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Linking crop- and soil-based approaches to evaluate system nitrogen-use efficiency and tradeoffs

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ABSTRACT

Increasing nitrogen (N)-use efficiency (NUE) is key to improving crop production while mitigating ecologically-damaging environmental N losses. Traditional approaches to assess NUE are principally focused on evaluating crop responses to N inputs, often consider only what happens during the growing season, and ignore other means to improve system efficiency, such as by tightening the cycling of soil N (e.g. with N scavenging cover crops). As the goals of improving production and environmental quality converge, new metrics that can simultaneously capture multiple aspects of system performance are needed. To fill this gap, we developed a theoretical framework that links both crop- and soil-based approaches to derive a system N-use efficiency (sNUE) index. This easily interpretable metric succinctly characterizes N cycling and facilitates comparison of systems that differ in biophysical controls on N dynamics. We demonstrated the application of this new approach and compared it to traditional NUE metrics using data generated with a process-based model (APSIM), trained and tested with experimental datasets (Iowa, USA). Modeling of maize-soybean rotations indicated that despite their high crop NUE, only 45% of N losses could be attributed to the inefficient use of N inputs, whereas the rest originated from the release of native soil N into the environment, due to the asynchrony between soil mineralization and crop uptake. Additionally, sNUE produced estimates of system efficiency that were more stable across weather years and less correlated to other metrics across distinct crop sequences and N fertilizer input levels. We also showed how sNUE allows for the examination of tradeoffs between N cycling and production performance, and thus has the potential to aid in the design of systems that better balance production and environmental outcomes.

1. Introduction

Mitigating the environmental impacts of nitrogen (N) use while maintaining or increasing crop production is a major challenge of modern agriculture (Reis et al., 2016). Productivity remains primarily constrained by the availability of N to crops in many soils (Connor et al., 2011; Sinclair and Rufty, 2012). However, only about half of the global N fertilizer inputs to farmland are recovered in harvested yield (Conant et al., 2013; Gardner and Drinkwater, 2009). Unused N fertilizer can be retained in soils, or it can be lost to water bodies and the atmosphere, triggering a cascade of adverse ecosystem effects (Billen et al., 2013; Erisman et al., 2007; Galloway et al., 2003). Nitrate (NO_3), the dominant source of soil N for many crops, can be leached to ground and surface waters where it contributes to drinking water pollution and aquatic ecosystem eutrophication (Robertson and Vitousek, 2009). Gaseous losses of N through nitrification and denitrification processes produce nitrous oxide (N_2O) as a byproduct. This greenhouse gas has ~300 times more radiative forcing than CO_2 and also contributes to stratospheric ozone depletion (Davidson and Kanter, 2014; IPCC, 2014). Therefore, increasing agricultural N-use efficiency (NUE) is widely viewed as the means to concurrently protect environmental quality and improve crop production (Cassman et al., 2002, 2003; Davidson et al., 2015; Foley et al., 2011; Mueller et al., 2017; Robertson and Vitousek, 2009; Zhang et al., 2015).

Agricultural research often focuses on how to modify crop sequences, improve genetics and adjust management practices to increase NUE under a range of conditions. Numerous metrics have been developed to address these questions (see Table 1a–b and reviews by Dobermann, 2007; Fixen et al., 2014; Hirel et al., 2011; Ladha et al., 2005) and advance our understanding of how plant physiology, genetics, and management contribute to NUE. However, these metrics often only consider what happens during the growing season and are

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Table 1
Review of nitrogen (N) use efficiency metrics traditionally used in agricultural sciences. We classified them according to their scope into: (a) agronomic, (b) regional, and (c) budget-based metrics. Definitions in (a) are based on the review performed by Dobermann (2007), and definitions in (b) are based on the review performed by Hirel et al. (2011). Metrics can also be classified according to type of relationship into: (I) mass or N yield per unit of N input, (II) unit of N output per unit of N input, and (III) mass or N yield per unit of N output.

	Type of Relationship		
	I	**II**	**III**
	kg mass or N yield kg^{-1} N input	kg N output kg^{-1} N input	kg mass or N yield kg^{-1} N output
	Expressions and formulae		
(a) Agronomic[a] Evaluate the crop response to N fertilizer as affected by management. Used mostly with data from short-term plot or field experiments	Agronomic efficiency (AE) AE = ΔYield/Fertilizer	Recovery efficiency (RE) RE = ΔUptake/Fertilizer	Physiologic efficiency (PE) PE = ΔYield/ΔUptake
(b) Regional[b] Study physiological, genetic, and management factors that affect crop response to N across environments and evaluate long-term trends. Useful in breeding programs	Partial factor productivity (PFP) PFP = Yield/Fertilizer	Uptake efficiency (UpE) UpE = Uptake/Fertilizer	Utilization efficiency (UtE) UtE = Yield/Uptake
(c) Budget-based[c] Evaluate environmental, management and genetic factors on performance and sustainability of cropping systems. Applied at field, regional and global scales	Crop N-use efficiency (NUE_{Crop}) NUE_{Crop} = N yield/N inputs	Soil N-use efficiency (NUE_{Soil}) NUE_{Soil} = N outputs/N inputs	System N-use efficiency[d] (sNUE) sNUE = N yield/N outputs

