Ecological Intensification and 4R Nutrient Stewardship: Measuring Impacts

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The impacts of improved management can be assessed through common production and nutrient balance measures.

However, the assessment of the sustainability of ecological intensification (EI) requires that these measurements be linked to changes in soil nutrient status and to farm level profitability.

The effective, productive, and efficient use of fertilizers is fundamental to feeding the global population, with around half of current food production made possible by balanced crop nutrient input. At the same time, there are parts of the world where fertilizers are under-used so that food security is threatened and soil fertility degraded, or where they are overused to the point of contributing to environmental pollution (e.g., N, P).

Farmers and their advisers turn to science to help define and then refine the ways inputs are used to produce adequate, good quality food, ensure minimal environmental impact, and maintain the soil resource. The IPNI Global Maize Project (GMP) provides data from over 20 sites that can be used to compare typical farmer practice (FP) to what scientists and local agronomists believe to be improved practices aimed at sustainably improving yields and meeting the standards for environmental quality—a goal termed Ecological Intensification (EI). These EI practices differ from region to region but include strategies for better cultivars, balanced nutrition, and improved soil and crop management. The initial EI treatments in the GMP were estimates of an ideal set of practices for accomplishing the objectives of EI at a given site. However, the long-term aspect of the GMP provides opportunities for the local agronomy team to make adjustments in the practices as observations and measurements suggest and to accommodate improved technologies or genetics as needed during the experiment.

Crop yield is a key measure of the response of any system to changed management practices, but this response can be considered in concert with selected nutrient use efficiency (NUE) metrics. System efficiency and effectiveness can be defined in many ways and a selection of these is shown in **Table 1**. Deciding on the most appropriate indicator will depend on the types of data available and the purposes to which they will be put.

Table 1. Four metrics commonly used to describe nutrient use efficiency (NUE) and some typical values for those indicators with reference to N in particular.

NUE metric	Calculated from	Typical values for N (maize or wheat, after Dobermann, 2007)
Partial Factor Productivity *PFP: kg grain/kg fertilizer*	Y/F	40-80
Partial Nutrient Balance *PNB: kg nutrient removed/kg fertilizer*	R/F	<1.0 = more supplied than removed >1.0 = more removed than supplied
Agronomic Efficiency *AE: kg grain increase/kg fertilizer*	$(Y-Y_0)/F$	10-30
Recovery Efficiency *RE: kg nutrient increase/kg fertilizer*	$(U-U_0)/F$	0.5 (whole-plant) 0.3 (grain only)

Y = crop yield with applied nutrients; Y_0 = crop yield with no applied nutrients; F = fertilizer applied; U = crop nutrient uptake into harvested portion with applied nutrients, U_0 = crop nutrient uptake with no applied nutrients.

Agronomic efficiency (AE) quantifies the yield gained or lost per rate of nutrient applied. It is directly related to the profitability of the nutrient application: the greater the AE, the greater the profitability.

Recovery efficiency (RE) estimates the proportion of the nutrient applied that is taken up by the crop. For a given set of conditions, some or all crop nutrient uptake needs will be met by the supply of nutrients in the soil. When the soil is unable to meet these needs, the shortfall must be made up by a nutrient application. Recovery efficiency quantifies how efficiently that application makes up the shortfall (Stanford, 1973). Higher recovery efficiencies mean the fertilizer is accessed and used more efficiently by the crop. There are many factors that affect RE, such as more efficient genotypes for nutrient uptake, the quantity of nutrients already present in the soil, and the degree to which nutrients transfer among soil pools.

Both RE and AE require a nil fertilizer application treatment to estimate the extra yield or nutrient uptake resulting from the added fertilizer. Such measures are normally only available on research plots (at research stations or on-farm), which limits their usefulness in non-research settings; however, there are two NUE indicators that are well-suited to evaluations at a field, farm, or regional level: partial factor productivity (PFP) and partial nutrient balance (PNB).

