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COMMENTARY **Open Access**

A better use of fertilizers is needed for global food security and environmental sustainability

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Abstract

The massive use of fertilizers during the last decades allowed a great increase in the global capacity of food production. However, in the last years, several studies highlight the inefficiency and country asymmetries in the use of these fertilizers that generated environmental problems, soil nutritional imbalances and not optimal food production. We have aimed to summarize this information and identify and disentangle the key caveats that should be solved. Inadequate global management of fertilization produces areas with serious nutrient deficits in croplands linked with insufficient access to fertilizers that clearly limit food production, and areas that are overfertilized with the consequent problems of environmental pollution affecting human health. A more efficient use of nitrogen (N), phosphorus (P) and potassium (K) fertilizers for food security while preserving the environment is thus needed. Nutrient imbalances, particularly the disequilibrium of the N:P ratio due to the unbalanced release of N and P from anthropogenic activities, mainly by crop fertilization and expanding N-fixing crops that have continuously increased the soil N:P ratio, is another issue to resolve. This imbalance has already affected several terrestrial and aquatic ecosystems, altering their species composition and functionality and threatening global biodiversity. The different economic and geopolitical traits of these three main macronutrient fertilizers must be considered. P has the fewest reserves, depending mostly on mineable efforts, with most of the reserves concentrated in very few countries (85% in Morocco). This problem is a great concern for the current and near-future access to P for low-income countries. N is instead readily available due to the well-established and relatively low-cost Haber–Bosch synthesis of ammonium from atmospheric N_2, which is increasingly used, even in some low-income countries producing an increasing imbalance in nutrient ratios with the application of P and K fertilizers. The anthropogenic inputs of these three macronutrients to the environment have reached the levels of the natural fluxes, thereby substantially altering their global cycles. The case of the excess of N fertilization is especially paradigmatic in several areas of the world, where continental water sources have become useless due to the higher nitrate concentrations. The management of N, P and K fertilizers is thus in the center of the main dichotomy between food security and environmentally driven problems, such as climate change or eutrophication/pollution. Such a key role demands new legislation for adopting the well-known and common-sense 4R principle (right nutrient source at the right rate, right time and right place) that would help to ensure the appropriate use of nutrient resources and the optimization of productivity.

Keywords Fertilizers, Food security, Environmental security, Nitrogen, Phosphorus, Potassium, Imbalance, Stoichiometry, Eutrophication, Global cycles

Introduction

The global population is expected to increase by about 35% over the next 40 years [87]. Agricultural output will need to increase substantially to accommodate the growing population. Most of the increase (in agricultural

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output) is expected to be from producing more fod on existing farmland (i.e., intensification), although some new farmland will likely be needed [26]. Such intensification and expansion might, however, lead to undesirable impacts on carbon (C) stocks in soil and vegetation and on biodiversity in the most productive croplands of the world [8].

Boosting crop yields and closing the gap between actual and attainable yields can be achieved by implementing and advancing numerous practices and technologies, e.g., the adequate use of fertilizers and efficient nutrient management can play key roles for global food security [82, 89]. However, the fertilization intensification of the last decades aimed to increase yields has produced some new global environmental and geopolitical problems, such as nutrient imbalances, [31, 50, 59, 61, 68], leaching of nutrients from crops to environment and the associated impacts [45, 68, 72, 85, 94], and increasing cost of fertilizers with serious geopolitical and economic problems for the food security in poor countries [3, 40, 57, 89]. The rise of fertilizer application at global scales has grown exponentially for N than for P and K (Lu and Tian [50]), [59, 60, 61, 75]. The levels of human driven N, P and K annual loads to environment have reached similar values than natural fluxes and a substantial rise in human driven N:P and N:K ratios [59, 60, 61, 72, 75].

