mean of three Ontario sites
[3] Mean of three products: 10-34-0, 6-24-6, 8-19-3

Source: Lauzon et al., 1995

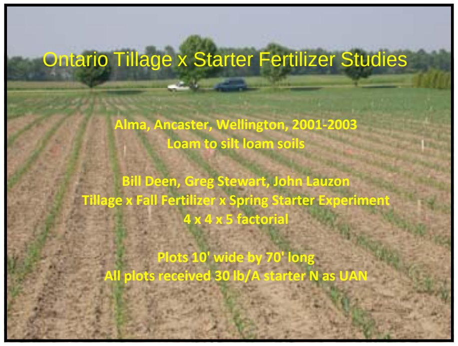
N Improves P Uptake

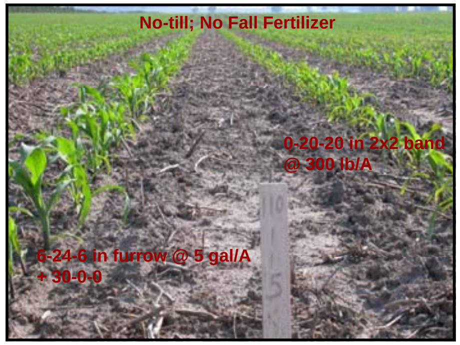
- When applied with N, P is more available to plants
- Ammonium (NH_4^+) N has significant effects on P availability and absorption.
- In high concentrations, NH_4^+-N slows P fixation reactions
- Ammonium absorption helps maintain an acidic condition at the root surface, improving P absorption

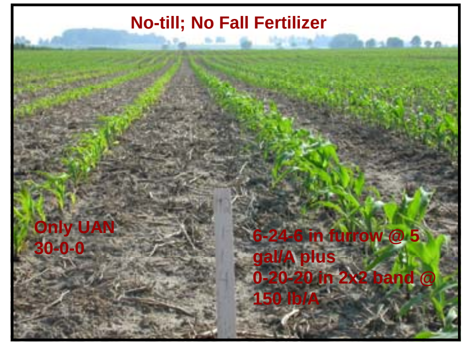


The Best Combination(s):

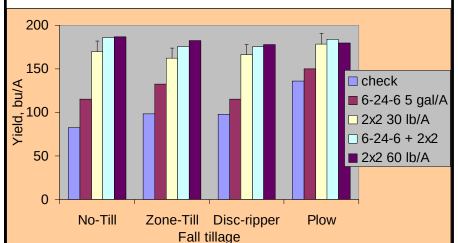
Broadcasting
- to build or maintain soil fertility levels
& Banding
- 2x2, or seed-placed, or both
- to optimize yield and profits





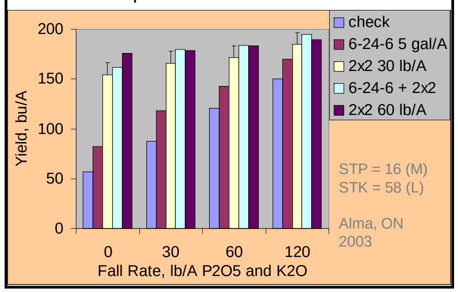


Less tillage more responsive to PK starter



Alma, Ontario 2003 STP = 16 (M); STK = 58 (L)

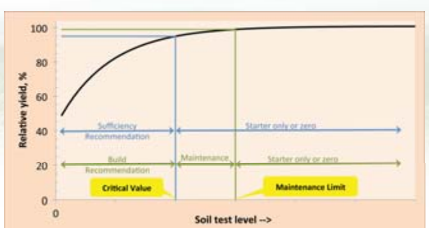
Fall P&K reduces but does not eliminate starter response



Tillage x Starter

- Alma 2003 was one of 9 site-years
- 8 of the 9 showed far smaller responses
- 5 more showed starter NP benefits in no-till but not in plowed soil
- 3 with high soil tests showed no response to applied fertilizer

Soil Test Levels and Management Approaches



(Adapted from Leikam et al., 2003)

