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

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

Soil Properties and Reactions

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

Capillary Water

Texture versus Structure

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/cm³, lb/ft³, t/m³)

- Depends on both texture & structure
- Clay soils can be heavier or lighter than sandy soils
**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

---

**Clay and Organic Matter Have Greatest Influence on CEC**

<table>
<thead>
<tr>
<th>Nutrient Element</th>
<th>Atomic Weight</th>
<th>Positive Charges</th>
<th>Equivalent Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>H     hydrogen</td>
<td>1</td>
<td>1</td>
<td>1/1000</td>
</tr>
<tr>
<td>N     nitrogen</td>
<td>14</td>
<td>1(0)</td>
<td>14</td>
</tr>
<tr>
<td>Mg    magnesium</td>
<td>24</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>K     potassium</td>
<td>39</td>
<td>1</td>
<td>39</td>
</tr>
<tr>
<td>Ca    calcium</td>
<td>40</td>
<td>2</td>
<td>20</td>
</tr>
</tbody>
</table>

Organic matter has a higher CEC

1 cmol/kg = 1 meq/100 g

---

**Understanding Equivalents for Cation Exchange**

<table>
<thead>
<tr>
<th>Nutrient Element</th>
<th>Atomic Weight</th>
<th>Positive Charges</th>
<th>Equivalent Weight</th>
</tr>
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<tr>
<td>H     hydrogen</td>
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<td>39</td>
</tr>
<tr>
<td>Ca    calcium</td>
<td>40</td>
<td>2</td>
<td>20</td>
</tr>
</tbody>
</table>

1/ atomic weight is the weight in grams of 6.022x10^23 atoms.
2/ equivalent weight is the weight in grams of 6.022x10^23 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

---

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

<table>
<thead>
<tr>
<th>Management Practice</th>
<th>Fertilization N-P-K (lb/A)</th>
<th>Grain Yield bu/A</th>
<th>Organic Matter %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous corn</td>
<td>115-70-30</td>
<td>104</td>
<td>3.6</td>
</tr>
<tr>
<td>Continuous corn</td>
<td>0-0-0</td>
<td>13</td>
<td>3.1</td>
</tr>
<tr>
<td>Rotation corn</td>
<td>115-70-30</td>
<td>145</td>
<td>4.4</td>
</tr>
<tr>
<td>Rotation corn</td>
<td>0-0-0</td>
<td>65</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Gregorich & Drury, 1996

---

Nitrogen-fixing Bacteria

Image courtesy of the USDA-NRCS.

Night crawlers and tillage

Image courtesy of the USDA-NRCS.

Soil Organisms are Nutrient Recyclers

- Affected by: Moisture, Temperature, Soil pH, Aeration, Nutrient supply, Cropping system

---

Soil Nutrition

<table>
<thead>
<tr>
<th>Soil Organism</th>
<th>Benefit to plant growth and soil health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arbuscular mycorrhiza</td>
<td>Increase nutrient availability and capture; some have symbiotic relationship with plant roots enable crops or pastures to obtain additional nutrients</td>
</tr>
<tr>
<td>Rhizobium</td>
<td>Break down SOM, cycle nutrients, bind soil particles; compete with disease organisms for soil resources; may be free living or symbiotic; Chemical degradation, biofilters</td>
</tr>
<tr>
<td>Fungi</td>
<td>Some attack harmful pathogens; regulate microbial populations, mineralize nutrients</td>
</tr>
<tr>
<td>Bacteria</td>
<td>Not specified for soil nutrition, some are symbiotic with plant roots and increase nutrient availability and uptake</td>
</tr>
</tbody>
</table>

Source: Soil Science Society of America

---

Soil Organic Matter and Available Water Capacity

<table>
<thead>
<tr>
<th>Percent SOM</th>
<th>Inches of Water/One Foot of Soil</th>
<th>Sand</th>
<th>Silty Loam</th>
<th>Silty Clay Loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.9</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
<td>2.4</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.1</td>
<td>2.9</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>3.5</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.5</td>
<td>4.0</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

---

Image courtesy of the USDA-NRCS.
Soil pH describes a soil’s relative acidity or basicity (alkalinity).

What is Soil pH?

