



Comparing mass balance-based nutrient management planning tools to support crop fertilisation decisions

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Abstract Nutrient management plan (NMP) tools aim to enhance crop production while minimising environmental harm from over-fertilisation by aligning applications with crop demands and with soil and atmospheric conditions. The characteristics of 14 widely used NMP tools from nine countries (Austria, Bulgaria, China, Czech Republic, Hungary, Italy, New Zealand, Spain, and United Kingdom) were compared. All tools employed a mass balance

approach at the field and seasonal scales. To evaluate the tools, matrices of the presence/absence of 24 desirable characteristics, 22 nutrient cycle processes and sources, and 38 required input data were compiled. To compare the NMPs, cumulative scores were calculated for each category evaluated. Additionally, two theoretical case studies compared fertiliser recommendations for winter wheat in arable and livestock farming systems. Cluster analysis classified the 14 tools into six clusters, reflecting distinct levels of complexity, usability, adaptability, and interoperability. The number of input data required was strongly and positively correlated with the number of nitrogen

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(N) processes and sources considered, confirming that input demand reflects tool sophistication. More comprehensive tools tended to recommend lower N application rates in the livestock system, suggesting that simpler tools overestimated N requirements by omitting key processes. However, practical usability characteristics did not determine different recommendations. While N recommendations were broadly aligned with national guidelines, P and K recommendations showed considerably higher variability reflecting the lack of harmonised guidelines for these macronutrients.

Keywords Nutrient management · Fertilisation · Digital tool · Soil fertility · Mass balance

Introduction

Nutrient management in agriculture aims to optimise crop yields while minimising negative environmental impacts due to over-fertilisation, through the targeted application of fertilisers. Determining fertiliser requirements involves integrating crop demand, soil nutrient supply, loss pathways, and management constraints.

A Nutrient Management Plan (NMP) is a tool based on the mass balance approach, designed to support optimal nutrient use on farms to increase profitability while managing environmental limitations (EIP-AGRI Service Point 2022). Tools that farmers use for fertilisation planning can be divided into four categories: reference tables, spreadsheets,

computer applications, and decision-support systems (EIP-AGRI Service Point 2022). Reference tables indicate the amount of nutrients to apply to single crops based on local conditions, usually at the national level (Jordan-Meille et al. 2023). Spreadsheet calculations are a digitalised form of this approach, typically considering more factors influencing crop nutrient requirements (Ravier et al. 2016). Calculation tools may be more complex by utilising purpose-made software, considering the soil-atmosphere-plant system to tailor the amount of nutrient input to pedo-climatic, management and crop conditions (Nicholson et al. 2013). The most complex tools are decision support systems that analyse the nutrient budget and other aspects of crop production, such as pest management, machinery monitoring, such as tractors, and economic balance (Gallardo et al. 2020).

Nutrient application rates are generally computed using a mass balance of inputs and outputs in the system. Fertiliser requirements should consider various processes (including fertiliser efficiency, soil organic matter—SOM—mineralisation, N fixation and P solubilisation) and be equivalent to nutrient removals from soil solution through crop uptake, volatilisation, denitrification, leaching losses and microbial immobilisation (Öborn et al. 2003). Most European farmers use tools that are directly or indirectly based on the mass balance (Klages et al. 2022). Nutrient cycles are complex, and their full modelling requires many variables and equations. Even for a static model (seasonal estimate using expected average data), estimating some processes might be too complex. For example, estimating crop nutrient uptake has high uncertainty, owing to (i) yield forecast uncertainty due to interannual variability (Ravier et al. 2016); and (ii) crop nutrient concentrations, that vary depending on pedoclimatic conditions (Jensen & Norton 2012). Regional-dependent factors further hamper the development of tools that are valid over large territorial areas, such as national fertilisation thresholds set by environmental regulations. For instance, Jordan-Meille et al. (2012, 2023) indicated that European countries adopt varying approaches for P and N fertilisation. Therefore, efforts are urgently needed to reconcile the opposing objectives of developing tools that are usable across different areas yet can be sufficiently site-specific to reliably estimate crop nutrient requirements.

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Several studies have examined nutrient management approaches across Europe, yet significant gaps remain in the comparative assessment of digital tools for fertilisation planning. Fertilisation guidelines across 23 European countries were surveyed (Higgins et al. 2023), revealing substantial differences in soil testing methods and recommendation calculations. N fertilisation methods were compared in 10 West European countries, identifying three main categories of calculation approaches and large discrepancies in recommended rates (Jordan-Meille et al. 2023). More recently, Raffa et al. (2025) and Jouini et al. (2025) surveyed the availability and adoption of over 100 agricultural decision support tools across Europe, highlighting persistent barriers to uptake and the need to improve interoperability and user engagement. However, these studies either focused on national regulatory methods rather than the specific digital tools available to farmers or presented aggregated results without describing individual tools in detail. Cooper et al. (2009) provide the only dedicated inventory of farm-level N management tools in the EU, with existing comparisons largely confined to Western Europe while excluding tools developed in Eastern Europe, China, or the Southern Hemisphere. No study has systematically compared the internal characteristics, underlying processes, required inputs, and quantitative outputs

of individual nutrient management planning tools under standardised conditions.

This study aims to fill these knowledge gaps by evaluating desirable features of some NMP tools used within defined territorial boundaries, from the perspective of different end users (researchers, technicians, farmers). It sets out a series of criteria for analysing and evaluating existing NMP tools and highlights their strengths and weaknesses. Therefore, the specific objectives of this study were to: (1) assess the degree of similarity between 14 selected NMP tools from 9 countries (Austria, Bulgaria, China, Czech Republic, Hungary, Italy, New Zealand, United Kingdom, and Spain), based on their characteristics, processes and inputs considered; (2) compare fertilisation recommendations for crops calculated using two theoretical case studies; and (3) define the overall relationship between the assessment of NMP tools and nutrient recommendations.

Materials and methods

NMP tools selection

Fourteen NMP tools were selected from those most used in the nine partner countries of the TUDI project (www.tudi-project.org), as shown in Table 1.

Table 1 List of NMP tools included in this study

Country	Tool name	Link	Type
Austria	LK-Düngerrechner	https://bwsb.ooe.lko.or.at/lk-d%C3%BCnngerrechner+2400+3586614	Spreadsheet
Bulgaria	Bulgarian tool		Reference tables
China	Nutrient Expert	www.nutrientexpert.cn	Online app
Czech Republic	Czech tool	http://www.nitrat.cz/	Spreadsheet
Hungary	MEM-NAK		Reference tables
Hungary	ProPlanta	https://owncloud.atk.hu/index.php/s/3LRszbX8rn57gEn/download	Local app
Italy	Digifert	https://servizi.regione.piemonte.it/catalogo/digifert-piani-concimazione-digitale	Online app
Italy	Fert_Office	https://agricoltura.regione.emilia-romagna.it/produzioni-agroalimenti/agricoltura-sostenibile/suolo-fertilizzazione	Spreadsheet
Italy	grano.net®	https://www.horta-srl.it/grano-net	Online app
New Zealand	Overseer®	https://www.overseer.org.nz	Online app
United Kingdom	PLANET and MANNER	https://www.planet4farmers.co.uk/	Local app
Spain	FertiliCalc	www.uco.es/fitotecnica/fertilicalc.html	Local app
European Union	Fast Navigator F3	https://tool.fastnavigator.eu/nutrients/13.html	Online app
European Union	TUDI	https://tudi-soil.web.app	Online app

A Local app needs to be downloaded before running it; an Online app does not require downloading

Tools were selected according to the following criteria: (i) approach based on a mass balance, (ii) working on a field scale as a spatial dimension and on a seasonal level as a temporal dimension (e.g. they provide fertiliser recommendations for a single crop grown in specific conditions), (iii) documentation available online or by interviewing developers or professional users.

NMP tools evaluation

For each tool, its characteristics were evaluated to facilitate its practical use, to identify relevant nutrient cycle processes and sources, and to quantify the input data required for fertilisation recommendations. To compare NMPs, cumulative scores were calculated for each category evaluated.

Assessment of characteristics

For the characteristics assessment, a list of desirable features was organised into four thematic categories: usability, degree of complexity, adaptability, and interoperability (Table 2).

The NMP tools were scored based on the presence/absence of each characteristic listed in Table 2 and S.I. 1. As each theme differed in the number of characteristics, their summed score was transformed into a scale from 0 to 10 by dividing the number of features present by the total number in each theme and then multiplying it by 10. The total score was judged “high” if it was greater than the mean + standard deviation, and “low” if smaller than the mean—standard deviation.

