PERSPECTIVE

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Classifying methods to quantify crop nitrogen input requirements

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Abstract In this short communication, we propose a framework that classifies methods for estimating crop nitrogen (N) input requirements along two dimensions: short-term versus long-term and current versus optimal crop management practices. The four resulting quadrants provide different perspectives on modelling methods, each distinctive in handling soil N supply, mineral versus organic N sources, management and yield levels. For each quadrant, study examples and data requirements are provided. We emphasise the importance of accurate and purpose-oriented selection of crop N requirement modelling methods and acknowledge the complexity and uncertainties inherent in N modelling, often due to a lack of data availability. The choice of methods to estimate N inputs strongly impacts model outcomes and conclusions, affecting agricultural practices, advisories, and policy strategies. Therefore, a decision tree is presented to support choices in assessing N input requirements so that models can help identify under and over-fertilisation hotspots, maintain soil fertility, and optimise crop yields, contributing to environmental protection and food security goals.
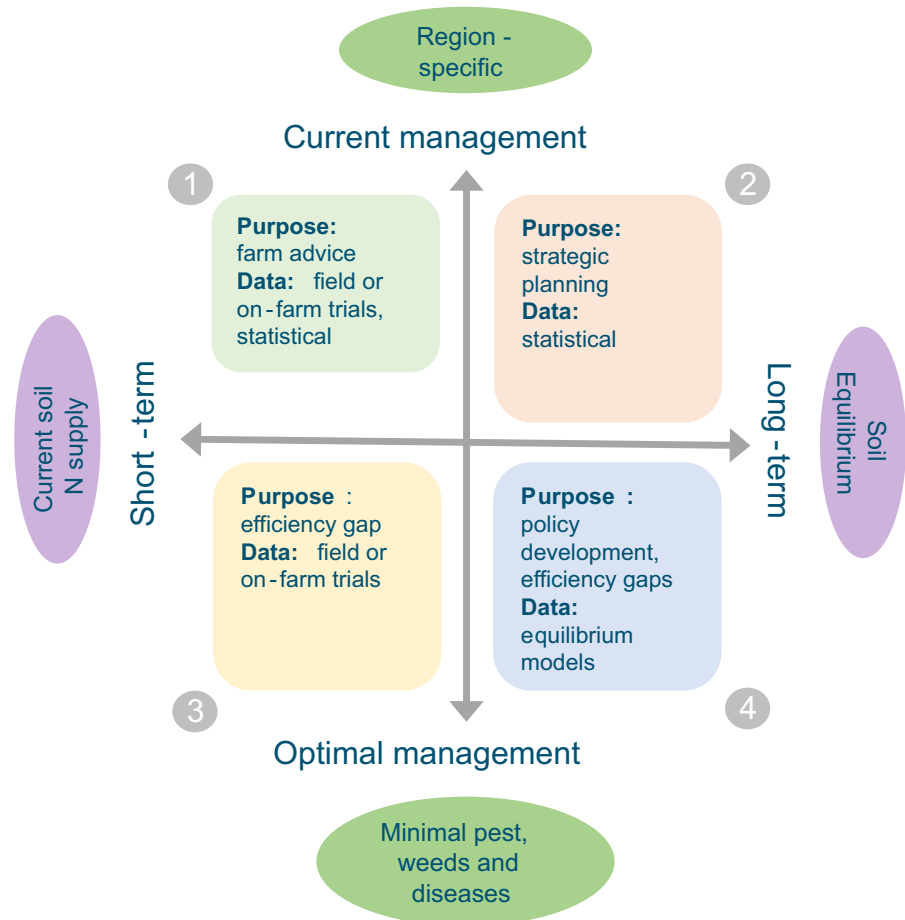
Model choices on estimating nitrogen (N) input requirements for cropping systems can lead to different conclusions for the same question. Therefore, the model selection process should be well-informed and purpose-oriented but is often limited by data availability constraints. This short communication aims to classify existing methods along two dimensions: short-term versus long-term and current versus optimal crop management practices (Fig. 1). Here, we focus on methods that can be used in the field and on higher spatial and systems scales (regions or food systems), omitting more detailed mechanistic modelling approaches such as Daycent or DNDC (Grant et al. 2016).