4R PLANT NUTRITION

Soil Test Extractants for P

Test	Extractants	pH	Ratio, solution:soil	Extraction time, min
Olsen P	0.5M sodium bicarbonate	8.5	20	30
Bray P1	0.03M ammonium fluoride + 0.025M hydrochloric acid	2.5	7	1
Mehlich-3 P	0.2M acetic acid, 0.25M ammonium nitrate, 0.015M ammonium fluoride, 0.13M nitric acid, 0.001M EDTA	2.5	10	5
Colwell P	0.5M sodium bicarbonate	8.5	100	960
Morgan	0.54 M acetic acid + 0.72 M sodium acetate	4.8	5	15
Exchange resins	Mixture of anionic and cationic resins			

4R PLANT NUTRITION

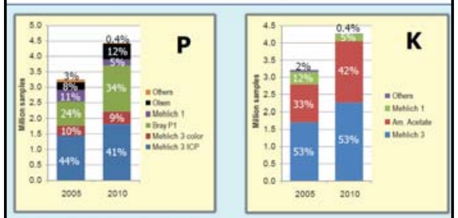
Different P soil tests give widely different #s

Phosphorus							
Ammonum Bicarbonate-DTPA	0-1	2-3	4-5	6-7	8-9	10-11	12-15
Bray and Kurtz P1	0-5	6-10	11-15	16-20	21-25	26-30	31-40
Bray and Kurtz P2	0-9	10-18	19-27	28-35	36-40	41-45	46-55
Kelowna, Modified	0-5	6-10	11-15	16-20	21-25	26-30	31-40
Lancaster P	0-5	6-10	11-15	16-20	21-25	26-30	31-40
Mehlich 1 P	0-3	4-6	7-9	10-12	13-15	16-18	19-24
Mehlich 2 P	0-5	6-10	11-15	16-20	21-25	26-30	31-40
Mehlich 3 P (colorimetric)	0-5	6-10	11-15	16-20	21-25	26-30	31-40
Mehlich 3 P (ICP)	0-9	10-18	19-27	28-35	36-40	41-45	46-55
Morgan, Cornell		0-0.9	1.0-2.3	2.4-3.6	3.7-4.4	4.5-5.3	5.4-6.9
Morgan, Modified	0-2.5	2.6-3.4	3.5-4.9	5.0-6.3	6.4-7.1	7.2-8.0	8.1-9.7
Olsen P (sodium bicarbonate)	0-3	4-7	8-11	12-15	16-19	20-23	24-30

*These equivalencies are not recommended for the purpose of determining appropriate rates to apply.

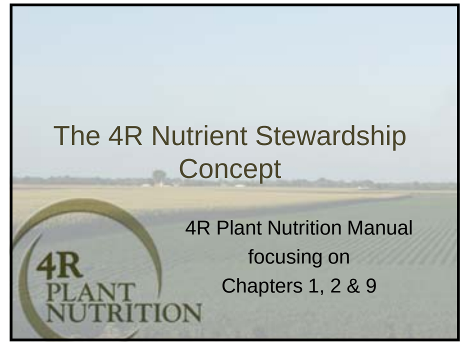
4R PLANT NUTRITION

Soil analysis methods across North America

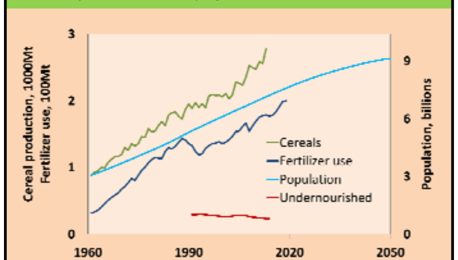


Summary – Phosphorus

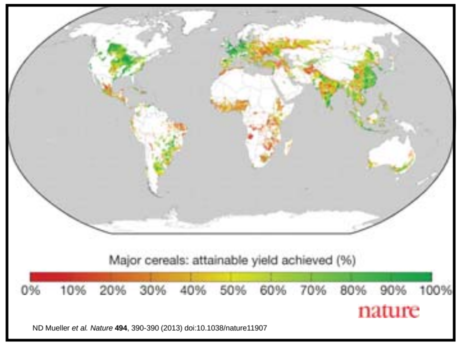
- Cycling: from mine to soil to crop to soil to sea
- Availability: mineral phase precipitation and sorption control solubility
- Movement: Slow, retained in soil matrix. Fast, in surface runoff and macropores.
- Sources: Mined minerals, manures, biosolids, derived products (e.g. struvite)
- Management: source, rate, time and place



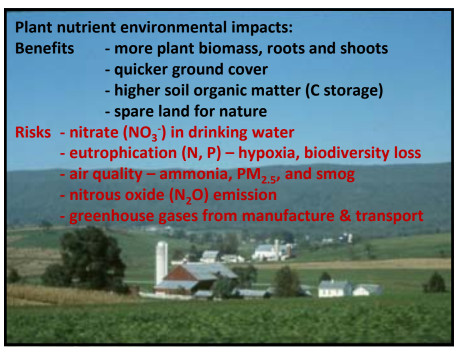
As population increases, increasing cereal production, supported by increased fertilizer use, is keeping undernourishment in check.



