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Perspective

LONG-TERM FERTILIZER NITROGEN MANAGEMENT IN CROP PRODUCTION AND SOIL HEALTH – A RETHINKING

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Mineral fertilizers for supplying nitrogen (N) to plants were introduced in the late 19th and early 20th centuries, but globally their use in crop production increased very slowly up to 1950. After World War II, large-scale production of N fertilizers became possible by the Haber–Bosch process and their use increased exponentially after 1950 to support food production for the rapidly growing human population. In India, N fertilizers were introduced in a big way as an integral component of the Green Revolution based on high-yielding varieties of wheat and rice. Initially, farmers were hesitant to apply fertilizer N to their soils but once they realized that high yields of rice and wheat could not be achieved without applying fertilizer N year after year, many of those who could afford started applying fertilizer N doses even higher than the recommended. This trend in fertilizer N use has continued since the 1970s and there exist three distinct groups of farmers who are applying fertilizer N to different crops in recommended doses, more than, and less than the recommended doses.

For more than 5 decades, the graphs showing continuously increasing food production with increasing fertilizer N consumption in India make the government administrators believe that the country can continue increasing food production simply by producing more urea and applying it in its fields. It is a misconception because fertilizer is not the only source of N for plants. Apart from biological N fixation and N deposition, soil organic matter constitutes a huge reservoir of N, and crop plants use a substantial amount of soil N even when fertilizer N is applied. Soil N pool in the top 30 cm layer of a typical agricultural soil containing 0.10 to 0.15 % N may hold about 5000 kg N ha^{-1}. Thus the mental model that fertilizer N simply replaces the N mineralized from soil organic matter needs to be revisited. In recent years, it has been revealed that soil health in terms of soil organic matter or soil N is greatly influenced by the magnitude of fertilizer N dose when applied on a long-term basis. Changes in soil health determine soil N supply to crop plants, which in turn dictates the magnitude of fertilizer N application to maintain high crop yield levels. In case soil health deteriorates, supply of soil N to plants is reduced and high doses of fertilizer N need to be applied to maintain crop yields. But high fertilizer N levels in turn may adversaly affect soil health and even higher fertilizer N doses may be required year after year (Fig. 1). Therefore to sustain high yield levels and keep soils healthy on a long-term basis, one needs to understand the cyclic relationship between long-term fertilizer N management, soil health, and adequacy of fertilizer N use.

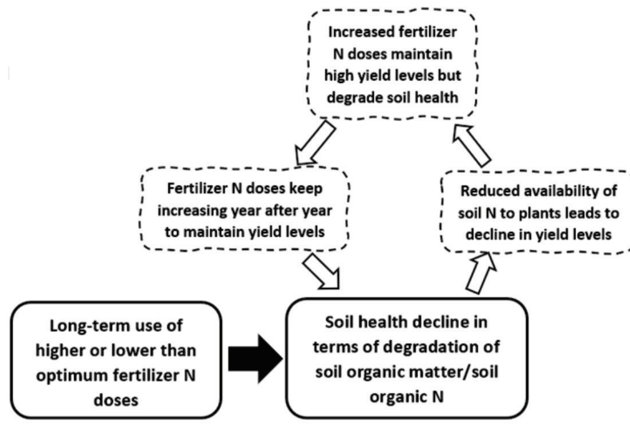

Fig. 1. Long-term fertilizer N management in crop production and soil health conundrum

Based on 93 studies on rice, wheat, and maize in which N was applied in the form of ^{15}N-labeled fertilizers, Ladha *et al.* (2005) revealed that 56% N in harvested grains and above-ground plant residues of the crops was derived from soil N rather than fertilizer. Yana *et al.* (2020) compiled data from 230 published papers and found that based on ^{15}N studies and zero-fertilizer control studies crops derived 59.8 % and 52.6 % N from soil N, respectively. Crops utilized remaining less than 50% N from the fertilizer N applied in the current year. Maize, rice, and small grains (wheat, barley, sorghum, oats, and millet) utilized 41%, 32%, and 37% N from the ^{15}N-labelled fertilizer applied in the current season. Even when ^{15}N-labelled fertilizers were applied at a high rate in 217 field-scale studies included in a meta-analysis conducted by Gardner and Drinkwater (2009), average N uptake by crop plants from soil N pool was to the extent of 60%. These studies explicitly suggest that in case the soil N pool gets depleted due to inadequate

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management or degradation of soil organic matter, the storehouse of soil N, enough N will not be supplied to crop plants and yields may decline unless heavy doses of fertilizer N are applied.