[a] Δ = change with respect to an unfertilized control.
[b] Sometimes use aboveground biomass instead of yield, and total plant available N (fertilizer + mineralization) instead of only fertilizer.
[c] N inputs include fertilizer or manure, atmospheric deposition, legume fixation; N outputs include N yield and environmental N losses.
[d] Defined in the present study.

generally applicable only to crops that receive N fertilizer or manure inputs. Cropping systems typically include sequences of crops that receive fertilizer (e.g. cereals) and crops that do not (e.g. legumes), and many processes that relate to N losses (e.g. mineralization-immobilization, soil water and temperature fluctuations) continue thru fallow periods. Hence, the evaluation of cropping system performance requires approaches that can reflect NUE at the cropping systems scale, irrespective of whether external sources of N are applied or whether crops are growing.

At the cropping system-level, NUE is often evaluated using N budgets (Fig. 1). These are accounts of N being added or subtracted from the system (Dobermann, 2007; Meisinger et al., 2008), with different methodologies arising depending on where the system boundaries are drawn (Cherry et al., 2008). In a crop-based N budget, the N balance is calculated by the difference between N inputs to the system and the N removed in crop yield (Oenema et al., 2003). System N inputs often include N fertilizer or manure, atmospheric deposition and legume fixation (Fig. 1). Nitrogen-use efficiency in the context of crop-based budgets (NUE_{Crop}) is then defined by how much N yield is achieved relative to how much N was added to the system (ratio of N yield to N inputs). When N yield is greater than N inputs (i.e. $NUE_{Crop} > 1$), this indicates a cropping system with a net removal of N. If the opposite is true (i.e. $NUE_{Crop} < 1$), then this implies a cropping system with a net surplus of N supply (i.e. either by fixation or applied inputs). The latter is often the case in intensified systems, where N inputs exceed what is removed by N yield over multiple years. Yet, it is unclear whether the surplus N is stored in the soil or lost to the environment (Maaz and Pan, 2017), although it is frequently argued that it is lost over the long-term (Cassman et al., 2002; Robertson et al., 2014; Thorburn and Wilkinson, 2013; Zhang et al., 2015). This crop-based view of NUE works well from an agronomic perspective when maximizing yield and minimizing inputs is prioritized. However, this approach has the potential to mischaracterize environmental impacts given the uncertainties related to the fate of N (Buczko et al., 2010; Cherry et al., 2008; Oenema et al., 2003; Özbek and Leip, 2015).

In a soil-based N budget, the N balance is calculated by summing N inputs then subtracting all system outputs (Cherry et al., 2008; Sainju, 2017). From this perspective, N outputs include the N removed in crop yield and all other N losses from the system (e.g. leaching of dissolved N to ground or surface waters, gaseous products of nitrification and denitrification, ammonia volatilization, etc.; Fig. 1). It is important to note that crop N uptake and mineralization-immobilization from soil organic matter (SOM) and crop residues are considered short-term internal cycling pathways, not long-term inputs or outputs (Norton et al., 2015). Nitrogen-use efficiency in the context of a soil N balance (NUE_{Soil}) can be then defined by how much N is lost from the system relative to how much was added to the system (ratio of N outputs to N inputs). When N inputs exceed N outputs over the long term (i.e. $NUE_{Soil} < 1$), it can be inferred that the soil is a net sink for N. When the opposite is true (i.e. $NUE_{Soil} > 1$), this indicates that the soil is a net source of N (Cherry

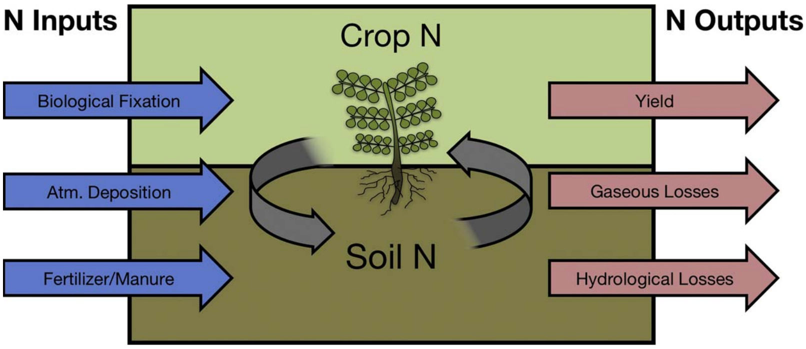

Fig. 1. Conceptual box diagram of the major N fluxes often used to calculate budgets and efficiency indices. Blue arrows: N inputs; Red arrows: N outputs; Grey arrows: internal crop-soil N cycling. Gaseous losses include ammonia volatilization, and gaseous products of nitrification and denitrification. Hydrological losses include dissolved organic and inorganic N in runoff, drainage, and deep seepage water. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)