Should soil nitrogen be mined?

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Abstract
Misunderstanding of the intricacies of nitrogen (N) cycling in agricultural soils has led to improper fertiliser N use in important global agroecosystems, ranging from excessive use to unsustainable exploitation (mining) of soil organic matter reserves. This must be addressed to avoid excessive N accumulation and to ensure adequate N reserve. Here we develop a framework for answering the question "Should soil organic N be mined, and if so, for how long?" to maintain sustainable agricultural production in major agroecosystems worldwide. Agricultural systems where external N input exceeds the capacity of the soil to form soil organic matter are prone to leak reactive N to the environment. Excessive additions need to be halted, and where excess reactive N remains in these systems it needs to be mined, at least for some time. In other agroecosystems, external N input is low and current use of the land mines N acquired through the mineralization of soil organic matter. Thus the paradox of mining soil organic N, where on the one hand it can be desirable for agroecosystem health and on the other threatens agroecosystem function. Untangling the paradox of mining soil organic N and revealing the residual effect of fertiliser N will contribute to answering the question of whether N use efficiency is as low as perceived. This has major implications for food security and environmental quality.

Key Words
Mining soil nitrogen, nitrogen use efficiency, agriculture, residual fertiliser nitrogen

Introduction
Historically crop production has been directly related to the amount of soil organic matter (SOM), the repository for soil organic nitrogen (SON) in the soil. Scholes and Scholes (2016) argue that unless action is taken to preserve soil fertility, i.e. conserve SOM, the world could suffer the same fate of civilisations in the past that failed because they did not prevent soil degradation. They note that although improved technology provides a false sense of security, about 1% of global land area is degraded every year (Scholes and Scholes 2016). Maintaining the SON reserve is central to maintaining soil fertility. Our lack of understanding of the relationship between fertilisation and the dynamics of SON in various agroecosystems limits our ability to solve the problem of how much, and for how long SON can be mined if an agricultural production system is to remain sustainable (Fig. 1). This is of particular importance in that to secure future food, global food production must increase to meet the demand of global population growth of about an additional two billion people by 2050 (Alexandratos and Bruinsma 2012).

Another issue that is directly related to mining SON is nitrogen use efficiency (NUE). Improving NUE (the fraction of N input harvested as product) is an effective means of increasing crop productivity while decreasing environmental degradation (Zhang et al. 2015). The importance of reconciling nutrient removal with nutrient additions has been recognised through the United Nations Environmental Program's (UNEP) view that there is a need to define and then assess trends in nutrient performance. The Sustainable Development Solutions Network has also proposed that crop NUE should be an indicator of progress towards a goal to end hunger, achieve food security, improve nutrition, reduce pollution, and promote sustainable agriculture. The actual critical values for NUE and the targets to be established are likely to vary from region to region and between farming systems. Science and industry have supported the development of appropriate indicators to represent the balance between underuse of N that can lead to low production and the depletion of soil fertility, and excess N that can lead to adverse environmental impacts (Norton et al. 2015). We report here the new framework to address this challenge.

Paradox of mining soil organic nitrogen
Agricultural systems where external N input (fertiliser N and biologically fixed N) exceeds the capacity of the soil to form SOM (a historically recent phenomenon) are prone to leak reactive N to the environment through leaching of nitrate and emission of ammonia and nitrous oxide to the atmosphere, degrading ecosystems. Excessive additions need to be halted, and where excess reactive N remains in these systems it needs to be mined, at least for some time (Fig. 1). In other agroecosystems, external N input is low and current use of the land mines N acquired through the mineralisation of SOM, but does not generate enough new SOM to replace

that mineralised (Figs. 1). Thus the paradox of mining SON, where on the one hand it can be desirable for agroecosystem health (where excessive N has accumulated) and on the other threatens agroecosystem function (insufficient N) (Fig. 1). To illustrate the extremes of the SON mining paradox we use examples of high and low input agricultural systems in Australia, China and the United States of America (USA).