That soil N pool and soil organic matter play a big role in the N nutrition of crops even when fertilizer N is applied establishes that these together constitute one of the most important indicators of soil health. It also corroborates that traditional assessment of the health of agricultural soils is closely linked to soil organic matter (Seufert *et al.,* 2012; Lehmann and Kleber, 2015). The fact is that microbial carbon (C) and N cycles in the soil are fundamentally coupled and soil organic matter acts as the largest source of N for plants because there exists a close correlation between the mineralization of C and N contained in it.

Soil health in terms of soil N is influenced by fertilizer N because a significant portion of the applied N in the current year converts into organic forms to become part of the soil N pool (Bijay-Singh and Sapkota, 2023). In a sugar beet (Beta vulgaris L.)–winter wheat crop rotation, Sebilo *et al.* (2013) applied ^{15}N-labelled fertilizer in the first year and unlabelled fertilizer N during the next three decades and found that only 61 to 65% of ^{15}N was used by the crops in three decades. Interestingly, 12 to 15% of the ^{15}N could still be recovered in the soil N pool three decades after its application. Thus, some fertilizer N applied in the current year is always incorporated into the soil N pool and becomes available for uptake by crop plants in subsequent years. It implies that unless adequate fertilizer N is applied to crops, the soil N pool will gradually be depleted, and soil quality adversely affected. If inadequate or less than optimum rates of fertilizer N are applied on a long-term basis and sufficient N is not applied even through organic manures and recycling of legume residues, soil N pool or soil health will not be maintained and will not enable full yield potential and soil biodiversity to be achieved. Another important implication of the incorporation of a part of fertilizer N into the soil N pool is that only that portion of fertilizer N applied in the current year is lost from the soil-plant system which is neither taken up by the plants nor gets converted into soil N (Bijay-Singh and Sapkota, 2023).

Soil health is not only adversely affected by applying less than optimum fertilizer N rates to crops year after year, but it is also deleteriously affected in terms of soil organic matter content by long-term application of more than optimum fertilizer N doses (Bijay-Singh, 2018). When applied up to the optimum dose, fertilizer N favours the build-up of soil organic matter through the production of an increasing amount of biomass that ends up in the soil. When applied in doses more than the optimum, fertilizer N does not further increase the biomass but results in the accumulation of residual inorganic N in the soil (Poffenbarger *et al*., 2017), which stimulates the mineralization of soil organic matter resulting in its net loss (Russell *et al*., 2009; Chen *et al.,* 2014). Excessive fertilizer N use can also adversely influence soil health by accelerating the decay process of crop residues by reducing their C: N ratio. Furthermore, in the presence of excess fertilizer N in the soil, the transformation of fertilizer N to the soil N pool is governed by the size of microbial activity rather than the amount of fertilizer N.

When fertilizer N is applied at agronomically correct rates, soil health is enhanced due to the build-up of soil organic matter through increased net primary productivity in terms of both above- and below-ground plant biomass. Mineralization of soil organic matter is indirectly reduced through increased net primary productivity which results in the lowering of soil moisture and temperature (Parton *et al*., 1987; Wang *et al*., 2006; Li *et al*., 2014). Also, when applied at the optimum rate, most of the fertilizer N is either assimilated by the crop or converted to soil N so that a very small amount of residual inorganic N remains available for mineralizing soil organic matter. Several meta-analyses based on long-term experiments have reported average increases in the range of 8 to 13.4% in soil organic C due to the application of optimum fertilizer N rates to different crops over unfertilized control (Ladha *et al*., 2011; Kőrschens *et al*., 2013; Geiseller and Scow, 2014; Geiseller *et al*., 2017). The reported increase in soil organic matter was over and above its possible loss due to soil tillage in experiments included in the meta-analyses. Huang *et al.* (2020) reviewed experiments in which soil C was isotopically labelled and reported that new soil C stocks were increased due to the application of fertilizer N.

Optimal use of fertilizer N in crop production not only ensures sustainable high crop yields but also maintains/enhances soil health in terms of soil N and soil organic matter status. Fertilizer N management strategies must consider the huge role played by soil N pool in the N nutrition of crops. Ideally, fertilizer N should be managed on a field-scale or site-specific basis to ensure sustainable high yields, healthy soils, and minimal N-related degradation of the environment. Long-term application of fertilizer N in doses higher or lower than the optimum may lead to soil health deterioration through reduced build-up or accelerated mineralization of soil N pool. When in the quest to obtain high yields, farmers continuously apply high doses of subsidized N fertilizers, a spiral of decline in soil health may occur, which necessitates the application of even higher N doses year after year to achieve the same yield level . In a way, soils become addicted to fertilizer N when soil health deteriorates due to long-term use of high fertilizer N rates in crop production.

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