Assessing nutrient use efficiency

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Objectives

1) Learn about the different indicators that can be used to assess nutrient use efficiency in agriculture
2) Understand which indicators to use for what purposes, and how to interpret their values
3) Focus on agronomically important indicators of fertilizer use, but also discuss indicators for environmental and system-level performance assessment
Resources


KEY POINTS

- Nutrient use efficiency indicators are important for sustainability and efficiency assessment in farming.
- Different indicators, with various combinations of nutrient outputs and inputs, are required to quantify nutrient use efficiency in relation to the multiple aims of responsible plant nutrition.
- Comprehensive assessment of sustainable crop production requires additional indicators.
Fertilizer Indicators

**Partial Factor Productivity (kg/kg)**

\[ PFP = \frac{Y}{F} \]

**Agronomic Efficiency (kg/kg)**

\[ AE = \frac{(Y - Y_0)}{F} \]

**Recovery Efficiency (%)**

\[ RE = \left( \frac{(U - U_0)}{F} \right) \times 100 \]

**Physiological Efficiency (kg/kg)**

\[ PE = \frac{(Y - Y_0)}{(U - U_0)} \]

Footprint for calculation:
- field trials, management zones, whole field, farm by crops, groups of farms, etc.

Time scale:
- one cropping season
Fertilizer Indicators

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**Measurements:**
- \( F \) – amount of (fertilizer) N applied (kg N/ha)
- \( Y \) – crop yield or total dry matter (kg/ha)
- \( U \) – crop N uptake (kg N/ha)

in field plots that receive no fertilizer and plots that receive fertilizer at different rates

**Footprint for calculation:**
- field trials, management zones, whole field, farm by crops, groups of farms, etc.

**Time scale:**
- one cropping season
Fertilizer Indicators

Partial Factor Productivity
= kg grain yield per kg N applied
→ soil fertility and fertilizer efficiency

Agronomic Efficiency
= kg grain yield increase per kg N applied
→ fertilizer management, genetics, crop management, weather
→ product of recovery efficiency x physiological efficiency of fertilizer

Fertilizer indicators:
Partial Factor Productivity (kg/kg)
PFP = Y/F or PFP = (Y₀ + ΔY)/F
Agronomic Efficiency (kg/kg)
AE = (Y - Y₀)/F

Gross return above fertilizer cost:
GRF = (Y x price of grain) – (F x price of F) – application cost
Fertilizer Indicators

Recovery efficiency (‘apparent’)
= kg increase in crop uptake per kg nutrient applied
→ Crop sink size and crop health
→ Fertilizer management (4R)

Physiological efficiency
= kg yield increase per kg increase in crop uptake
→ Climate, crop variety & crop management

Fertilizer indicators:
Recovery Efficiency (fraction, %)
\[ RE = \frac{U - U_0}{F} \]
Physiological Efficiency (kg/kg)
\[ PE = \frac{Y - Y_0}{U - U_0} \]
### Fertilizer Indicators: Application & Interpretation

<table>
<thead>
<tr>
<th></th>
<th>Indonesia (2004-05, N=20)</th>
<th>Nebraska, USA (2002-03, N=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield potential (t/ha)</td>
<td>8-14</td>
<td>15-20</td>
</tr>
<tr>
<td>Grain yield 0N (t/ha)</td>
<td>5.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Grain yield +N (t/ha)</td>
<td>9.1</td>
<td>14.1</td>
</tr>
<tr>
<td>Fertilizer-N (kg/ha)</td>
<td>200</td>
<td>158</td>
</tr>
<tr>
<td>$PFP_N$ (kg/kg)</td>
<td>46</td>
<td>89</td>
</tr>
<tr>
<td>$AE_N$ (kg/kg)</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>$RE_N$ (%)</td>
<td>37</td>
<td>65</td>
</tr>
</tbody>
</table>

Indonesia: rainfed and irrigated maize, on-farm trials, same N rate at all sites, 3 N applications

Nebraska: irrigated maize, on-farm trials, location-specific N rate based on UNL-algorithm (includes yield goal, SOM, soil NO$_3$-N, and other N credits), 2-3 N applications
# Fertilizer Indicators: Influencing Factors

\[
PFP_N = \left( Y_0 + \Delta Y_N \right) / F_N
\]