In this commentary, we aim to discuss the problems caused and associated by the exponential of fertilizers use such as environmental pollution, global nutrient imbalances and food security mainly in poor countries, their causes, interactions, and consequences, both for current conditions and for the coming decades, also disentangling the potential solutions to mitigate and adapt to this global change driver, the human driven global changes in N, P and K stocks, cycling and stoichiometry produced by continuous temporally and spatially asymmetric consumption of fertilizers. This should improve a global view linking human use of fertilizers, with global food security and environmental quality and environmental services potential. We aimed to make so by summarizing and connecting the main bibliography on this topic.

We have checked the current bibliography and reports about global use of fertilizers and their relationships and impacts on food production and environment. We have checked google, google scholar and Web of Science. We have used combinations of words, such as: "fertilizer & environment", "fertilizer & food security", "fertilizer & phosphorus", "fertilizer & nitrogen", "fertilizer & potassium" "N:P ratio & fertilizer & environment", "N:P ratio & phosphorus & nitrogen & fertilizer & environment", "environment & food security & poor countries", "nitrogen & phosphorus & N: ratio", "fertilizer & phosphorus & nitrogen", "fertilizer & phosphorus & nitrogen & potassium", " We have thereafter selected the studies of the last 30 years with a global perspective.

N fertilization

N fertilization has increased by an order of magnitude in the last six decades [66]. Converting atmospheric N_2 to ammonium as a source for N fertilization has been the main process responsible for the increased agricultural yield since the end of World War II [24]. The average increase in yield during 1930–2000 attributable to inputs of N fertilizers generally ranged from about 40–64% in temperate climates (USA and England) and tended to be much higher in the tropics [24, 82]. Higher N inputs to improve crop yield should be possible without exceeding the critical regional N concentration in runoff in some areas of the world, such as southeastern Asia, Latin America, Oceania, the Caribbean and sub-Saharan Africa (except South Africa) [8].

The response of agricultural systems to increased N fertilization has evolved differently in countries during the last five decades. Some countries have improved their agro-environmental performances, but increased fertilization in other countries has produced low agronomic benefits and higher environmental losses [43], such as accelerated emissions of nitrous oxide leading to global climate change and high N loadings leading to contaminated drinking water and toxic algal blooms in downstream ecosystems [17, 30]. In addition to the strictly environmental impact, excess N fertilization has also been associated with threats to human health, such as cancer, upper respiratory diseases [101] and immunogenic pathologies, such as coeliac disease [59].

Achieving a worldwide reduction of total anthropogenic inputs of N into the biosphere and humans is thus a major challenge that requires sustained actions to improve the management practices of N fertilization and reduce the losses of N to the environment. More N, though, will be needed to feed the additional 1.5–2 billion people that will be added to the global population before population growth stabilizes later in this century [46]. Some studies have observed that an adequate management of N fertilizers in several countries has influenced N pollution much more than crop yields and that the trade-off between reducing N pollution and increasing yields was small. Countries that have caused 35% less N pollution than their neighbors generally only had a 1% loss of potential yield. Explanatory variables of which countries cause the most pollution relative to their crop yields include economic development, population size, institutional quality and foreign financial flows to land resources and overall agricultural intensity and share in the economy. These findings provide consistent evidence that many national governments have an impressive capacity to reduce global N pollution without having to sacrifice much agricultural production [97]. Unique measures could likely resolve this complex issue, and a combination of measures should probably be immediately applied at the global scale.

Several options for reducing the environmental effects of the food system while improving world capacity to supply food to humans have been proposed. Their synergistic combination will be needed to sufficiently mitigate the projected increase in environmental pressures [8]. These options include dietary changes toward healthier, more plant-based diets, improvements in technologies and management and reductions in the loss and waste of food [12, 37]. However, scenario projections indicate that supply-side measures such as the improvement of N-use efficiency are more important than demand-side efforts for food security when introducing regional N targets. International trade also plays a key role in sustaining global food security under N-boundary constraints if only a limited set of mitigative options is deployed [8].