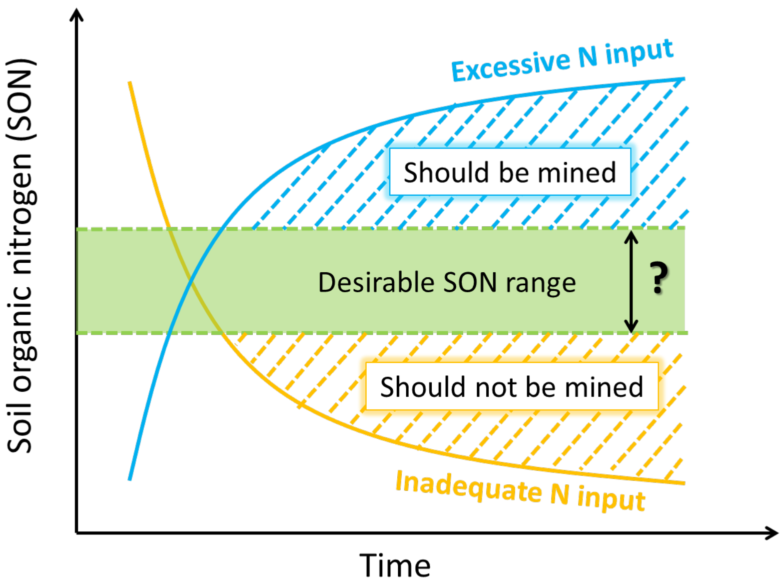

Figure 1. Paradigm of maintaining SON

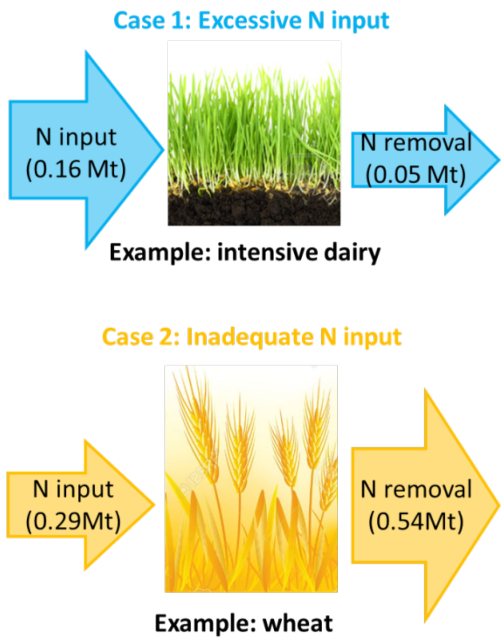

Figure 2. Paradox of mining soil N in two Australia agricultural systems

Systems with excessive N input (Fig. 2, Case 1)

Intensive dairy pasture production systems in Australia

Eckard et al. (2007) conducted an N balance study for a non-irrigated temperate grass/clover pastures grazed by dairy cows in south-eastern Australia. N inputs and losses were measured for 3 years from pastures receiving either no N fertiliser (control) or 200 kg N ha^{-1} applied annually as ammonium nitrate or urea at the Ellinbank Dairy Research Institute, in west Gippsland, Victoria. Estimated total N inputs from fertiliser and N fixation by the clover, averaged over the 3 years, were 154, 314, and 321 kg N ha^{-1} yr^{-1} for the control, ammonium nitrate, and urea treatments, respectively, while corresponding N outputs in meat and milk were 75, 99, and 103 kg N ha^{-1} yr^{-1}. The corresponding calculated N surplus was 79, 215, and 218 kg N ha^{-1} yr^{-1} for the 3 treatments, and the ratio of product N/total-N inputs ranged from 50% in the control to 32% for both fertiliser treatments; this corresponds to the N efficiency found by Gourley et al. (2012).

Crop production in China

Chen et al. (2011) used a model-driven integrated soil-crop system management (ISSM) approach to demonstrate a maize production system that achieved mean maize yields of 13.0 t ha^{-1}, almost double current farmer's practice (FP) of 6.8 t ha^{-1}, with less N fertiliser input, in 66 on-farm experimental plots (Table 1). To attain 15 t ha^{-1} production in high yield (HY) maize trials, more than three times the amount of fertiliser N input was required. Assuming that the fertiliser N applied was all taken up by crops, then the N input – N output was –12, 457 and 127 kg N ha^{-1} in ISSM, HY and FP practices, respectively. If one assumes that a more realistic 80% of fertiliser was taken up by crops, and that other sources of N (e.g. atmospheric deposition) were small, then the ISSM system was mining at least 60 kg N ha^{-1} yr^{-1} to produce the crop. In the short term, the build up of nitrate that had not been leached below the root zone was likely being mined (beneficial mining that may occur for a few cropping sequences to utilise excess soil nitrate) (Castellano et al. 2014), however in the long term SON mining would occur. For how long can Chinese cropping systems maximise production and use relatively low rates of fertiliser N, while drawing on the SON reserve?

Table 1. High yield maize production and N fertiliser use in China (Chen et al. 2011).

	ISSM	HY	FP
Maize grain yield (tonnes/ha)	13	15.2	6.8
N input (kg N/ha)	237	747	257
N removed in harvest (kg N/ha)	250	292	132
Input – harvest (kg N/ha)	–12	457	127

ISSM: integrated soil–crop system management, HY: high yield study, and FP: farmer practice.

Is nitrogen use efficiency as low as perceived?

