INTERNATIONAL FERTILIZER ASSOCIATION

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REGIONAL NUTRIENT USE EFFICIENCY TRENDS AND SUSTAINABLE FERTILIZER MANAGEMENT

This paper is based on the Nitrogen Use Efficiency (NUE) trends of six countries with different profiles (Brazil, China, Denmark, India, Nigeria and USA) and provides key insights about factors that could potentially favour or hinder fertilizer management improvements across different regions.

The importance of fertilizers for global food security is widely recognized, as it is estimated that **half the food we eat today is produced thanks to mineral fertilizers** (Erisman *et al*., 2008). Their importance will continue to grow in coming years: with the world population expected to reach almost 10 billion people by 2050, the agricultural sector will need to increase its productivity by about 50% between 2012 and 2050 to meet an increasing global demand in food (FAO, 2018), which cannot be achieved without fertilizers.

However, as fertilizers are applied into leaky biological systems, they are naturally subject to losses to the environment. Therefore, plant nutrient sources need to be carefully managed and applied according to crop- and site-specific needs to achieve the "triple wins" of food security, environmental protection, and climate change adaptation and mitigation.

This backgrounder focuses on **nutrient use efficiency**, i.e. the proportion of nutrients applied from all sources that are taken up by the crop; a useful indicator to determine the efficiency of fertilizer management, whilst minimizing environmental losses.

Nitrogen Use Efficiency[1] is measured as the **ratio between the nitrogen (N) output** (the amount of N removed from the field with the harvested product) and the **N input** (the sum of the amounts of N applied to cropland from mineral fertilizers and livestock manure, and biological N fixation by leguminous crops [e.g. soybean], rice and sugarcane[2]).

Low output/input ratios, **below 50%**, often reflect risks of nutrient losses to the environment, while high ratios, **above 100%**, reflect soil nutrient mining practices[3] that reduce soil fertility if practiced over several years. **Both cases are unsustainable.** The N output/input ratio is generally considered close to the optimum around 60-90%, depending on the farming system and the crops cultivated, where crop productivity is high.

NUE trends vary widely between regions and countries because of the diversity of soils, crops, climate, farmers' access to technology and knowledge, policy priorities and fertilizer management. For instance, crops such as fruits and vegetables have typically a lower NUE due to their high requirements in N inputs to grow, whereas leguminous crops (e.g. soybean) have a high NUE due to their ability to convert N from the air into forms of N they can use, a process called Biological N Fixation (BNF). Similarly, sandy soils have a lower NUE potential than loam soils owing to their lower ability to retain nitrates.[4]

1 The choice of NUE as an indicator for this submission is due to the fact that N fertilizers are the most consumed globally, and the N output/input ratio is a helpful metric to assess the efficiency of N fertilization (from all sources).

2 In absence of robust historical time series per country, atmospheric N deposition has not been taken into account in this analysis.

3 These practices result in a negative nutrient balance in soils, where nutrient losses exceed nutrient inputs.

4 The greatest potential for high NUE is on loam soils, intermediate between sandy and clay.

Figure 1 below summarizes the NUE trajectory observed in many countries, where N surpluses (N inputs minus N outputs) increase with crop yield if the knowledge and technology are not easily available to farmers; indeed, before countries adopt N fertilizers, their NUE is very high, often well over 100%, as they do not have enough N from manure or BNF to offset N removal with harvests. As N fertilizers become available (and sometimes subsidized to stimulate demand), consumption generally increases much faster than removal by crops. As a result, NUE drops quickly.

A turning point is typically reached once medium to high yields are attained, when farmers, policymakers, scientists and other stakeholders prioritize the improvement of NUE to limit N losses to the environment. At this "turning point", N surpluses stabilize or decrease owing to access to improved knowledge, inputs and technologies. Such improvements protect crop productivity while reducing N losses. Countries vary widely in their crop productivity and NUE and many appear to be on different points of the U-shape curve illustrated below.

For several of them (particularly in sub-Saharan Africa), building on experiences of developed countries and countries with economies in transition, taking environmental considerations into account from the beginning and adopting policies that simultaneously encourage greater and more efficient use of N fertilizer would allow them to "tunnel through" the U-shaped curve and avoid a turning point at an unsustainable low NUE level.

