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Perspective

Robust relationship between yields and nitrogen inputs indicates three ways to reduce nitrogen pollution

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Abstract

Historic increases in agricultural production came at the expense of substantial environmental burden through nitrogen pollution. Lassaletta *et al* (2014 *Environ. Res. Lett.* **9** 105011) examine the historic relationship of crop yields and nitrogen fertilizer inputs globally and find a simple and robust relationship of declining nitrogen use efficiency with increasing nitrogen inputs. This general relationship helps to understand the dilemma between increased agricultural production and nitrogen pollution and allows identifying pathways towards more sustainable agricultural production and necessary associated policies.

Keywords: nitrogen use efficiency, nitrogen, fertilizer, nitrogen pollution, agriculture, yields, mitigation

The response of crop yields to fertilizer inputs is a long-standing topic of agricultural science. The 'law of the minimum' by Carl Sprengel (1828) according to which plant growth would be limited by the scarcest nutrient, was replaced by Ehrlich Alfred Mitscherlich (1909) through the 'law of diminishing returns' of plant growth to additional nutrient inputs. Lassaletta *et al* (2014) now show in a comprehensive analysis of historic data for 124 countries of the past 50 years that this law is often valid for the relationship between crop yields and nitrogen inputs on a country-level and over a long time-span. They observe that the nitrogen in crop yields (Y) generally responds to organic and inorganic nitrogen fertilizer inputs (F) according to a Michaelis–Menten functional relationship, approaching a maximum yield (Y_{max}); i.e. $Y = (Y_{max} \times F)/(Y_{max} + F)$. However, they also observe that the general agronomic practices can improve, leading to an upward shift of the production frontier (Y_{max}).

The relationship between yield and fertilization is not only of interest to understand plant growth, but also helps to comprehend the dynamics of nitrogen use efficiency (NUE). Currently, the global NUE, which is the share of the nitrogen fertilizer taken up by the crops ($\text{NUE} = Y/F$) is only about 50% (Bodirsky *et al* 2012), while the remainder pollutes the air and ecosystems, also harming human health substantially (Sutton *et al* 2013). Increasing the NUE is therefore one of the key nitrogen mitigation options in the agricultural sector (Sutton *et al* 2013), and can contribute a similar share to nitrogen mitigation as improved livestock management, reduced food waste and reduced consumption of Nr intensive animal products (Bodirsky *et al* 2014). Sutton *et al* (2013) therefore propose a global aspirational goal to improve the NUE by 20% until 2020 and to reach, in the long-term, a NUE above 70% in all countries.

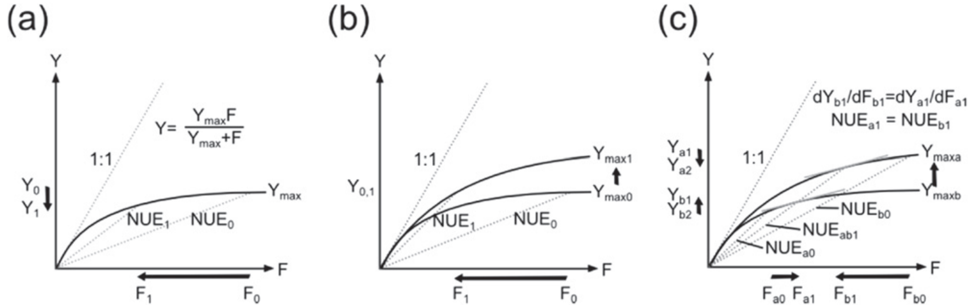

Figure 1 Three options to improve nitrogen use efficiency (NUE). (a) Extensifying production by fertilizing for a lower yield (Y_1 instead of Y_0) reduces fertilizer consumption over-proportionally (from F_0 to F_1), constituting an increase in NUE (from NUE_0 to NUE_1). (b) Advancing the technology frontier: by increasing the production frontier (from Y_{max0} to Y_{max1}), the same yield ($Y_{0,1}$) can be attained with lower Nr inputs (F_1 instead of F_0) and higher efficiency (NUE_1 instead of NUE_0). (c) Reallocation of Nr fertilizers from country B to country A (aligning $dY_a/dN_b = dY_b/dN_b$) can reduce total Nr inputs ($F_a + F_b$) without reducing total production or cropland area.