The chemical equilibrium of water is:

\[ H_2O \rightleftharpoons H^+ + OH^- \]

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

Soil pH Measures Hydrogen Ion Activity in Soil Water

<table>
<thead>
<tr>
<th>Soil pH</th>
<th>Magnitude of the Acidity/Basicity compared to pH 7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.0</td>
<td>100x Basicity</td>
</tr>
<tr>
<td>8.0</td>
<td>10x Basicity</td>
</tr>
<tr>
<td>7.6</td>
<td>Neutral</td>
</tr>
<tr>
<td>6.9</td>
<td>10x Acidity</td>
</tr>
<tr>
<td>6.0</td>
<td>100x Acidity</td>
</tr>
<tr>
<td>4.8</td>
<td>1,000x Acidity</td>
</tr>
</tbody>
</table>

Soil pH Distribution

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

North America

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
- KNO₃: -2.0

Why Acid Soils Should Be Limed

- 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

- Reduces Al and other metal toxicities
- Improves the physical condition of the soil
- Stimulates microbial activity in the soil
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\(^+\):
  \[\text{Al}^{3+} + \text{H}_2\text{O} \rightarrow \text{Al(OH)}^{2+} + \text{H}^+\]

- Carbonate ions (CO\(_3^{2-}\)) from aglime react in the soil solution, creating excess OH\(^-\) (hydroxyl) ions which combine with H\(^+\) ions forming water
  \[\text{CO}_3^{2-} + \text{H}^+ \rightarrow \text{HCO}_3^-; \text{HCO}_3^- + \text{H}^+ \rightarrow \text{H}_2\text{O} + \text{CO}_2\]

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

\[\text{Al}^{3+} + \text{H}_2\text{O} \rightarrow \text{Al(OH)}^{2+} + \text{H}^+\]

Reserve vs. Active Acidity

\[\text{HA} \leftrightarrow \text{A}^- + \text{H}^+\]

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

Selecting a Liming Material:
- neutralizing value (CCE) and fineness
- Particle Size Determines Lime Reactivity

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

Selecting Lime Material:
- Neutralizing value
- Particle size determines lime reactivity

Relative Neutralizing Values of Some Common Liming Materials

<table>
<thead>
<tr>
<th>Liming material</th>
<th>Relative neutralizing value, %</th>
<th>Relative neutralizing value, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium carbonate</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Dolomite lime</td>
<td>95-108</td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td>85-90</td>
<td></td>
</tr>
<tr>
<td>Baked oyster shells</td>
<td>80-90</td>
<td></td>
</tr>
<tr>
<td>Wood ashes</td>
<td>56-59</td>
<td></td>
</tr>
<tr>
<td>Bird droppings</td>
<td>56-59</td>
<td></td>
</tr>
<tr>
<td>Baked lime (CaO)</td>
<td>150-179</td>
<td></td>
</tr>
<tr>
<td>Burnt oyster shells</td>
<td>90-110</td>
<td></td>
</tr>
<tr>
<td>Hydrated lime</td>
<td>125-135</td>
<td></td>
</tr>
<tr>
<td>Basic slag</td>
<td>56-59</td>
<td></td>
</tr>
<tr>
<td>Wood ashes</td>
<td>46-50</td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td>56-59</td>
<td></td>
</tr>
</tbody>
</table>

*Relative neutralizing value is used interchangeably with calcium carbonate equivalent.
Mining phosphate rock

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

<table>
<thead>
<tr>
<th>Country</th>
<th>2011-12 Production</th>
<th>Reserve</th>
<th>Reserve</th>
<th>ML</th>
<th>Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morocco</td>
<td>28</td>
<td>150,000</td>
<td>1790</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>1.3</td>
<td>1,500</td>
<td>800</td>
<td>4</td>
<td>92</td>
</tr>
<tr>
<td>India</td>
<td>6.5</td>
<td>1,500</td>
<td>230</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>1.1</td>
<td>1,300</td>
<td>110</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>19</td>
<td>1,400</td>
<td>62</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>85</td>
<td>3,700</td>
<td>43</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>World Total</td>
<td>204</td>
<td>67,000</td>
<td>328</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Source: USGS, 2013

Crops Take Up Large Quantities of Phosphorus

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield level/A</th>
<th>Uptake P2O5 lb/A</th>
<th>Removal P2O5 lb/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>5 ton</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Corn</td>
<td>150 bu</td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>Soybeans</td>
<td>50 bu</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Wheat</td>
<td>75 bu</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>Potatoes</td>
<td>400 cwt</td>
<td>70</td>
<td>50</td>
</tr>
</tbody>
</table>

4R PNM 4-2

Phosphorus is Taken Up by Plants as:
- primary orthophosphate ion: $H_2PO_4^-$ (pH < 7.0)
- secondary orthophosphate ion: $HPO_4^{2-}$ (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

<table>
<thead>
<tr>
<th>Crop</th>
<th>Plant part</th>
<th>P content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>Grain</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Stover</td>
<td>0.17</td>
</tr>
<tr>
<td>Soybeans</td>
<td>Grain</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0.18</td>
</tr>
<tr>
<td>Wheat</td>
<td>Grain</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Straw</td>
<td>0.12</td>
</tr>
<tr>
<td>Potatoes</td>
<td>Petioles</td>
<td>0.2-0.4</td>
</tr>
<tr>
<td></td>
<td>Tubers</td>
<td>0.15-0.25</td>
</tr>
</tbody>
</table>

Structure of DNA

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

Photosynthesis & Respiration

$\text{CO}_2 + \\text{ATP} + \\text{NADP} \rightarrow \\text{ADP} + \\text{NADPH} + \\text{Pi}$