Agricultural sustainability, defined as the ability to use soil crops to produce continuous food without environmental (basically soil) degradation and other environmental impacts [99], proposes a large list of new or changed practices that can be applied including the inoculation of Arbuscular mycorrhizal fungi (AMF), cyanobacteria, and beneficial nematodes, which enhance water use efficiency and nutrient availability to plants, phytohormones production, soil nutrient cycling, and plant resistance to environmental stresses [99]. Farming practices have shown that organic and/or regenerative farming with conservation tillage, manual and biological weeding and pest control and use of farming and crop waster as fertilizers to reduce the need to apply industrial fertilizer, smart intercrop and crop rotation managements; all them improving soil health by increasing the abundance, diversity, and activity of microorganisms [21, 33, 42, 76, 84, 91].

Precision farming has allowed to make a step forward in the technology application to improve fertilizers and other resources use efficiency and diminish environmental impacts is [29]. Precision farming aims to use the most advanced technology tools to tailor management to site crop type and environmental conditions. It is based on the "diagnostic" of the situation of crop and in base to this provide the application of adequate tools. For instance, the spectral indexes are one of the most precise diagnostic tools. The sensors and scanner are frequently mounted on tractors and provide information of soil nutrient status along crop fields, allowing a site-specific fertilization [20, 55]. Similarly, advances can be also applied in the case of N to increase its use efficiency such as those based on smart agriculture including new fertilityty management that included N fertilizers with slow N releasing, sensors in soil crops to monitor the actual status of soil N, and an adequate combination of crop species in intercropping or crop rotation improving the use of N_2-fixing crops [35].

P fertilization

P fertilization has increased much less than N-fertilization in the last decades [68]. The demand for P fertilizers, however, is expected to increase in the next decades; the global peak in P production has been predicted to occur around 2030 [14]. Estimates of when existing P reserves could be exhausted, however, range widely from the next 40–400 years [15, 57], US [88]. The exact timing of peak P production is disputed, but the quality of the remaining phosphate rock is widely acknowledged to be continuously decreasing [18, 36], so production costs are increasing and thus hindering the access of low-income countries to P fertilizers. The situation can be more problematic, because some models project that the global needs of P fertilizers can be doubled by 2050 [56] and also project an increase in the loss of soil P, including croplands, by soil erosion linked to climate change, which will increase the need for P fertilizers to sustain crop production [1].

The situation is further complicated by the distribution of mineable sources of P, which are concentrated in very few countries (85% in Morocco) [57]. This unequal distribution and the unequal economic capacity of different countries has caused large surpluses in most of eastern Asia, western and southern Europe, the coastal USA and southern Brazil but deficits in Africa [52, 89]. Over-fertilized soils are frequently saturated with P because of their historically high applications [15, 60]. P deficits occur across 30% of the world's cropland area, and prolonged P deficits can deplete soil P and limit crop yields [52]. The low-income and food-deficient countries in sub-Saharan Africa, central Asia and Latin America generally suffer from low P inputs (0–5 kg ha^{-1}) to their systems of agricultural production. P scarcity is thus seriously threatening soil fertility, agricultural production and global food security in several areas [15, 100].

Managing this scarcity, however, is possible. Up to 80% of the initial P supplied to overfertilized crops is estimated to be lost before consumption, mostly due to the erosion of soil [1, 15, 57]. Reductions in waste could free up this resource for low-income, food-deficient countries [57]. If the current volumes of P fertilizers were to be redistributed and used more efficiently at the global scale, cropland would not be deficient in P. If 21% of the P fertilizers used in all areas with high surpluses were to be redistributed across all P-deficit cropland, the total crop requirements for P in these locations would effectively be met, eliminating all P deficits globally [52]. Opportunities for recovering P and reducing demand are thus also possible and constitute an institutional challenge [14]. To achieve P sustainability, several actors must contribute, farmers need to use P more efficiently and societies and states should develop technologies and practices to recycle P from the food chain [23]. For instance, the global increase in livestock production by threefold for human consumption over the last five decades has been a key driver of scarcity, environmental distribution, and decrease in the efficiency of P use [50]. Currently monogastric livestock, as pigs and poultry, suppose a 70% of the global livestock production, and taking into account the low capacity of these species to absorb P from phytases drive to the production of manure very rich in P and with low N:P ratios leading to a very low P use-efficiency [58, 62, 92], that, moreover, has contributed to exacerbate the environmental imbalances in N:P ratios [52, 59, 60, 77]. Thus, advance in a global change of human diet behavior toward a diet more based on plant-based foods should be considered for several reasons but also for a higher global P-use efficiency in food production [65, 96]..