While Lassaletta *et al* (2014) mainly focus on the analysis of historic trends and discuss the role of management options, such as crop–livestock interaction or biological N fixation, their formalization of the *Y*–*F* relationship allows for identifying three general mechanisms to increase NUE and reduce Nr pollution (figure 1):

Extensifying production by reducing yields. From the Michaelis–Menten form of the *Y*–*F* relationship, it follows that $NUE = Y/F = 1 - (Y/Y_{max})$. This rule reveals that the yield-gap caused by low N inputs ($1 - Y/Y_{max}$) is equal to the NUE ($NUE = Y/F$). This relationship constitutes the dilemma of extensification as a strategy to mitigate Nr pollution: halving nutrient losses on the fields (i.e., increasing NUE from 0.5 to 0.75) implies halving yields (i.e. a drop of Y/Y_{max} from 0.5 to 0.25). Increasing NUE to 0.75 can therefore only be reached under current management conditions if cropping area is doubled or if overall production is halved. While a strong increase in cropping area cannot be seen as a sustainable solution given the negative externalities of land-expansion, a reduction in production could be reached sustainably by demand-side mitigation measures like a reduction of household waste and consuming less animal products. Applying this rule to projections for demand-side mitigation (Bodirsky *et al* 2014) shows the additional benefit of this mechanism: if food waste was reduced to 20% of food demand by 2050, then NUE would increase by 8 percentage points if production area were held constant. Similarly, reducing the share of livestock products within diets to half of the current western level would increase NUE also by 4 percentage points. This means that demand-side measures have a double-positive effect (reduced production and higher efficiencies through extensification), which has not been accounted for so far in assessments of the future Nr pollution. However, these estimates hold only under the assumption of fixed production area. As land use is in reality elastic to production, a lower production will also lead to a reduced land expansion or to the abandonment of unproductive land, resulting in only modest extensification. Although this dilutes the positive effect on NUE, the associated reduced land use could have additional benefits for nature and resource conservation.

Advancing the technology frontier. Lassaletta *et al* (2014) also show that it is possible to move the fertilizer-yield relationship to a more efficient level by shifting Y_{max} upwards. The most striking examples can be found in Europe after the 1980s, where yields (*Y*) increased simultaneously with reduced fertilizer inputs (*F*). Such shifts in the production frontier can be reached through better nutrient management, providing the nutrients to the plant in the right amount, at the right place, in the right time, and as the right type fertilizer (4R) (Mikkelsen 2011). Next to nutrient-specific management improvements like precise monitoring, nutrient budgets, and micro-nutrient amendments, also non-nutrient co-limitations have to be removed, for example through improved plant breeds, water management, or protection from pest and diseases (Conant *et al* 2013, Sutton *et al* 2013).

Reallocation. Nitrogen intensity of production varies strongly between countries. Reallocating N inputs from intensive to extensive producers, such that the marginal yield-increases to fertilizers (dY/dF) converge between countries, bears large potential to improve global NUE. Mueller *et al* (2014) show that an optimal reallocation between countries could decrease excess N by 49%–67% while holding global production constant. Again, the Michaelis–Menten functional form has insightful properties. In contrast to most other functions, NUE (Y/F) is equal for all points where the marginal yield increase (dY/dF) is equal, independent of Y_{max}. This means that a given global production can be reached with minimal global nitrogen losses when the NUE is uniform between countries, independent of their individual production frontiers (Y_{max}).

When designing policies to increase NUE, the insights of Lassaletta *et al* (2014) should be considered. Firstly, to allow for extensification of agriculture, policies should target a reduction in crop demand by lowering food waste and the consumption of animal-based products. Policy instruments can include altered state consumption in canteens of schools and other public institutions, awareness raising campaigns against food waste and against unhealthy overconsumption of animal products, education programs to increase household management and cooking skills, improved product labelling, abolishing dysfunctional subsidies or pricing externalities (Ingenbleek *et al* 2012). Secondly, policy instruments can effectively stimulate improvements in agronomic practices (Oenema *et al* 2011) as the European example illustrates, where the steep rise in Y_{max} in the 1980s coincides with policies like the Geneva Convention on long-range transboundary air pollution (Convention on Long-Range Transboundary Air Pollution 1979) or the Nitrates Directive (EEC 1991). While these policies could be a guidance for other legislators (Ju *et al* 2004), they could be further amended by public investments into agricultural research, development, and dissemination, or designed as more flexible economic instruments like taxes on fertilizers, emissions, or farm-gate N surplus (Oenema *et al* 2011). Thirdly, the reallocation argument indicates that policies targeting at a modest intensification in areas where yields are strongly limited by N scarcity (e.g. in large parts of Sub-Saharan Africa (Sanchez 2002)) is paradoxically not contrary to an improvement of global NUE, as the additional production may crowd out more intensively produced imports. NUE, being more communicable than dY/dF, can thereby serve as a good indicator and focal point to harmonize policy goals internationally and avoid leakage.

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