Nitrogen use efficiency calculations based on short-term field trials find typically that fertiliser recovery is less than 50%. However, using short term recovery rates as an indicator ignores a possible residual effect of fertiliser N that is not generally considered. Such a residual effect might store N in the soil, increasing N availability for subsequent crops (Sebilo et al. 2013). Yan et al. (2014) obtained measurement results of cropland soil N content in 1980 and 2007 to compare the change in the soil N pool. With the increase in fertiliser N input, annual direct fertiliser N recovery efficiency decreased and was indeed low (below 30% in recent years), while its residual effect increased continuously, to the point that 40–68% of applied fertiliser was subsequently used for crop production. The residual effect was evidenced by a buildup of soil N and a large difference between the NUE of long-term and short-term experiments. Is this observation generally true? If so, actual fertiliser N recovery (efficiency) is likely to be higher than that perceived, analogous to accumulative phosphorus recovery (Sattari et al. 2012).

Systems with inadequate N input (Fig. 2, Case 2)

Dryland wheat production in Australia

Currently, N fertiliser management in Australian wheat production is based on supplemental N fertilisation after the pre-planting soil N mineralisation has occurred. Summers in southern Australia are typically hot and dry and SOM mineralises rapidly when rain falls in the autumn before winter wheat is planted. This “autumn break” mineral N can be considerable and highly variable (Angus 1998). As shown in Table 2, N-fertiliser addition to all of Australia’s wheat production lands in 2011 (ABS 2011) was about 15 kg N ha^{-1} less than that needed to maintain the soil N reserve (N deposition and biological N fixation are assumed to be small). The data indicate that the current fertilisation practice for Australian wheat production is mining soil N.

Table 2. Wheat production and N fertiliser use in 2011 in Australia (ABS 2011)

	Total amount
Wheat grain yield (tonnes)	27,000,000
Grain N (tonnes) (assuming 2% N)	540,000
Fertiliser N input (tonnes)	360,000
N removed from soil (tonnes)	180,000

Dalal et al. (2011) show that continuous dryland wheat cropping for 40 years in a Vertosol (heavy clay soil) in Queensland resulted in large losses of SOM. Significant effects of N fertilisation and residue management treatments on total SON were primarily confined to the top 0.1-m depth where total SON exponentially declined in all treatments even though NUE during this period (1969–2008) was only 46 and 59% of N applied at 90 and 30 kg N ha^{-1}, respectively. The top 0.1 m of soil of the zero N treatment contained 1670 and 1110 kg total N in 1976 and 2008, respectively. The Dalal et al. (2011) study also shows that wheat production was highly correlated with the total organic N content of the surface 0.1 m of soil.

Dryland wheat production in the USA

Wheat-fallow is the common practice for growing dryland winter wheat in the Great Plains and western part of the USA. Long term studies show that, analogous to annual dryland wheat cropping in Australia, soil organic carbon (C) and N content of the soil typically declines immediately after cultivation and continues to decline over time (Rasmussen and Parton 1994). In the wheat-fallow system, during the fallow period water is stored and SON is mineralised and available for the wheat crop. As in Australia, the amount of N mineralised per year continues to decline and now is not sufficient to support wheat production, necessitating the use of synthetic N fertiliser. Rasmussen and Parton (1994) show the data from a long-term study that was initiated in 1931, near Pendleton, Oregon in the USA, to determine residue management effects on crop yield and soil organic C and N in a winter wheat-fallow system. Treatments per hectare per crop included 22.4 Mg manure, 2.24 Mg pea vine residue, 0, 45, and 90 kg N with and without spring burning of straw, and 0 kg N with autumn burning of straw. Manure, which supplied 111 kg N ha^{-1} crop^{-1}, consistently produced the highest yield and maintained the highest soil C and N contents. Other treatments initially yielded from 80 to 90% of the manure treatment, but yields progressively declined in direct response to decreasing soil N content. Where no manure or fertiliser N was applied yields were only about 50% of that achieved with the manure. The change in soil C and N with time was nearly linear for all treatments, and highly correlated with residue input.

Summary and implications

Nitrogen input, particularly when fertiliser is used, into grazing-based dairy farms in Australia typically exceeds output in milk and meat. It is well established that N losses rise exponentially as N inputs approach diminishing returns. This is a large risk to the dairy industry given the clear trend towards greater N inputs with further intensification. Do dairy pasture soils accumulate N over time as SOM increases under permanent pasture, or is it all released to the environment? If N is accumulating in these soils (as we expect), can it be mined to limit excessive N accumulation and decrease N input demand (Fig. 1)? If so, for how long? On the other hand, continuous wheat cropping depletes SOM and N fertilisation helps to limit the depletion through increased biomass production thus increased residue return to the soil. These types of observations are ubiquitous to the global crop production picture. As a generalised statement, however, we do not know how much soil N can continue to be mined before economically viable crop production cannot be maintained (Fig. 1).

Untangling the paradox of mining soil N will provide economic (cost-effective food production) and environmental benefits (minimisation of ecological consequences due to excessive N input), and ensure sustainable agriculture under the pressure of growing population and food security. This is a global issue but no solution is currently available.

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