<table>
<thead>
<tr>
<th>Management and environmental factors</th>
<th>Influence on ( Y_0 )</th>
<th>Influence on ( \Delta Y_N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Genotype</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Soil drying, longer fallow periods (rice)</td>
<td>**</td>
<td>*</td>
</tr>
<tr>
<td>Manure, crop residues, legume as previous crop</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Land preparation and crop establishment</td>
<td>**</td>
<td>*</td>
</tr>
<tr>
<td>Balanced nutrition and amelioration of mineral toxicities/deficiencies</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Water management</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Weeds, insects and diseases</td>
<td>*</td>
<td>***</td>
</tr>
<tr>
<td>Timing and amount of N applications</td>
<td>-</td>
<td>***</td>
</tr>
<tr>
<td>New fertilizer products (slow/controlled release fertilizers, supergranules, N-inhibitors)</td>
<td>-</td>
<td>***</td>
</tr>
<tr>
<td>Placement of fertilizer</td>
<td>-</td>
<td>***</td>
</tr>
</tbody>
</table>

- no significant influence; * some influence; ** moderate influence; *** strong influence
Fertilizer Indicators: improvement over time

FFP – Farmers’ fertilizer practice
SSNM – Site-specific nutrient management (field-specific adjustment of N, P, and K)

Means of 23 rice farms in Jinhua District, Zhejiang Province, China, 1998 to 2000
E – early season rice; L – late season rice

1998: Field-specific N rate (SSNM)
1999 & 2000: Field-specific N rate (SSNM) + in-season N adjustment (chlorophyll meter)

6 consecutive rice crops grown in the same fields
Impact of genetic improvement: maize hybrids in the USA

Crop Indicators

**Crop indicators:**

- **Internal Efficiency (kg/kg)**
  \[ \text{IE} = \frac{Y}{U} \]

- **Nutrient Concentration (%)**
  \[ \text{NC} = \frac{R}{Y} \]

- **Nutrient Harvest Index**
  \[ \text{NHI} = \frac{R}{U} \]

**Footprint for calculation:**
field, farm by crops, groups of farms, etc.

**Time scale:**
one cropping season

**Major uses:**
breeding, biofortification (genetic, fertilizer), nutrient management for crop quality (e.g. protein, minerals)
Impact of genetic improvement: maize hybrids in the USA

A mineral plant nutrient is an element which is essential or beneficial for plant growth, development or the quality attributes of the harvested product.

What is a plant nutrient? Changing definitions to advance science and innovation in plant nutrition

Patrick H. Brown · Fang-Jie Zhao · Achim Dobermann
Selenium enrichment through fertilizers in Finland

Fertilizer Se enrichment levels (mg Se/kg fertilizer)
Nutrient balance based on inputs and outputs (partial balance)

\[ \text{Nbal} = (W+D+B+M+F) - R \]

Nutrient use efficiency based on outputs and inputs

\[ \text{NUE} = \frac{R}{(W+D+B+M+F)} \]

System indicators:

Footprint for calculation:
field, farm, group of farms (customers), region, state, country, world, etc.

Time scale:
cropping season, cropping system (year), several years
System Indicators: Nutrient Balance and Nutrient Use Efficiency

Nutrient inputs

- Seed
- Fertilizer
- Manure
- Agricultural BNF
- Deposition

Nutrient outputs

- Volatilization/emission (e.g., NH$_3$, NO, N$_2$O, N$_2$)
- Crop product + by-product
- Leaching/runoff (e.g., NH$_4^+$, NO$_3^-$, DON, PON)

Nutrient balance = Inputs – Outputs
Nutrient use efficiency = Outputs/Inputs

Both based on partial nutrient balance

Calculation is simple and based on:
- Farm records (e.g. seed, fertilizer, manure, crop yield)
- Average values (coefficients) for other components (e.g. biological N fixation, atmospheric N deposition, grain nutrient concentration, manure nutrient content)
System NUE: Application & Interpretation

• Plot N output vs N input
• N output represents productivity
• Slope from any point to origin represents NUE
• N surplus can also be plotted as a line
• Very high NUE can degrade soil (nutrient depletion)
• Very low NUE represents risk of environmental pollution and waste of money

https://www.eunep.com/
System NUE: Application & Interpretation

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<table>
<thead>
<tr>
<th>Interpretation</th>
<th>Nitrogen Use Efficiency (NUE) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cropping systems</td>
</tr>
<tr>
<td>Soil N mining</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Risk of soil N mining</td>
<td>90-100</td>
</tr>
<tr>
<td>Balanced N fertilization</td>
<td>70-90</td>
</tr>
<tr>
<td>Risk of N losses</td>
<td>50-70</td>
</tr>
<tr>
<td>High risk of N losses</td>
<td>&lt;50</td>
</tr>
</tbody>
</table>