To classify the NMP tools according to their similarity, we performed a cluster analysis on the original matrix of characteristics in the R programming language (R Core Team 2026) using Jaccard distance and Ward’s algorithm (Finch 2005). Thus, we used the *Dist* function from the *amap* package (Lucas 2024) and *hclust* function from the *base* package. The *dendextend* package (Galili 2015) plotted the dendrogram, while the *ggplot2* package (Wickham 2016) created the other figures.

Assessment of processes and sources

In addition to assessing the characteristics, the scientific basis of the relevant processes and sources of nutrients included in the tools were considered (Table 2, S.I. 1 and S.I. 2). Many tools did not quantify nutrient losses in the budget. Instead, an efficiency coefficient was applied to mineral and/or organic fertilisation, considering losses as an inefficient part of the additions. Consequently, the efficiency coefficient approach was also included in the description of processes.

We based the scoring of NMP tools processes and sources on the presence/absence of each one listed in Table 2 by summing them, without further conversion.

Assessment of inputs

The most considered inputs within NMP tools were also evaluated (Table 2, S.I. 1). The categories analysed concern information about the farm, crop type, soil properties, irrigation, tillage, climate data, mineral and organic fertilisers management.

We based the scoring of NMP tools inputs on the presence/absence of each one listed in Table 2 by summing them, without further conversion.

Formulas for estimating crop requirements

In reviewing the NMP tools, the formulas used in estimating crop requirements, and the description of nutrient processes and sources is summarised in Tables 3 and 4. The full review of NMP tools is available in S.I. 2.

Case studies

We tested the various tools by comparing the fertiliser recommendations provided for two previously described specific theoretical case studies (Jordan-Meille et al. 2023) comprising arable winter wheat and livestock farming systems. The inputs for the case studies were integrated with soil P and K contents and climate data (Tables 5 and 6) and simplified to a single soil layer (as all tools only included one layer). No tools were common to our study and Jordan-Meille et al. (2023), although three countries (Italy, United Kingdom, and Spain) were.

Table 2 List of desirable characteristics, nutrient cycle processes and processes, and common inputs for Nutrient Management Plan (NMP) tools

Domain	Category	Details
<i>A. Desirable characteristics of a NMP tool</i>		
Usability	Input simplicity	Requires fewer than 20 input data points
	Output flexibility	Provides outputs based on farm objectives (max yield, reduced environmental impact)
	Administrative use	Supports Nitrates Directive, Natura2000, organic/integrated production, and supply chain contracts
	Data management	Allows saving input data; includes commercial/standard mineral fertiliser lists
Complexity	Accessibility	Available online and free of cost
	Nutrient scope	Provides a plan for all three main nutrients (N, P, K)
	Crop coverage	Includes more than one crop type
	Manure efficiency	Fertiliser efficiency varying with timing, soil, and weather conditions
	Mass balance	Losses are estimated and included in the mass balance
Adaptability	Scientific basis	Based on scientific papers and the algorithms are transparent
	Economics	Includes an economic evaluation
	Crop parameters	Crop uptake and residues are tailorable (harvest index, humidity, NPK concentrations)
	Soil & climate	Processes vary with soil and climate characteristics
	Manure flexibility	Manures tailorable at farm level (sub-categories, NPK concentrations)
	Validation	Tested in at least two different environments
	Language	Can be used in different languages
Interoperability	Local databases	Linked to farm data, soil data, and other local databases
	Modules	Linked to GHG, nutrient losses, irrigation, manure storage modules
	Temporal detail	Linked to sub-seasonal applications (e.g. fertilisation timing)
	Forecasting	Linked to modules enabling forecasting analyses
<i>B. Relevant nutrient cycle processes and nutrient sources</i>		
Nitrogen	SOM mineralisation	Soil organic matter mineralisation contributes plant-available N
	Past organic fert	Residual N from previous year organic fertilisation
	Atmospheric dep	N deposited from the atmosphere
	N-fixation	Biological nitrogen fixation by legumes
	Irrigation	N supplied through irrigation water
	Losses	Leaching, volatilisation, denitrification, and immobilisation
Phosphorus	Runoff & erosion	P losses through surface runoff and soil erosion
NPK	Crop residues	Release of nutrients from mineralisation of previous crop residues
	Initial soil stock	Soil contribution of freely available N, P, and K
	Fertiliser efficiency	Part of mineral and organic fertiliser considered inefficient
<i>C. Most common inputs for NMP tools</i>		
Farm	Identification	Farm ID, field ID, field surface area, location
Crop	Crop details	Crop type, yield, sowing date, cropping system
	Previous crop	Previous crop type, yield, and management
Soil	Physical properties	Texture class, depth, slope
	Chemical properties	SOM content, total N, pH, available P, exchangeable K, CEC
Irrigation	Irrigation data	Method, amount, water N concentration

Table 2 (continued)

Domain	Category	Details
Tillage	Tillage type	Type of tillage practice
Climate	Climate data	Annual/winter precipitation, mean temperature, atmospheric N deposition
Mineral fert	Application data	Type, previous dose, NPK concentration, strategy for P & K, distribution method
Organic fert	Application data	Type, previous dose, NPK concentration, distribution method and timing

N = nitrogen; P = phosphorus; K = potassium; SOM = soil organic matter; CEC = cation exchange capacity; GHG = greenhouse gases

Table 3 Summary of formulas used in nutrient balance calculations. The full review of NMP tools is available in S.I. 2

NMP tool	N formula	P formula	K formula
LK-Düngerrechner	$N_{mf} = N_{cu} - N_{cr} - N_{of} - N_f - N_{irr}$	$P_{mf} = P_{cu} - P_{of}$	<i>Not computed</i>
Bulgarian tool	$N_{mf} = (N_{cu} - N_{of} - N_f - N_{cr} - N_s) \times N_k$	$P_{mf} = (P_{cu} - P_{of} - P_{cr} - P_s) \times P_k$	$K_{mf} = (K_{cu} - K_{of} - K_{cr} - K_s) \times K_k$
Nutrient Expert	$N_{mf} = (1/I_e) (N_{cu} - N_{of} - N_{cr} - N_s)$	$P_{mf} = (1/I_e) (P_{cu} - P_{of} - P_{cr} - P_s)$	$K_{mf} = (1/I_e) (K_{cu} - K_{of} - K_{cr} - K_s)$
Czech tool	$N_{mf} = N_{cu} - N_{of} - N_{cr} + N_l$	$P_{mf} = P_{cu} - P_{of} - P_{cr}$	$K_{mf} = K_{cu} - K_{of} - K_{cr}$
MEM-NAK	$N_{mf} = N_{cu} - N_{of} - N_{cr} - N_s$	$P_{mf} = P_{cu} - P_{of} - P_{cr} - P_s$	$K_{mf} = K_{cu} - K_{of} - K_{cr} - K_s$
ProPlanta	$N_{mf} = N_{cu} - N_{of} - N_{cr} - N_{atm} - N_{irr} - N_f - N_s$	$P_{mf} = P_{cu} - P_{of} - P_{cr} - P_s$	$K_{mf} = K_{cu} - K_{of} - K_{cr} - K_s$
Digifert	$N_{mf} = N_{cu} - N_{of} - N_{cr} - N_{atm} - N_f - N_{som}$	$P_{mf} = P_{cu} - P_{of} - P_{cr}$	$K_{mf} = K_{cu} - K_{of} - K_{cr}$
Fert_Office	$N_{mf} = N_{cu} - N_{of} - N_{cr} - N_s - N_{atm} - N_f - N_{som} + N_{leach} + N_{imm}$	$P_{mf} = P_{cu} - P_{of} - P_{cr} - P_s + P_{imm}$	$K_{mf} = K_{cu} - K_{of} - K_{cr} - K_s$
Grano.net	$N_{mf} = N_{cu} - N_{of} - N_{cr} - N_s - N_{atm} - N_{irr} - N_f - N_{som} + N_{leach} + N_{imm}$	$P_{mf} = P_{cu} - P_{of} - P_{cr} - P_s$	$K_{mf} = K_{cu} - K_{of} - K_{cr} - K_s$
Overseer	$N_{mf} = N_{cu} - N_{of} - N_{cr} - N_{atm} - N_{irr} - N_f - N_{som} + N_{leach} + N_{vol} + N_{den} + N_{imm}$	$P_{mf} = P_{cu} - P_{of} - P_s - P_{cr} - P_{run}$	$K_{mf} = K_{cu} - K_{of} - K_s - K_{cr}$
PLANET and MANNER-NPK	$N_{mf} = N_{cu} - N_{of} - N_s - N_{som} - N_{cr} + N_{leach} + N_{vol} + N_{den}$	$P_{mf} = P_{cu} - P_{of} - P_s$	$K_{mf} = K_{cu} - K_{of} - K_s$
FertiliCalc	$N_{mf} = (I/(I-n)) (N_{cu} - N_{atm} - N_f - N_s)$	$P_{mf} = P_{cu} - P_s$	$K_{mf} = K_{cu} - K_s$
FaST Navigator	$N_{mf} = N_{cu} - N_s - N_{irr} - N_f - N_{som} + N_{leach} + N_{vol} + N_{den}$	$P_{mf} = P_{cu} - P_s$	$K_{mf} = K_{cu} - K_s$
TUdi	$N_{mf} = N_{cu} - N_{of} - N_{cr} - N_{atm} - N_{irr} - N_f - N_{som} + N_{leach} + N_{vol} + N_{den}$	$P_{mf} = P_{cu} - P_{of} - P_{cr}$	$K_{mf} = K_{cu} - K_{of} - K_{cr}$