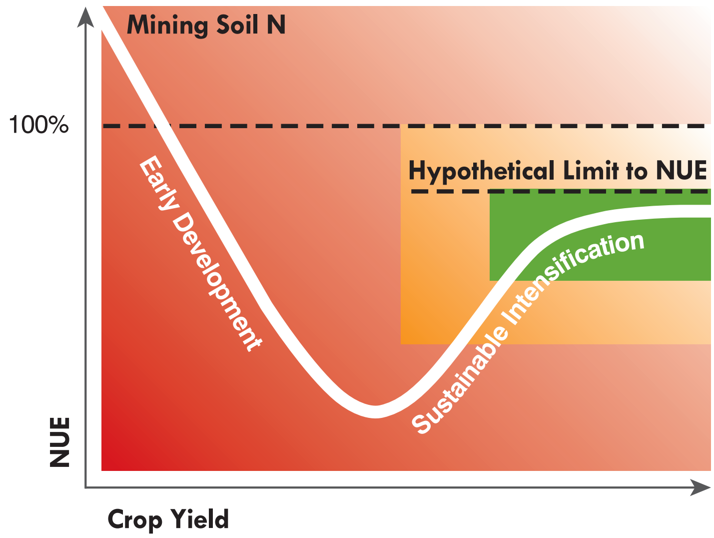

Figure 1: Typical NUE trend relative to crop yield over time (adapted from Zhang *et al.* 2015)

NUE declined in most developed countries until the 1980s, before improving since then, while most large fertilizer-consuming developing countries have had further gradual decline. With developed countries and China, nowadays, it is almost 60% of world fertilizer consumption that follows a virtuous NUE trend. Sub-Saharan African countries, who have currently an NUE of over 100% due to widespread underuse of fertilizers, are also adopting a more virtuous NUE trend, reflecting rising N fertilizer use and crop yields.

At the global level, following a drop until the end of the 1980s, NUE is steadily rising for three consecutive decades, driven by continuous improvement in developed countries and, more recently, in China. Global NUE is estimated at 59% in 2017.

NUE COUNTRY PROFILES

The following six case studies provide an overview of the diversity of country NUE profiles in the world. They also highlight options for each country that could lead to an improvement of nutrient management, which would contribute to environmental protection, food security and climate change adaptation and mitigation.

BRAZIL:

High NUE due to the prominent place of soybean in the crop mix in intensified grain systems

Brazil's NUE estimates have remained high since the 1960s, ranging from 70% to 90%, with a temporary decrease in the mid-1970s (from 70% to 62%) followed by a rapid rebound, that reflected poor harvests relative to N inputs followed by an accelerated use of all N inputs (BNF, manure and fertilizer) compared to growth in crop production. During this time period, Brazilian agriculture diversified from prominently sugarcane, coffee, tobacco and rubber production to include maize, soybean, wheat, fruits and vegetables. Agricultural productivity began increasing rapidly in the 1970s thanks to the adoption of soil amendments, such as lime, NPK fertilizers and adapted crop varieties.

Subsequently, NUE increased in the early 1980s and again in the mid-to-late 2000s, during periods where growth of the N output outpaced that of N inputs. Brazil has sustained its productivity growth coupled with a high NUE, with the latter averaging 91% in 2017. While Brazil's high NUE was a result of low N input in the 1960s, the country has maintained its NUE amidst increasing productivity primarily due to the contributions of BNF in soybean and, to a lesser extent, sugarcane systems. Furthermore, its tropical and subtropical climates permitted the rapid increase of soybean and maize production within intensified double-cropping systems in the Cerrados region. Notably, inputs from fertilizer and manure sources have also continued to increase.

USA:

Adoption of fertilizer BMPs by corn growers and a large area planted to soybean contribute to a high average NUE level

USA's country-level NUE declined sharply in the 1960s, reflecting the rapid adoption of fertilizers relative to crop production gains, before stabilizing in the 1970s and 1980s due to gains in crop productivity keeping pace with additional BNF and fertilizer inputs. Since the mid-1990s, USA's NUE has largely improved, reflecting further enhancements in productivity and a slowing growth in N inputs other than BNF. In 2017, the USA had a high NUE of 72%, largely attributable to high technology adoption (fertilizer, seed, crop protection and precision agriculture), broad implementation of the 4Rs and the predominance of soybean and cereals in the crop mix.

Agricultural production, and thus NUE, varies regionally in the USA, and the national trends are largely driven by one region (the Corn Belt) characterized by a high proportion of BNF and lower proportion of manure in the total N input (Swaney *et al.*, 2018). Site- and crop-specific fertilizer management, digital farming and continual improvement in crop varieties are needed to further enhance NUE in the decades to come.

DENMARK:

Nitrogen policies improved NUE by imposing organic and mineral nutrient application limits; however too low limits have impacted the quality of Danish wheat

Denmark's NUE trend is characterized by a decline until the mid-1970s, followed by a steady increase since then from 24% in 1976 (unsustainably low) to 62% in 2017 (near optimal). The initial decrease in NUE was caused by a rapid increase in fertilizer N inputs in the 1960s and 1970s, which exceeded the growth in productivity (e.g. limited crop responsiveness). During this time, manure N inputs already exceeded crop N removal. Denmark's NUE began improving as manure N inputs declined and fertilizer consumption plateaued in the 1980s.