Furthermore, it is already possible to improve P use efficiency based on available new technologies, including the use of modern chemically modified phosphate fertilizers with controlled release of phosphorus [34] and new crop genotypes genetically engineered to be more efficient in P mobilization, capture and use [32]. All these methodological and technological advances drive to a more efficient management of N and P fertilization avoiding imbalances in N:P ratios and excessive use of fertilizers and subsequent associated cascades of food security and environmental problems [13, 63, 69, 95].

K fertilization

Fertilization with industrial fertilizers containing the third key nutrient, K, from mineable reserves has continuously increased since the Industrial Revolution. As with P, we are currently in a scenario, where rich countries tend to overfertilize with K, implying environmental problems and even potential threats to human health, whereas poor countries frequently have problems with access to K fertilizers, limiting their crop production. This dichotomy parallels a scenario of increasing limitation of mineable K sources and an increase in aridity under climate change and the potential demand by crop intensification [72]. Future access to K is thus urgently needed in regions most threatened by increasing aridity and food security (e.g., the Sahel, areas with Mediterranean climates and parts of Asia and South America) due to the crucial role of K in the uptake, transport and use efficiency of water by plants ([72], 2021). Insufficient K supply is becoming an important constraint to crop production in developing countries [4]. This constraint can be increased by climate change, with terrestrial areas consequently becoming increasingly arid and semi-arid (Huang et al., 2016), [78]. Very low rates of application of potash fertilizer in agricultural production in India and other developing countries lead to the rapid depletion of K in the soil. The depletion of plant-available K in soils has a variety of negative impacts, including preventing optimal uses of N and P fertilizers, threatening the yields of the cropping systems and decreasing farmer income [4, 54].

The imbalances among fertilizers

This complex situation between N, P and K fertilizers leads to imbalances in their use around the world [50, 59, 60]. The case of the African continent is paradigmatic: P fertilization should be increased 2.3-fold to be optimal given the current inputs of N. Inputs of N that would allow Africa to close the gaps in yield should be increased at least fivefold, so the application of P fertilizer should be increased 11.7-fold [89]. Arranging all these imbalances in P provision would greatly increase the pressure on the current global extraction of P resources, which is not an easy solution due to the scarcity and high cost of mineable P, and/or as commented previously, with a net "transfer" of P fertilizers from overfertilized to under fertilized areas. In addition, if P fertilizers cannot be made increasingly accessible, the projections of crop yields of the Millennium Ecosystem Assessment imply an increase in nutrient deficits in developing regions [61]. In fact, some studies have found that cropland areas receiving high doses of P fertilizers have low P-use efficiencies in cropland yield production [52], and similar observations for N fertilization have been provided [2, 64]. These imbalances are a particular concern, because anthropogenic inputs of these three macronutrients to the environment have reached the levels of the natural fluxes, thereby substantially affecting their global cycles. The impacts could thus seriously affect cropland N:P:K ratios but also those of other ecosystems, both terrestrial and aquatic [59, 61, 73, 74]. The impacts of the changes in these ratios have been widely observed to alter the structure and function of several ecosystems around the world [59, 61, 73, 74].