Overall comparison

To define the overall relationship between sum of score for the characteristics, number of processes and number of inputs of NMP tools and nutrient recommendations, a correlation analysis used the *cor.test* function from *stats* package (R Core Team

2026). To this purpose, only the N dose recommendations for the livestock system were used, as they are the most representative in terms of the nutrient processes, sources and inputs considered. The Bulgarian tool was excluded from the comparison regarding N dose recommendations as its very low nitrogen application rate (72 kg N ha⁻¹) was mainly attributable to an overestimation of the N available

Table 4 Definition of the components of the mineral fertiliser requirement formula. The full review of NMP tools is available in S.I. 2

Symbol	Description
<i>Nmf</i> / <i>Pmf</i> / <i>Kmf</i>	Mineral fertiliser requirement—the amount of mineral fertiliser N, P, and/or K needed by the crop after accounting for all other nutrient sources, crop uptake and loss pathways. This is the main output of the mass balance calculation.
<i>Ncu</i> / <i>Pcu</i> / <i>Kcu</i>	Crop uptake—the total nutrients removed by the crop, typically calculated as expected yield multiplied by the nutrient concentration in the harvested product. In LK-Düngerrechner, yield is classified into discrete classes (five for N, three for P) rather than using a continuous value, and uptake also depends on soil P content class. MEM-NAK and ProPlanta allow the nutrient concentration to vary with site conditions and soil nutrient supply category. PLANET and MANNER base uptake solely on crop type and soil nutrient supply index, with no explicit yield term. Grano.net is the only tool that differentiates crop uptake by cultivated variety. FertiliCalc and FaST Navigator compute uptake as above-ground biomass including a fraction of the roots and crop residues, not just the harvested product. Nutrient Expert scales maximum attainable yield for a geographic region according to site characteristics and nutrient interactions. The other tools follow the general rule.
<i>Nof</i> / <i>Pof</i> / <i>Kof</i>	Organic fertiliser supply—the plant-available nutrients contributed by organic amendments such as manure, slurry, or compost. In most tools, availability is adjusted by an efficiency coefficient. In the Bulgarian tool, total amount is multiplied by standard nutrient content and an efficiency coefficient based on time of application. In Digifert, availability depends on soil status and timing through an efficiency coefficient. Grano.net varies availability with type, soil texture, and timing of distribution. Fert_Office considers type, frequency of application and soil texture. MANNER-NPK computes readily available NPK and slowly available N after mineralisation based on growing degree days and manure type. Overseer includes manure, compost, dairy and piggery effluents with month of application as a risk factor for losses. LK-Düngerrechner provides detailed information on organic fertilisers such as stock, handling and application technique.
<i>Ncr</i> / <i>Pcr</i> / <i>Kcr</i>	Previous crop residues—nutrients released from the residues left by the preceding crop. In Fert_Office, residues can either provide extra N or immobilise it, depending on the residue C/N ratio. Grano.net considers residues from both the main crop and cover crops. The other tools follow the general rule.
<i>Ns</i> / <i>Ps</i> / <i>Ks</i>	Soil nutrient supply—the nutrients already available in the soil, determined through soil analysis. For N, this typically refers to mineral N (nitrate and ammonium) in the root zone. For P and K, it refers to plant-available forms determined by extraction methods (e.g., Olsen P, exchangeable K). In MEM-NAK, N is classified based on humus content, while P and K are classified based on ammonium lactate soluble forms. PLANET and MANNER express soil status as semi-quantitative indices (0–5 for N, 0–9 for P and K). In Overseer, only P and K soil supply are considered. FertiliCalc considers only the residual mineral N at the end of the growing season (default 10 kg N ha ⁻¹). In Digifert, P and K soil supplies are not included as direct sources but as a factor that reduces requirements in nutrient-rich soils. FaST Navigator considers initial and final mineral N, available P and exchangeable K. The other tools follow the general rule, which accounts directly for the soil analysis.
<i>Nf</i>	Symbiotic N fixation—atmospheric nitrogen fixed biologically by leguminous crops through their root-nodule bacteria. In LK-Düngerrechner and in the Bulgarian tool, fixation is only crop-specific. FertiliCalc estimates fixation depending on whether the legume is annual or perennial and on SOM content. Overseer adjusts N fixation for clover coverage, development status, herd grazing, and field-level N budgeting.
<i>Natm</i>	Atmospheric deposition—nitrogen that is deposited on the soil surface from the atmosphere through wet and dry deposition processes. FertiliCalc uses a default value of 10 kg N ha ⁻¹ . Overseer uses 2 kg N ha ⁻¹ year ⁻¹ . TUDI uses country-based reference tables.
<i>Nirr</i>	Nitrogen from irrigation—nitrate or other N forms supplied via irrigation water. FaST Navigator computes this from irrigation type, amount, and irrigation water N concentration. The other tools follow the general rule, considering the irrigation volume and nitrate concentration.
<i>Nsom</i>	SOM mineralisation—nitrogen released from soil organic matter decomposition. In Digifert, it is based on SOM content and a texture-dependent coefficient. In Fert_Office, it depends on soil texture, SOM content and C/N ratio. FaST Navigator estimates it based on SOM content, soil humidity and soil texture. In PLANET and MANNER, N from SOM mineralisation is included into soil N supply index. In the Bulgarian tool, SOM mineralisation is not a separate term but is embedded within the efficiency coefficient (Nk), which can decrease the requirement when SOM content is above a certain threshold.

Table 4 (continued)

Symbol	Description
<i>Nleach</i>	Nitrogen leaching—nitrate lost below the root zone, added to the balance as an output. In Fert_Office, it is estimated as a function of winter rainfall and soil mineral N content. In grano.net, it is related to winter rainfall rate. PLANET and MANNER estimate it considering soil type, historical rainfall and temperature at a monthly timescale. FaST Navigator considers agro-climatic zones, seasonal and annual rainfall, and soil drainage characteristics. Overseer estimates N leached as from urine patches. In FertiliCalc, leaching is not a separate term but is included within the combined loss fraction (n).
<i>Nvol</i>	Ammonia volatilisation—gaseous NH ₃ losses from the soil or manure surface. In PLANET and MANNER, it considers manure type, soil moisture content, wind speed, soil incorporation technique and timing. FaST Navigator varies it with crop type, fertiliser type and application mode, climate type, soil pH and CEC. TUDI considers fertiliser type, temperature, soil pH and emission coefficients for good management options. In FertiliCalc, volatilisation is not a separate term but is embedded in the combined loss fraction n.
<i>Nden</i>	Denitrification—N lost as N ₂ O or N ₂ under anaerobic soil conditions. FaST Navigator computes denitrification as an exponential function of the amount of N applied from fertilisation. TUDI computes N ₂ O emissions using the IPCC standard for direct emissions, considering fertiliser amount, type, efficiency and climate. Overseer estimates denitrification from urine-derived N. In FertiliCalc, denitrification is embedded in the combined loss fraction n.
<i>Nimm / Pimm / Kimm</i>	Nutrient immobilisation—nutrients temporarily locked in the soil microbial biomass or fixed by clay minerals, making them unavailable to the crop. In Fert_Office, N immobilisation depends on soil texture, C/N ratio and oxygen availability; P immobilisation considers soil texture and soil CaCO ₃ content; K immobilisation and leaching consider clay content. In the Bulgarian tool, immobilisation is embedded within the efficiency coefficient (Nk) that increases the requirement for clay-rich soils.
<i>Nl</i>	Nitrogen losses from external damage—crop N losses due to external influences such as drought or flooding. This term is used only in the Czech tool and represents the only loss pathway considered by that tool.
<i>Prun</i>	Phosphorus runoff—P lost in surface runoff from manure, particulate and dissolved sources. This term is used only in Overseer, which is focused on grazed grassland systems where P losses through surface runoff from manure deposited on the field, and particulate and dissolved nutrients derived from sediment, are significant pathways.
<i>Nk / Pk / Kk</i>	Efficiency coefficient—a multiplier applied to the entire balance that increases or decreases the requirement -, used only in the Bulgarian tool. The Nk coefficient increases the requirement to account for volatilisation or immobilisation in clay-rich soils or decreases it to account for SOM mineralisation above a certain SOM content threshold. An additional soil status coefficients (Pk and Kk) adjust P and K requirements based on their soil content and soil pH, and can be greater or smaller than 1.
<i>Ie</i>	Internal nutrient efficiency—that is defined as the amount of grain produced per unit of nutrient taken up by the plant, used only in Nutrient Expert. It is incorporated in the quantitative evaluation of the fertility of tropical soils (QUEFTS) model, on which Nutrient Expert is based.
<i>n</i>	Fraction of applied N lost—a combined loss coefficient used in FertiliCalc representing the aggregate of leaching, volatilisation, and denitrification losses. For leaching estimation, total annual rainfall, rainfall during autumn and winter, soil hydrological groups and nitrate water content are considered. For NH ₃ volatilisation, soil pH, cation exchange capacity and climatic conditions are considered. The P and K formulas in FertiliCalc do not use this loss coefficient; instead the user can select different P and K input strategies (sufficiency, accumulation and maintenance at minimum or maximum yield, or maintenance when soil analysis is unavailable).