Since 1985, Denmark has introduced a series of Nitrogen Policies aimed at reducing N losses by limiting the application of N fertilizers (from mineral fertilizers and manure). As part of the implementation of the EU Nitrates Directive, Denmark has determined a "Nitrate Vulnerable Zone" covering its entire national territory and has established a Code of good farming practices to be implemented on a mandatory basis for farmers to comply with.

The current regulation in Denmark is based on a plan for sustainable agriculture developed in 1991, where N quotas and fertilizer accounts were introduced (Knudsen, 2016). The regulation led to a reduction in the use of mineral N fertilizers by 50% over the period 1991-2003, and it has remained fairly stable since then. As these quotas were based on sub-optimal rates (and only revised in 2017), they have resulted in a higher loss of income for agriculture than originally expected by Danish decision-makers. Under-fertilization has increased because the need for N has grown over time due to higher yield potentials, and lower mineralization of N from the soil because of lower input. In addition, increasing prices of protein have led to higher demands for N.

In a nutshell, the Danish Nitrate Action Program was for long based on fertilization limits by crop, which were below the economic optimum. It has led to the steady decline of Danish wheat quality.

CHINA:

Still comparatively low NUE owing to limited adoption of fertilizer BMPs, but significant improvements have occurred in the last 10 years

From the 1960s to the 1990s, China's country-level NUE declined dramatically, reflecting the rapid adoption of fertilizers relative to crop production gains. China's NUE stabilized in the 1990s, and N inputs plateaued in the 2000s while crop production continued to grow. Over the past 10 years, NUE has begun improving, presumably due to improved fertilizer, soil and crop management (He *et al*., 2018). Substantial increases in NUE among millions of smallholder farmers between 2005 and 2015 have been documented (Cui *et al*., 2018) and opportunity exists to further extend the implementation of enhanced practices. China had an average NUE of 47% in 2017, which is still lower than many other countries. Its relatively lower NUE is largely attributable to the large share of less efficient fruits and vegetables in the crop mix, prevalence of smallholder farming and low levels of technology adoption.

China's NUE is expected to continue improving under China's zero growth policy adopted in 2015, and through greater mechanization and further technological improvements. Both fertilizer application rates and yield gaps for most crops remain large, which are indicative of sub-optimal management practices. Fertilization remains not only important for closing yield gaps, but also for maintaining productive agricultural systems. Along with reduced tillage, adequate and balanced fertilization helps to prevent losses of soil organic matter in China's agricultural systems (Huang and Sun, 2006).

INDIA:

Low and stable NUE owing to fertilizer subsidies and low adoption of fertilizer BMPs by farmers

Since the beginning of the 1960s, India's NUE has declined from 101% (unsustainably high) to 37% in 2009 (low NUE), and it has stabilized at about 40% since then. This decline is in part due to the release of high-yielding rice and wheat varieties in the 1960s, which led to the rapid adoption of N fertilizers. Over time, fertilizer N consumption outpaced the steady increases in agricultural productivity. Since 1985, the decline in NUE slowed, reflecting changes in N consumption patterns with continual improvements in output. In 2000, fertilizer consumption stabilized for several years, but growth resumed in the mid-2000s before temporarily plateauing in 2013. India has not yet been able to increase its NUE since 2013. The Indian Nitrogen Assessment states that imbalanced fertilization (e.g. excess N and phosphorus [P] relative to potassium [K], Sulphur [S], and micronutrients), and in turn declining soil health, is responsible for its low NUE.

Fertilizer consumption in India is strongly influenced by fertilizer subsidies (Gulati, 2017). Since the inception of the fertilizer subsidy program in the 1960s, urea (the main fertilizer used in the country) has remained heavily subsidized. In 2010, changes to the fertilizer subsidy scheme have also freed prices for P, K and non-urea N fertilizers. This change led to a significant price gap that has encouraged imbalanced and inefficient fertilization practices and continued low NUE. Farmers' low adoption of BMPs is an additional constraint to improving NUE. The outlook for the country's NUE will be primarily driven by future changes to the fertilizer subsidy policy.

NIGERIA:

NUE levels well above 100% reflect too low input rate and continuous soil mining, which undermines crop productivity

Nigeria's NUE is unsustainably high and consistently exceeded 100% since the 1960s. This is indicative of soil N mining, where N removal exceeds N inputs into the system. As of today, Nigeria's agriculture continues to be characterized by low N inputs and low yields. During the last 10 years, the country's average NUE fluctuated between 120% and 190%. High year-on-year variations largely reflect changes to the fertilizer subsidy scheme.