The time dimension is especially relevant when modelling *N input requirements from mineral or organic sources*. Most N from mineral fertiliser becomes available in the growing season when it is applied. In contrast, organic fertilisers release N over a more extended period. To capture the difference in N release between mineral and organic fertiliser, N fertiliser replacement values (NFRV) are commonly used. NFRV is the ratio of organic

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Fig. 1 Classification of crop nitrogen input requirement modelling approaches in four different quadrants along the dimensions of short- and long-term N requirements and current and optimal crop management

Region - specific

Current management

1

Purpose: farm advice
Data: field or on-farm trials, statistical

2

Purpose: strategic planning
Data: statistical

Current soil N supply

Short - term

Long - term

Soil Equilibrium

Purpose: efficiency gap
Data: field or on-farm trials

3

Purpose: policy development, efficiency gaps
Data: equilibrium models

4

Optimal management

Minimal pest, weeds and diseases

fertiliser N uptake related to N uptake from equal amounts of mineral fertiliser N. However, the value for NFRV depends on the assumed timeframe for which the N input requirements are modelled. In the short term, NFRVs below one are observed for organic fertilisers, while in a long-term assessment, an equilibrium state can be assumed, leading to an NFRV of around 1 for amendments such as animal manure (Hijbeek et al. 2018; Schröder 2005).

The second component related to time is handling *soil N supply*. This component hinges on how we define available N, depending on the timeframe we want to evaluate. From a short-term perspective, how much N is available this year from the soil is especially relevant. However, with stable management over the long term, a soil equilibrium will be reached in which soil N mineralisation equals the build-up of soil organic N (van Grinsven et al. 2022).

The *crop management* dimension (apart from nutrients) includes a range of practices like planting date, weed, pest and disease control, and irrigation. The assumption of management interweaves tightly with the choice of yield levels. Modelling current management requires data on actual yields and N inputs while modelling optimal management requires estimating the theoretical maximum N use efficiency under optimal conditions (with optimal planting, effective weed, pest and disease control, and efficient irrigation). Optimal management can also be assumed with current yields but lower N inputs, meaning its maximum yield at a given N input.

In summary, the assumptions around those three components—mineral vs organic N, soil N supply, and management—are interconnected and need consideration when modelling N input requirements for both monocropping and crop rotations. An example in which data used and timeframe are not aligned is

the current NFRVs used in legislation: In Dutch legislation, for example, N applied as farmyard manure only counts 30–60% compared to N in mineral fertilisers (RVO 2023). This methodological choice for regulations leads to higher organic N applications. The result is a systematic overfertilisation of farmland, driven by an approach that fails to recognise the need for long-term planning in fertiliser application.

Methods to model N input requirements can be divided into four quadrants (Fig. 1) with a related decision tree (Fig. 2). In the first quadrant, crop N requirements are modelled based on current management practices with a short-term perspective (*green* squares in Figs. 1, 2). The actual yield and N requirements can be determined using empirical (e.g. field experiments) or statistical data (e.g., national statistics or farm surveys). *The advantage of this quadrant lies in its ability to capture over-fertilisation and provide practical N rates for specific locations based on detailed crop or statistical data.* Disadvantages of statistical data (e.g., for N application rates) include the lack of a dynamic link between yield data and N inputs. This approach is best suited for realistically representing current systems, modelling only minor

changes to existing systems, identifying fertilisation issues, and providing practical farmer and policy advice (Janssen et al. 1990; Velthof et al. 2009).

In the second quadrant, crop N requirements are modelled under current management practices with a long-term focus (*orange* squares in Figs. 1, 2). Data can come from long-term field experiments, and statistical yields can be used to calculate N inputs. *The main advantage is the linkage between yields and N requirements, ensuring balanced fertilisation with changing yields for specific scenarios.* While assuming current management, this approach does not account for occurrences of over- or underfertilisation. It is most suitable for modelling systems with balanced fertilisation (N input equates N output) and often applies to high spatial and system scale food system models for strategic planning (Van Grinsven et al. 2022; van Zanten et al. 2023).