Partial factor productivity compares yield to the quantity of fertilizer applied. It answers the question *"How productive is this cropping system in comparison to its nutrient input?"* It will usually decline with increased nutrient inputs because of the principle of diminishing returns, although at rates well below the optimum rate, linear yield responses can occur.

Partial nutrient balance compares the quantity of nutrient being taken out of the field to the amount of nutrient applied. A ratio is used to quantify PNB; however, it can also be converted to mass balance (net kg or lb of nutrient removed or added), termed nutrient balance intensity.

System level PNB only indicates the fate of nutrients removed in harvested produce. It does not consider other

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium. IPNI Project GBL-GM17

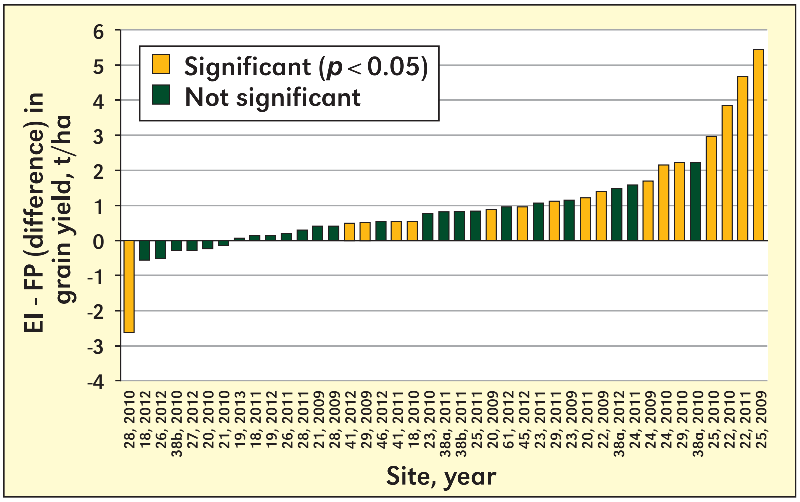

Figure 1. The difference in grain yield between Ecological Intensification (EI) and Farmer Practice (FP) for 41 sites in the Global Maize Project.

transfer processes, and so does not necessarily indicate the risk or amount of nutrient losses to the environment. Further, none of these indicators reference soil health or soil nutrient levels, so are incomplete in their description of sustainability impacts. More discussion on selecting appropriate nutrient performance indicators can be found in Fixen et al. (2015) and Norton et al. (2015).

In this paper, we discuss the impacts of the EI management treatments on the specific nutrient use efficiency (NUE) indicators listed in **Table 1**. The experimental designs implemented in the GMP make it possible to quantify all four indicators only for N. For P and K, only PNB is presented.

Effective Use of Nutrients

Raising grain yield (t/ha) is one of the main objectives of improved management, with the ultimate purpose of increasing the profitability of maize production. Here, we simply express it as the yield gain due to EI. Of the 41 site-years compiled to date for the GMP, 16 site-years showed a statistically significant increase ($p<0.05$) in yield of EI over FP, while only one site-year produced lower yields with the EI compared to the FP. The lower yield was at Celaya, Mexico, 2010, where very high N rates were used. At the other site-years, there were no statistically significant differences between EI and FP. **Figure 1** shows the yield differences between FP and EI across all 41 site-years.

Productive Use of Nutrients

Even though yields may increase as a result of EI, the relative role of nutrients in contribution to this increase can be assessed with reference to the PFP. PFP is a simple production efficiency metric that can be easily calculated from smallholder farmer's fields to whole nations where there are reliable records of yield and nutrient inputs. PFP is only applicable where a single product (e.g., maize, milk, canola) is the output of the system, so is of lesser value in assessing efficiencies of mixed farming systems that produce a range of products.