from manure (50 kg N ha⁻¹). The results plots show Pearson's correlation coefficient and the corresponding p-value.

Results

Evaluation of the NMP tools

The tools were classified into three branches and six clusters based on the degree of similarity (Fig. 1).

The first branch (I) comprises reference tables (a), the second branch (II) comprises spreadsheets (b) and local or online apps (c), while the third branch (III) comprises decision support systems (d) and advanced local or online apps (e).

The six clusters differed across tool characteristics, nutrient cycle processes and sources and input data considered (Fig. 2). Cluster a (Bulgarian tool, MEM-NAK) showed average complexity but low usability, adaptability and interoperability, reflecting its limited scope: few N cycle processes and sources,

Table 5 Soil properties of the 0–30 cm soil layer used for the case studies

Soil parameters	Unit	Value
Stones > 2 mm	g kg ⁻¹	0
Clay	g kg ⁻¹	194
Silt	g kg ⁻¹	539
Sand	g kg ⁻¹	267
Total CaCO ₃	g kg ⁻¹	0
Active CaCO ₃	g kg ⁻¹	0
Organic C	g kg ⁻¹	10.3
Organic matter	g kg ⁻¹	17.7
Total N	g kg ⁻¹	1
pH		6.5
C/N		10.8
CEC Metson	cmol kg ⁻¹	9.7
CEC saturation	%	99
Bulk density	g cm ⁻³	1.3
Available P (Olsen)	ppm of P	30
Exchangeable K	ppm of K	150

average P and K processes and sources, and a correspondingly low number of inputs required. Cluster b (LK-Düngerrechner, Czech tool spreadsheet) was the simplest group overall, combining high usability with the lowest number of processes and sources across all nutrients and the fewest inputs, which suggests a simplified approach, but with limited application. Cluster

c (PLANET and MANNER, Fert_Office, Digifert) performed at an average level across most characteristics, with high scores in N processes and sources—except for Digifert—and average P and K processes and sources—, and except for PLANET and MANNER—resulting in a moderate number of inputs and low adaptability. Cluster d (grano.net, Overseer) was the most comprehensive group, achieving high usability, adaptability and interoperability, supported by the highest number of processes and sources for all nutrients and the greatest number of inputs considered. Cluster e (Fast Navigator, TUDI, FertiliCalc) was characterised by high complexity and adaptability, driven by a high number of N processes and sources but low P and K processes and sources. An exception was TUDI that considered a moderate number of processes and sources for P and K and a relatively high amount of input data. Finally, cluster f (Nutrient Expert, Pro Planta) combined high usability with average complexity, adaptability and interoperability; it considered high numbers of P and K processes and sources, while N processes and sources varied between tools, being low for Nutrient Expert and average for Pro Planta, with a moderate total input count.

Table 6 Crops and farming systems used for the case studies

	Type of farming system	
	Arable	Crop, livestock
Main crop	Wheat (for cattle feed)	
Target yield at 15% moisture	7 tons ha ⁻¹	5 tons ha ⁻¹
Key-dates	Sowing: 15th October; Harvesting: 15th July	
Key-depths	Root depth: 60 cm; Ploughing depth: 30 cm	
Irrigation	no	
Average annual temperature	12.5 °C	
Total annual rainfall	800 mm	
Winter rainfall (1st Oct–1st March)	400 mm	
Straw management	Left on the field	Exported
Preceding crop	Rape seed (4 tons ha ⁻¹) Fertilised with 140 kg N ha	Grass ley (2 years), mown + grazed
Cover crop	Phacelia / Brassica terminated in early October	
Manure	Not applied	15 tons ha ⁻¹ Farmyard manure (5.5 kg N/t) spread in September in the previous year

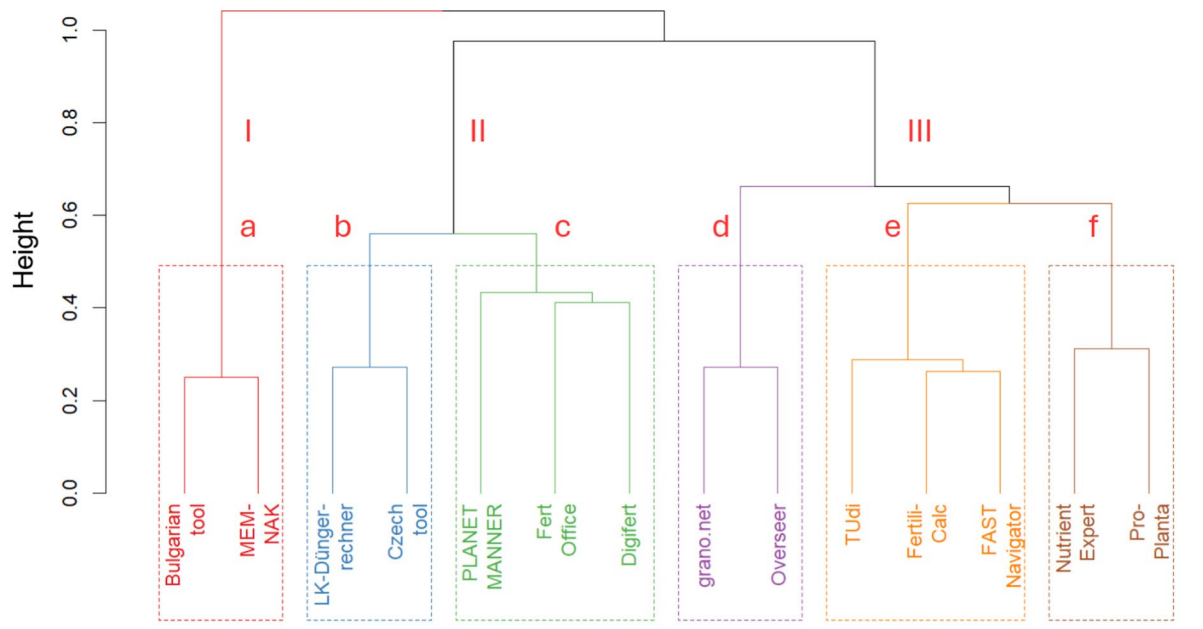


Fig. 1 Dendrogram of the characteristics of NMP tools resulting from the cluster analysis

Nutrient recommendations

All tools provided a fertiliser requirement for N and P, and most of them also regarding K. In general, the recommendations were relatively stable between tools for nitrogen (coefficient of variation of 20%), while they varied more for phosphorus (coefficient of variation of 60%) and potassium (coefficient of variation of 70%) (Fig. 3). Specifically, in the arable system case, MEM-NAK recommended the highest amount of N (217 kg N ha^{-1}), while ProPlanta recommended the lowest amount (115 kg N ha^{-1}) (Fig. 3). A similar range was observed for P recommendations: from 6 kg P ha^{-1} for ProPlanta to 119 kg P ha^{-1} for MEM-NAK, while for K recommendations the range was higher: from 0 kg K ha^{-1} for ProPlanta to 140 kg K ha^{-1} for MEM-NAK. Compared to the arable system, the overall nutrient amounts required for the livestock system were reduced by approximately 30% and 40% for N and P respectively, and increased by approximately 25% for K (Fig. 3). In the livestock system, the highest N dose recommendation was suggested by PLANET and MANNER (150 kg N ha^{-1}) and the lowest by the Bulgarian tool (72 kg N ha^{-1}). The highest P recommendation was from MEM-NAK (62 kg P ha^{-1}) and the lowest from PLANET and

MANNER (3 kg P ha^{-1}). The highest K recommendation was from FertiliCalc (172 kg K ha^{-1}) and the lowest from PLANET and MANNER (0 kg K ha^{-1}).