Proposed for different farm types in Europe

https://www.eunep.com/
System NUE: Application & Interpretation

• Good for analyzing and benchmarking farms and tracking progress over time

Example:
• NUE in farms in the Netherlands during 2015–2017 cultivating cereals and ware potato (WP), cereals, seed (SP) and starch potato (StP), and cereals, sugar beet (SBt) and spring onion (SO)
• Self-recorded by farmers in commercial farm management systems for crop registration

Silva et al. 2021. Field Crops Research
https://doi.org/10.1016/j.fcr.2021.108176
System NUE: National to Global Application

- Good for analyzing and benchmarking countries and regions and tracking progress towards a target

Example:
- NUE of all global cropland, 1960-2021
- Based on FAO-IFA Cropland Nutrient Balance database (national statistics)
- Indicated is a global target of 70% NUE (dashed line)
System NUE: National to Global Application

FAOSTAT domain Cropland Nutrient Balance
USA

- Low N surplus
- Increasing NUE – much soybean
- Local hotspots & opportunities

2002-2021: +782 kg N/ha

EU27

• Declining N surplus
• Room to improve NUE
• Very diverse among countries and systems

China

• Rapidly decreasing surplus – but still large
• Rising NUE (2011: 35%; 2021: 50%)
• Change in policy is showing results


2002-2021: +3712 kg N/ha
India

- Large, increasing N surplus
- Low NUE, no improvement
- High fertilizer subsidies = lack of incentives

General trajectory of nitrogen use and use efficiency in agriculture

Labels indicate the approximate current status of a country or region.
Definitions & Indicators

Nutrient input and output flows in soil-crop systems

Fertilizer indicators:
Partial Factor Productivity
\[ \text{PFP} = \frac{Y}{F} \]
Agronomic Efficiency
\[ \text{AE} = \frac{(Y-Y_0)}{F} \text{ or: } \text{AE} = \text{RE} \times \text{PE} \]
Recovery Efficiency
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System indicators:
Nutrient use efficiency based on outputs and inputs
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Nutrient Indicators: Application & Interpretation

Research:
• Rigorous field evaluation of new products, technologies, management practices
• Development and evaluation of decision support solutions for nutrient management/precision farming
• Use all fertilizer indicators: PFP, AE, RE, PE, GRF
• Crop indicators for breeding, biofortification: NC, IE, NHI

Farming:
• Quantify and understand fertilizer efficiency
• Performance analysis (agronomic, economic) to guide field (farm) management, including benchmarking against desirable targets or leading farmers
• Monitoring of changes over time (progress in efficiency improvement), including environmental and soil health
• Most useful indicators: PFP, GRF, NUE and Nbal
  → PFP, NUE and Nbal are simple to calculate and important for farmers because they integrate the use efficiency of both indigenous and applied nutrients
What should we aim for?

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Desirable levels for N efficiency in well-managed cereal crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery Efficiency</td>
<td>0.50-0.80 kg N in plant/kg N applied (50-80%)</td>
</tr>
<tr>
<td>Physiological Efficiency</td>
<td>&gt;50 kg grain/kg fertilizer N taken up</td>
</tr>
<tr>
<td>Agronomic Efficiency</td>
<td>&gt;25 kg grain/kg N applied</td>
</tr>
<tr>
<td>Partial Factor Productivity</td>
<td>&gt;50 kg grain/kg N applied</td>
</tr>
<tr>
<td>N balance</td>
<td>&lt;50 kg N/ha surplus</td>
</tr>
<tr>
<td>System NUE</td>
<td>70-80%</td>
</tr>
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</table>

→ But this may vary substantially
Summary

• **Research and development**: use a range of fertilizer and crop indicators and ensure complete experimental designs and measurements to calculate them, including proper controls and nutrient response curve.

• **Agronomic guidance and farm management**: use PFP, GRF and system indicators (Nutrient balance and NUE).

• **Farm monitoring and benchmarking, large-scale agricultural and environmental monitoring/progress evaluation, policy setting**: use system indicators (Nutrient balance and NUE).