PFP does not consider the contribution of soil reserves to crop yield, and because of the typical shape of a yield response curve to nutrients, PFP will usually be largest for the first unit or units of fertilizer and then decline as additional nutrient is supplied. Therefore, a very high PFP indicates that the system is operating at lower yields than when the PFP is lower, and/or that a large proportion of crop N is supplied from soil N. A very low PFP value indicates that there has been little yield response to the fertilizer applied, and this may be a consequence of high inherent soil fertility, or due to other factors limiting yield such as pests, disease, or adverse weather.

Figure 2 is a summary of the PFP values for maize in response to N applications at the GMP sites. There were seven site-years when the PFP_N for the FP treatments was 100 kg grain/kg N or more, compared to a typical value of 40 to 80 kg grain/kg N (Dobermann, 2007). So, while this indicates a large return of grain for fertilizer N supplied, it suggests that these sites were at the lower end of the yield response curve. In 24 site-years, EI treatments lowered the PFP_N, although some values were already low—indicating that those low PFP_N sites were less responsive sites than where PFP_N for the FP treatments was higher.

Efficient Removal of Nutrients

Partial Nutrient Balance reflects only one of several transfer processes that operate with crop nutrients. A PNB of 1 indicates that the same amount of nutrient (e.g., N, P, or K) was removed in the grain as was supplied as fertilizer. If the value is more than 1, more nutrient is being removed than is being applied, so that soil reserves are likely being depleted. Alternatively, if the value is less than 1, more nutrient is being applied than is being removed. This ratio does not indicate the fate of the extra nutrients, nor if the "surplus" is likely to be ecologically damaging or benign. Where low soil nutrient status is present, PNB less than 1 could indicate improvement in the inherent soil fertility; but where PNB is very low, there may be a higher risk of loss to the environment. Interpreting the PNB values

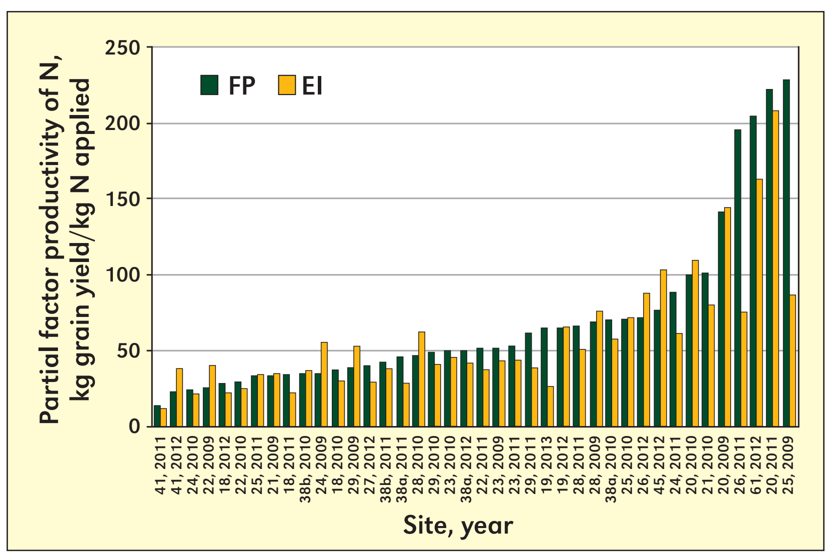

Figure 2. The partial factor productivity for N (PFP_N) for Ecological Intensification (EI) and Farmer Practice (FP) compared over 17 of the sites in the Global Maize Project where PFP_N values were statistically different between the practices.

Table 2. Changes in PNB for N, P, and K with Ecological Intensification (EI) compared to Farmer Practice (FP) at the Global Maize Project sites for different yield responses. Not all nutrient removals were measured at all sites.

Yield	PNB_N Better	PNB_N Same	PNB_N Worse	PNB_P Better	PNB_P Same	PNB_P Worse	PNB_K Better	PNB_K Same	PNB_K Worse
EI > FP	6	4	3	8	1	-	5	2	-
EI = FP	5	12	4	3	13	3	2	7	7
EI < FP	-	-	1	-	1	-	-	1	-
Totals		35			29			24	

requires reference to soil test values or indigenous nutrient supplies over several seasons or years to assess the true effect on soil reserves.