Data sources: United Nations Food and Agriculture Organization (FAO), International Fertilizer Industry Association (IFA)



Global Eutrophication Challenges



UN Sustainable Development Goals 2015-2030

- Building on the 8 Millennium Development Goals
- Open Working Group proposal July 2014 – 17 goals
- Achieving food security will involve fertilizers; achieving it sustainably will require better nutrient use efficiency (NUE)
- SDSN goals and indicators – more specifically addressing nutrients and NUE

4R: "right" means sustainable

Nutrient Stewardship Metrics for Sustainable Crop Nutrition

DRAFT

Enablers (process metrics)

- Extension & professionals
- Infrastructure
- Research & innovation
- Stakeholder engagement

Actions (adoption metrics)

[Require regional definition of 4R]

- Cropland area under 4R (at various levels)
- Participation in programs
- Equity of adoption (gender, scale, etc.)

Outcomes (impact metrics)

- Food & nutrition security
- Productivity
- Nutrient use efficiency
- Land quality, soil health
- Air & water quality
- Economic value
- Land conservation, natural habitat

Source, rate, time, and place describe any nutrient application

Examples of Key Scientific Principles

	The Four Rights (4Rs)			
	Source	Rate	Time	Place
Key Scientific Principles	• Ensure balanced supply of nutrients • Suit soil properties	• Assess nutrient supply from all sources • Assess plant demand	• Assess dynamics of crop uptake and soil supply • Determine timing of loss risk	• Recognize crop rooting patterns • Manage spatial variability

- Chapters 3-6 for greater detail

Equal attention to all 4Rs

- Balance attention to all 4Rs
- Rate: easily overemphasized
- Source, Time, Place: often require major changes and investments

Stakeholders have a say on performance indicators

- Stakeholders define goals
- Indicators relate to goals
- Producers choose practices

Producers choose practices

- Practices selected to suit local site-specific soil, weather, and crop conditions
- Conditions may change even on the day of application
- Local decisions preferred

4R Nutrient Stewardship Plans

The plans document progress toward sustainability goals, with two principal purposes

- Recording all crop management practices relevant to plant nutrition
- Tracking performance of implemented practices

Managing Environmental Impacts of N

- Aboveground plant uptake of applied N in the growing season of application is usually between 30 and 70%
- Site-specific 4R Nutrient Stewardship can lead to:
  - Improved recovery of N by plants from the soil
  - Reduced N losses to the environment

but…

Managing Environmental Impacts of N

…requires in-depth knowledge of

- fertilizer N sources
- soil characteristics and properties
- weather conditions (moisture, temperature)
- cropping system nutrient demands and balances
- the complexity of the N cycle

and

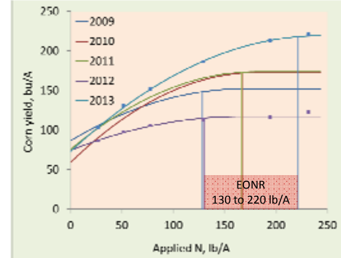
- water management and irrigation efficiency

Many Paths to Choose in Improving N Use Efficiency

- Improved crop genetics
- Newer fertilizer technologies
- Better timing and split applications, where appropriate
- Advances in fertilizer application technologies – VRA, GPS, GIS
- PSNT
- Adapting N recommendations for weather

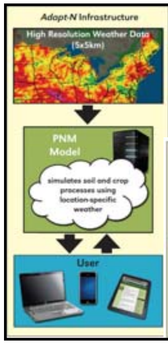
Weather influences corn yield response

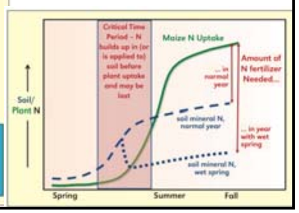
first 5 years, Elora, Ontario (IPNI-2008-CAN-ON29)



Deen, Lauzon, Stewart, & Bruulsema; not yet published.