$\text{CO}_2 + \\text{ATP} + \\text{NADPH} + \\text{Pi} \rightarrow \\text{ADP} + \\text{NADP} + \\text{SUCC}$

$\text{CO}_2 + \\text{ATP} + \\text{NADP} \rightarrow \\text{ADP} + \\text{NADPH} + \\text{Pi}$

$\text{CO}_2 + \\text{ATP} + \\text{NADPH} + \\text{Pi} \rightarrow \\text{ADP} + \\text{NADP} + \\text{SUCC}$
Cell Membranes (phospholipids)

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

Factors Influencing Availability of Added P
- Soil pH
- Amount of clay
- Type of clay
- Time of application
- Crop grown
- Temperature
- Mycorrhizae

Fixation of Added P

Effect of fertilizer P on corn mycorrhizae.

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

Michigan State University
Before P application & tillage
(May 12th)

TD1 TD2

TD1 TD2

For:

Humid

5.0

DRP

Silt loam

3.0

Tile depth:

2.0
1.2
1.4
1.0
1.0
1.0

DRP (mg/L) DRP (g/ha)

As effective

TD1

0.0
0.0
0.08
Avg DRP (mg/L) = 0.08

TD2

2.12
Avg DRP (mg/L) = 2.12

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

2 Mean of three Ontario sites

Source: Lauzon et al., 1995

Fall Strip-Till Banding

• Puts the P in the soil
• Keeps residue on the soil
• 97% GPS for precision planting

Choice of practice considers both advantages and limitations.

N Improves P Uptake

• When applied with N, P is more available to plants
• Ammonium (NH₄⁺) N has significant effects on P availability and absorption.
• In high concentrations, NH₄⁺ 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
No-till, No Fall Fertilizer

6-24-6 in furrow @ 5 gal/A
+ 30-0-0

No-till; No Fall Fertilizer
0-20-20 in 2x2 band @ 300 lb/A

Less tillage more responsive to PK starter

Soil Test Levels and Management Approaches

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 Extractants for P

Test | Extractants | pH | Solution:soil | Extraction time, min
--- | --- | --- | --- | ---
Glen P | 0.05M sodium bicarbonate | 8.5 | 20 | 30
Bray P | 0.025M 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 | 60
Morgan P | 0.5M M acetic acid | 4.8 | 5 | 15
Exchange resins | Mixtures of anionic and cationic resins | | | |

Different P soil tests give widely different #s

These equivalencies are not recommended for the purpose of determining appropriate rates to apply.
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
- Sources: Mined minerals, manures, biosolids, derived products (e.g. struvite)
- Management: source, rate, time and place

The 4R Nutrient Stewardship Concept

4R Plant Nutrition Manual focusing on Chapters 1, 2 & 9

Global Eutrophication Challenges

Plant nutrient environmental impacts:

Benefits - more plant biomass, roots and shoots
- quicker ground cover
- higher soil organic matter (C storage)
- spare land for nature

Risks - nitrate (NO₃⁻) in drinking water
- eutrophication (N, P) – hypoxia, biodiversity loss
- air quality – ammonia, PM₂.₅, and NH₃
- nitrous oxide (N₂O) emission
- greenhouse gases from manufacture & transport

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)
- SDN goals and indicators – more specifically addressing nutrients and NUE

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

4R: “right” means sustainable
Examples of Key Scientific Principles

<table>
<thead>
<tr>
<th>Key Scientific Principles</th>
<th>Source</th>
<th>Rate</th>
<th>Time</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source balanced supply of nutrients</td>
<td>Assess nutrient demand from all sources</td>
<td>Assess dynamics of crop uptake and soil supply</td>
<td>Determine timing of risk</td>
<td>Manage spatial variability</td>
</tr>
<tr>
<td>Soil properties</td>
<td>Assess plant properties</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• 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

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
  - 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

Potential 4R Corn Nitrogen Practice Definitions

<table>
<thead>
<tr>
<th>Level</th>
<th>Source</th>
<th>Rate</th>
<th>Time</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Guaranteed or known analysis</td>
<td>Rate based on LGU or adaptive management</td>
<td>Spring; not on frozen soil</td>
<td>Broadcast &amp; incorporated, injected or subsurface band</td>
</tr>
<tr>
<td>Intermediate</td>
<td>+ with inhibitors if surface applied</td>
<td>+ Split application, or enhanced efficiency source</td>
<td>+, or sidedress, with inhibitors if surface applied</td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

4R practices need regional, evidence-based definition

Western Lake Erie: DRP trends worsening since 1992

2. Crop removal is increasing with yield.

Developing 4R Nutrient Stewardship Certification

The IJC supports 4R but calls for mandatory measures.
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 recommendations.
- 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.
- 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

http://ipni.net

Thank You

nane.ipni.net