Managing N fertilizers better could also help to resolve these general imbalances and the asymmetrical distribution of fertilizer. The maximum anthropogenic use of N fertilizers needed to prevent the substantial eutrophication of aquatic ecosystems is considered to be around 62 Tg N y^{-1} from industrial fertilizers and N-fixing crops [19], but we have already surpassed this threshold by at least threefold [81]. A few agricultural regions with very high rates of N application are the main contributors to the transgression of this "de Vries" boundary, suggesting that a redistribution of N could simultaneously boost global crop production and reduce the transgression of the "de Vries" boundary at the regional level [81]. In the absence of N mitigation or redistribution, pressure on the environment will probably increase [79], even though the need of N fertilizers for sustaining the global human population is certainly large, even with the efficient use of the fertilizers [19]. The total amounts of N fertilizers needed to feed the human population in 2030 under the current distribution of fertilizers could reach 271 Tg N y^{-1} [49], 4.5-fold higher than the threshold estimated by de Vries et al. [19]. Maintaining the equilibrium of the fertilizer N:P:K ratios in this scenario would require annual increases in the application P and K fertilizers that could strain the fertilizer markets even more [57], with unknown impacts on global food security, especially in low-income countries. The environmental effects of the food system in the scenario for 2050 could increase by 50–90% in the absence of technological changes and dedicated mitigative measures due to expected changes in population and income levels, reaching levels much higher than acceptable planetary boundaries that define a safe operating space for humanity [8].

The use of N, P and K fertilizers is greatly unbalanced around the world, including in the largest countries, such as India [7] and the USA [90], in all cases leading to deficient production of food [50, 68, 90]. Nutrient balance is essential for achieving global food security [6] and for conserving N and P fertilizers [53]. Lu and Tian [50] found a global increase in the fertilizer N:P ratio of 0.8 ($g\ g^{-1}$) per decade ($p<0.05$) during 1961–2013, which may have an important global implication for anthropogenic impacts on agroecosystem functions in the long term. These imbalances can alter soil stoichiometry and have been observed to differ in important cropland areas [90]. The inexorable change in the stoichiometry of C and N relative to P has no equivalent in Earth history [61], 2020). The N:P ratio of atmospheric deposition in several parts of the world has reached values over 100–200 on a mass basis [9]. This anthropogenic imprint on the N and P cycles and N:P stoichiometry has already had consequences in several natural ecosystems to the structure, functioning, and diversity of terrestrial [38, 59, 60, 61] and aquatic [22, 59, 60, 61, 73] organisms.

The role of the N:P ratio has been widely studied, and its importance for the growth of crop plants and for the structure, diversity and functioning of other ecosystems has also been widely observed [22, 61, 73], 2020), but the importance of N:K and P:K ratios has been studied less. Some studies, however, have observed that optimal N:K and P:K ratios in fertilizers are important for plant growth and yield in diverse crops [25, 41, 51]. N:K and PK ratios have been associated with the trade-off between plant growth and energy production [51], and different abilities in the efficiency of energy production among N, P and K for plant growth and development have been inferred [51]. The most probable trade-off that may, at least in part, determine the optimal N:K ratio is that between the allocation to growth (where *N* is more determinant) versus the allocation to anti-stress defense, mainly against water stress, where the role of K is more important [44, 71, 72]. *Erica multiflora*, a sclerophyllous Mediterranean shrub, has the highest foliar N:K and P:K ratios in spring, coinciding with the period of growth, and the lowest foliar ratios in summer, coinciding with the period of water stress [67]. K fertilization, however, can also be important for plant and yield production, but only when the N supply reaches a specific level [5]. N:K ratios are larger in in non-crop plant–soil systems due to N deposition [28], affecting the resistance of plants to stresses, such as drought [70]. The role of the P:K ratio in non-crop ecosystems, however, has rarely been studied. Optimal N:K and N:P ratios can be different and higher for plants under elevated atmospheric CO_2 concentrations, because higher net photosynthetic rates under elevated CO_2 concentrations increase the plant demand of all three macronutrients but with a higher proportion of N, mainly to reach a higher maximum rate of carboxylation [16]. The impacts of the unbalanced use of N and P fertilizers with K fertilizer on non-crop ecosystems, however, remains to be widely studied.

Toward a more rational use of fertilizers

The present and future management of N, P and K fertilizers at the global scale is directly linked to food security and environmental health and, therefore, to human life, health and well-being. Human food security and environmental health cannot be accomplished without measures leading to strategic and adequate N, P and K fertilization, which should be addressed simultaneously for the three nutrients.