Concerning the classification of the tools, only the cluster *b* (LK-Düngerrechner and Czech tool) suggested similar nutrient recommendations for N and P, with differences lower than 20 kg ha^{-1} .

Overall comparison

Figure 4 highlights how the sum of characteristics, inputs considered and processes of N in NMP tools are positively correlated between them (panels (a), (b), and (d), $r=0.78\text{--}0.94$, $p<0.001$). Panels (c) and (f) show the negative correlation between the amount of input data or N processes and N dose recommendations ($r=-0.70$ and -0.63 , respectively). The sum of characteristics and N dose recommendations (panel e) are not correlated ($r=-0.39$, $p=0.191$). The Bulgarian tool is a consistent outlier across all panels and was excluded from relevant statistical analyses for N dose recommendations.

Discussion

Characteristics and adoption of NMPs

Classifying the 14 analysed NMP tools into six groups highlighted their structural differences and similarities, distinguishing simple and more complex tools based on characteristics evaluated. However, the classification did not fully correspond to tool type (spreadsheet, local app, online app): the least advanced tools were printed tables or manuals, while advanced local apps and digital decision support systems achieved the highest levels of complexity. Some clusters reflected the evolution of NMP tools. For example, the FertiCalc local app was used to develop part of the Fast Navigator and TUDI tools, explaining their classification within the same group.

The number of processes included in the various tools was much higher for N, as P and K were described in a much more simplistic way. This is partly due to the greater complexity of the N cycle and its more numerous loss pathways, but also the greater attention that N fertilisation has received from both science and policy. As EU policy and particularly the Nitrates Directive stimulated the development of NMP tools, it emerges that policy may promote tools that bridge complex scientific knowledge with practical field-level questions. Indeed, Raffa et al. (2025) noted that policy is the primary driver for farmers to adopt NMP tools by supplying economic incentives, but also by ensuring administrative certifications.

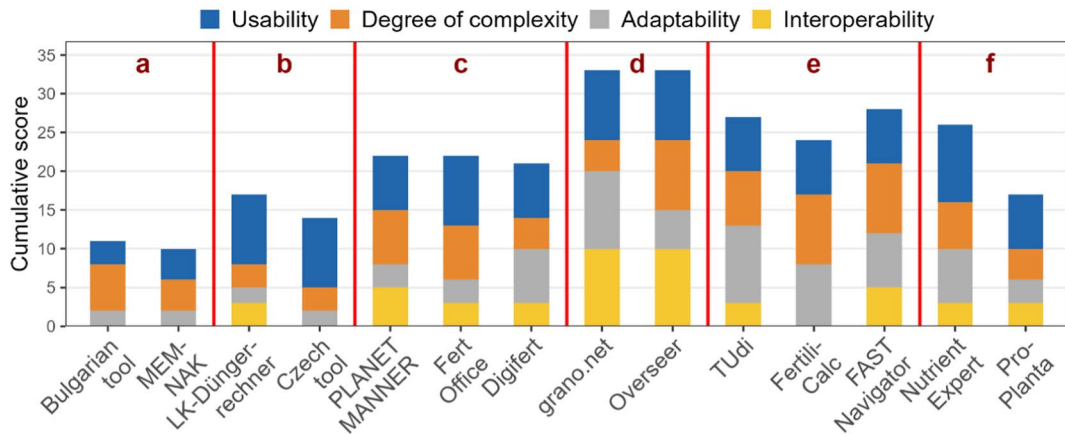
Our results showed that the number of processes involved and inputs considered was positively correlated with the sum of characteristics (Fig. 4), confirming that input demand reflects tool sophistication. Ravier et al. (2016) has identified discrepancies between the complexity (for example, the number of processes taken into account when estimating nutrient requirements) and the applicability (for example, not taking into account the nutrient requirements of new crop varieties) of NMP tools; consequently, farmers may prefer simple tools to more complex ones, particularly those with limited digital skills. Printed tables and spreadsheets were most widely used in the Czech Republic, Hungary, and Italy (Klages et al. 2022). In United Kingdom, the adoption rate of the PLANET and MANNER software was estimated at 13% (DEFRA 2025), while the global adoption rate

of Nutrient Expert was estimated at 5% (Sida et al. 2023). These adoption rates should be interpreted cautiously because sampling frames and adoption definitions differ between studies. Despite substantial efforts in developing tools with a high degree of complexity, adaptability and interoperability, most end users prioritise simplicity and usability above other characteristics.

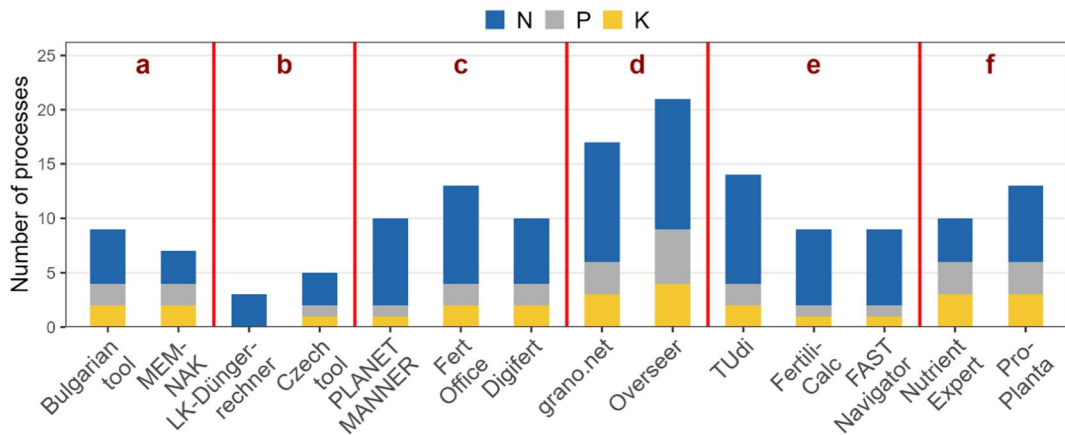
Based on these findings and previous studies on adoption (Raffa et al. 2025; Jouini et al. 2025), three practical recommendations emerge to enhance the usability and uptake of NMP tools. First, tool designers should adopt a tiered architecture, in which novice users can obtain a reliable recommendation with minimal inputs and well-chosen default values, while advisors and agronomists can access advanced modules to refine the calculation. Second, interoperability with farm management information systems, soil and weather databases, and satellite-derived indices should be prioritised to reduce data entry burdens, which represent one of the most cited adoption barriers (Munz et al. 2020; Jouini et al. 2025). Third, sustained engagement with end users through multi-actor co-development processes and continuous training is essential to build trust and ensure that recommendations are perceived as locally relevant (Rossi et al. 2014). Without these elements, even technically excellent tools risk remaining underused.

