A Hierarchical Framework for Unpacking the Nitrogen Challenge

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Abstract

Managing Nitrogen (N) is fundamental, yet challenging, for sustainable development: N is essential for producing crops and livestock and consequently important for food security. However, the rising N inputs from human activities to the biosphere has gone beyond a "planetary boundary for a safe operating space", leading to severe environmental issues, ranging from local water and air pollution to global climate change. To address the N challenge, more N-efficient technologies in crop or livestock production alone are insufficient. A broader understanding of the complex trade-offs and responses of markets, governments, and consumers is needed. Here we present a hierarchical framework encompassing the complex cycles of N in human activities and natural systems, yet simple enough to guide policies and day-to-day actions: The **C**ropping system is nested within **A**nimal-crop system, which is nested within the **F**ood system, and finally nested within watershed **E**cosystem (***CAFE***).

The ***CAFE*** framework is designed to manage N, a classical "wicked problem", which involves many stakeholders, including multiple economic sectors and governmental ministries, with differing or even competing interests across multiple spatial scales. Moreover, relevant decisions and policies are made on the farm, at the grocery store, in corporate board rooms, at regulators' desks, and in legislative sessions, making it very challenging to inform and coordinate actions and policies that would improve the efficiency of N management while meeting various stakeholders' needs. Numerous studies have quantified N budgets at specific spatial scales, from the farm gate to the globe, but none has applied consistent approaches across all scales and aligned the definition of N budgets with stakeholders' primary interests.

To unpack this "wicked problem", the new framework, ***CAFE***, defines four N management systems in a hierarchical manner (Fig. 1), of which the basic functions are meaningful for all stakeholders and for which data are often available. The **C**ropping system considers cropland as its system boundary, which receives N inputs from chemical fertilizer, manure, biological fixation, and deposition. The system's productive output is N in harvests for human consumption and animal production (Fig. 1). Integrating livestock with crop production, the **A**nimal-crop system imports N from the **C**ropping system plus other N inputs, such as N input to pasture, and imported feed. Manure application to cropland is N recycled within the system. The N embedded in non-feed crop and animal products are the productive output of the integrated **A**nimal-crop system. The **F**ood (**F**iber and crop-based bio**F**uel) system traces N from the **A**nimal-crop system to marketplaces and to consumers; its productive output is N imbedded in the products used/uptake by consumers. The **E**cosystem receives N inputs to the whole watershed, such as N deposition, in addition to N inputs to the **F**ood system. Products exported from the watershed constitute for productive outputs, since N in products consumed within the watershed is either retained or carried away as pollutants downwind and downstream. The **E**cosystem serves another important function for enabling a healthy living environment by retaining some N in vegetation, soils, and sediments, and converting some to harmless dinitrogen gas. For each ***CAFE*** system,

major stakeholders should focus on the productivity of the system, careful management of N inputs, and efforts to reduce N surplus (difference between N inputs and productive outputs), thereby lowering environmental N burden.

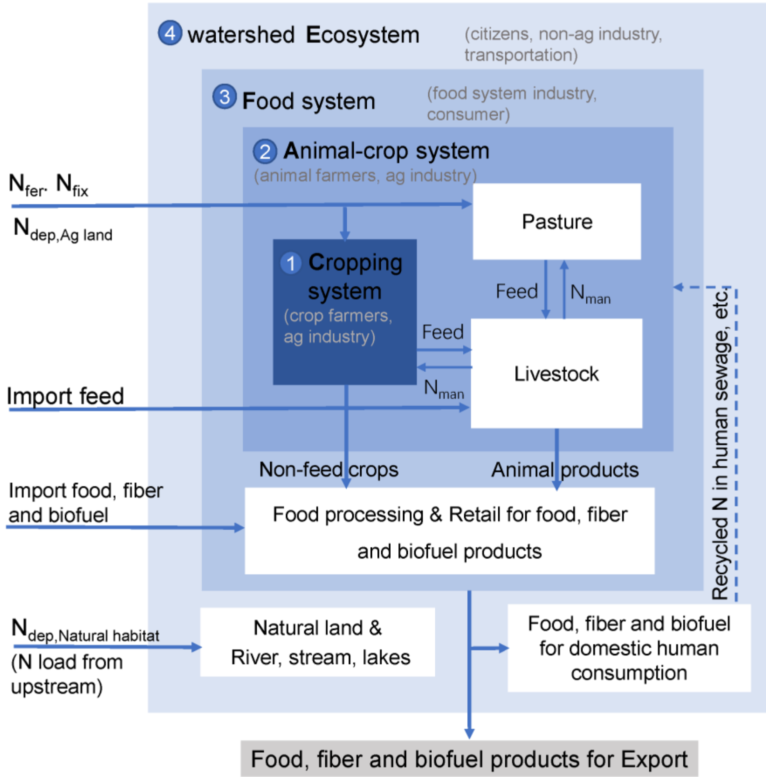

Fig. 1 The N budgets for ***CAFE*** framework. For graphical simplicity, nonproductive products, such as air and water pollution, are not shown.