Several strategies have been proposed to balance the N:P:K input ratios in fertilization management to optimize yield increases and the quantity and quality of production while minimizing nutrient losses and thus environmental impacts. Precision farming is thus a key tool at this regard [29]. Adoption of the 4R principle (right nutrient source at the right rate, right time and right place) should also help to ensure the appropriate use of nutrient resources and to optimize productivity [82].

New legislation considering the different fertilizers altogether is also urgently needed for achieving these objectives, and in fact, it is already in the agendas of some high-income countries, such as the European Union [93]. We, however, need more international agreement about a global strategy of fertilization, because adequate fertilizer use increases water-use efficiency, crop and food production, the resistance of crop production against aridity and the preservation of environments and biodiversity and can provide several feedbacks to mitigate climate change [59, 60, 98]. In this context and at this moment, the European Union is a paradigm; in fact, European Sustainable Phosphorus Platform for an Integrated Nutrient Management Action Plan (INMAP) is fully in line with these ambitions and its pressure on European Commission in principle will act to reduce nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility, with a short-time scenario of a reduction of the use of fertilizers by at least 20% by 2030 [93]. Unfortunately, apart from general declarations, concrete law measures to more controlled, efficient and environmentally friendly use of fertilizers are at this moment effective in very few other parts of world. Recently, in Canada the government has proposed a reduction of a 30% in the use of industrial fertilizers within the global country plan to reduce greenhouse emissions [27]. Theoretically, China is another state with strict legislation of fertilizers use [11], being prohibited to import, produce, sell or use un-registered fertilizers, and fertilizer sold in China shall also meet relevant product standards. However, there is still a lot of room in most countries to take a more serious policy about fertilizer use and to endorse all the technical improvements to reduce fertilizer use while increasing use efficiency [10, 83, 89]. It is necessary to overcome the constrains imposed by conventional intensive agriculture and the scarce economical capacity and little access of farmers of several countries to adequate information [10, 83, 89].

Conclusions

Human-driven N and P loads to environment have reached levels comparable to natural fluxes. The continuous exponential increases of N loads rising faster than P and K loads have increased N:P ratios in several areas of the world with unprecedented impacts on ecosystems and their services capacities. These imbalances have serious impacts on food production capacity, mainly in poor countries, where the increases in N:P and N:K ratios are further favoured by the higher costs of K and mainly P fertilizers than the costs of N fertilizers. In the case of the excess of N, its consequences can also affect human health by the pollution of waters and excessive N fertilization. Aridity is expected to increase in the next decades and more lands will be affected by decreased availability of water. Future access to K is thus urgently needed in regions most threatened by this increasing aridity (e.g., the Sahel, areas with Mediterranean climates and parts of Asia and South America) due to the crucial role of K in the uptake, transport and use efficiency of water by plants, that makes K a necessary tool to try to maintain acceptable levels of food production under increasing water scarcity. In the case of P, if it is sufficiently applied, it can be stored in soil in not available forms, whereas mine reserves can be emptied faster and its access can progressively become prohibitive for poor countries. This can, moreover, be related to higher prices of P fertilizers which can hinder even more the access to fertilizer of millions of farmers in poor countries and decrease even more the already low efficiency of crop production in several areas of poor countries, such as in Africa or Asia impairing even more their food security. There are though several new technologies and crop management methodologies that can help to improve fertilize use and efficiency. Smart, precision and regenerative agriculture approaches together with new biotechnologies application can help to correct this global change driver, so they should be quickly at global scale. Meanwhile, new legislation adopting the well-known and common-sense 4R principle (right nutrient source at the right rate, right time and right place) would help to ensure the appropriate use of fertilizers and the optimization of crop productivity for food security and environmental sustainability.

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Author contributions

JP and JS designed the study, JP, FC and JS gathered the information and wrote this comment. All authors read and approved the final manuscript.

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Availability of data and materials

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Declarations

Ethics approval and consent to participate

We approve and consent.

Consent for publication

We consent.

Competing interests

Authors declare no competing interests.

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