In the third quadrant, crop N requirements are modelled under the assumption of optimal management with a short-term perspective (*yellow* squares in Figs. 1, 2). *The advantages include identifying short-term efficiency gaps for local systems.* However, this approach can be data-intensive and faces challenges
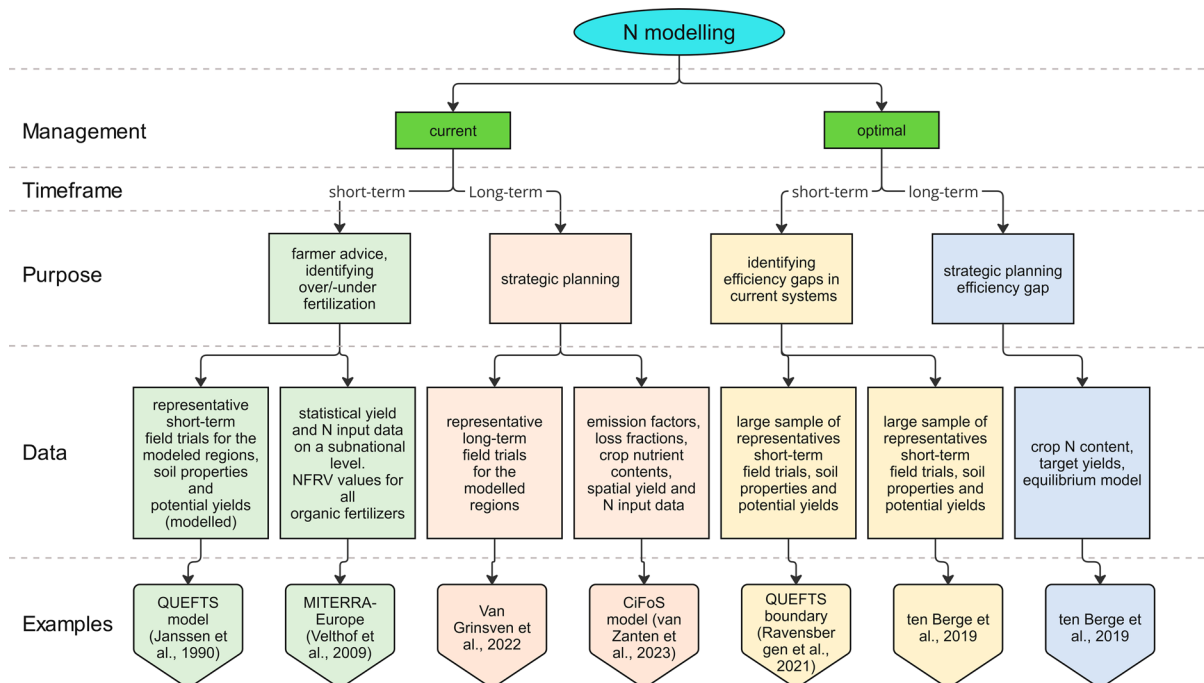

Fig. 2 Decision tree for finding the appropriate N input requirement modelling method with decision variables Management, time frame, Purpose, Data and illustrative modelling studies

in accurately estimating potential yields for various crops. This quadrant is best suited for understanding the yield gaps of a system and the corresponding minimum N requirements for reaching attainable yields and providing best-practice advice (Ravensbergen et al. 2021; ten Berge et al. 2019).

The fourth quadrant focuses on long-term outcomes under optimal management (*blue* squares in Figs. 1, 2). *The advantages include the strength of the theoretical basis and the low data needs.* However, the reliance on increased assumptions increases uncertainty in the modelling process. This quadrant is particularly suited for modelling future potential systems in an optimal world over a long-term timeframe, providing a vision for sustainable pathways into the future representing best-case agricultural scenarios (ten Berge et al. 2019).

Data quality and availability are currently the main limitations for methodological choices in N input requirement modelling, especially at high spatial and systems scales, such as food system models. A modeller might aspire to use a sophisticated method only to discover that the data needed for this approach is unavailable, only available in highly aggregated form, or limited to specific geographic regions or certain crops. Crop-specific fertilisation rates are further highly scattered or missing. Simplified methods and assumptions often prevail in practice due to practical constraints such as unrealistically long model runtime (e.g., global food system level) and limited data access. All these data aspects can drastically narrow the choices for N input modelling approaches. *Validating* N requirement modelling methods, especially at higher spatial and system scales, is difficult. This challenge arises from the inherently high uncertainty in national and global census data (e.g., FAOSTAT). These data sets are often highly aggregated and usually align poorly across different databases or between domains within a database. This lack of validation poses an ongoing challenge regarding validation approaches, adding complexity to the effective utilisation and interpretation of models using crop N requirements in decision-making processes. Securing dependable organic *N fertilisation baseline data* is a significant obstacle, especially in models that focus on circularity aspects of organically sourced N. For example, it is challenging to find reliable data on animal manure and the fertiliser effect of crop rotations and other organic fertilisers, including compost and crop residues and their distribution across crops. Irrigation is another N source for cropping systems that is challenging to quantify and often neglected (Serra et al. 2023). While it may be considered a new N input at the field scale, it can be represented as a recirculation of previous N inputs at higher spatial scales, demonstrating the importance of *system boundaries* in drawing conclusions.

We hope the presented classification will support informed crop N input modelling choices. By accurately estimating N input requirements, models can help identify under and over-fertilisation hotspots, maintain soil fertility, and optimise crop yields, contributing to environmental protection and food security goals. Future research should expand crop data, explore interactions between fertilisers and soil properties, and refine models and data sets to include a broader range of variables and crops. Our overview has shown that data-related challenges can limit the options of N input modelling approaches. Addressing these challenges and knowledge gaps is vital for advancing modelling N flows in cropping and food systems.

Declarations

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