The tools analysed here represent only some of the European NMP tools available, and several other widely adopted tools from countries with very active nutrient management programmes share the mass balance framework adopted in our study. In France, AzoFert® (Machet et al. 2017) and its predecessor Azobil® apply a dynamic predictive balance sheet and have been incorporated into the official frameworks used by the regional Nitrate Groups under the EU Nitrates Directive (Ravier et al. 2016). In Germany, N-Expert (Fink and Scharpf 1993) represents the reference DSS for field vegetables, with explicit modelling of crop N uptake, SOM mineralisation, crop residues mineralisation and unavoidable losses. In the Netherlands, NDICEA (Van der Burgt et al. 2006) simulates nitrogen dynamics on a weekly time step and is used in both organic and conventional arable farming. In Belgium, the N-Index expert system (Geypens et al. 1994) has long supported nitrogen recommendations in Flanders, while in Wallonia AzoFert® has been adapted and validated by the

a) Characteristics of NMP tools



b) Number of processes considered



c) Number of inputs considered

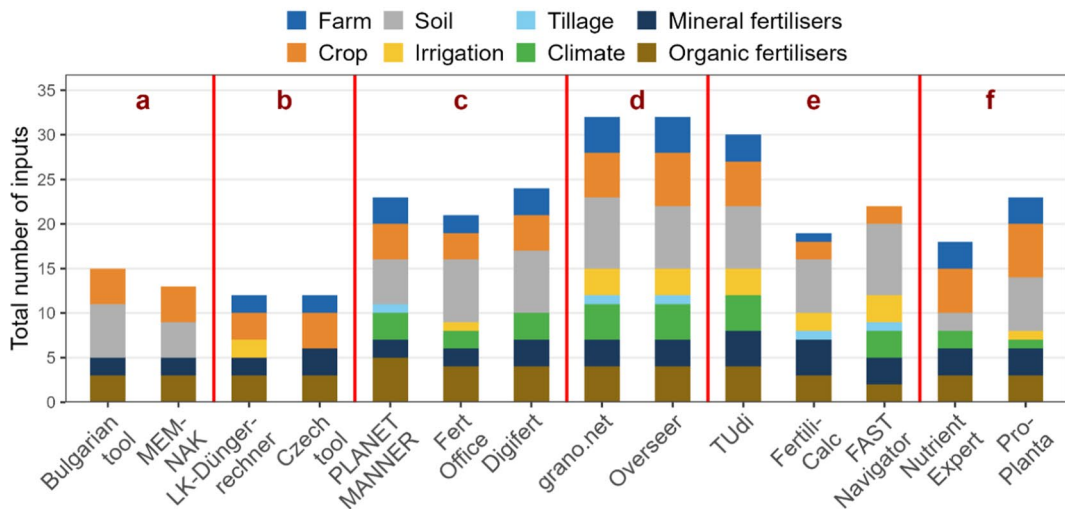


Fig. 2 Comparison of 14 NMP tools across the six groups (a–f) identified by cluster analysis. **a** Cumulative scores for usability, degree of complexity, adaptability, and interoperability (each theme on a 0–10 scale). **b** Number of nutrient cycle processes and sources considered in the calculation of the fertiliser requirement for N, P, and K. **c** Total number of inputs considered by each NMP tool for the livestock case study, divided by categories (farm, crop, soil, irrigation, tillage, climate, mineral fertilisers, and organic fertilisers)

REQUASUD laboratory network (Abrás et al. 2013). These tools are conceptually comparable to the most comprehensive clusters identified in our analysis (clusters d and e), since they incorporate dynamic process simulation of SOM mineralisation, crop residue effects, and nutrient losses. Including them would not change our overall classification logic, but reinforces the conclusion that NMP tool development across Europe is heterogeneous and shaped by national regulatory contexts and research traditions.

Nutrient recommendations

The most important input data required to run NMP tools concerned soil properties, crop type and fertiliser management (Fig. 2, Table S.I. 1–3). Almost all NMP tools (except LK-Düngerrechner and the Czech tool) consider soil properties as primary input data. Although soil nutrient content, soil structure, pH and SOM content are fundamental to tailored fertilisation planning (Higgins et al. 2023), this information is not always available to farmers at the field scale. This could affect the reliability of the results relating to fertiliser recommendations, suggesting that policies could encourage more widespread soil sampling, at least in areas where such sampling is currently limited or absent.

Crop data ranks second in terms of number of inputs, and crop uptake is the main output of the balance and the item with the highest value in all balance computations. Crop uptake estimates differed numerically and in the estimation method. For example, in FertiCalc and Fast Navigator, the percentage of crop residues left on the field affects crop nutrient requirements. Export of straw residues leads to higher K recommendations, as the majority of plant K resides in the stalks (Chuan et al. 2013). The same tools also estimate root system nutrient uptake which increases crop uptake even though roots remain in the soil after harvest. Regarding climate-based yield adjustments,

Nutrient Expert corrects based on risk scenario, grano.net uses seasonal weather forecasts, and FertiCalc and Fast Navigator include a coefficient of variability for the target yield. With climate change, interannual variability will have a greater impact on crop yields (Zhang et al. 2022) and nutrient cycling (Chiriak et al. 2025a), thus its inclusion in NMP tools might grow in importance. Moreover, a spatial coefficient of variability of up to 30% for crop N uptake at field scale is related to variation in soil properties (Chiriak et al. 2025b). Nevertheless, only the most advanced NMP tools consider the spatial variability: grano.net includes NDVI maps of the crop and Overseer incorporates soil maps.

Using the same case studies but with national guidelines, the NMP tools analysed here recommended similar average N applications in the arable system (161 kg N ha⁻¹ vs. 159 kg N ha⁻¹ in Jordan-Meille et al. 2023) but slightly higher average N dose recommendation for the livestock system (113 kg N ha⁻¹ vs. 88 kg N ha⁻¹ in Jordan-Meille et al. 2023). Considering the standard deviation of approximately 30 kg N ha⁻¹, these recommended application rates are within the same range. Therefore, the N dose recommendations align with the national guidelines even if there are some differences: e.g. PLANET recommended +20 kg N ha⁻¹ for the arable system and +30 kg N ha⁻¹ for the livestock system whereas Nutrient Management Guide and Digifert suggested –20 kg N ha⁻¹ and –40 kg N ha⁻¹ than national guidelines for integrated crop production. Other macronutrients showed large variation in nutrient recommendations, with a coefficient of variability of almost 60% for P and 70% in K. This reflects large differences in crop P and K concentrations (Jensen & Norton 2012), thresholds for soil nutrient supply (Jordan-Meille et al. 2012), available nutrients supplied from organic fertilisers (Almeida et al. 2019), and from previous crop residues (Torma et al. 2018), that affect the final mineral fertilisation recommendations.

In general, more complex N management tools requiring more input data and modelling more N processes, tend to recommend lower N doses (Fig. 4). Simpler tools appear to overestimate N needs because they omit key N supply pathways such as mineralisation and residual N from previous crops. However, failing to account for N losses (leaching, denitrification, volatilisation) would have the opposite effect, leading to an underestimation. Consequently, the