PNB_N was calculated for 35 site-years in the GMP. PNB_N was not significantly different between FP and EI in 16 site-years. **Figure 3** shows the PNB_N for EI and FP at 19 site-years where there were significant differences between the two management systems, with the Y-axis reset to a PNB of 1. In terms of balancing nutrient input and output, moving higher or lower is not necessarily better or worse, but raising low values and lowering high values can be environmentally and sustainably significant. Of the statistically significant effects, at six site-years PNB_N values above 1.25 under FP were lowered in the EI treatment. At another four site-years, PNB_N less than 0.75 under FP was raised with EI. Across all 19 site-years with statistically significant treatment effects, 14 saw reductions in PNB_N with the EI treatment; however, at five of these, the decline was relatively small (<0.15), even though statistically different. The impact of the low PNB_N will depend on the antecedent soil N status and the susceptibility of the N to environmental losses. Low PNB_N where soil test levels are low could result in soil fertility improvement or higher N losses where there is susceptibility.

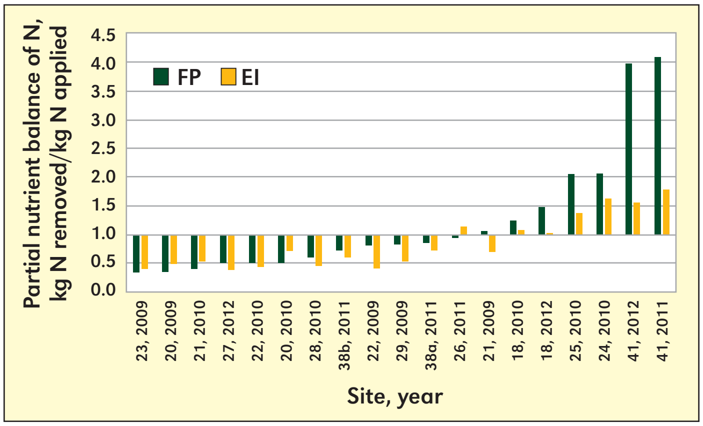

Figure 3. Comparison between Ecological Intensification (EI) and Farmer Practice (FP) in terms of partial nutrient balance for N for 19 sites in the Global Maize Project where the balances were statistically different between the practices.

Nutrient Efficiency Interactions

Because of the interactions among nutrients, management, and the environment, improved production system(s) performance cannot be adequately assessed by a single measure. Higher yields often mean more nutrient is removed, so that PNB can decline as the crop removes more nutrient from the soil. As a result of the higher yield, PFP can increase but at the expense of soil reserves. **Table 2** summarizes the changes in PNB for N, P, and K between the EI and FP treatments, at different yield responses from the GMP sites where nutrient removal was measured. PNB was considered to improve (better) where a low PNB (PNB<0.8) was raised, or a high PNB (>1) was lowered. In these metrics, the goal would be to maintain or improve yield while improving or maintaining PNB (green shading), and from the GMP, this has been achieved at 27 site-years for N, 25 site-years for P, and 16 site-years for K. The sites in cells colored yellow or orange require additional consideration of the management practices to either improve yield or PNB.

The impact of changes in PNB should not be considered without an assessment of the changes in soil reserves of the nutrients. If the soil nutrient reserves are at optimum levels, then the target PNB may be near unity. If soil nutrient reserves are adequate or plentiful, it may be appropriate to exploit those fertility reserves, so a PNB>1 may be appropriate. Conversely, if soil fertility is depleted, extra nutrient(s) may be required to increase nutrient reserves by applying more nutrient than is removed (PNB<1).

These performance indicators of sustainable plant nutrition from the IPNI Global Maize Project underscore the importance of tracking crop yields, PNB, and PFP linked to soil nutrient supplies. In addition, it is important to understand the economic costs and benefits for the farmer, since farmer profitability must also be improved or maintained for both short- and long-term success. BC

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