A holistic approach is necessary for increasing the country's crop productivity, including access to and integration of fertilizer inputs, soil conditioners, crop protection, seed technology, irrigation and other inputs, as outlined by Nigeria's recent "Agricultural Promotion Policy" (Federal Ministry of Agriculture and Rural Development, 2016).

In a long-term perspective, based on demographic projections to 2050, Nigeria will have to reduce its yield gap from about 80% today to 20% only, should the country want to maintain its current level of self-sufficiency for cereals. Such an ambitious productivity gain can only be achieved through a significant increase of the N input to cropping systems (ten Berge *et al*, 2019), which should at least offset N removal with the harvested crops.

KEY FINDINGS

BASED ON THESE SELECTED COUNTRY PROFILES:

- Too high and too low output/input ratios (NUE) levels are equally unsustainable;
- Countries typically follow a U-shape NUE trend;
- NUE must be interpreted within the context of crop production systems;
- Countries with a large share of their area planted to leguminous crops have a higher NUE while countries with a high proportion of less N use efficient crops (e.g. fruits and vegetables) have a lower NUE;
- Countries where farmers use improved crop varieties, irrigation, fertilizer best management practices and technology (e.g. precision farming) have a higher NUE;
- Countries where fertilizer price is heavily subsidized have a lower NUE;
- Countries with high livestock production density (i.e. higher percentage of total inputs as manure N) have a lower NUE;
- Sub-Saharan African countries (and countries with similar low fertilizer application rates and low crop yields) can learn from experiences elsewhere and potentially avoid the U-shape trend.

CONCLUSIONS

These selected country profiles demonstrate how plant nutrition varies importantly across regions, and that factors such as cropping systems, soil types, climate, access to technology, policies/subsidy schemes and adoption of fertilizer Best Management Practices (BMPs) can influence measurably the overall nutrient use efficiency trends in the country.

Adopting and implementing **fertilizer Best Management Practices (BMPs) tailored to site- and crop-specific conditions** are required to enhance NUE and reduce losses to the environment while increasing yields. The fertilizer industry actively promotes fertilizer BMPs around the world to encourage farmers to use fertilizers in an efficient and effective way: it has developed the global **"4R" nutrient stewardship framework, which entails applying the Right nutrient source, at the Right rate, at the Right time, in the Right place.** In addition to the suites of application decisions and practices that are utilized within the 4Rs, the industry is advancing innovative products and technologies that enable further improvements in NUE relative to selecting the Right source. Research and development to further improve productivity with reduced loss to the environment is underway across the fertilizer industry.

The industry also endorses fertilizer BMPs such as **balanced fertilization** (i.e. assuring a proper supply of all macronutrients and micronutrients in a balanced ration throughout the growth of crops); and **Integrated Plant Nutrient Management (IPNM)** which combines mineral and organic nutrient sources, building on their respective advantages. Empirical evidence suggests that a combination of mineral fertilizer and organic fertilizer seems most promising for sequestering soil carbon in agricultural soils (Hijbeek *et al.*, 2019). These approaches to fertilizer BMPs complement and support one another.

IFA encourages policymakers to take into consideration their countries' specificities in terms of soils, crops and climate, and to tailor their plant nutrient recommendations according to these. **Site- and Crop-Specific Nutrient Management,** including a balanced use of all essential crop nutrients is key to achieving sustainable and resilient agricultural systems, as it allows growers to match the nutrient supply with crop requirements, minimizing losses to the environment while maintaining soil fertility and optimizing yields.

5 NUE is also impacted by the use of the other nutrients, and it improves when all essential plant nutrients are used in a balanced manner meeting plants' requirements.

Precision agriculture, aided by technology, has proven to increase productivity while reducing greenhouse gas emissions, steering agricultural systems towards a sustainable, input-optimized model. The fertilizer industry and its research partners have developed several precision agriculture solutions, including mobile applications that allow farmers to send pictures of their crops and receive tailored fertilizer recommendations; hand-held sensors that can measure the N status of crops; water sensors that can assess the water requirement of plants by measuring pressure on leaves; and even simple tools like a Leaf Color Chart that can guide farmers with their N fertilization based on leaf greenness.

An important challenge for the implementation of fertilizer BMPs is reaching out to the world's 500 million farmers, especially smallholders, to make them knowledgeable in site- and crop-specific plant nutrition. National governments can play an important role in that regard, by adopting policies prioritizing farmers' access to knowledge, inputs and markets. Subsidy schemes should also be tailored to each country's nutrient management performance, to promote the efficient and balanced use of plant nutrients, or to ensure farmers have access to inputs where they are under-used.

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