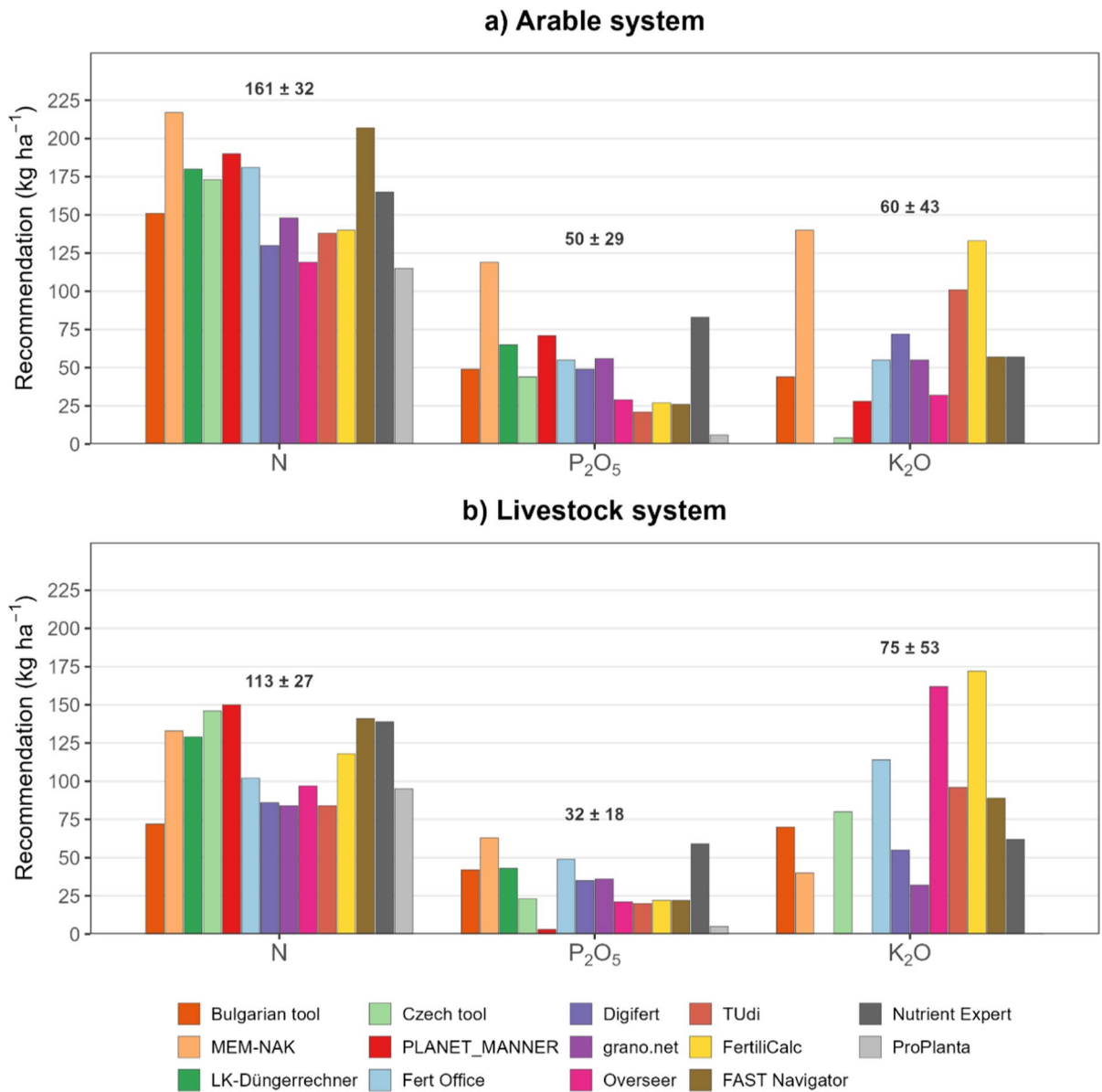
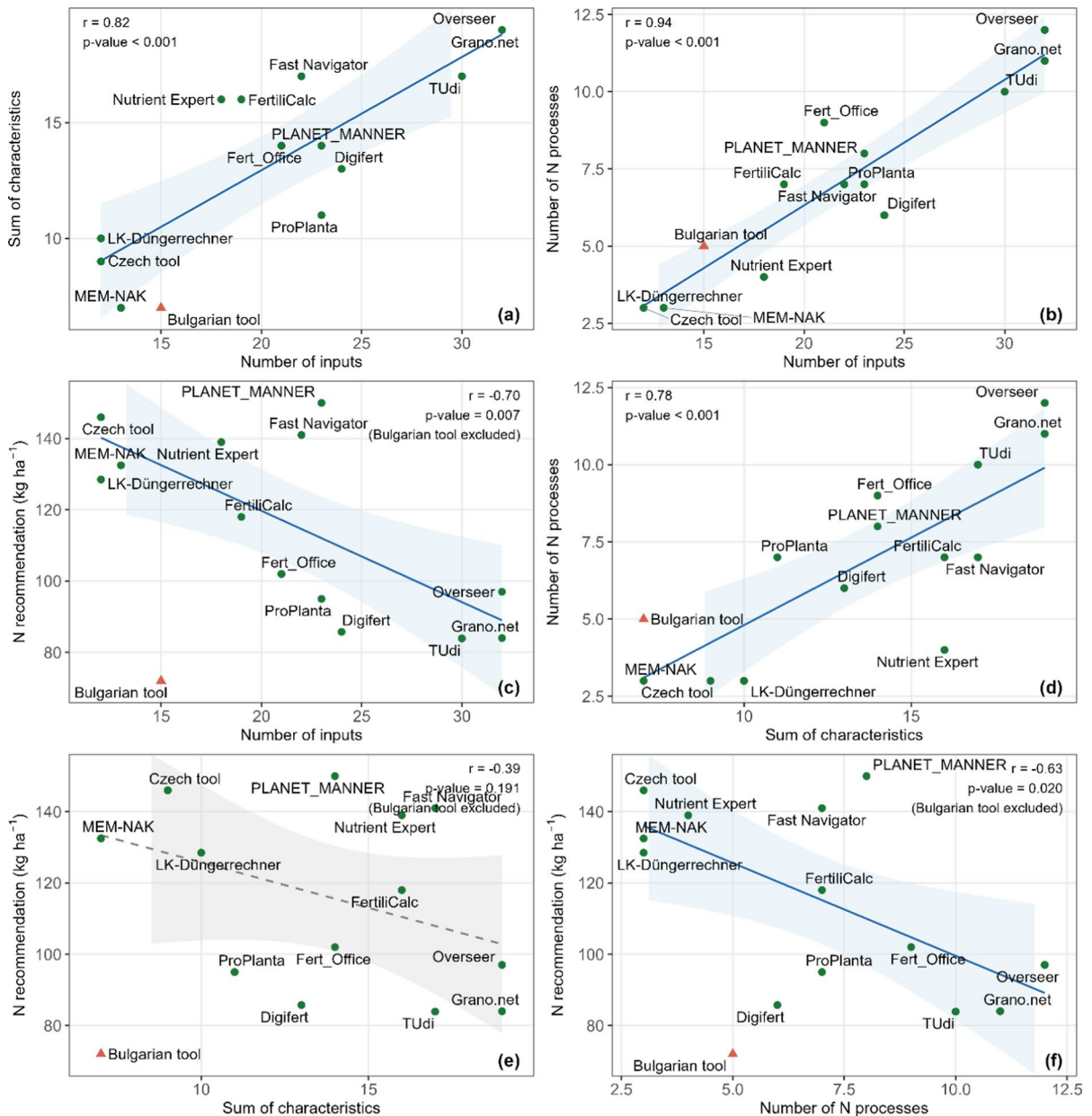


Fig. 3 Nutrient recommendations of the NMPs for the (a) arable and (b) livestock systems. The mean and standard deviation for each nutrient are shown above the bar plots

recommendations of the simpler tools depend on the relative magnitude of the inputs and losses that are omitted. Nutrient recommendations were determined more by the number of N processes modelled than the overall score of characteristics of the tool, in contrast to earlier research (Jordan-Meille et al. 2023). Thus, the choice of NMP tool can meaningfully influence N dose recommendations. Furthermore, the evaluation method based on presence/absence criteria is

limited to certain aspects of NMP tools and does not consider their importance to the end user. Thus, we limited our analysis to what NMP tools ‘offer’, leaving the choice of tool to the end user.



▲ Bulgarian tool: shown in all panels but excluded from r and p-value in (d) and (e) ● Other NMP tools Shaded band = 95% confidence interval of linear trend | All 6 pairs shown | dashed grey line = non-significant trend (p ≥ 0.05)

Fig. 4 Correlation plots showing the relationship between the number of inputs and the sum of characteristics (a), the number of N processes (b) and the recommended N dose in the livestock system (c), and between the number of processes of

N and the sum of characteristics (d), and between the recommended N dose in the livestock system and the sum of characteristics (e) and the number of processes of N (f)

Conclusions

Users who need comprehensive recommendations (e.g. researchers and specialist advisors) are

best supported by decision support systems considering a high number of nutrient cycle processes and requiring the most input data (e.g. grano.net and Overseer). Their more detailed mass balances

tended to produce lower, arguably more refined, N fertiliser recommendations, although not all are available free of charge; TUDI and Fast Navigator represent valid free alternatives. By contrast, moderately complex tools such as PLANET and MANNER, Fert_Office, and Digifert offer a practical compromise between scientific rigour and ease of use, making them well suited for technicians and informed farmers, with recommendations generally consistent with national guidelines (Jordan-Meille et al. 2023). Although simpler, more accessible tools, require fewer inputs and consider only essential processes (e.g. reference tables such as MEM-NAK and the Bulgarian tool), they produced the widest range of recommendations and demonstrated limited adaptability. In general, more comprehensive tools produce lower, presumably more accurate N dose recommendations, while simpler tools risk over-fertilisation with potential environmental consequences. Greater efforts from scientists are required to estimate processes and sources more accurately when making P and K recommendations, and on the part of policymakers to adopt clear regulatory frameworks to ensure their implementation.

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Data availability The datasets generated and analysed during the current study are available as supplementary information.

Declarations

Competing interests B.V. and M.R. are employees of Horta s.r.l., the company that developed grano.net.