Common elements of model-based nitrogen decision support

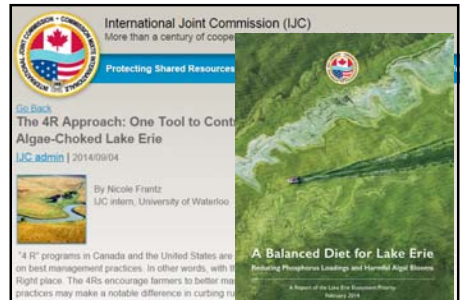




Potential 4R Corn Nitrogen Practice Definitions

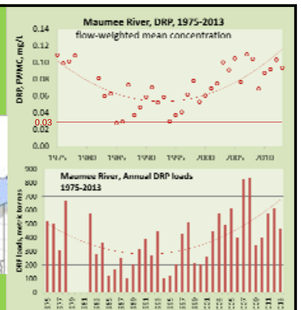
Level	Source	Rate	Time	Place
Basic	Guaranteed or known analysis	Rate based on LGU or adaptive management	Spring; not on frozen soil	Broadcast & incorporated, injected or subsurface band
Intermediate	+ with inhibitors if surface applied	+	+ Split application, or enhanced-efficiency source	+, or sidedress, with inhibitors if surface applied
Advanced	++	+ and using tools such as crop sensors, PSNT, Adapt-N or models	+	++

4R practices need regional, evidence-based definition

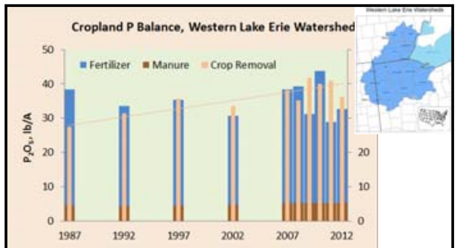


The IJC supports 4R… but calls for mandatory measures.

Western Lake Erie: DRP trends worsening since 1992



David Baker et al., National Center for Water Quality Research, Heidelberg U, Tiffin, OH



1. Application rates short of crop removal since 1991.
2. Crop removal is increasing with yield.

Developing 4R Nutrient Stewardship Certification

4R Certification for Agri-retailers in the Lake Erie Watershed

Key criteria:

- Recommendations are consistent with the land-grant university, allowing for adaptive management.
- A certified professional reviews the nutrient recommendations made for the grower customers.
- **Source**: All sources of fertilizer are accounted for in the nutrient recommendation.
- **Rate**: Soil tests are less than four years old; application equipment is calibrated annually.
- **Time**: Avoids spreading on frozen or snow-covered fields; no broadcast prior to a predicted heavy rainfall.
- **Place**: Phosphorus is applied below the soil surface whenever possible; nutrient application setbacks are followed in sensitive areas.

http://4Rcertified.org/

Certified Crop Adviser Specialties

Proposed:

- **Sustainability Specialty**
  - Supported by United Soybean Board
    1. Communicating Sustainability
    2. Resources & Environmental Stewardship
    3. Value Chain
  - Modules and Exams coming in 2016
- **4R Nutrient Management Specialty**
  - involves CCA representatives from Illinois, Iowa, Minnesota, Wisconsin, and Michigan
  - basic knowledge standard; what USDA-NRCS and other view as needed to be certified in preparing Nutrient Management Plans

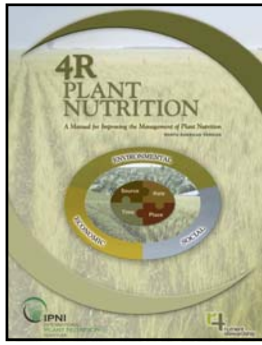
4R Research Fund

environmental, social, economic impacts

- Established by the fertilizer industry to support research on 4R sustainability impact across North America – aiming for $7M over 5 years.
- **Meta-analysis:** 5 projects, 2014-2015.
- **Measurement:** 4 projects, 2014-2019.
- For additional information: www.ipni.net

Summary – 4R Practices

- **Implement the principles to optimize management**
- **Determine appropriate sustainability goals**
- **Choose metrics to monitor progress**
- **Manage by nutrient management plan**
- **Track nutrient balances**
- **Connect your metrics to a sustainability reporting system**



Thank You

nane.ipni.net