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References

- Abras M, Goffart J-P, Destain J-P (2013) Perspectives d'amélioration du conseil prévisionnel de fertilisation azotée à la parcelle en Wallonie par l'utilisation du logiciel AzoFert®. *Biotechnol Agron Soc Environ* 17(1):215–220
- Almeida RF, Queiroz IDS, Mikhael JER, Oliveira RD, Borges EN (2019) Enriched animal manure as a source of phosphorus in sustainable agriculture. *Int J Recycling Org Waste Agric* 8(Suppl 1):203–210
- Chiriac OP, De Petris S, Zavattaro L, Cammarano D (2025a) Exploring the spatial variability of nitrogen balance and its relationship with soil properties. *Precision Agric* 26:100. <https://doi.org/10.1007/s11119-025-10294-6>
- Chiriac OP, Pittarello M, Moretti B, Zavattaro L (2025b) Factors influencing nitrogen derived from soil organic matter mineralisation: results from a long-term experiment. *Agric Ecosyst Environ*. <https://doi.org/10.1016/j.agee.2024.109444>
- Chuan L, He P, Jin J, Li S, Grant C, Xu X, Qiu S, Zhao S, Zhou W (2013) Estimating nutrient uptake requirements for wheat in China. *Field Crop Res* 146:96–104. <https://doi.org/10.1016/j.fcr.2013.02.015>
- Cooper J, Carmichael A, Stockdale E, Quemada M, Thorup-Kristensen K, van der Burgt GJ, Scholberg J (2009) Inventory of existing decision support tools for farm level N management in the EU. *Toolbox of cost-effective strategies for on-farm reductions in N losses to water: WP 1 deliverable, 1*
- DEFRA (2025) Accredited official statistics—Nutrient management. <https://www.gov.uk/government/statistics/farm-practices-survey-february-2025/nutrient-management>
- EIP-AGRI Service Point (2022) Digital tools for sustainable nutrient management. <https://ec.europa.eu/eip/agriculture/en/focus-groups/digital-tools-sustainable-nutrient-management.html>
- Finch H (2005) Comparison of distance measures in cluster analysis with dichotomous data. *J Data Sci* 3:85–100
- Fink M, Scharpf HC (1993) N-expert—a decision support system for vegetable fertilization in the field. *Acta Horticult* 339:67–74. <https://doi.org/10.17660/ActaHortic.1993.339.6>
- Galili T (2015) dendextend: an R package for visualizing, adjusting and comparing trees of hierarchical clustering.

- Bioinformatics 31(22):3718–3720. <https://doi.org/10.1093/bioinformatics/btv428>
- Gallardo M, Elia A, Thompson RB (2020) Decision support systems and models for aiding irrigation and nutrient management of vegetable crops. *Agric Water Manag* 240(April):106209. <https://doi.org/10.1016/j.agwat.2020.106209>
- Geypens M, Vandendriessche H, Bries J, Hendrickx G (1994) Experience with a nitrogen-index expert system: A powerful tool in nitrogen recommendation. *Commun Soil Sci Plant Anal* 25(9–10):1223–1238. <https://doi.org/10.1080/00103629409369111>
- Higgins S, Keesstra SD, Kadziuliene Ž, Jordan-Meille L, Wall D, Trinchera A, Spiegel H, Sandén T, Baumgarten A, Jensen JL, Hirte J, Liebisch F, Obor S, Löw P, Kuka K, De Boever M, D’Haene K, Madenoglu S, Özcan H, Chenu C (2023) Stocktake study of current fertilisation recommendations across Europe and discussion towards a more harmonised approach. *Eur J Soil Sci* 74:5. <https://doi.org/10.1111/ejss.13422>
- Jensen T, Norton R (2012) Wheat grain nutrient concentrations: wide-scale average values may not be adequate for field nutrient budgets. *Better Crops Plant Food* 96(3):24–25
- Jordan-Meille L, Denoroy P, Dittert K, Cugnon T, Quemada M, Wall D, Bechini L, Marx S, Oenema O, Reijneveld A, Liebisch F, Diedhiou K, Degan F, Higgins S (2023) Comparison of nitrogen fertilisation recommendations of West European Countries. *Eur J Soil Sci* 74:6. <https://doi.org/10.1111/ejss.13436>
- Jordan-Meille L, Rubæk GH, Ehlert PAI, Genot V, Hofman G, Goulding K, Recknagel J, Provolò G, Barraclough P (2012) An overview of fertilizer-P recommendations in Europe: Soil testing, calibration and fertilizer recommendations. *Soil Use Manag* 28(4):419–435. <https://doi.org/10.1111/j.1475-2743.2012.00453.x>
- Jouini M, Raffa DW, Delin S, Dirnèna B, Trinchera A, Kasparinskis R, Demir Z, Baratella V, Erdal Ü, Räsänen TA, Hanegraaf M (2025) Scaling decision-support tools to promote soil health: insights from stakeholders in Europe and Turkey. *Eur J Soil Sci* 76:e70113. <https://doi.org/10.1111/ejss.70113>
- Klages S, Heidecke C, Buis E, Elings L, Eory V, D’Haene K, Higgins S, Hofman G, Luostarinen S, Nesheim I, Provolò G, Salo T, Spiegel A, Surdyk N (2022) Aspects of implementing Farm to Fork nitrogen targets with tools, measures and policy instruments across Europe [Conference presentation]. In: International interdisciplinary conference on land use and water quality: agriculture and the environment, Maastricht, Netherlands
- Lucas, A. (2024). *amap: another multidimensional analysis package_*. R package version 0.8–20, <https://CRAN.R-project.org/package=amap>
- Machet J-M, Dubrulle P, Damay N, Duval R, Julien J-L, Recous S (2017) A dynamic decision-making tool for calculating the optimal rates of n application for 40 annual crops while minimising the residual level of mineral n at harvest. *Agronomy* 7(4):73. <https://doi.org/10.3390/agronomy7040073>
- Munz J, Gindele N, Doluschitz R (2020) Exploring the characteristics and utilisation of Farm Management Information Systems (FMIS) in Germany. *Comput Electron Agric* 1:70. <https://doi.org/10.1016/j.compag.2020.105246>
- Nicholson FA, Bhogal A, Chadwick D, Gill E, Gooday RD, Lord E, Misselbrook T, Rollett AJ, Sagoo E, Smith KA, Thorman RE, Williams JR, Chambers BJ (2013) An enhanced software tool to support better use of manure nutrients: MANNER-NPK. *Soil Use Manag* 29(4):473–484. <https://doi.org/10.1111/sum.12078>
- Öborn I, Edwards AC, Witter E, Oenema CO, Ivarsson K, Withers PJA, Nilsson SI, Richert Stinzing A (2003) Element balances as a tool for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context. *Eur J Agron* 20(1–2):211–225. [https://doi.org/10.1016/S1161-0301\(03\)00080-7](https://doi.org/10.1016/S1161-0301(03)00080-7)
- R Core Team (2026) R: A language and environment for statistical computing (Version 4.5.3). R Foundation for Statistical Computing. <https://www.R-project.org>
- Raffa DW, Räsänen TA, Trinchera A, Jouini M, Delin S, Kasparinskis R, Dirnèna B, Demir Z, Erdal Ü, Hanegraaf M (2025) Agricultural decision support tools in Europe: what kind of tools are needed to foster soil health? *Eur J Soil Sci* 76:2. <https://doi.org/10.1111/ejss.70097>
- Ravier C, Jeuffroy MH, Meynard JM (2016) Mismatch between a science-based decision tool and its use: The case of the balance-sheet method for nitrogen fertilization in France. *NJAS Wageningen J Life Sci* 79:31–40. <https://doi.org/10.1016/j.njas.2016.10.001>
- Rossi V, Salinari F, Poni S, Caffi T, Bettati T (2014) Addressing the implementation problem in agricultural decision support systems: the example of vite.net®. *Comput Electron Agric* 100:88–99. <https://doi.org/10.1016/j.compag.2013.10.011>
- Sida TS, Gameda S, Chamberlin J, Andersson JA, Getnet M, Woltering L, Craufurd P (2023) Failure to scale in digital agronomy: An analysis of site-specific nutrient management decision-support tools in developing countries. *Comput Electron Agric*. <https://doi.org/10.1016/j.compag.2023.108060>
- Torma S, Vilček J, Lošák T, Kužel S, Martensson A (2018) Residual plant nutrients in crop residues - an important resource. *Acta Agric Scand Sect B Soil Plant Sci* 68(4):358–366. <https://doi.org/10.1080/09064710.2017.1406134>
- Van Burgt GJHM, Oomen GJM, Habets ASJ, Rossing WAH (2006). The NDICEA model, a supporting tool for nitrogen management in arable farming. Evaluation of two integrated and two organic crop rotations. *NJAS Wageningen J Life Sci* 53(3–4):263–275. [https://doi.org/10.1016/S1573-5214\(06\)80008-1](https://doi.org/10.1016/S1573-5214(06)80008-1)
- Wickham H (2016) ggplot2: elegant graphics for data analysis (3.4.2). <https://ggplot2.tidyverse.org>
- Zhang R, Yang Y, Dang T, Zhu Y, Huang M (2022) Responses of wheat yield under different fertilization treatments to climate change based on a 35-year in situ experiment. *Agriculture* 12(9):1498. <https://doi.org/10.3390/agriculture12091498>

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